

LEARNING FROM FAILURE: HYBRID FABRICATION OF A GRID SHELL CANOPY STRUCTURE USING TIMBER BATTENS AND 3D PRINTERS

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Abstract

Construction courses are fundamental to architectural education, and prototyping is an effective way to engage students in hands-on learning and one of the most effective methods for teaching practical skills. Furthermore, these courses must incorporate digital technologies, as current professional trends increasingly demand their use. But how can we integrate these elements into lecture-based courses that are constrained by limited time and resources? This paper describes the design, fabrication, and assembly of a free-form gridshell structure as part of an undergraduate course at the Faculty of Architecture, Yaşar University. The prototype was constructed using a hybrid fabrication technique that combines timber battens with 3D-printed connections, facilitating both assembly and potential disassembly. Over the course of 14 weeks, students developed the structure through an iterative design-build process, gaining a unique, hands-on learning experience in experimental construction. The paper highlights how the development of the structure proceeded deliberately, with reflections on failures between iterations. This approach not only facilitated learning but also led to relevant research findings. The final prototype serves as a proof of concept for the advantages of hybrid fabrication, making it suitable for temporary structures within architectural and engineering curricula. The insights gained from this practical experience can contribute to both structural engineering and architectural education by providing valuable knowledge on digital production and structural design processes. Additionally, the study contributes to the ongoing discussion about the performance of 3D-printed nodes under challenging structural conditions, highlighting both the potential and the limitations of this emerging technology.

Keywords: 3D printing, Hybrid fabrication.

1. INTRODUCTION

1.1. Construction and management processes as multidisciplinary practices

Building construction is a crucial part of the architectural profession. As a process, it encompasses all aspects related to the planning, fabrication, production, management, assembly, and disassembly of buildings. Consequently, it is closely tied to the state of the construction industry, which has undergone sig-

nificant changes in recent years. In response to the demands of 21st-century global society, construction professions have had to become more multidisciplinary, particularly in areas related to technology and management (Chan Edwin H. W. et al., 2002).

At universities, technical courses are often taught through lecture-based sessions. However, studies have shown that these types of sessions tend to result in low student engagement (Shareef & Farivarsadri, 2020). Therefore, to properly prepare students for profes-

sional practice, universities must move away from traditional curricula and instead adopt teaching and learning materials that embrace a more proactive and multidisciplinary approach to building construction courses. In this context, preparing students for multidisciplinary practice means that, as professionals, they will not be confined by the traditional roles of architects, builders, engineers, or surveyors (Chan Edwin H. W. et al., 2002).

1.2. The importance of prototyping

During their education, architecture students often lack practical assignments that involve building at 1:1 scale. As a result, they rarely experience the full design cycle, which begins with conceptual elaborations and ends up with a real scale physical object. This gap is particularly problematic in building construction courses, as these courses should be designed to provide students with both the applied knowledge of building construction and the management skills necessary for their professional activities.

Working with real-scale prototypes promotes an active learning environment, where students learn by making. By physically engaging with their subject matter, students can fully develop their creative thinking and problem-solving abilities. The hands-on experience they gain enhances their design capabilities, increases their awareness of their own learning progress, and prepares them for professional practice (Morales-Beltran, 2023). The ability to understand the entire design process – from conception to delivery – is a particularly needed in a construction industry where professionals are expected to oversee and manage project development and the construction process.

1.3. The use of computational tools

The widespread integration of digital technologies in the construction industry is reshaping business models and driving firms to focus on resilience and adaptability. This "digital shift" necessitates a corresponding "cultural shift," emphasizing the development of soft skills such as collaboration, flexibility, and adaptability. To succeed in a digitally-driven environment, students must learn to work across traditional silos, embrace risk-taking, and avoid an overreliance on commercial software (Papadonikolaki et al., 2020).

Moreover, the increasing role of digital tools in architectural practice highlights the importance of students acquiring both basic computational skills and an understanding of new technologies to accelerate

design, fabrication, and assembly processes. The rapid development of digital tools in architecture has raised the need to integrate these technologies into architectural curricula more effectively. Graduating architects must be equipped with the ability to use digital modes of design and fabrication, which integrate traditional skills of drawing and making into computational contexts. This approach not only enhances design thinking but fosters new conceptualizations of space and geometry (Soliman et al., 2019; Tepavčević, 2017)

1.4. The relevance of hybrid fabrication

Hybrid materiality refers to the integration of both digital fabrication techniques and traditional craft practices, allowing for a blend of modern technology with age-old methods. Hybrid design expands on this idea, merging the forms and qualities of traditional craftsmanship with digital fabrication to explore new creative possibilities (Bernabei & Power, 2018). This fusion enables greater flexibility in architectural design, fostering innovation in both form and function. While digital fabrication, especially 3D printing, presents exciting opportunities for customization and efficiency, it is inherently limited by its reproducibility, unlike handmade artefacts which offer uniqueness and individuality. A key example of this is seen in the practice of combining digital fabrication with object restoration, where 3D printing is used to repair or recreate crafted items (Zoran & Buechley, 2013).

In architectural education, the hybrid use of both digital and analogue fabrication techniques plays a significant role in enriching design learning. By engaging students in both methods, they gain deeper insights into the advantages and limitations of each technique. These active learning experiences help students explore the relationships between space, geometry, and material performance, and encourage creative thinking. This process, enhanced by computational tools like parametric design software, not only accelerates the design process but also enables exploration of non-conventional geometries and structural forms, contributing to innovation in both pedagogy and architectural production methods (Morales-Beltran et al., 2021).

Despite the potential for innovation, there are challenges associated with hybrid fabrication techniques. While digital tools such as 3D printing are increasingly accessible, they are still not fully suitable for large-scale construction due to high costs and limitations in material applications. However, ongoing research is working to make 3D printing and other

digital fabrication methods more feasible for broader use in construction (Lee et al., 2024). Combining additive and subtractive manufacturing techniques can lead to efficient production, where large, simple components are made using traditional methods, and more complex, customized elements are produced through digital fabrication. This hybrid approach offers exciting possibilities for both pedagogy in architectural education and practical applications in construction, as seen in projects like 3D-printed nodes for gridshell structures (Seifi et al., 2018) or bio-composite connections for bamboo space structures (van Wassenhove et al., 2021).

1.5. The challenge of integrating construction of prototypes in architectural curricula

While the above components are essential to a comprehensive architectural curriculum, several challenges hinder their inclusion. The growing demand to reduce the number of courses, shorten course contents, and the shortage of specialized instructors leaves little room for integrating construction exercises that address the full design cycle within a single-semester course. Additionally, while the use of digital technologies (e.g., drawing software or 3D-printed modeling) is highly desirable, a significant portion of any course incorporating such technologies must be dedicated to teaching students how to use 3D modeling software. This further limits the time available for the design, fabrication, and assembly of physical prototypes.

To add to this, while studio classes are often compressed to just two days per week, regular courses (i.e. not studios) are confined to a few hours per week. This leaves students with even less time to engage deeply with the full scope of the course content.

This paper presents the settings and outcomes of an undergraduate elective course on structures, in which students designed and fabricated a full-scale prototype over 14 weeks. The primary objectives of the project were to provide students with hands-on experience in designing and constructing a gridshell prototype using a hybrid approach, combining timber battens and 3D-printed nodes, and to enhance students' abilities to create free-form structures using standard building materials and common 3D printers. However, a series of both expected and unexpected events not only extended the duration of the whole exercise but also led to failure-driven design and learning processes.

2. SETTING UP THE COURSE AS AN EXTENDED DESIGN-BUILD WORKSHOP

2.1. Method

To achieve the goal of designing and building a full-scale prototype, the course was organized as an extended design-build workshop. Inspired by the ProtoLAB workshops (Latka, 2023), the course centred around a specific topic, with students receiving short, application-based, and result-oriented inputs. It was divided into two main phases: design and build. The requirement that "it has to be built" informed all decisions throughout the process, driving constant discussions on feasibility (e.g., Can we build it within n weeks? Do we have all the materials? Can 11 people complete this?), budget (e.g., Can we afford X material? Who will pay for it?), and associated risks (e.g., Is the location safe? What happens if it collapses?).

The course was planned to enable 11 students to design and build a full-scale structure using hybrid production methods within a 14-week semester. The key components and materials used in the course are described below.

2.2. Schedule

The course was organized into four major stages, each lasting three weeks (see Table 1):

- Understanding – including lectures & workshops focusing on form-finding methods,
- Designing – where students propose and select a gridshell to build,
- Making – where nodes are 3D printed and timber battens are prepared, and
- (Dis-) assembling – where the final prototype is installed and then disassembled.

After the Designing stage, which coincided with the official midterm exam week, students were required to submit designs for all the nodes and have them ready for 3D printing.

2.3. Introducing structural principles early in the design process

Since students do not have enough time to perform any sort of structural analyses, a compulsory step in the process of prototyping any student's design is the introduction of a structural logic as early as possible in the design process. To this end, the course offers the students two key inputs:

Table 1.
Initial course schedule

week	Stage	Contents / activity
2	Understanding Freeform Gridshell Structures	Form-finding methods workshop I (computational)
3		Form-finding methods workshop II (physical)
4		Designing a freeform using gridshell structures
5	Designing a Freeform Gridshell Structure	Design proposals: fabrication and disassembly issues
6		3D model development (nodes, battens, organization)
7		Design of nodes & battens
8	Midterm Exam Week	Delivery: Design of all nodes / 3D printing setup
9	Making a Freeform Gridshell Structure	3D printing / fabrication of battens
10		3D printing / fabrication of battens
11		Assembling of parts
12	(Dis-) assembling a Freeform Gridshell Structure	Test Installation on campus
13		Disassemble / Re-assemble
14		Final Installation
15	Final Exam Week	Delivery: Report & digital archive

1. Physical form-finding workshop – for the students to grasp the physical principles that rule funicular structures.
2. Parametric design of a shell as a digital file – for the students to explore design variations. This file is a Grasshopper (GH) model, containing a generic shell model based on catenary curves. This file allows students to modify parameters such as the number of supports, curves, plan area, layout, and height of the structure. Its use allows students to design freely, while the parametric model ensures that the final design respects the structural logic of catenary curves.

2.3.1. Workshop with fabric and melted candle wax

This simple workshop introduces students to funicular systems, whose forms are linked to the manner loads are transferred to the supports through simple surface stresses. Students use fabric, dipped in melted candle wax, to quickly realize how the material's type and shape influence the resulting form. The process involves (Figure 1):

- Dipping 30 x 30 cm (approx.) pieces of fabric into melted wax.
- Hanging the waxed fabric upside down on a cardboard base using clothespins.
- Allowing the fabric to dry using temporary timber supports.



Figure 1.
Physical form-finding workshop: funicular membranes using fabric and candle wax

- Once dried, flipping the fabric to form a compression membrane structure.

2.4. Internal competition – Design considerations

The internal competition is designed to choose a single design to be developed as a team. This design must have already incorporated a structural logic, increasing its “buildability”. Students are required to prepare proposals using the provided parametric GH file, which models a generic gridshell structure based on catenary curves.

To ensure the feasibility of the designs, students are limited to 110 nodes and a maximum timber batten length of 100 cm. These limitations are based on insights gained from previous similar projects (Morales-Beltran et al., 2021).

2.5. Materials

The materials were largely available through leftovers from a previous research project, so students only needed to purchase a few items (such as bolts and cables). The materials included:

- Software: Rhinoceros 3D – henceforth referred to as Rhino – and GH for modelling (McNeel, 2022), Prusa Slicer and Ultimaker Cura for preparing G-codes files
- 3D printers: Prusa i3 MK3, Wanhao Duplicator 9, Creality Ender-3 S1
- Filaments: PLA+, PETG (used in the second prototype)
- Timber: Siberian pine (cheap and widely available in Türkiye)

3. RESULTS

3.1. Internal competition - selection of the design for prototyping

The students self-organized and proposed seven designs (Figure 2). The selection committee was composed of the students themselves, who presented their proposals to one another for discussion. The designs were evaluated based on factors such as size, apparent complexity, and other considerations related to time constraints, available materials, and fabrication techniques. Three of the proposals were relatively large, which presented logistical and implementation challenges. From the four designs that appeared more feasible in terms of scale, students – in an open vote – chose the cantilevered canopy proposal. The fact that most of the other proposals strongly resembled variations of the given gridshell design, may have been perceived as too similar to attract much interest. Interestingly, the students behind the selected canopy proposal moved away from this obvious solution. Instead, they developed a tree-like form using a pattern of Voronoi cells.

3.2. Revising the proposal for prototyping

The first modification to the design was driven by the need to ensure the stability of the structure. Given the temporary nature of the prototype, anchoring was not a viable option to provide the cantilever structure with the required self-balance. As part of a collective class effort, several key design strategies were proposed: enlarging the base (the area in contact with the ground), increasing the canopy's angle of inclination, and adding tension cables. These changes

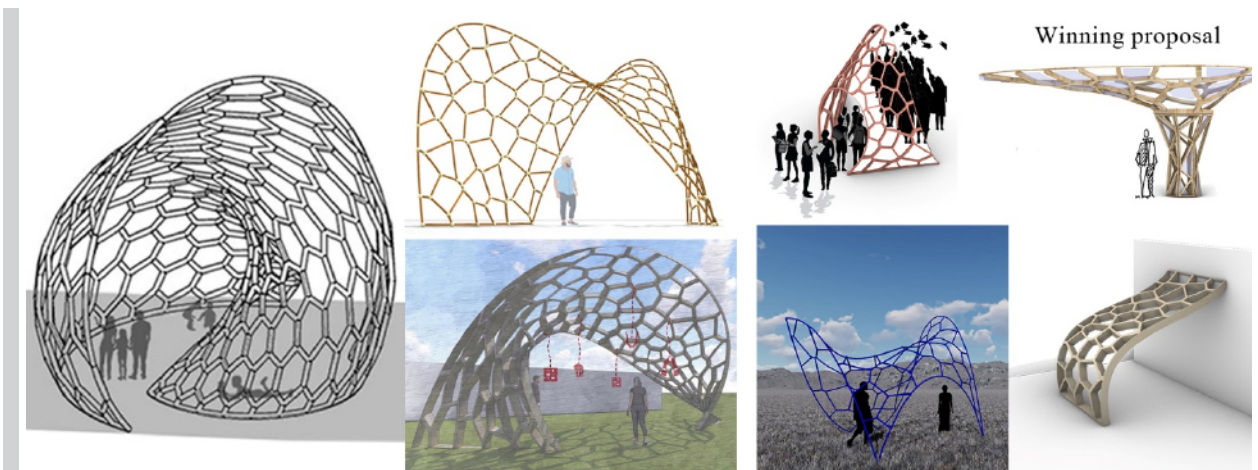


Figure 2.

The seven proposed designs (depicted at similar scale): three large gridshell structures on the left, smaller proposals – including the selected one – on the right

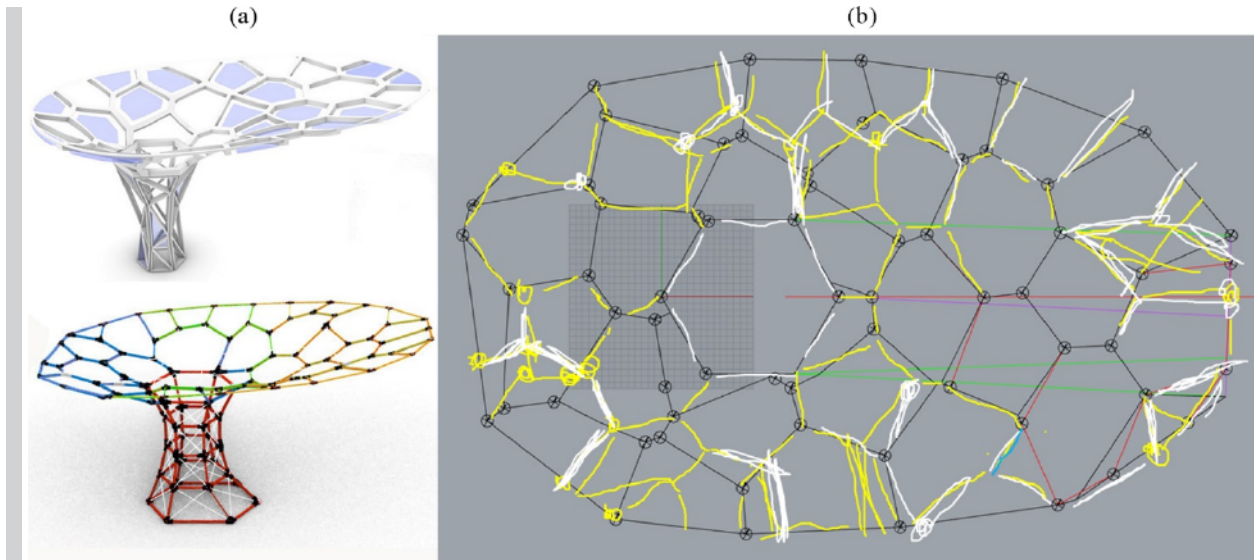


Figure 3.

(a) Pre- and post-revised versions of the prototype, and (b) sketch used during the discussion on the design of the canopy for structural enhancement

helped improve the stability of the prototype by lowering its centre of gravity (Figure 3a).

Next, the arrangement of battens in the cantilever section, henceforth referred to as the ‘canopy,’ needed to be revised to ensure that the length of the timber battens did not exceed one meter. Reducing the length of the battens required splitting them and adding new nodes to the structure. As a result, the redesign of the canopy became a trade-off between the number of battens and the number of nodes (Figure 3b). An additional constraint in this process was that no more than three battens should meet at a single node, with the exception of the nodes where the canopy connects to the supporting structure. Fortunately, this condition was met by adhering to the Voronoi pattern.

In line with the goal of bringing the centre of gravity closer to the axis of the vertical part of the structure, henceforth referred to as the ‘column,’ the cross sections of the timber battens vary depending on their position within the structure (Figure 4). Along the longitudinal axis, battens of varying section sizes are arranged to ensure a balanced distribution of the canopy’s mass. The use of smaller sections in the canopy (Table 2) reduced its overall weight, while positioning the larger sections in the column helped lower the centre of gravity, thereby increasing the overall stability of the structure.

The final design included 168 timber battens and 103 nodes.

3.3. Design of the nodes

After the canopy was redesigned, a new digital model was created in Rhino, incorporating all the battens at their correct sizes. Next, the 103 nodes were distributed among the 11 students, with each of them assigned 9 to 10 nodes to design for 3D printing. Although there were no fixed rules for the design, students were instructed to minimize the size of the nodes in order to reduce material usage and printing time. In addition, the nodes had to include several compulsory components (Figure 5): boxes to hold the timber battens and holes for fixing the battens into the boxes. Some nodes also required additional holes for inserting tension cables.

Table 2.

Characteristics of the 168 timber battens

Section	Quantity	Cross section (cm)	Average length (cm)	longest - shortest (cm)
Column	54	4.4 x 2.4	49.1	94.3 - 32.6
Canopy	41	4 x 2	43.1	83.9 - 20.9
	25	4 x 1.5	46.5	75.5 - 32.8
	48	3.5 x 1.5	49.4	83.1 - 19.8

While all nodes were designed to optimize strength and facilitate assembly with the wooden pieces, their characteristics varied depending on whether they connected battens with different cross sections. The variation in cross sections led to nodes with boxes of

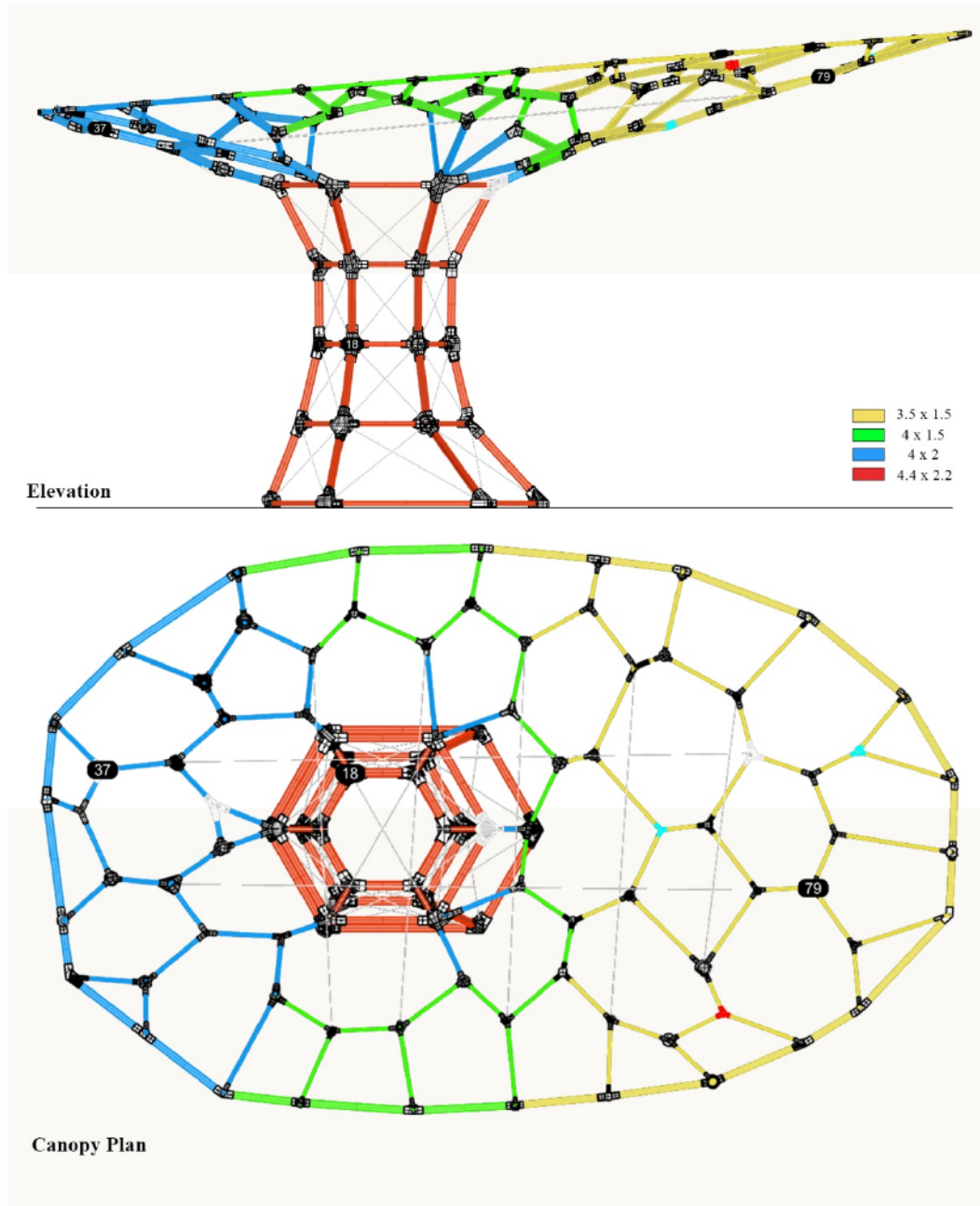


Figure 4.
Distribution of the 168 timber battens across the structure

different sizes and wall thicknesses (Table 3). Since the battens are inserted into the nodes, not all nodes could be assembled by simply sliding the battens into the boxes. To address this, some nodes were designed to be split into two parts, allowing them to be connected after the battens were attached.

Table 3.
Characteristics of the 103 nodes

Section	Quantity	wall thickness	Cross section (cm)	bolt diameter (mm)
Column	54	7 mm	4.4 x 2.4	5
Canopy	41	5 mm	4 x 2	4
	25	4 mm	4 x 1.5	4
	48	3 mm	3.5 x 1.5	3

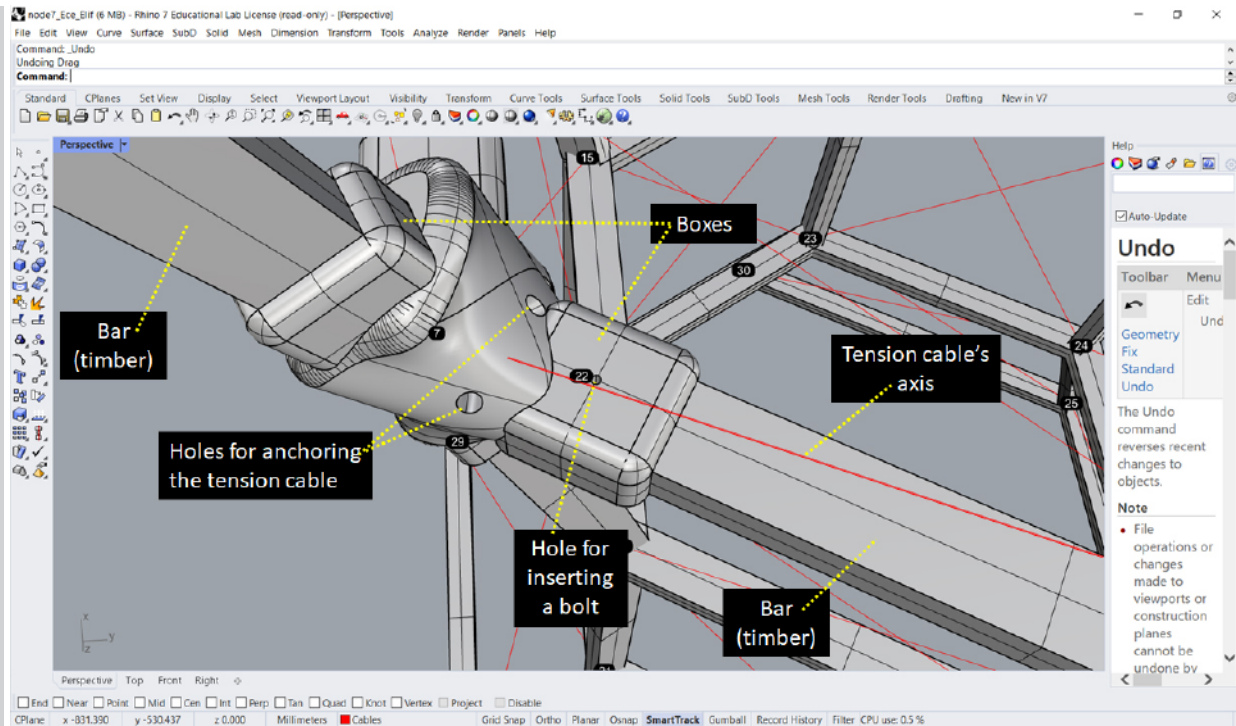


Figure 5.
Standard design components of a node

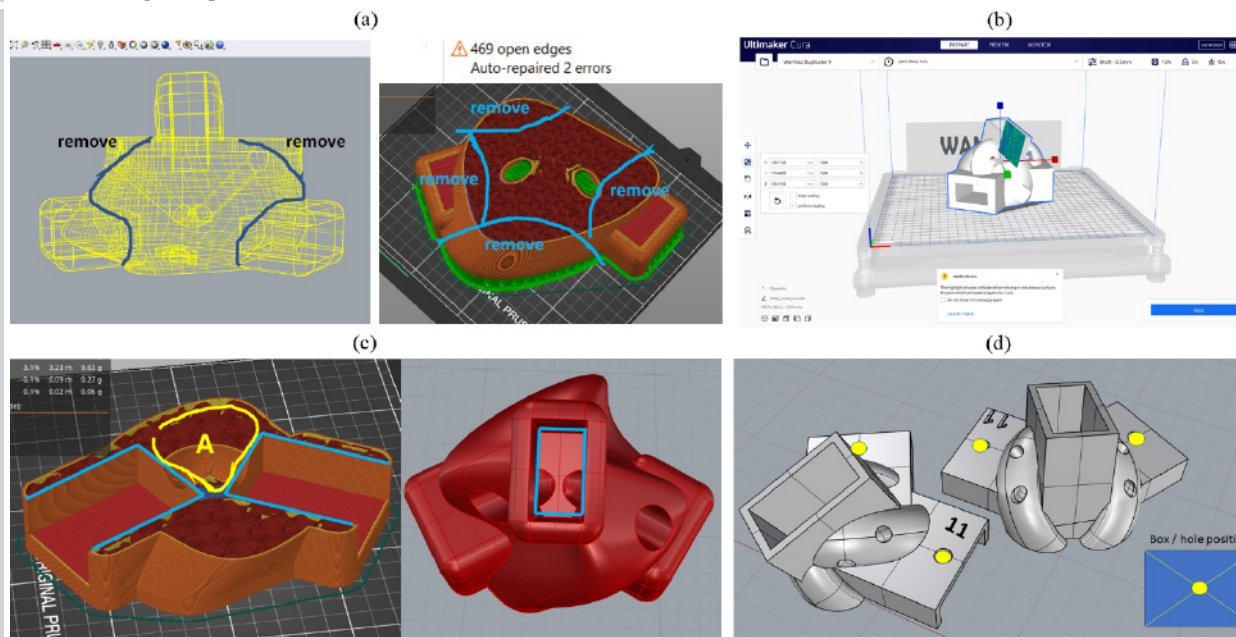


Figure 6.
Most common mistakes during the early design of the nodes: (a) excessive use of material, (b) open edges in the models, (c) cable holes interfering with timber battens, and (d) wrong positioning of the bolt holes

Despite the design process initially appearing straightforward during the planning stage, it became an iterative process in practice. This was because the initial designs featured mistakes, such as unnecessary use of material (e.g., excessive volume or the inclu-

sion of additional elements), inconsistencies with assembly requirements (e.g., cable holes interfering with boxes or wrong size of the box), and issues with the required strength (e.g. holes placed at points where the structural integrity of the node, or part of

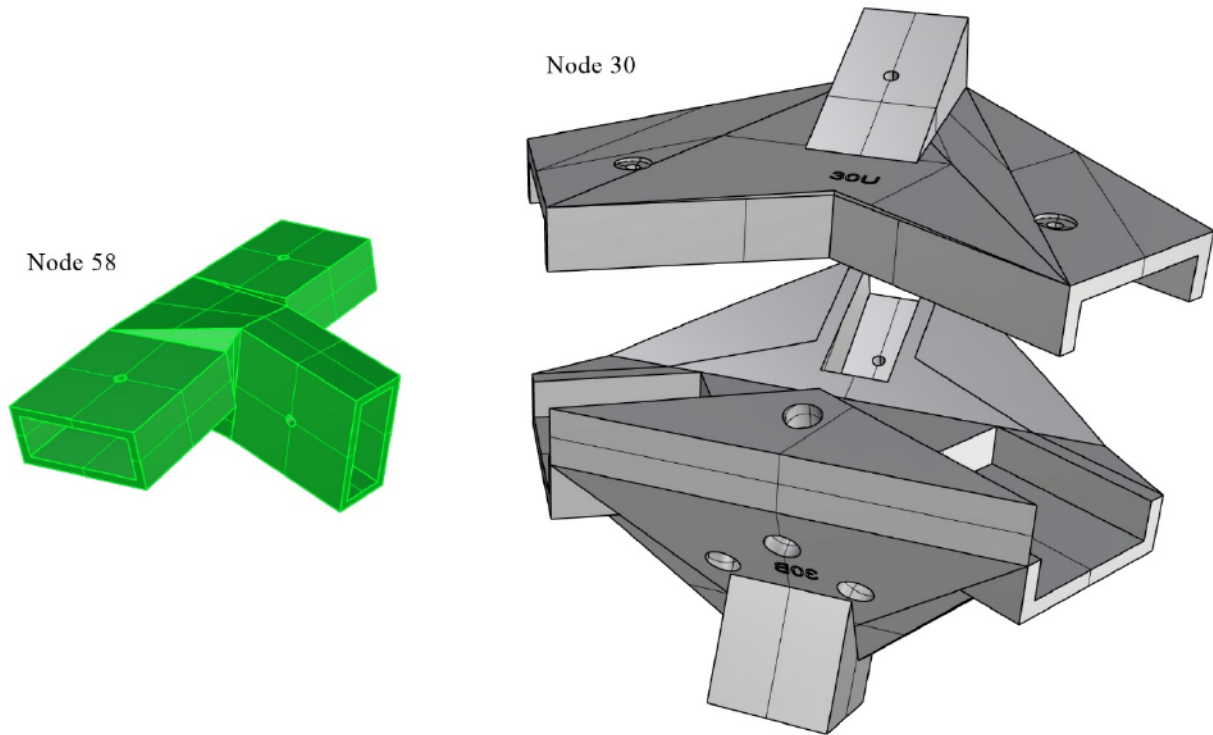


Figure 7.

Contrasting sizes and complexities of the nodes. Node 58 connects battens of the smallest cross-section (3.5 x 15 cm), while node 30 connects battens of the largest cross-section (4.4 x 2.2 cm), as well as the “column” and “canopy” sections. It also includes holes to anchor the tension cables. Since node 30 is split for assembly, the letters U and B are added after the node number to indicate the “upper” and “bottom” positions

it, was compromised) (Figure 6). As a result, students were required to make multiple design revisions based on feedback from the course instructor. After these iterations, the node designs became quite varied, with some even contrasting significantly (Figure 7).

3.4. Fabrication process

3.4.1. 3D printing process

Since the team knew that the 3D printing process was very time-consuming, nodes had to be printed as soon as they were ready. On the other hand, given the experimental nature of the prototype, each printed node had to be tested for assembly immediately after printed to correct any unforeseen mistakes. For these reasons, the column section was planned to be built first. The 3D printing strategy was determined by this assembly sequence: the students prepared the g-code files for the column nodes first, considering parameters such as the type of filament (PLA+), printing time, infill percentage, and orientation. The main purpose was ensuring that nodes were printed quickly and in a way that guarantees proper strength.

Once the column section was ready, the nodes for the canopy were designed and then printed. Due to the smaller section of the canopy battens, these small nodes were printed comparatively faster. The last nodes to be designed and printed were those connecting the canopy to the column, which were also the last to be assembled in order to complete the structure.

The nodes were printed using three different 3D printers, which occasionally led to unexpected variations in the strength of the printed nodes. Nonetheless, regardless of the 3D printer used, all printing was planned following the idea of minimizing both printing time and use of material – especially for the support structures required for the irregular shapes of the nodes during printing. Initially, the nodes were oriented in a way that maximized the contact area with the printing bed, saving significant amounts of support material. However, this strategy resulted in the use of support material inside the nodes' hollow sections, making post-printing removal difficult. To address this challenge, the node orientations were adjusted so that the hollow sections could be printed without internal supports.

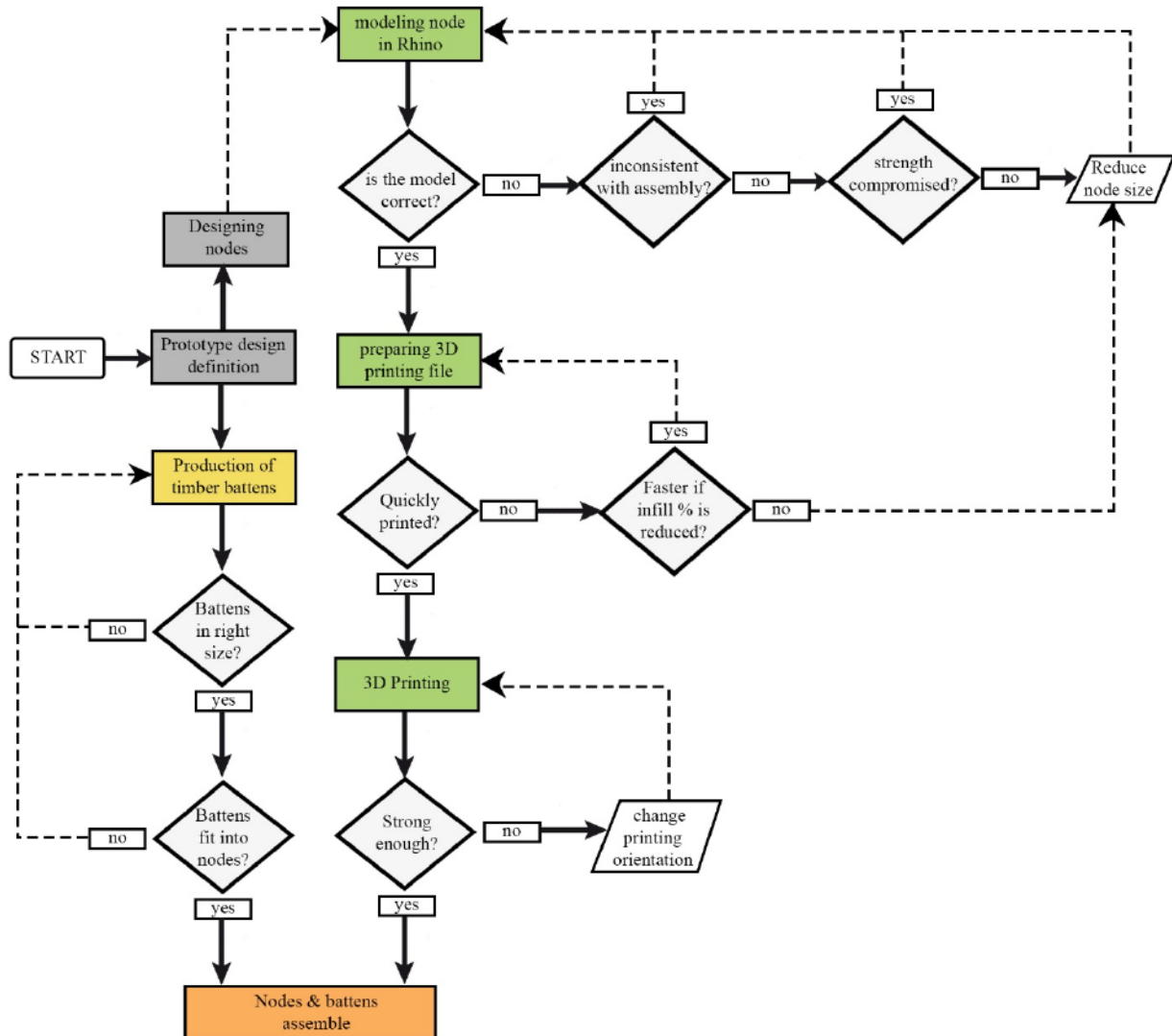


Figure 8.
Flowchart of the iterations in the design and production processes

3.4.2. Production of the timber battens

The production of the timber battens began with cutting them to the dimensions specified in the Rhino model. As with the nodes, battens for the column were prepared first, followed by those for the canopy section. Once a batten and its corresponding nodes were ready, the team tested the fit to ensure the connection was neither too tight nor too loose. If any issues arose, either the node or the batten was adjusted. After confirming a proper fit, the portion of the batten that would be inserted into the node was marked with the corresponding node number – to facilitate assembly. These marked portions were kept clean during the varnishing process.

3.4.3. Fabrication as an intrinsically iterative process

Due to several mistakes made during the design and fabrication stages, as well as the constant need to revise the outcomes, the entire process became highly iterative (Figure 8). While some degree of iteration was expected, the effect was that the 3D printing stages extended to the point where they consumed nearly all of the time originally allocated for assembly and disassembly. In addition to common 3D printing setbacks, such as running out of filament or objects detaching from the printing bed, the major delays during the design and preparation stages were caused by:

1. Modelling issues: Students modelled nodes in software other than Rhino, which led to mesh deficiencies (e.g., open edges) when preparing the printing



Figure 9.
Assembly process of the first prototype in an open area of the campus

- files. As a result, all files had to be redone in Rhino.
2. **Printer malfunction:** One of the printers produced weaker nodes due to a mechanical issue with the printing layers, which initially went undetected. These nodes had to be reprinted using the other 3D printers.
 3. **Material support challenges:** Attempts to reduce material support in order to save printing time resulted in instability during printing, leading to the need to reprint some of the nodes.
 4. **Time constraints:** Students often lacked sufficient time to address all issues, and small errors sometimes resulted in several days of delays.

3.5. Assembly of the first prototype

The assembly process, involving all students and the instructor, was carried out in two stages: column assembly and full prototype assembly (Figure 9). The column was assembled first, approximately three weeks before the canopy was completed. This stage took about six hours, with most of the time spent ensuring the battens fit correctly into the nodes.

Unlike the column, which was assembled bottom-up,

the canopy was assembled upside down. This approach was chosen because, by design, all perimeter battens were placed on the same virtual plane using the ground as a reference. As long as the perimeter battens were correctly connected, this strategy minimized the risk of assembly errors. The entire canopy assembly process took about 18 hours, with most of the time again dedicated to ensuring the battens fit properly into the nodes.

Once the canopy was assembled, it was flipped and placed on temporary supports. The team used benches, tables, ladders, and long sticks to lift the canopy until it could be positioned beneath the column. The final step involved connecting the canopy to the column by securing the appropriate nodes and tensioning cables to adjust the canopy into the correct shape. This took an additional three hours.

4. STRUCTURAL PERFORMANCE & REDESIGN OF THE PROTOTYPE

A few hours after installation, during the night, the structure was destroyed by a strong wind. The post-collapse evaluation determined that one of the nodes in the column had been overstressed and broke

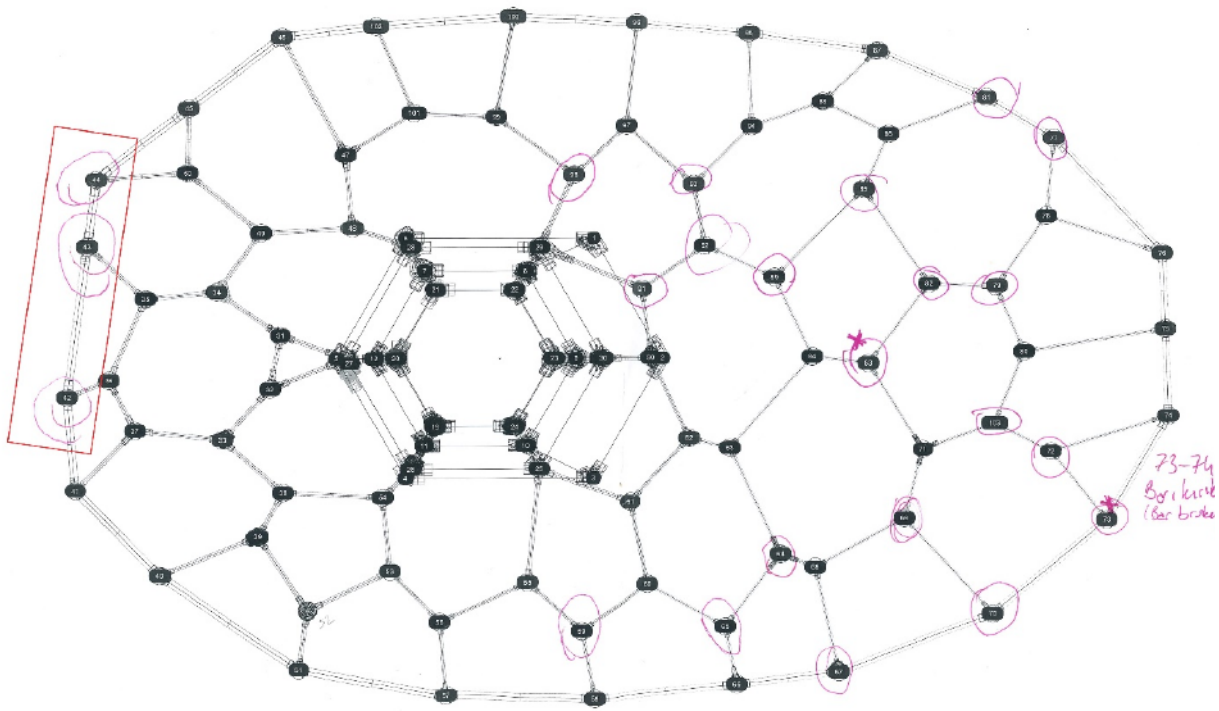


Figure 10. Broken nodes in the canopy before redesign. The hand note says ‘broken bar’ and it refers to the only timber battens broken as a result of the collapse. The failure of the 3 highlighted nodes at the back was surprising

down, triggering the general loss of stability of the structure. As a result, the canopy collapsed forward, breaking several nodes at the front, including one batten (Figure 10). Unexpectedly, some nodes at the rear of the canopy were also damaged. This damage seems to have been caused by excessive deformations during the collapse. These nodes connected battens of significantly different lengths, which may have led to an imbalanced distribution of the bending moment at the node, causing the node boxes to break apart.

4.1. Redesign of the nodes of the column section in PETG

During the examination of the column, it became clear that most, if not all, of the broken nodes were the white ones (Figure 11a, b). These nodes were printed using the defective 3D printer – before the extent of the problem was fully realized. Worse, they were relatively small and/or had smaller boxes, which reduced their contact surface area with the battens. As a result, when subjected to strong wind-induced vibrations, the column’s ultimate strength capacity relied on the bolts, which, unsurprisingly, surpassed the shear capacity of the PLA+ wall layers, leading to local failure. Given the distribution of the white

nodes in the column, local failure of these nodes ultimately led to the collapse of the entire structure.

In addition to the role of the white nodes in the collapse, two other issues increased the likelihood of structural failure: wet battens and split nodes. A few days before the full assembly, the column section was exposed to rain, causing some battens to become wet and swell in size. This increase in size led to early cracks in some of the node boxes. Furthermore, since all nodes, except those in contact with the ground, were split into two parts, the overall stiffness of the structure was reduced. This allowed for small movements between the parts, which, over time, led to loosening.

The redesign of the column section was driven by avoiding all those previous mistakes. The new design (Figure 11c) included the following changes:

- **Material Change:** All nodes, except those connecting the canopy section, were 3D printed using PETG instead of PLA+. This decision was based on the superior strength capacity of PETG-based components when subjected to similar structural demands (Morales-Beltran et al., 2022).
- **Node Revisions:** Since all nodes needed to be reprinted, their designs were revised to include

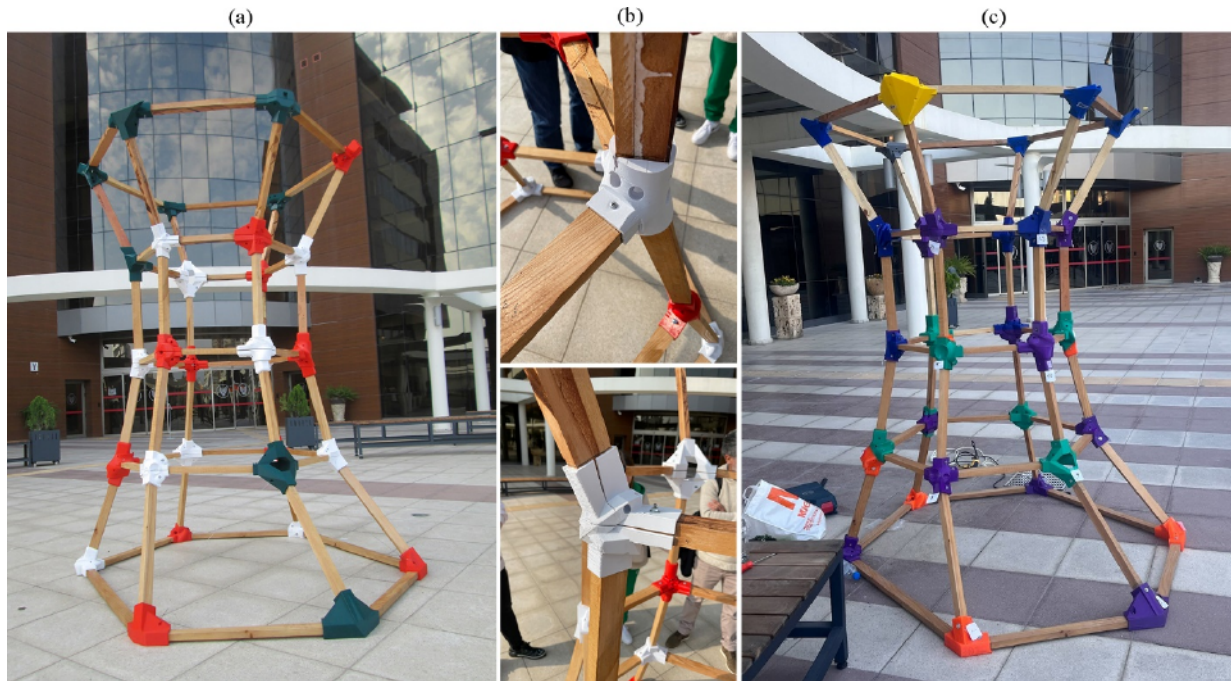


Figure 11. View of the (a) original column; details of some nodes (b) with poor performance, and (c) revised version of the column in PETG nodes

5.1 mm diameter holes for bolting and a wall thickness of 10 mm for the node boxes.

- **Monolithic Nodes:** Realizing that only half of the nodes needed to be split for assembly purposes, the other half were redesigned as monolithic nodes, which increased the overall stiffness of the column section.

In total, seven nodes were completely redesigned due to their previous low structural performance (i.e., overall weakness and/or lack of stiffness). However, modifications to the position and length of the boxes were avoided, as doing so would have required changes to the corresponding timber battens. Instead, the modifications focused on increasing the wall thickness of the node boxes and/or increasing the infill percentage to 20%, in order to improve their strength and stiffness.

4.2. Assembly of the second prototype

Out of the initial 11 students, only four remained actively involved in the redesign and reprinting of the now PETG nodes. This was likely due to the students' busy schedules, as this work was not officially part of their coursework. As a result, their involvement in the later stages of the project was voluntary. For the same reason, the design and printing processes took several weeks. Since there was no time available dur-

ing the semester, the assembly of the new prototype was scheduled for the summer break.

The assembly took three full days and followed the same order as the previous prototype: first, the column section was assembled, followed by the canopy section, and finally, the two were connected to complete the prototype (Figure 12). An additional three students joined the team specifically for the assembly, bringing the total team size to eight.

4.3. The effect of hot weather on the structure

The second version of the canopy weighed approximately 35 kg, distributed as follows: 17 kg for the 3D-printed nodes, 15 kg for the timber, and 3 kg for bolts, washers, and nuts. Despite its lightweight design, the structure performed well in terms of strength and stability. However, a few days after assembly, the team noticed that the tip of the canopy had lowered significantly. By design, the tip of the canopy – the highest point of the structure – was intended to be 2.89 meters above the ground. Immediately after assembly, this height was 2.50 meters, which was initially attributed to natural adjustments in the structure due to the changes made during assembly.

A week after the assembly (Day 17), the deflection became more noticeable, so the team began measuring it (Figure 13). This coincided with a summer rain



Figure 12.
Assembly process of the second prototype

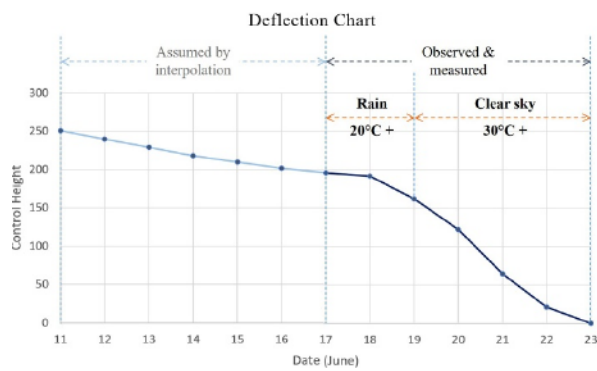


Figure 13.
Deflection of the canopy

and a slight increase in temperature (above 20°C). Over the following days, temperatures rose above 30°C, causing the nodes to literally melt. This led to significant deflections in the canopy, and eventually, the tip of the canopy touched the ground.

The water absorbed by the battens was not a factor in the overall strength of the new prototype (Figure 14a). However, due to the extreme deformations experienced by the structure, almost all nodes suffered some degree of damage. Common types of damage included torsional, shear, and bending moment-induced failure (Figure 14b). The size of the nodes also influenced their behavior during the extended deformations caused by the hot weather. For example, smaller nodes tended to become more flexible and absorbed most of the rotations by deforming their boxes. In contrast, most of the larger nodes developed cracks due to their lack of ductility – except for the node depicted at the bottom of Figure 14c, which suffered no damage whatsoever.

5. DISCUSSION: REFLECTIONS ON FAILURES BETWEEN ITERATIONS

5.1. Considering the iterative process in the schedule

During the production and assembly phases, the team learned that the design-to-production process is inherently iterative. Problems identified during production often required a return to the design phase, where adjustments were made. While the first two stages of the course were completed more or less according to the original plan, the design and 3D printing of the nodes took up most of the remaining time (Table 4). The most obvious omission in the original schedule was the lack of adequate time allocated for the iterative process – particularly for revising the node designs. The original versions were full of mistakes, and the reprinting of the nodes was required not only due to design changes but also because of adjustments in printing settings, such as infill percentage, printing orientation, and filament type.



Figure 14.
Performance of the nodes during the extreme deformation of the canopy

Table 4.
Implemented schedule

week	main activity	tools / equipment
2 - 3	lectures on form-finding methods & gridshell structures (principles)	none
4	workshop on funicular models & design competition explained	spare fabric & melted candle wax
5	Selection of proposal for prototyping	visualizations - Rhino / GH models
6	Redesign of the selected proposal & 3D model development	Rhino / GH models
7	Final design was ready / Column nodes are distributed among students for design	Rhino model
8	All column nodes were ready	Rhino model
9 - 11	Column: 3D printing (after G-codes are prepared) & preparation of timber battens; Canopy: design of nodes is developed	Rhino model, Prusa / Wanhao / Creality 3D printers, Prusa Slicer, Timber (@University's workshop)
12	Assembly test of the column	basic power tools
13 - 15	Canopy: All nodes are designed and 3D printed. Preparation of all timber battens.	Rhino model, Prusa / Wanhao / Creality 3D printers, Prusa Slicer, Timber (@University's workshop)
16*	Full assembly of the first prototype	basic power tools, scaffolding

* After all semester final exams were over

5.2. Technology revisited: the importance of leveling software and tools

Three major factors related to technology influenced the delays and iterations throughout the entire process. First, a lack of awareness regarding incompatibilities between Rhino and other software created complications in the production process and led to significant time losses. These experiences have shown that software compatibility should be considered at the outset of the design process to avoid such issues in the future.

Second, variations in printer quality further complicated the process, producing nodes with inconsistent strength. The resulting design changes in the canopy caused connection problems with the battens and extended both the redesign and reprinting phases.

This study also examined the structural capacity and durability of nodes produced with 3D printers, highlighting the strengths and limitations of the technology. The issues encountered with the PLA+ nodes in the column section of the first prototype underscored the importance of selecting the appropriate material based on the expected environmental conditions. This aligns with findings of previous research (Morales-Beltran et al., 2021), which emphasized the need for careful material selection and early-stage planning to mitigate structural integrity issues in digitally fabricated designs.

5.3. Learning from failure as preparation for professional life

The project emphasized teamwork, allowing students to collaborate on the design, fabrication, assembly, and disassembly of a gridshell prototype. This required coordination among team members and provided them with valuable opportunities to develop communication skills. As Carpenter (1997) noted, “students learn that architecture is a collaborative effort and not an exercise in isolation.” For the students, adapting to challenges and rapidly solving problems based on lessons learned was crucial in overcoming obstacles. Effective time management also played a key role in the successful completion of the project, from initial design to final assembly. Creating and adhering to a clear timeline was essential to avoid delays.

This aligns with the construction industry's need for graduate architects who not only possess modern technological and computational design skills but also the ability to oversee and manage project development and construction processes (Chan Edwin H. W. et al., 2002). The knowledge and experience gained from this course will significantly enhance students' ability to improve and expedite the design, production, and assembly of building structures and components.

6. FUTURE WORK

The project demonstrated both the structural possibilities and limitations of 3D-printed nodes in challenging cantilever gridshell structures. It also identified key parameters for node design and material selection, highlighting the importance of considering these factors for the success of similar projects, particularly with respect to environmental conditions.

Based on these findings, future research could focus on material diversity and the use of different or composite materials to enhance the durability of structures, especially in the context of hybrid fabrication under extreme environmental conditions. Experimenting with various climatic conditions can help optimize material and design choices for specific environments.

Additionally, while there is abundant research on the material properties of common filaments used in 3D printing, much less attention has been paid to the design of the nodes, particularly when connecting elements made of different materials (i.e., hybrid fabrication). The connection type used in this project provided sufficient bending capacity but also allowed water to accumulate when the structure was exposed to rain. A more refined design could incorporate gutters or drainage features to allow water to escape, helping the timber dry properly. This simple adjustment would prevent damage to the nodes, and future research in this area is needed to explore such solutions.

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Appendix 1 – Credits / Full list of participants

Course: ARCH4480 Advanced Construction and Structural Systems, Department of Architecture, Yasar University, Izmir, Türkiye

Semester: Fall 2022 (second prototype was built in summer 2023)

Instructor: Mauricio Morales-Beltran, PhD

Gridshell Canopy Structure

Original Design Proposal: Gökalp Kalfa, Zehra Çelik

Prototype Design: Mauricio Morales-Beltran, Gökalp Kalfa

Design of the Nodes (1st Prototype): Gökalp Kalfa, Elif Kır, Ece Hepmutlu, Zeynep Diker, Emirhan Duğral, Zehra Çelik, Berkin Değirmenci, Ecenaz Adıgüzel, Bengisu Şengün, Murat Şen, Mauricio Morales-Beltran

Redesign of the Nodes (2nd Prototype): Gökalp Kalfa, Elif Kır, Ece Hepmutlu, Zeynep Diker, Mauricio Morales-Beltran

3D printing: Mauricio Morales-Beltran, Elif Kır, Gökalp Kalfa, Ece Hepmutlu

Timber cutting (YUTAM): Soner Batı (YUTAM), Mauricio Morales-Beltran, Elif Kır, Ece Hepmutlu

1st Prototype assembly: Gökalp Kalfa, Mauricio Morales-Beltran, Elif Kır, Ece Hepmutlu, Zeynep Diker, Emirhan Duğral, Zehra Çelik, Berkin Değirmenci, Ecenaz Adıgüzel, Murat Şen, Ecenur Kızılörenli

2nd Prototype assembly: Gökalp Kalfa, Mauricio Morales-Beltran, Elif Kır, Ece Hepmutlu, Zeynep Diker, Utku Özer, Göktuğ Ünlü, Denizhan Şallı, Ecenur Kızılörenli