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“R-Evolution of Shapes: Sustainability, Re-Use, and New Design Paradigms”

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Exploring form and force through topology and stiffness: Tools for early sketching processes in architectural education

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Abstract

Based on the structural mechanics principle *force follows stiffness* a set of interactive computational tools for architectural and engineering education has been developed. The concept of stiffness includes topology, geometry, material properties, boundary conditions, as well as structural mechanisms of action such as tension/compression, bending, and prestressing. The theoretical underpinning draws on the concept of stress trajectories, first introduced by James Clerk Maxwell and later developed by Karl Culmann. Stress trajectories show the natural pathways through which internal forces propagate within a structure, providing both a visual and analytical framework for understanding load transfer and structural efficiency. The software *ForcePAD*, allows users to sketch lines and surfaces, in which shading intensity represents stiffness. Real-time feedback of force flow and deformation transforms classical structural theory into an intuitive and exploratory design medium. The software *pointSketch* and *ObjectiveFrame* takes departure in a successively growing topology of discrete points, where users may manipulate and investigate how stiffness affect stability and force distribution. The article discusses the pedagogical concepts behind and demonstrates their role as active design instruments within the architecture program at Chalmers. Rather than treating structural analysis as a final stage of verification, the computer tools reposition structural reasoning as a generative force in architectural design.

Keywords: architecture, structural engineering, structural design, architectural design, education, interactive, form finding, stress trajectories, flow of forces, computer tool, ForcePAD, pointSketch

1. Introduction

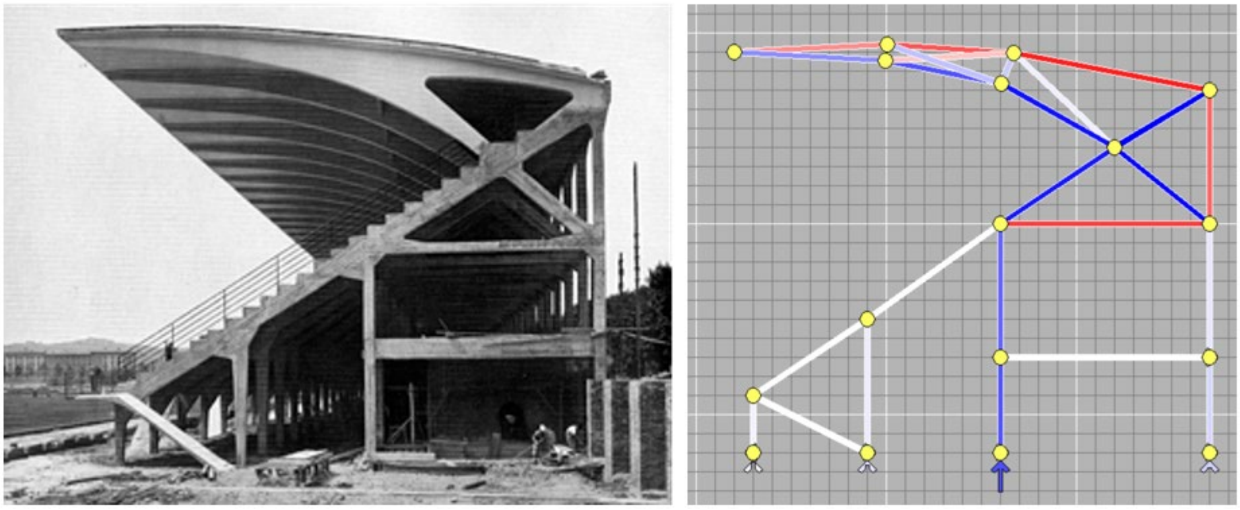

Figure 1: Florence Municipal Stadium [Ingg. Nervi & Bartoli, societa per Azioni] and an interpretation in terms of internal forces [pointSketch]

The Florence Municipal Stadium by Piero Luigi Nervi (1930-32 and 1950-51) demonstrates an exceptional synthesis of structural efficiency, spatial clarity and architectural expression, Figure 1. How can this building be a means of engaging in a dialogue with architecture students about space and structure, force and form? The dialogue brings forward the thin lines perfectly balancing compression (blue) and tension (red), how the 2-dimensional truss model could get its necessary support conditions from the 3rd dimension, how bending could be reduced thanks to the underlying stable truss action, and how bending still is visible through the different dimensions of the structural members, specifically where the spectators adds weight.

These conversations take place within the second-year structural design course for architecture students at Chalmers in Gothenburg. The example forms a part of the applied section of the course, and follows the structural typologies presented in Heino Engel's *Structural Systems* [1]: form-active, vector-active, section-active and surface-active structures. Following the previous investigation of vector-active structures (trusses), this example supports a transition to the section-active structures and the phenomenon of bending.

From the first part of the course, students have got a theoretical foundation mainly consisting of:

- The origin of forces, force resultants, and alternatives for representation
- Gravity as human experience and frame of reference, and the main shaping load for buildings
- Representations used by architects and engineers across different material and spatial dimensions
- Principles and concepts for external and internal stability of bodies and structures
- Topological ordering of structures for vertical and horizontal loading
- Topological ordering of free-form structures for arbitrary loading
- Equilibrium across different material and spatial dimensions.

Although these concepts are abstract, they are consistently demonstrated through architectural precedents and through physical and digital experiments. The ambition is not simply to teach structural calculation, but to cultivate structural intuition: an ability to recognize how force, material, geometry, and spatial intention interact from the earliest stages of design. This pedagogical ambition has driven the collaborative development of the educational software tools ForcePAD [2] and pointSketch [3] between Chalmers and Lund University. The latest step in this software development, ObjectiveFrame [4], is presented in a separate article. Similar open-source computer tools for education and with the aim to bring forward basic physical quantities and relationships in a form finding process are eQuilibrium [5], and EduBeam [6].

Architectural design is fundamentally inseparable from the design of a load-bearing structure. Decisions concerning space, light, circulation, openness, and materiality simultaneously define structural possibilities and limitations. Yet in conventional practice, structural reasoning often enters the design process too late, reducing engineering to verification rather than participation in form generation.

The software tools discussed in this article seek to address this disconnect. They support exploratory analysis of built precedents, comparison of structural concepts, and intuitive experimentation during sketch-based design processes. Rather than replacing engineering expertise, the tools provide architects with conceptual access to structural behaviour during the formative stages of design.

2. Common concepts for ForcePAD and pointSketch

The most important shared principles underlying both pointSketch and ForcePAD are:

- low thresholds
- immediate feedback
- an interaction that instantly inspires and guides new design actions.

The tools are intended to support collaborative sketch-based discussions in which all participants can contribute directly to the development of structural ideas. Low thresholds are achieved through simplified interfaces with a limited number of variables and clear visual overviews. This deliberate reduction of complexity foregrounds the underlying structural principles rather than software operation itself. Students are typically able to begin meaningful experimentation after only a brief introduction. The principle of immediate feedback is implemented differently in the two programs. ForcePAD represents stiffness as a continuous field based on plane stress behaviour, whereas pointSketch connects discrete nodes through bar elements with assigned stiffness properties.

In pointSketch, an eigenvalue solver operates continuously in the background, enabling the program to visualise structural mechanisms as systems are assembled. Free-moving nodes progressively connect until stability is achieved. This transforms stability from an abstract theoretical concept into a directly observable phenomenon. Once stable, users can investigate the influence of nodes, bars, supports, and loads by adding, removing, moving, or modifying elements and their associated stiffness values. Structural behaviour is visualised simultaneously in parallel windows representing construction and response. This immediate reciprocity between action and structural consequence is central to the pedagogical approach. Rather than analysing completed forms retrospectively, students learn to think structurally while designing.

ForcePAD enables a broader range of material and geometric investigations, although analysis occurs after the sketch has been established and within a single working environment. Together, the programs bridge intuitive sketching and structural reasoning in a manner rarely achieved in conventional engineering software.

3. ForcePAD

ForcePAD emerged from an environment of close collaboration between teachers and researchers in architecture and structural mechanics at Lund University and Chalmers University of Technology. The aim was to develop new computer-based pedagogical tools for teaching structural design to architects. One important point of departure was an interpretation of the architectural principle *form follows function*, famously articulated by architect Louis Sullivan. The principle proposes that architectural form should emerge naturally from purpose and structural logic rather than from predetermined aesthetic intentions. From the perspective of structural mechanics, this idea can be reformulated as *force follows stiffness*, since the distribution of forces is fundamentally governed by topology, geometry, material properties, boundary conditions, and mechanical behaviours such as tension, compression, bending, and prestressing.

The concept of stress trajectories, first introduced by James Clerk Maxwell and later elaborated by Karl Culmann, inspired Morten Lund and Karl-Gunnar Olsson to undertake a series of numerical simulations using the finite element method. Their aim was to explore stress patterns associated with structural tasks relevant to the architectural design process (Figures 2 and 3). In these simulations, material stiffness became the primary variable: both different stiffness distributions and directional stiffness behaviours were investigated. This raised a central question: could architects and engineers together generate form by "combing forces"?

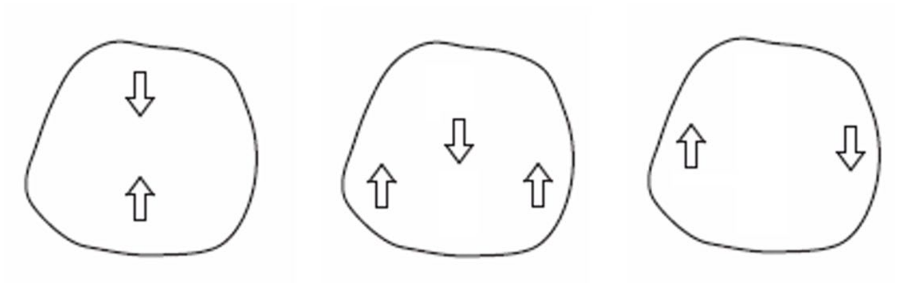

Figure 2: Structural tasks

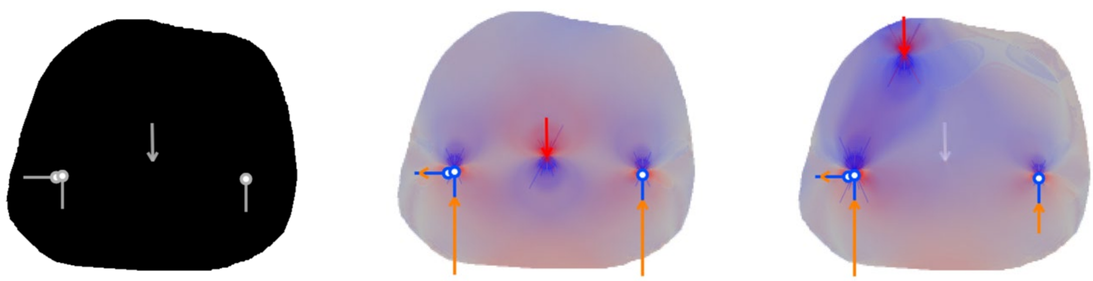

Figure 3: ForcePAD explorations of the task "spanning a space"

A third source of inspiration emerged through discussions with the architecture professor Ulf Janson at Chalmers regarding architects' sketching processes. Janson described how architects often search for space and form by drawing many light exploratory lines, gradually identifying shapes to develop further before reinforcing selected lines with greater pressure. In terms of two-dimensional continuum mechanics, the graphite deposited on the paper can be interpreted as stiffness. For a two-dimensional representation of plane stress conditions in an isotropic material, stiffness corresponds to the material stiffness, E, multiplied by the thickness, t. With the graphics editor Microsoft Paint as a conceptual model, the idea was born to create a tool that would allow users sketch or "paint" directly with stiffness. Within a few weeks, Jonas Lindemann at Lund University had taken the concept from idea to a first prototype [8], [9], [10], [11].

The ForcePAD user interface consists of three modes, Sketch mode, Physics mode and Action mode. The Sketch mode allows sketching with a pencil, predefined shapes or a paint bucket. For each of these, a size of the "stiffness" (material stiffness times thickness) can be chosen from a palette. The simple supported beam on the canvas, Figure 4, shows a rectangular shape of full stiffness with a void of no stiffness. In the Physics mode load and support have been added to the model, and in the Action mode the resulting stress patterns are shown and with ability to be manipulated. The user can toggle between different representations such as principal stress pattern, von Mieses stress representations, and the deformation of the shape, and carry out an optimisation of the beam.

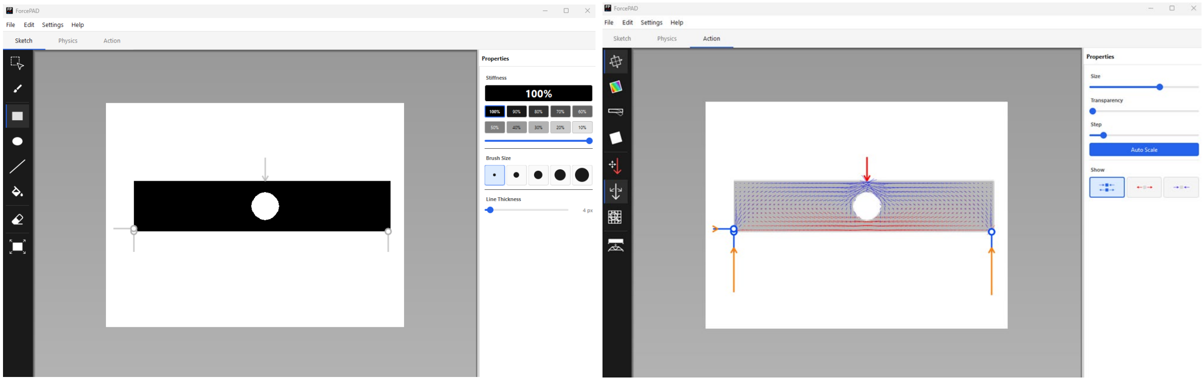

Figure 4: ForcePAD user interfaces Sketch mode and Action mode

For the second-year architect students, and in connection to surface active structures in Heino Engels typology, the students could now experiment with 2-dimesional load bearing surfaces for different structural tasks.

4. pointSketch

The software *pointSketch* was developed by Pierre Olsson in a doctoral project in 2006 [12]. Since then, it has become a central pedagogical tool within structural design education for architects at Chalmers. Although its primary use has been within architectural education, pointSketch has also been applied in engineering education. To promote engineering training in mathematical coding the software has a built-in ability to be a preprocessor for generating manipulable code for the Matlab version of CALFEM (Computer Aided Learning of the Finite Element Method) [13].

The interface consists of two parallel windows, Figure 5. The left window, *Physics mode*, is used to construct the structural model, while the right window, *Action mode*, visualises structural response. Four primary elements define the modelling environment: *Node* defines geometric locations, shaping the geometry. *Bar* creates structural connections between nodes, thus building a structure as a topology of interconnected nodes. *Support* represents external constraints, limited to lock movement in one specified direction. Through *Load* external point loads can be applied, and because gravity is the dominant load in most buildings, a dedicated *Dead load* function is also included.

When a structure is built, or during the construction process, there are three possibilities for special editing. With *Delete* built elements not dependent on other elements, can be removed. With *Move* in combination with Node, Support or Load, nodes can be moved and supports and loads can be rotated. With *Specify magnitude*, values for the different variables can be changed. For example, bar stiffness has a predefined value EA=1.

The pedagogical strength of pointSketch lies in its ability to reveal structural behaviour during the act of construction itself. When nodes are unconstrained, their movement is animated to illustrate instability. Mechanisms are visualised through zero eigenmodes, allowing students to observe the direct relationship between topology and stability. Once stability is achieved, internal force distributions are displayed, with red indicating tension and blue indicating compression.

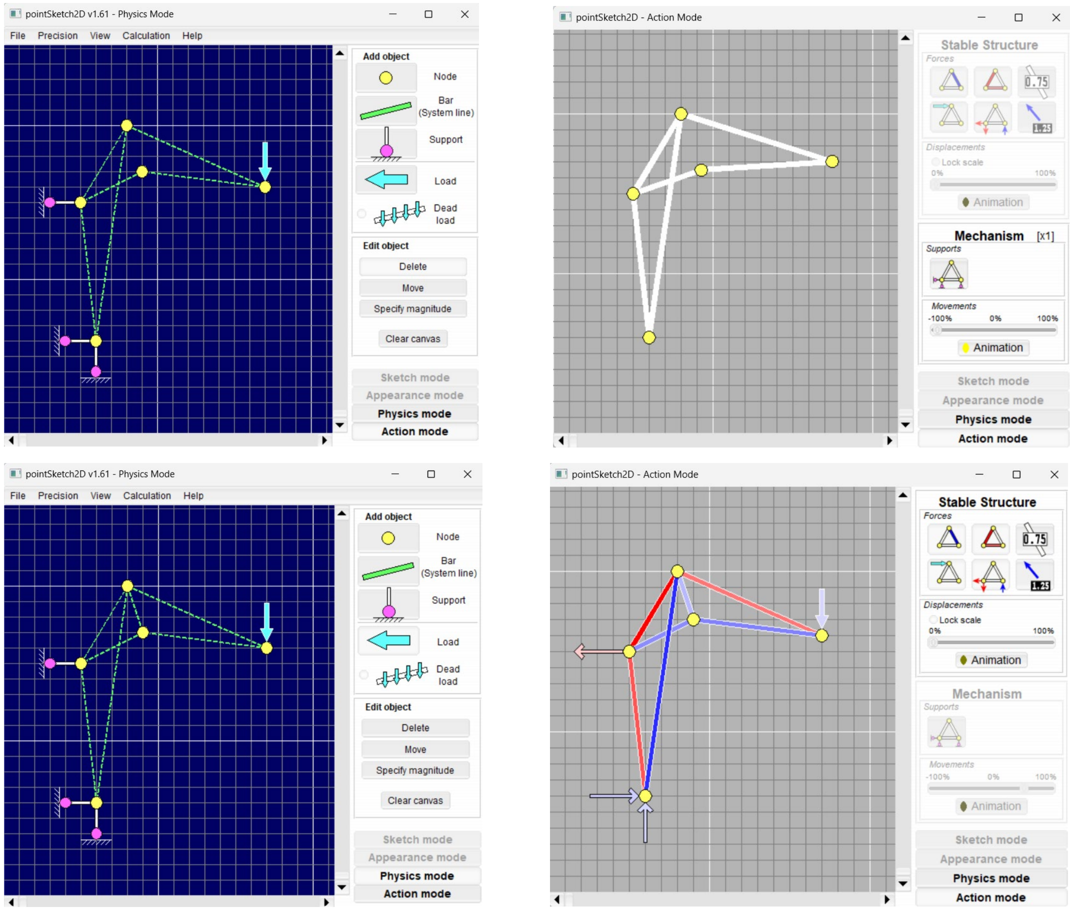

Figure 5: pointSketch user interface

The top two images of Figure 5 show a model that lacks sufficient internal or external support to be stable. A mechanism is shown, determined by the only remaining zero eigenmode. Below another bar is added, guided by the shown movement of the mechanism. The two bottom images show a stable structure with red for tension and blue for compression. Numbers showing the sizes of the forces can be added and the deformations simulated.

The student exercise shown in Figure 6 and 7 begins with a comparative study of alternative stabilisation systems. For a chosen alternative, students then investigate different geometric configurations while maintaining the same underlying topology. By moving nodes within the model, they immediately observe change in spatial expression and how force distributions migrate through the structure. This immediacy is critical. Instead of treating structural behaviour as hidden numerical output, the software makes force flow visually and spatially intelligible. Students begin to understand not only *whether* a structure works, but *how* and *why* it works.

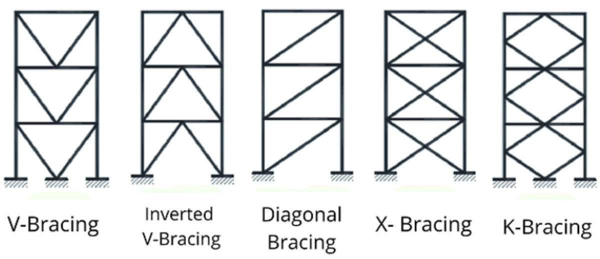

Figure 6: Structural systems for wind bracing

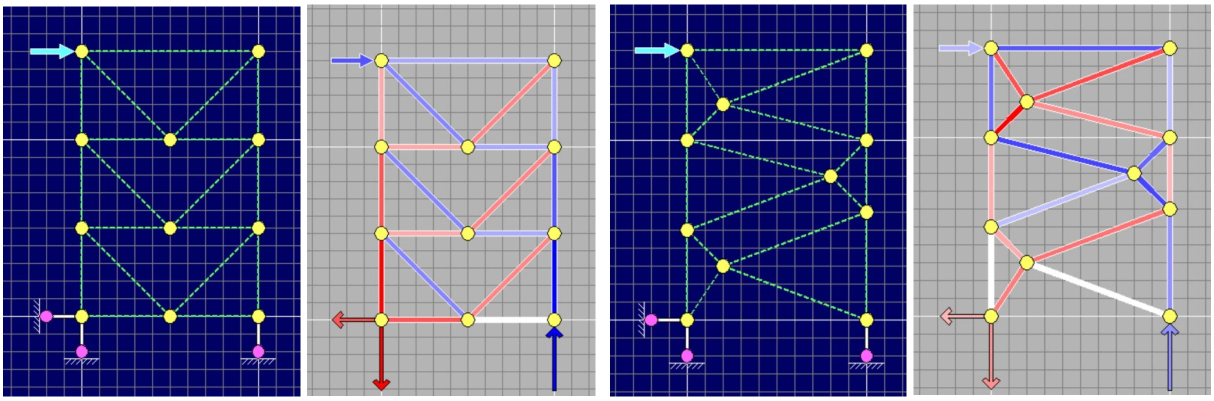

Figure 7: Topology exercise.

The final exercise in the second-year course challenges students to span a 90 cm opening using no more than 130 grams of material. Figure 8 demonstrates a case in which compression forces, leading to buckling, were correctly predicted in pointSketch, but the full buckling behaviour was insufficiently addressed. The subsequent failure analysis illustrates an important pedagogical insight: for a three-dimensional structure, two-dimensional models must be investigated for all the three projections, the three green arrows in Figure 8.

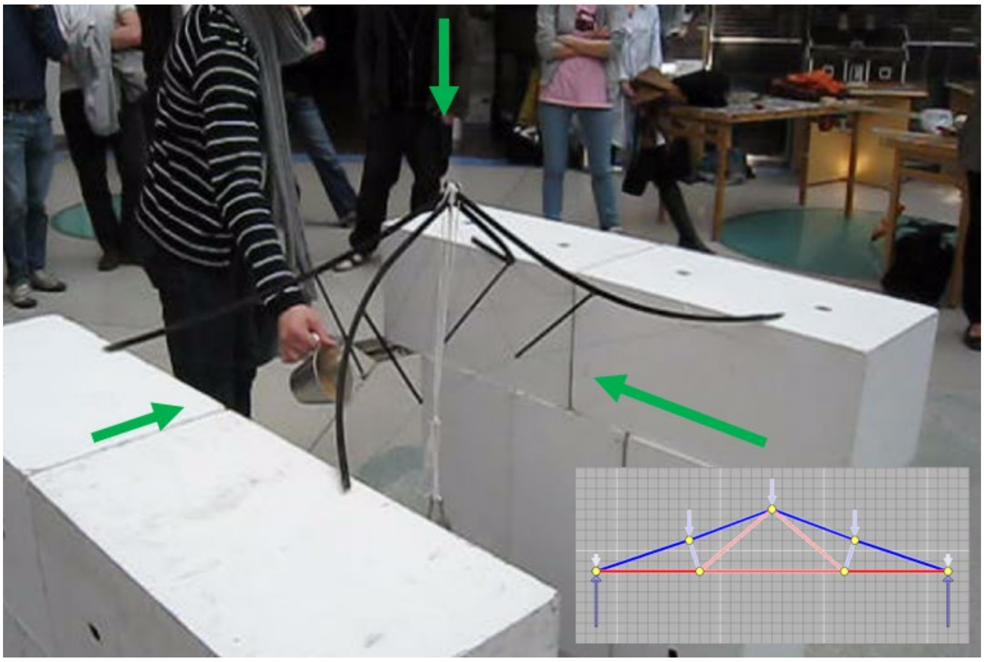

Figure 8: Buckling behavior predicted in pointSketch and shown in a physical experiment

5. Discussion and conclusions

ForcePAD and pointSketch complement one another both pedagogically and analytically. Investigations of continuous load-bearing surfaces in ForcePAD may inspire the development of materially efficient truss systems in pointSketch, while discrete topological studies in pointSketch may in turn inform spatial investigations in ForcePAD. Together, the tools establish a productive dialogue between continuum behaviour and discrete structural systems, between intuition and analysis, and between architectural and engineering modes of thinking. Figure 9 shows an experiment where the concept of a "column" is first investigated by use of ForcePAD, and articulated and evaluated in pointSketch.

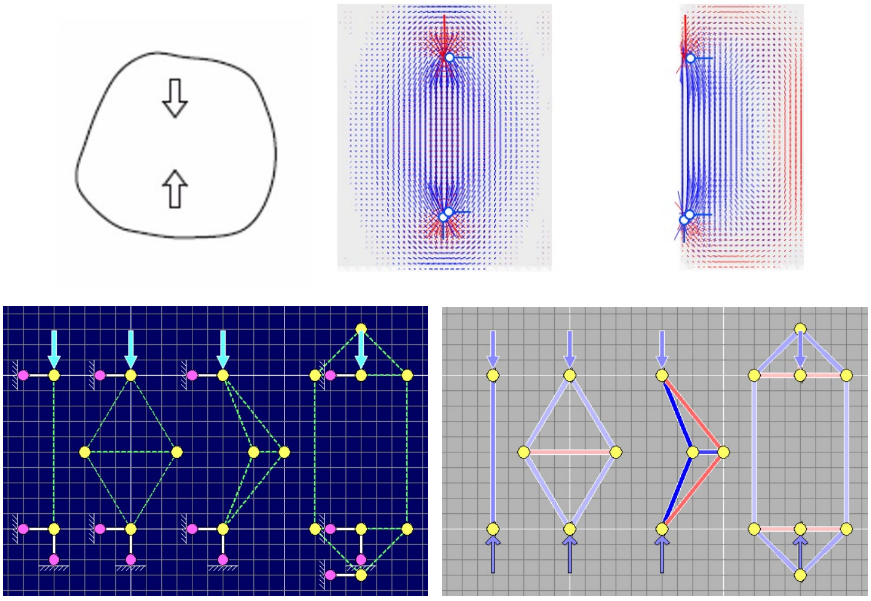

Figure 9: Comparative studies of the concept “column”

Finally, an example on the use of pointSketch in a third-year bachelor thesis project. Through their third-year bachelor's thesis, architecture students are expected to produce an independent architectural design work. Figure 10 shows input drawings where the question is about the design of the roof truss. Spatial concepts were expressed as lightness and visual connection from the attic to the lower located spaces for dining and studio work.

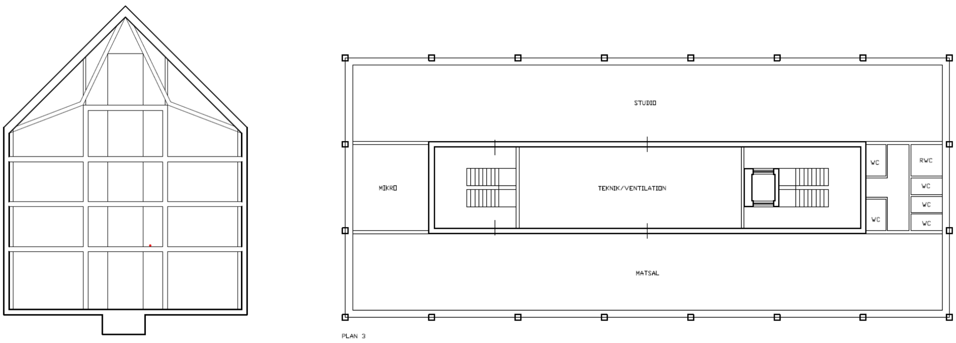

Figure 10: Input for a structural design dialogue [Alicia Borg, A3 2026].

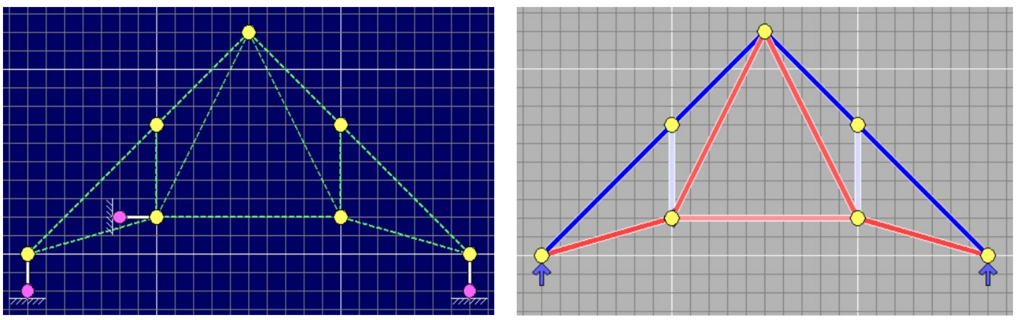

Figure 11: The first interpretation of the drawings in pointSketch.

A first interpretation of the drawing associates the structural concept of a Polonceau roof truss, already functional without redesign. The horizontal support (pink key) in the pointSketch model represents a stabilising from the 3rd dimension and linked to all roof trusses. The bending of the principal rafter could be somewhat decreased by a slight inclination of the vertical elements – what does inclined railing do for the contact with the underlying spaces? But immediately another spatial question arose. Could the top room be improved if the inclined tension straps were removed and a collar beam were added?

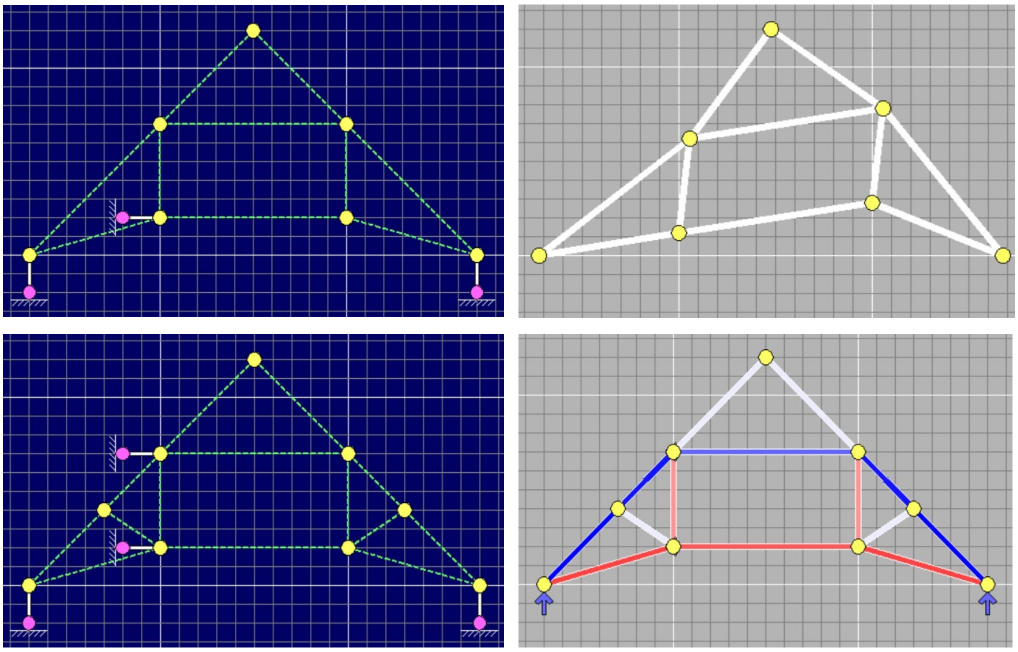

Figure 10. The redesigned roof truss analysed in pointSketch.

Immediately pointSketch shows a mechanism, Figure 10 at the top. By adding a support at the level of the collar beam, representing a cross bracing in the longitudinal direction of the building, the structure becomes stable. In the last iteration a compressed strut has been added to reduce bending and make the roof truss slenderer. On the drawing board appears the shape of a queen's post roof truss, well known as an historic archetype for roof trusses.

The two examples demonstrate how the software supports informed design dialogue in which spatial, formal, and structural considerations evolve simultaneously throughout the design process. Historical precedents such as the Polonceau truss or the queen-post truss are not treated as static typologies to imitate, but as structural concepts to reinterpret, test, and adapt.

The pedagogical principles underlying the programs aim to promote:

- informed use of historical precedents;
- understanding of the relationship between physical forces and architectural representation;
- experimental investigation of structural concepts and behaviours;
- exploration of generative structural mechanisms prior to formal resolution; and
- confidence in the design of load-bearing structures.

More fundamentally, the tools challenge the traditional separation between architectural form-making and structural reasoning. By embedding structural feedback directly within exploratory sketching processes, they enable structural behaviour to participate in the earliest stages of architectural thought.

The educational significance of this approach extends beyond technical competence. Students learn to perceive structure not as an external constraint imposed upon architecture, but as a fundamental generator of spatial quality, material expression, and architectural meaning.

The conclusion emerging from this work is therefore not simply that digital tools can support structural education, but that appropriately designed computational sketching environments can fundamentally reshape the relationship between architecture and engineering within the design process itself.

One central learning objective for the courses in structural design is that architect students should be able to conduct an initiated design dialogue with expertise in the field. This involves understanding, at a conceptual level, the possibilities and limitations of different structural systems and design approaches. Although only a small number of students continue to use the digital tools after completing the course, the experience of working with them provides valuable preparation for future collaboration with structural engineers, particularly during the early stages of the design process.

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