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Correlated physical and parametric FEM modeling for computational design and engineering workflows – a way to facilitate understanding of structural behavior.

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Abstract

This paper proposes the use of a physical structural modelling kit to enhance understanding of structural behaviour derived from equivalent computational parametric models. It has been noticed that architecture master's level students (year 5) from different global regions may lack consistent exposure to basic structural design concepts due to varying teaching approaches, therefore challenging the integration of structural analysis with computational parametric workflows. The proposed method suggests that these knowledge gaps can be facilitated with the aid of design intuition enabled by appropriate tangible modelling elements and manual application of simple loads. The integration allows students to gain structural behaviour visibility of their proposed geometries in both realms, physical and digital. This understanding is crucial especially at the concept design level, a key moment in the architectural design process where important geometric decisions have a direct influence in structural performance.

Keywords: Conceptual Design, Computational Geometry, Parametric Structural Analysis, Finite Element Modelling, Parametric Form Finding, Physical Structural Modelling.

1. Introduction

It has been noted that in the teaching of parametric computational design, integrating structural analysis requires a minimum understanding of structural behaviour. Master's level architectural students may lack consistent exposure to structural analysis, posing a challenge to the integral understanding and enjoyment of parametric geometry modelling with structural behaviour as a driver for computationally generated morphologies. At early design stages, certain geometrical decisions are crucial and directly influence structural efficiencies. This knowledge gap associated with the aim of providing geometrical structural performance at the outset of a project has motivated us to experiment with the integration of a physical modelling structural kit to facilitate visualization and understanding of structural elements, as well as the application of simple loads and their reactions on structural forms.

Within the sphere of merging physical and digital realms to foster comprehension of structural behaviour, a notable research gap exists, particularly in the realm of structural engineering education, as addressed in this paper. While some articles may provide valuable insights into the integration of physical and computational models, guidance on pedagogical approaches, educational objectives, and practical implementation strategies, they typically lack a concrete proposal for a specific physical model that can be easily adopted across various educational settings.

GraspIt is one example of a product that attempts illustrates some of the challenges [1]. Whilst the intention of the application is relevant, as one can visualise quantitative values of applied loads to a physical model, there are limitations, the key being that the kit only allows structural modelling in 2 dimensions.

With the advancements in parametric computational design and the integration of plugins that provide advanced structural analysis, such as the Finite Element Method, within the same platform, there is an opportunity to iterate through geometrical morphologies with an awareness of structural behaviour from the outset of the design process. However, there exists a significant discrepancy in the levels of understanding of structural behaviour among students of architecture from different institutions and backgrounds. Therefore, we have identified a challenge to ensure that this potential is fully understood and worked upon. While some physical models aim to provide quantitative outputs of forces, reactions, and graphs, they often lack the complexities of modelling in three dimensions. The full integration of physical and digital realms in Euclidean or other more complex parameter spaces may be a substantial undertaking. This manuscript aims to demonstrate that a qualitative evaluation of physical structural elements and forces applied to simple or complex 3D physical models can aid and enhance the understanding of their digital counterparts, paving the way for informed and potentially more efficient and complex models in both realms.

In this paper, we explore the use of the Mola Structural System [2], which offers fidelity in structural elements and connections to enhance understanding of computationally integrated structural analysis through parametric form finding and Finite Element Modelling using Grasshopper [3], Karamba3D [4] and Kangaroo [6].

This paper initiates by addressing the challenges encountered when integrating structural analysis into parametric computational geometry for master's students of architecture. It proceeds to review current research on similar approaches provided by physical structural kits and integrations, while also outlining the proposed approach. The methodology is then elaborated upon, illustrating how basic structural concepts were selected and tested through the creation of physical models and their corresponding digital counterparts. We then demonstrate how this methodology was applied in both classroom settings and workshops. Following this, an evaluation of successes and failures is conducted, identifying opportunities, and outlining next steps. These involve the construction of more complex geometries and further testing, all of which are presented in the results, discussion, and conclusion sections.

2. Background

While the existing literature on this topic is still relatively limited, there is a growing recognition of the potential benefits of such integration in facilitating students' comprehension of structural design concepts and fostering problem-solving skills.

Studies have explored the integration of physical and computational models in educational settings, highlighting the potential synergies between these two approaches. However, many of these studies have not proposed specific methodologies or products that can be readily replicated in diverse educational contexts. This gap in the literature may stem from the limitations associated with existing physical modelling tools commonly used in educational settings.

Traditional physical models often possess characteristics that hinder their effectiveness as teaching tools in structural engineering education. For instance, these models are typically large and non-portable, limiting students' hands-on experience and interaction with the structural elements. Furthermore, most existing physical models are designed to represent specific structural systems, offering little flexibility for students to explore alternative design solutions. Additionally, the inability to modify structural configurations, as such boundary conditions, in these models restricts students' ability to conduct experiments and test different design scenarios.

One example of a product that attempts to bridge the gap between physical and computational modelling is Graspit [1]. While it combines physical components with digital augmentation to visualize quantitative values of applied loads, it is constrained by certain limitations. For instance, Graspit only allows for structural modelling connected to a board, in two dimensions, similar to a computer screen, thereby limiting its applicability to three-dimensional structures such as space frames or more complex systems. Moreover, depending on the size of the class, the dimensions of the Graspit board further restrict the hands-on experience for all student, positioning it more as a demonstration tool rather than a versatile hands-on educational resource.

The limitations underscore the need for innovative solutions that address the shortcomings of existing physical modelling tools and facilitate seamless integration with computational parametric models. The proposed methodology outlined in this paper seeks to fill this gap by introducing a physical structural modelling kit that enables students to gain hands-on experience and an intuitive understanding of structural behaviour. By incorporating tangible modelling elements and manual application of loads, this approach aims to bridge the gap.

3. Methods

The objective was to perform a qualitative correlation between physical and digital models. It was assumed that such studies would take place at the early stages of a project, when the designer is still exploring structural systems. The first step was to define which platforms would be most suitable for the experiment, followed by the selection of relevant topics considered as the building blocks for understanding. Then, a correlation evaluation was conducted to ensure consistent comparisons could be made and to identify any limitations. Finally, the experiment was delivered in class and workshop.

3.1. Platform utilized

The initial study was conducted during a 3-hour lecture on structural analysis, which was the seventh lecture in a series of 11. These lectures form a theoretical module introducing students to computational design. Topics covered include principles of parametric design, trigonometry, vectors. The module progresses with geometry types, NURBS curves and surfaces and meshes followed by physics and integration of environmental and structural analysis. Finally, it concludes with optimization methods and principles of written programming.

The method was designed to be part of the structural analysis session, revisiting concepts learned in physics, such as simulating funicular forms [7]. All activities are conducted parametrically, utilizing Grasshopper, McNeel's Rhinoceros parametric engine, as the platform of choice. In the physics session, form-finding is carried out using Kangaroo for Grasshopper [6]. Given the parametric environment, we determined that Karamba3D [4], a finite element method model developed as a plugin for Grasshopper, was the most robust choice for achieving our objectives. The Finite Element Method is a numerical technique used to solve partial differential equations by subdividing complex geometries into smaller, simpler elements and approximating behaviour within each element using interpolation functions [8].

In the physical realm, the Mola Structural Kits emerged as the preferred tool due to their comprehensive features. These kits incorporate not only the necessary physical components but also provide detailed illustrated guidance through accompanying book-manual [9][10][11]. This combination of tangible elements and instructional resources streamlines the learning process, enabling students to grasp complex structural concepts with ease. By using Mola Structural Kits, students are relieved from the burden of constructing physical models themselves, allowing them to focus their attention squarely on understanding the intricacies of structural behaviour. This approach ensures that the learning experience remains centered on the core principles without being sidetracked by logistical challenges associated with physical model construction.

3.2. Definition of relevant topics

The initial approach was to select physical models that demonstrate fundamental behaviours of supports, connections, and elements such as beams and columns. Additionally, other more complex behaviours such as grids, shells, and form-finding approaches were also considered. Karamba3D components in Grasshopper have a special user interface that reflects the peculiarities of the analytical model. Some components have radio buttons, drop-down menus, and sliders with preset number ranges, etc. [5]. These settings are crucial to understand as they influence analysis results. Given the lecture's time constraints, we chose three examples: a simple beam, a grid of beams, and a shell model. With these, we would be able to address different connection types, linear and non-linear behaviour, and demonstrate forces, reactions, and deflections.

The first topic, supports, which are defined by the six degrees of freedom in space: three translations and three rotations. In Mola1, these can be illustrated using fixed and pinned connections, combining the magnetic plate, the ground connection, rigid connection magnets, and a bar (spring). The Karamba3D interface facilitates experimentation with the effects of different degrees of freedom combinations and their visualization.

Figure 1: Supports and the 6 degrees of freedom demonstrated in Karamba 3D [4] - support component and graphical representation and with Mola components and forces demonstrating reactions [9].

The second is the definition of model elements. In Karamba3D, columns, beams, trusses and springs are defined by lines and slabs and shells, by meshes. In the first example it was decided to start with a simple beam. The component ‘Line to beam’ makes the conversion into structural model element. In Mola Structural Kit 1 [2], beams are represented by the spring component. Because springs are great elements to visualise deformations (tension and compression) it was chosen as the name of the product – mola means springs in Portuguese, where the kit originated [12]. As Presenger, C. [4] mentions, for static analysis, the structure needs to be supported somehow. With the Mola Structural Kit, we could use ground connections, columns and the diagonal components to assist in forming a rectangular frame to aid the display reactions formed by different connection types.

Figure 2: Component that converts lines to beam elements in Karamba3D [4] and with Mola components assisted to create rectangular frame and demonstrate connection types, reactions and deformations [9].

The third, the definition of the loads. The load component has a drop-down menu and allows for choice of different loads to be applied when selected, each load type display its peculiar settings. The great aspect of the Mola Structural Model [2] is that one can simply apply loads with their hands and directly visualise the reactions.

Figure 3: Some loads possible in Karamba3D [4] and with Mola the loads applied manually and direct visualization of reactions, deformations and displacements [9].

One can also define materials and cross sections in Karamba3D, however if they are not identified default values are picked. One last step to define a simple beam in Karamba3D is to assemble the model, which combines all the elements previously described into a simulation model, and finally the choice of algorithm for analysis and the result visualisation.

On the second model we introduced a grid composed of a mesh of beams arranged in two directions [10] to aid understanding the concept of a system where the loads can be distributed to all elements making it more efficient and consequently lighter. The mesh of beams can be arranged in different patterns; rectangular, diagonal, triangular. This assembly was appropriate to introduce the concept of continuous connections and load transfers that can make more than one element work as a continuous element. In Karamba3D we had the opportunity to quickly test the model for continuous or segmented elements at nodes and explain that in many cases the geometry must be discontinuous at intersections/nodes. It was also an opportunity to introduce cross section components and the concept of cross section optimisation.

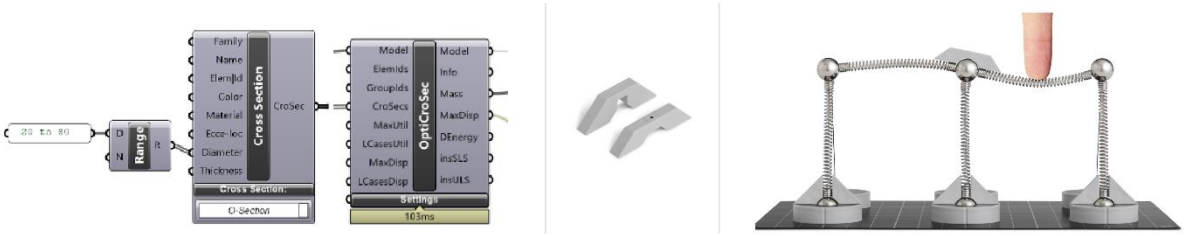

Figure 4: Concepts introduced with quad grid of beams in Karamba3D – cross sections and their size optimisation and with Mola Structural Kit 2 the effects of continuous connections were demonstrated [10].

On the third model we built a shell initially utilising a flat mesh as input. The definition of supports was similar to the beam and located at the four corners of the mesh. The Karamba3D component used ‘mesh to shells’ makes the conversion from geometry to structural element. In order to address more settings, we have introduced material selection and cross section selection, which can be specified to a constant thickness shell when simulating these kinds of elements. Again, we assembled, analysed and visualised the model.

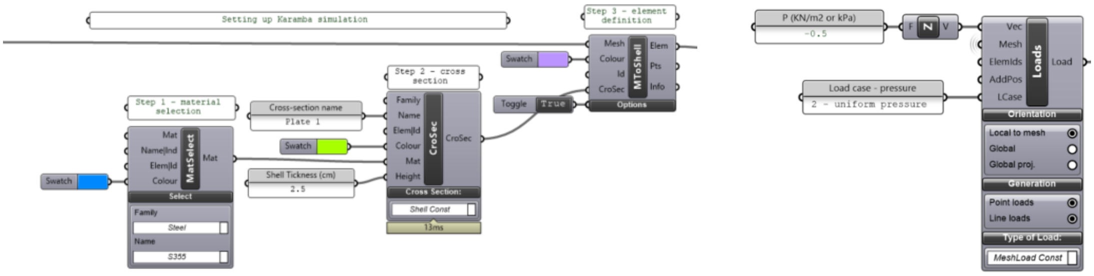

Figure 5: Simple shell element in Karamba3D introducing specific material properties, cross sections and mesh load cases.

With shells however there wasn't much correlation that could be done with Mola components, so we decided to integrate Kangaroo [6] to form-find a shell before getting the geometry to Karamba3D. We made a correlation between the hanging chain of Mola Structural Kit 3 [11] to understand the reactions after form-finding.

Figure 6: Simple shell element in Karamba3D prior to Kangaroo form-finding simulation and with Mola Structural Kit 3 components assisted using ground connections, cables and cable connection components [11].

3.3. Model correlation

These concepts were modelled physically and computationally verifying the possible consistent correlation between both media. A qualitative correlation was assumed in the first instance based purely on the tactile load testing on the physical model and the display of displacements of equivalent loads on the digital model.

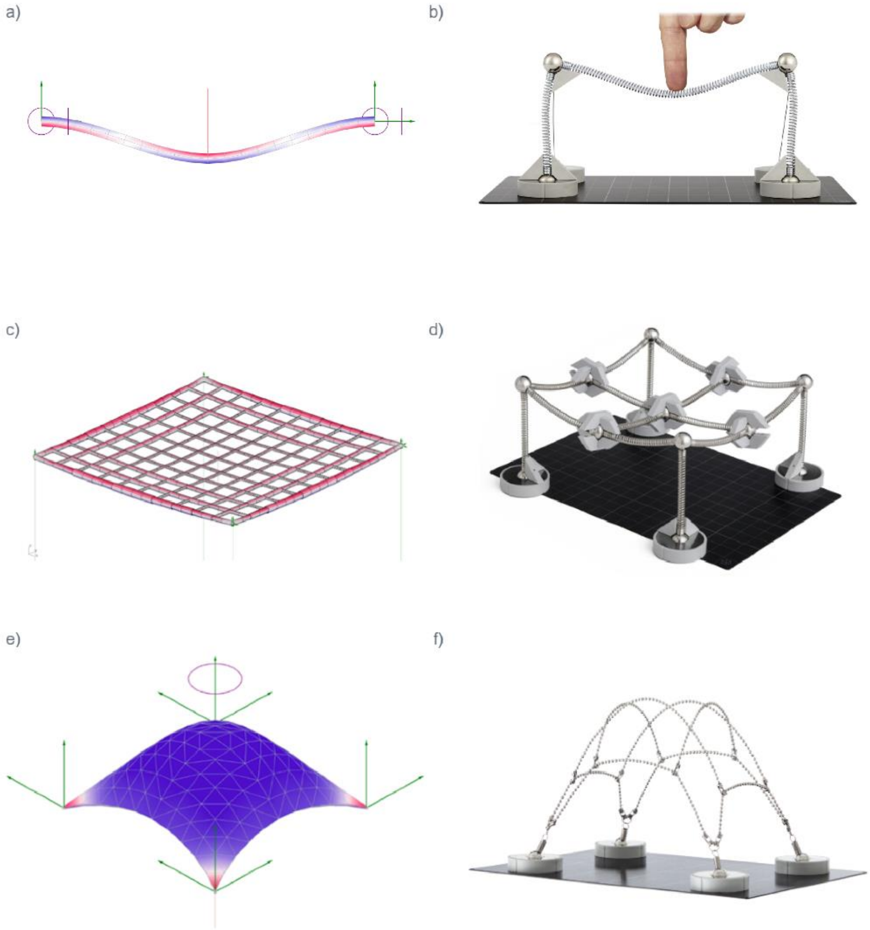

Figure 7: Model correlations tested in class a) a simple beam and its support conditions displaying material utilisation, b) equivalent physical model with similar loads, c) a beam grid with optimised cross sections displaying axial stress, d) a simple beam grid physical model, e) a simple form-found shell displaying stress/strength ratio. f) a simple catenary cable model image flipped upside down;

Some adaptation had to be carried to approximate results and obtain a consistent correlation between both medias. At qualitative level, this correlation was obtained through the visual evaluation of correlated structural displacements in both models.

3.4. Delivery

Three examples were tested in a class of 23 students during a three-hour lecture. Some examples were initially computationally modelled and then physically assembled, while others followed the inverse approach. In the afternoon of the same day, we continued with a three-hour workshop format. The students were presented with further structural concepts, then divided into groups to focus solely on assembling physical models of their choice. Their homework task for the week was to computationally develop the models they built during the workshop.

4. Results and reflection

4.1 Findings in relation to the learning process

Preliminary results indicate that correlations are possible, particularly as participants reacted positively to the approach. An improvement in interest and focus was observed compared to previous years when only computational models were presented. It is believed that this improvement stems from the intuitive and visual understanding that the physical models brought to a primarily computational discipline, enabling students to quickly grasp the behaviour of the assembled morphologies.

The findings also suggest that the methodology can be integrated into the lecture series, facilitating better understanding and integration between geometry, parametric modelling, and structural behaviour workflow, with the intent to assist in finding efficient and potentially sustainable structural solutions at early ideation and concept design stages. Furthermore, the students completed the home assignment mostly correctly, indicating that they can be directed to intermediate and potentially more challenging structural systems after physically modelling them.

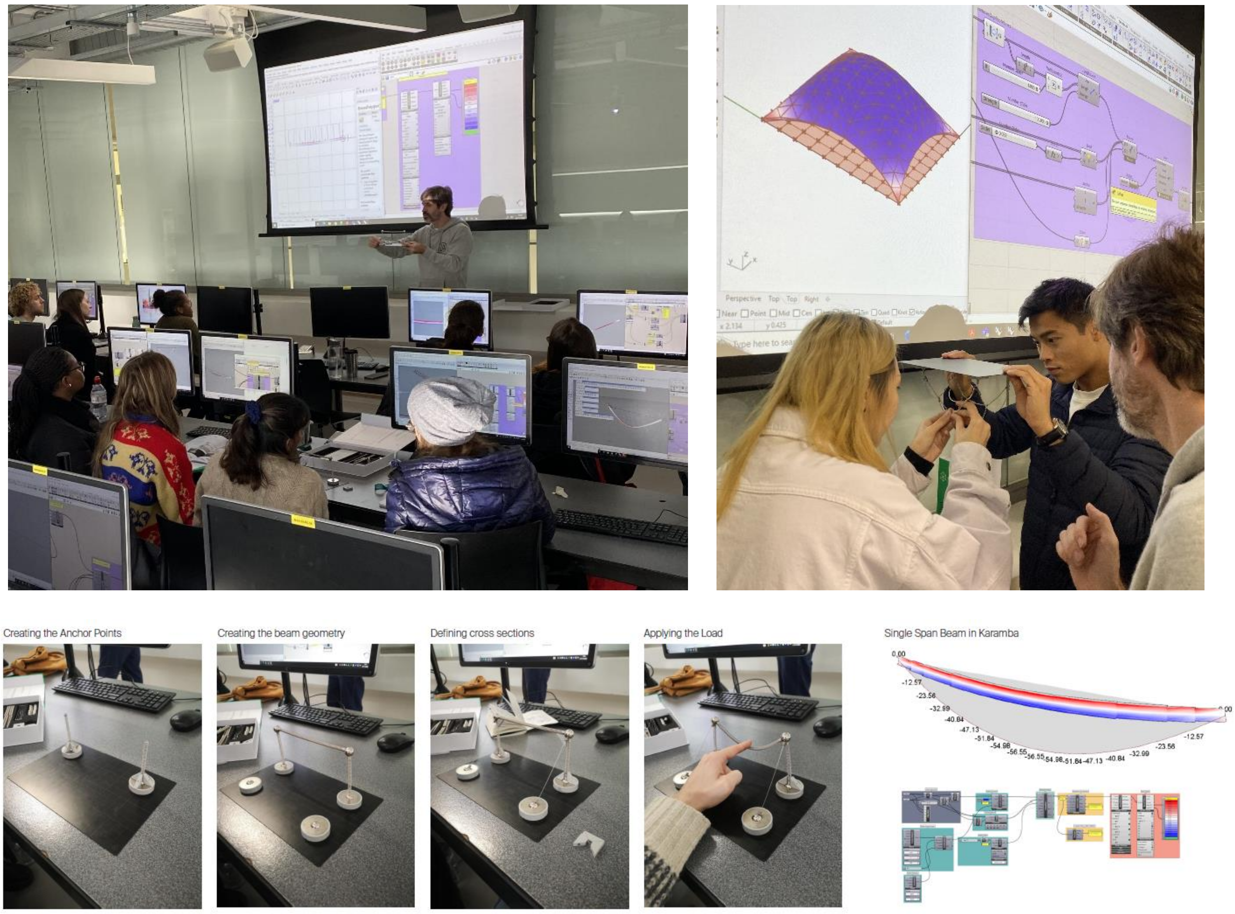

Figure 8: Model correlations tested in class. Top left and bottom, a simple beam and its support conditions displaying material utilisation and equivalent physical model being tested. Right, a simple form-found shell displaying stress/strength ratio and simple catenary cable model being assembled.

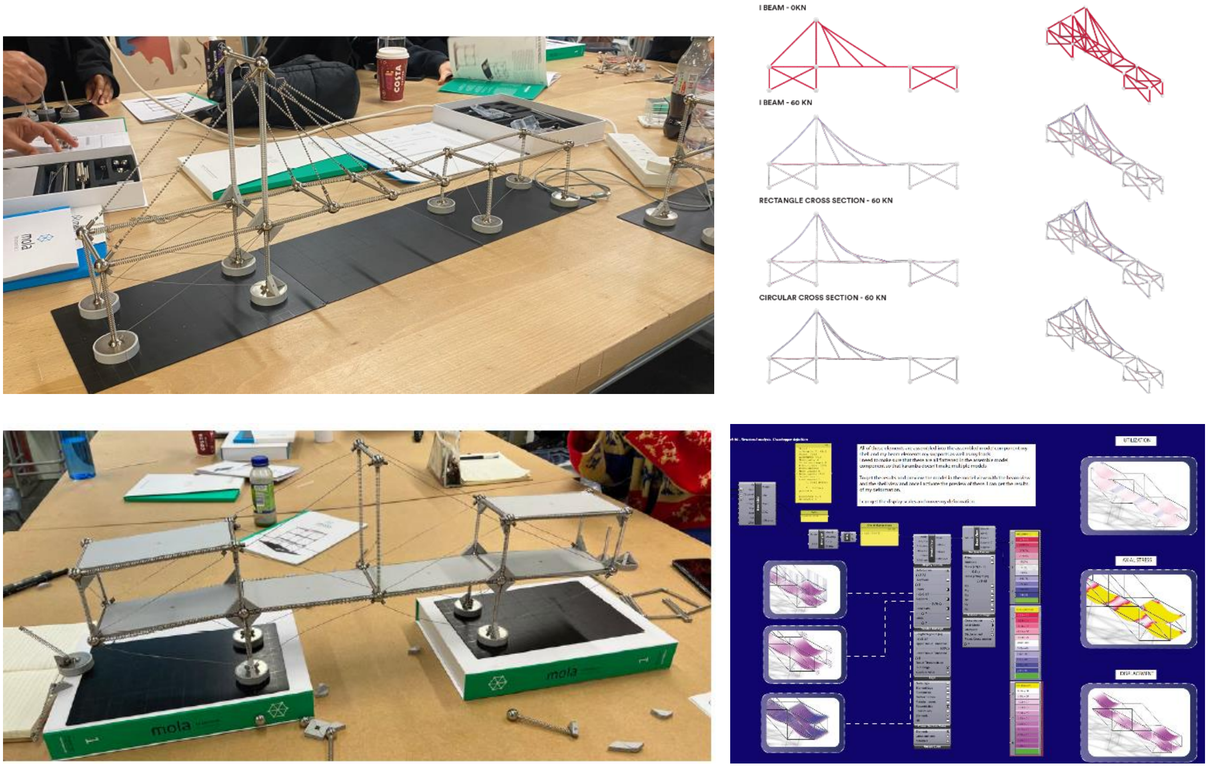

Figure 9: Independent modelling. Left, workshop assembled bridges. Right, computational analysis homework.

4.2 Findings in relation to physical and computational model correlations

In terms of correlations between physical and digital models, several aspects are noteworthy. In the simple beam example, correlations were easily achieved across all aspects. Depending on the applied loads' strength, displacements on both models closely correlated visually.

However, in the beam grid, we encountered a challenge. While it was easy to parametrically change the number of beams in each direction, attempting to correlate higher beam densities with the physical model resulted in heavy and time-consuming assembly, thus limiting correlation to smaller grid densities. Nevertheless, regarding connections and displacements, the models were qualitatively correlated.

The catenary example also presented challenges. Mola had limitations in regards to shells, so we introduced form-finding in Kangaroo as an intermediate step. Although we could achieve a similar form by relaxing the catenaries with no connections between them in two perpendicular directions, it's worth noting that in reality, these are computationally simulated as a mesh. Creating nodal connections between the catenaries in two perpendicular directions would result in a different structural system, one that could be replicated computationally, but not with the specific goals we aimed to demonstrate regarding shell behaviour.

5. Conclusion

These findings suggest that the methodology can be integrated into the lecture series, enhancing understanding and fostering integration between geometry, parametric modeling, and structural behavior at the beginner level. The workflow also seems to facilitate the discovery of efficient, stable, and potentially sustainable structural solutions at a critical juncture in the design process—the early ideation and concept stages. Furthermore, some of these solutions might be overlooked by practitioners using traditional, non-integrated parametric workflows.

The authors believe that correlations between discrete element morphologies are feasible. Connections, columns, portal frames, trusses, continuous beams, grids, geodesics, funicular and cable beams, tensioned cable nets, cabled roofs, cable and suspension bridges, and tensegrity structures can be correlated with their digital counterparts despite certain physical model limitations, particularly regarding scale and size. The next steps would involve testing and documenting these limitations, exploring possibilities to overcome the shell simulation challenge, and continuously examining more complex structural arrangements.

This paper presented a novel workflow for quantitatively correlate digital and physical structural models. It described the method being utilized to teach parametric structural behavior, modeling, and analysis to final-year architectural master's students. The paper introduced challenges, evaluated current approach limitations, and described the methodology used. Finally, results, successes, limitations, and next steps were reported.

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