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PREPARED SYNTHETIC WOOD BEAMS: THEIR FEASIBILITY AND POSSIBLE DEVELOPMENTS IN ARCHITECTURAL DESIGN

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ABSTRACT: This study presents the concept of a “Prepared Synthetic Wood Beam,” a glued-laminated wood beam with a deformed section designed for specialized applications in building elements such as roofs, claddings, and louvers. We have developed various beam profiles integrated with environmental functions, including heat collection, water retention, and natural light diffusion, to enhance their applicability in functional architectural designs. Based on this concept, multiple design proposals were developed to evaluate its feasibility in timber architecture.

KEYWORDS: glued-laminated wood, deformed section, lateral deflection, axial torsion, biomimetic architecture

1 – INTRODUCTION

This study develops the “Prepared Synthetic Wood Beam,” a glued-laminated synthetic wood beam with a deformed section tailored for specialized architectural applications.

During the 1960s and 1970s, reinforced concrete beams were subjected to similar technical advances. Notable examples include industrial buildings featuring repetitive beams designed by Angelo Mangiarotti [1] and the post-tensioned shell beams used in the Kimbell Art Museum by Louis I. Kahn and August E. Komendant [2]. In timber construction, a well-known handbook documented various sectional configurations of standard wood members [3] .

The authors thought it is highly beneficial to pursue this approach further due to the inherent advantages of wood, such as its adaptability to complex prefabrication, high strength-to-weight ratio, effective thermal insulation, and potential for carbon sequestration. By using these attributes, we develop timber building that integrate biomimetic systems.

Figure 1 illustrates our fundamental concept: in nature, plants mediate direct sunlight by reflecting and absorbing rays, regulate water through collection, absorption, evaporation, and redistribution, and contribute to stabilizing the climate while simultaneously providing oxygen, food, and energy. As essential mediators between natural and human environments, plants offer an architectural innovation model. How can we develop architectural solutions that achieve a similar level of sophistication? This question serves as the fundamental motivation for this study.

The term “prepared” in the title is inspired by John Cage’s *Sonatas and Interludes for Prepared Piano*, in which a conventional instrument is modified to produce

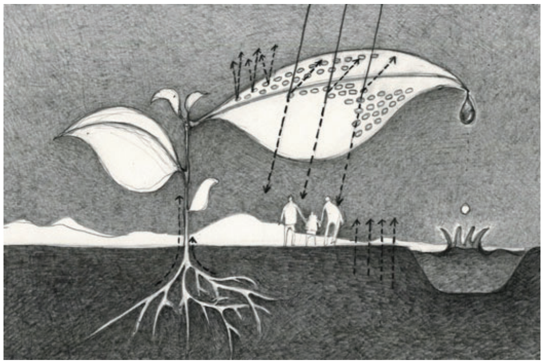

Figure 1. PLANT as the most fundamental mediator between natural and human environments: a concept sketch

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unique musical expressions. Similarly, the proposed approach transforms standard structural elements into specialized components that are optimized for specific architectural functions.

2 – BACKGROUND

2.1 PLANT-MIMETIC VISION

This section explains the technical concept derived from the "plant-like" system. Unlike animals, which rely on central controllers (such as brain) and engines (such as the heart), plants are separate from most engineering systems, including air conditioning in buildings.

In plants, functions are distributed throughout their structure and are driven by minimal pressure differences created by osmotic, vapor, capillary, thermal, and mechanical phenomena. Their morphological structure mainly consists of tube or fiber bundles and membrane layers. These micro-functional elements operate independently without central control but remain organically synchronized.

There are many things that designers can learn from plant systems. Although this concept may appear new, it is, in fact, a dominant strategy in nature. Plants serve as fundamental mediators between natural and human environments, whereas architectural efforts represent only a small component of this larger system. In this context, timber architecture should evolve beyond mere construction materials. Instead, wood should be regarded as an idealistic resource and/or functional stimulator. This approach would elevate timber architecture beyond a superficial "eco-friendly" esthetic, in which timber is only used as cladding in conventional building designs.

2.2 FUNCTIONS TO BE IMPLEMENTED

Under this vision, various beams with deformed cross-sections (e.g., The U-, Y-, and T-shapes) can serve as functional elements. These beams span between 9 and 12 m, are arranged repetitively to form an integrated and functional roof system. The expected functions include the following:

Functions related to water:

Rainwater is an essential resource for all life forms on Earth and plays a crucial role in thermal and potential energy systems. U- or V-shaped beams can collect, store, and channel water to designated locations. These beams can also function as planting pots. The incorporation of sponges and splays, they may serve as absorbers or evaporators, helping to regulate the thermal conditions of interior space. To achieve these functions, effective water-sealing techniques are essential, ideally without on additional materials such as sheet metal roofing.

Functions related to sunlight:

Sunlight is the most effective natural light source for interior spaces when properly managed. To moderate direct sunlight, architects have developed numerous daylighting techniques, including skylights, clerestories, diffusers, louvers, and reflectors.

Solar energy is an inexhaustible power source that drives nearly all natural processes on Earth. Solar cells can be integrated on these beams at optimal angles and connected to electrically conductive sheets embedded between lamina layers.

Functions related to heat:

Heat can be harnessed through solar collector that generate hot air, water, or other media for energy circulation within the building. This technique can be combined with solar cells in a "co-generation" system. Cooling function can also be realized through nighttime radiation or by using accumulated snow on the roof.

By incorporating Phase Change Materials (PCMs), wood can function as a thermal storage medium. Many PCMs, primarily paraffin waxes, can be absorbed into the cavities within wood fibers. This integration allows timber floors and walls to act as thermal stabilizer, regulating indoor temperatures.

Additionally, dissolving wood fibers and expanding them into a cotton- or sponge-like foam can produce high-performance thermal insulation materials. Placing these materials in the central part of beams or panels can reduce thermal transmission losses while maintaining the overall rigidity of the structure.

Functions related to air:

Ventilation, air cleaning, and purification functions can be incorporated through features such as louvers, slits, and shutters. Wind energy can also be used as a mechanical force to drive vertical tubes equipped with serial micro check valves, functioning as natural pumps.

Wind pressure conducted through wood could also generate electricity using piezoelectric cells. This energy could power microcontrollers or LED sanitizers embedded within the wood structure.

Functions related to vibrations:

Plywood shock absorbers are widely used in furniture design. Additionally, traditional Japanese tatami mat serve as notable examples of multipurpose cushion or dumping element in building construction. Integrating similar shock-absorbing features into timber structures could enhance their performance in reducing vibrations and impacts.

2.3 LEVELS OF BUILDING COMPOSITION

In general, a building is an assembly of materials or components arranged in staged compositions at different levels. Figure 2 illustrate this concept, referred to as “compositional levels.” The upper represents various building components at different levels, while the lower row outlines the corresponding manufacturing or processing methods at each transition. The figure indicates that materials are combined to certain building elements, which are then assembled into spatially contained structural units. These structural units are subsequently integrated to create the complete building structure.

In timber construction, various wood-based materials undergo processing to form planer elements such as lumber, plywood, laminated veneer lumber (LVL), cross-laminated timber (CLT), and glued-laminated (glulam) beams of different rectangular cross-sections. These elements are then assembled into trusses, frames, folded planes, and box structures, which function as structural units. These structural units are aligned, connected, or accumulated to form the overall building framework.

Prepared synthetic wood beams are categorized under building elements in the chart. However, unlike conventional stick and planar elements, they possess inherent functional capabilities. Typically, environmental functions in building such as air conditioning, piping, and electrical distribution, are provided by independent systems that are attached to the building framework. In contrast, prepared synthetic wood beams represent an evolutionary step in integrating these functions at the building element level, similar to the structural adaptations seen in plants.

2.4 DESIRED SUPPORTING TECHNIQUES

To integrate functional capabilities into timber elements, further advancements in a broad range of wood-related technologies are required. Below is a comprehensive overview of the key technological developments needed:

Assembling and connecting techniques:

Adhesive technology is essential for prepared synthetic wood elements. Although various adhesives already available, there is a demand for more organic and durable materials. Lignocellulose-based adhesives seems to align with current sustainabilty requirements.

At the frame construction level, a broader range of mechanical connections is necessary. For example, bamboo nails, traditionally used to secure roofing shingles in Japanese architecture, have demonstrated long-term durability. Biscuit joints, commonly used in furniture manufacturing, hold potential for further adaptation in large-scale building application.

Lining and laminating techniques:

To achieve water resistance in roofs and piping, lining or laminating technics are employed to attach a water-resistance membrane, such as metal foil or plastic sheets, to timber elements. For fireproofing applications, aramid paper may serve as a suitable material for combination.

When using small pressure differences to circulate water or air, pressurized cavity performance is necessary. Ensuring leak-proof and non-inflating cavities is essential for maintaining functionality.

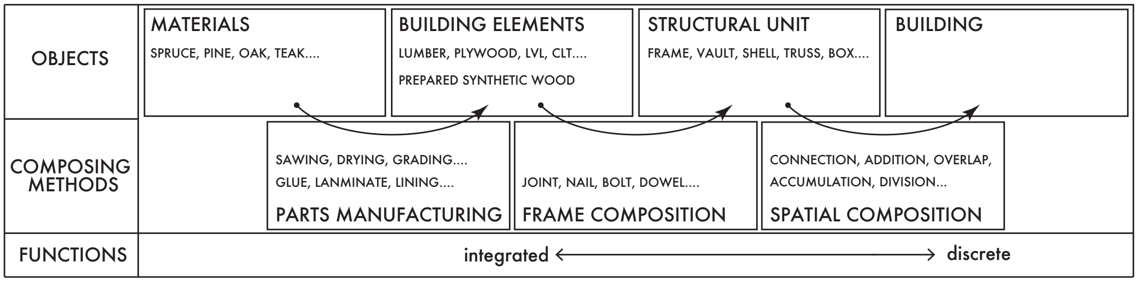

Figure 2. Compositional levels of building construction and functional integration

Foaming and filling techniques:

To minimize heat loss and improve air conditioning efficiency, reducing thermal conductivity through the building enclosure is essential. Foaming and filling techniques can be applied to enclosing elements to enhance insulation performances while simultaneously reducing weight.

Infiltration and coating techniques:

To apply corruption-resistant solvent, heat storage wax, or similar functional materials, infiltration techniques are necessary. Additionally, an appropriate coating must be applied to prevent leakage of absorbed materials.

Continuous molding techniques:

To achieve high production efficiency, a continuous molding process is preferable. Traditionally, glued-laminated wood members are manufactured individually, clamped along their full length within a jig. If a serial processing system can be implemented, including glue application, clamping into the desired shape, hardening, and finishing in a continuous manner, productivity would significantly surpass current manufacturing methods. This advancement would also allow for greater formal variation and customization.

3 – PROJECT DESCRIPTION

To explore the broad range of issues, demands, and possibilities, this study incorporated the following steps:

1) Developing sectional variations of beams and classifying them morphologically (Section 4.1).

2) Conducting bending tests on scale-model specimens to analyze the structural tendencies of different sections and provide recommendations for further developments (Section 4.2).

3) Creating design proposals that demonstrate nature-friendly architecture and plant-mimetic applications of beam sections (Section 4.3).

Finally, key research elements, including expected applications, research objectives, required techniques, and available resources, were systematically mapped to provide a comprehensive overview of the feasibility of the proposed synthetic wood (Chapter 5). All design outcomes were modeled Japanese cypress (Hinoki) in archival quality to showcase the potential of this concept for architectural applications.

4 – DESIGN PROCESS

4.1 CREATING SECTIONAL VARIANTS

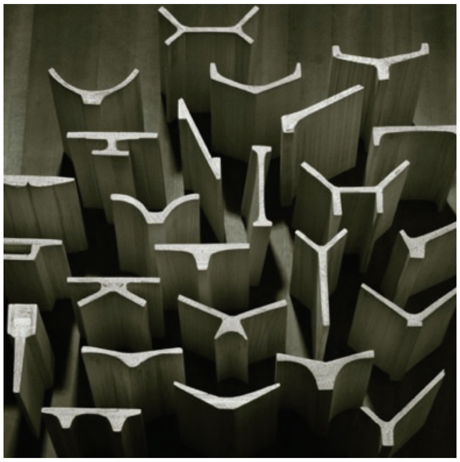

Figure 3. Sectional variants developed for prepared synthetic wood beams

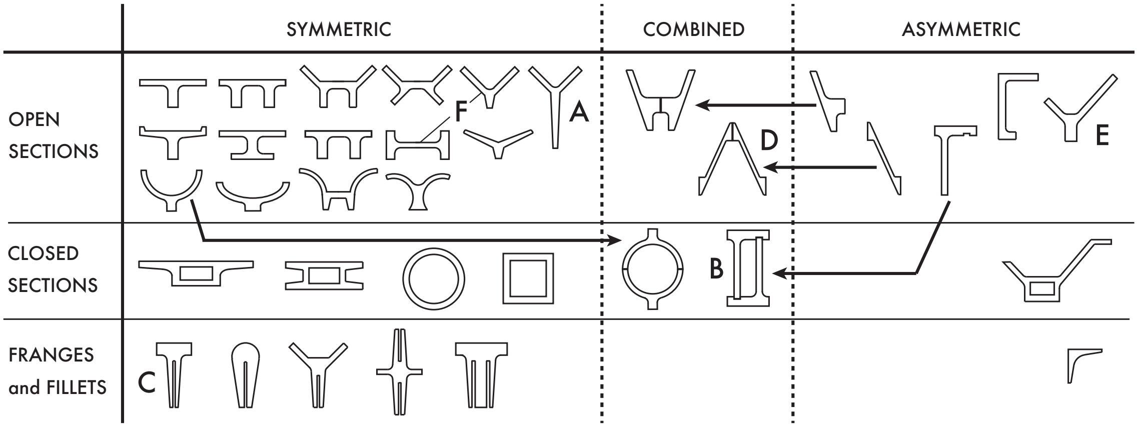

Figure 4. Sectional variants classifications

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Figure 3 illustrates the variety of sectional models developed during the initial stage. These sections can be used for roofing, lighting louvers, and other purposes. Each section is designed to remain constant along its length. Adequate fillets were applied at the corners to mitigate excessive stress concentration.

Figure 4 presents the morphological classification of the sectional variants based on the contrasting characteristics of symmetry versus asymmetry and open versus closed sections. Open sections seem to be more feasible for manufacturing, whereas closed sections offer advantages for applications such as pipes and ducts.

Closed sections can be created subsequently by combining multiple members, either different or identical in sectional shape. This technique is particularly useful for accommodation various functions while simplifying the manufacturing process.

The bottom row of the chart showcases the application of reinforcing flanges, joiners, or molding fillets for LVL panels. These prepared components are intended to facilitate the construction of long-span beams on-site.

4.2 SCALE-MODEL EXPERIMENT

To investigate the general bending characteristics of a diverse range of sections, a 1/20 scale-model experiment was conducted, with result previously reported in 2016 [4] in Japanese. Here, we present the key findings and discussion.

Scale-model experimentation is advantageous in the early stages of development, allowing for the exploration of various shapes within a short timeframe and at a lower costs. All specimens were 1/20-scaled wooden models, each measuring 450 mm in length, designed to span 9 m at 900 mm intervals in real scale. The testing method employed four-point bending, as depicted in Figure 5. According to Japanese regulations, the deflection ratio must remain below 1/300 under the specified snow load.

Figure 6 presents the experimental results. None of the specimens exhibited critical failure, such as fracture or excessive elastic deformation. The bending rigidity of the symmetric-sectioned specimens exceeded the target value and corresponded with calculated predictions, whereas the asymmetric-sectioned specimens significantly underperformed in comparison to both the target and calculated values.

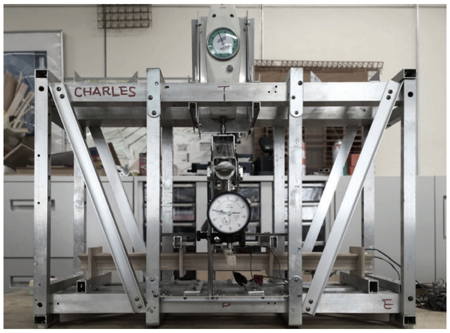

Figure 5. Setting of the scale-model experiment

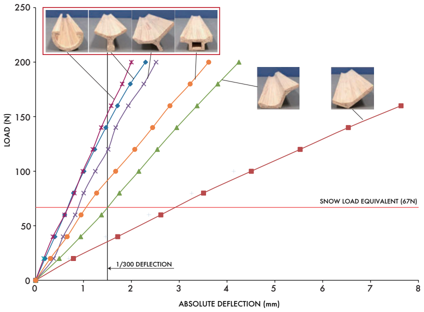

Figure 6. Load vs absolute deflection relationship

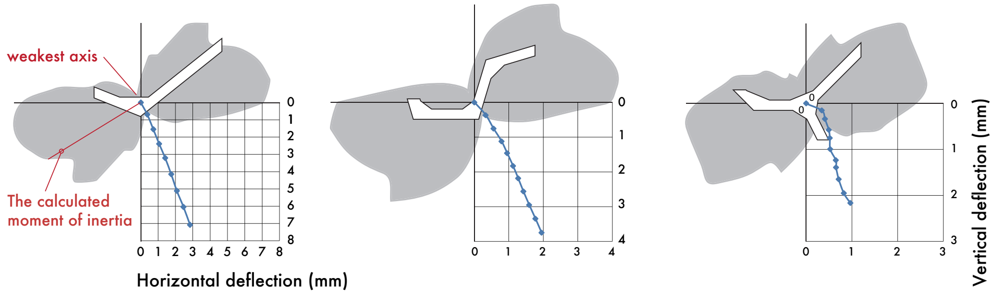

Figure 7. Swaying deflection caused by the asymmetric distribution of moment of inertia

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This discrepancy arose from the asymmetric distribution of the moment of inertia around the beam axis. Figure 7 illustrate these relationships, displaying the calculated moment of inertia profiles for each asymmetrical section alongside the experimental results for vertical and horizontal deflections. The findings indicate that deflections followed the weakest bending rigidity axis, resulting in substantial reductions in bending performance.

These results suggest a potential risk of beam deflection due to swaying and/or torsional displacements. This risk may be intensified by the asymmetrical distribution of dead or live loads on the beams. Designers are advised to carefully account for these structural planning.

4.3 DESIGN PROPOSALS

This section presents design proposals demonstrating how prepared synthetic wood beams can be used in innovative ways, leading to fresh architectural forms.

An open-air concert hall with Y-shaped louvers (A):

Figure 8 (a–c) depicts an outdoor concert hall incorporating Y-shaped beams (Figure 4, A), which serve as large horizontal louvers at the sides. These louvers function as spaced roofing elements for rain protection and sunlight reflection. The beams are fixed to primary bracing columns, with the two flanges of the Y-beam intersecting at a right angle to form an inherently rigid joint. In this case, one flange is cut out to fit into the columns, while the other is positioned against the column surface to secure the slant. This design is well-suited for moderate climatic conditions or seasonal use, similar to the Tanglewood Concert Hall near Boston, utilizing its open design to eliminate the need for thermal control systems.

A gymnasium with a solar-collecting membrane roof with box rafters (B):

Figure 9 (a–c) illustrates a gymnasium featuring a solar collector integrated into the roof structure. The collector

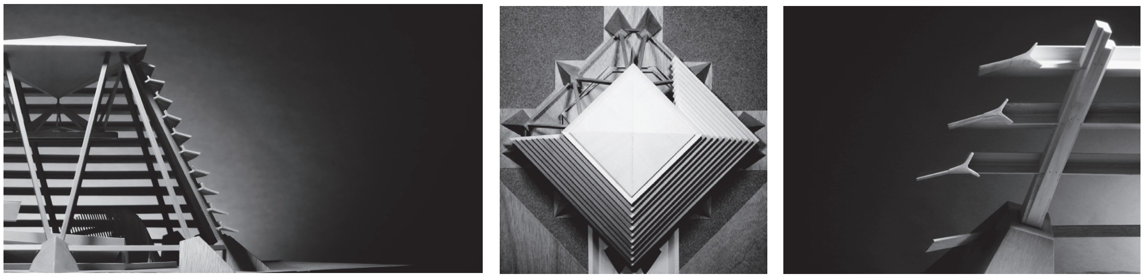

Figure 8 (a–c). An open aired concert hall with Y-shaped louvers (Figure 4, A)

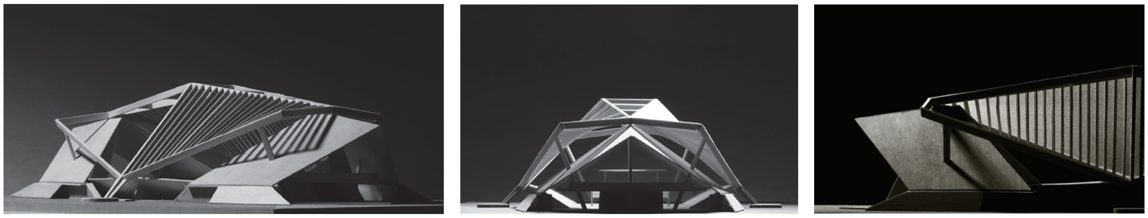

Figure 9 (a–c). A gymnasium with dual membrane roof supported by closed section rafters (Figure 4, B) used for solar energy collector.

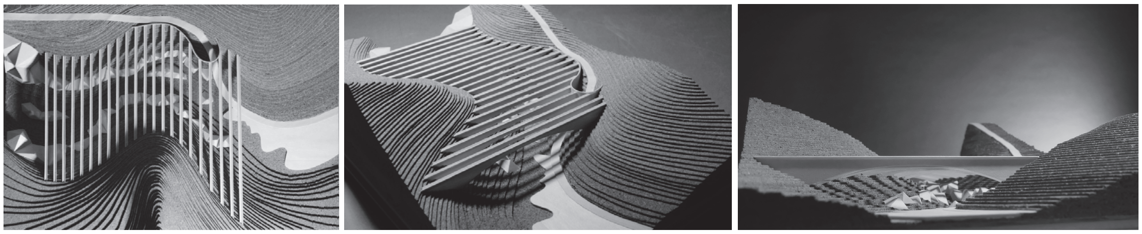

Figure 10 (a–c). A gigantic repetition of arches combined with LVL and prepared flange (Figure 4, C) over the river spa to make natural space being interior atmosphere.

comprises double-sided membrane surfaces attached to repetitive piping rafters, which consist of paired asymmetrical-sectioned beams (Figure 4, B).

In this system, solar-heated air is drawn upward into the rafter pipes and circulated downward for space heating. Since air leakage has minimal impact on wooden materials, it serves as an efficient heat conveyor. The collector adopts a hyperbolic shape, ensuring a consistent heat collection output despite variations in the sun's angle.

A roof bridging over a natural river with flanged LVL beams (C):

Figure 10 (a–c) showcases a long-span repetitive bridges constructed over a river featuring a natural spring spa. This structure creates an enclosed yet natural atmosphere by transforming the surrounding environment into an interior-like space. Due to the varying span lengths influenced by the terrain, an arched beam profile is ideal for reducing dead load and material consumption.

This challenge was addressed by combining prepared synthetic wood flange (Figure 4, C) with LVL webs. This configuration allows the web height to be adjusted according to structural demands, optimizing material use. This proposal exemplifies how minimal artificial interventions can humanize natural outdoor spaces while preserving their inherent characteristics.

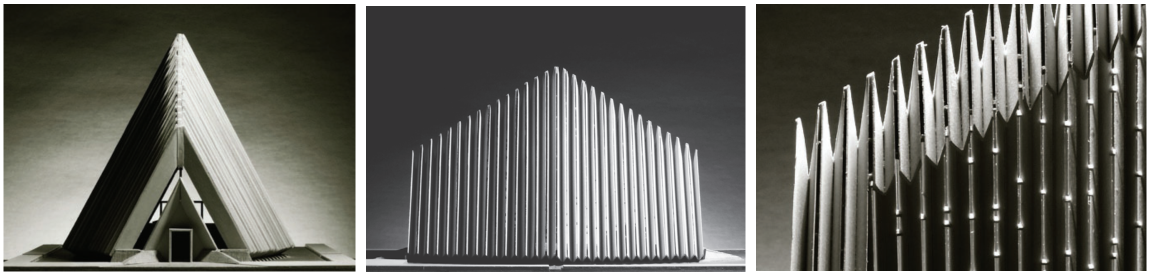

Figure 11 (a–c). A chapel with splitted A-shaped rafters (Figure 4, D) sandwiched with transparent layers introducing natural light.

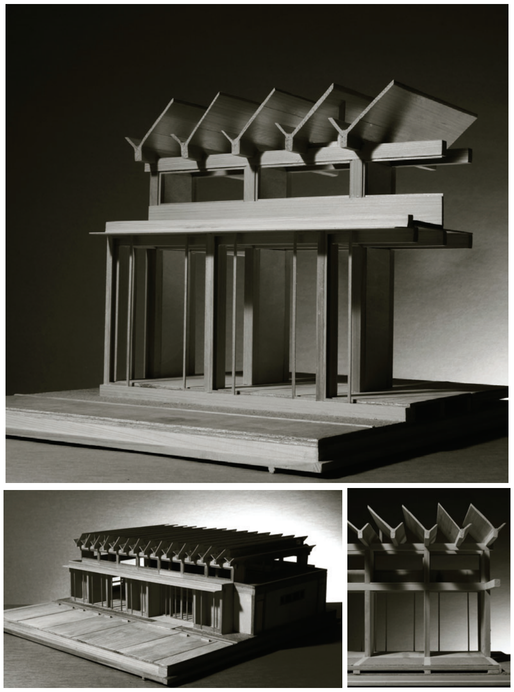

Figure 12 (a–c). A drugstore with asymmetrical Y-shaped beams (Figure 4, E) served as top lights, solar cells, and water collecting girders.

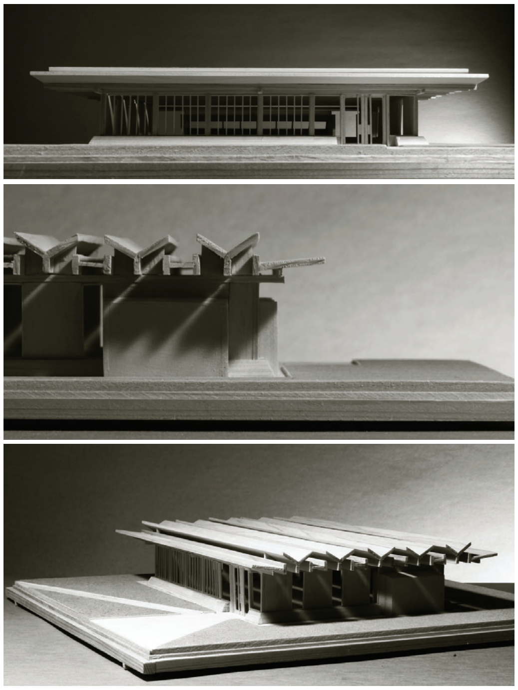

Figure 13 (a–c). A canteen with repetitive Y-shaped and H-shaped beams (Figure 4, F) composing continuous natural lighting fixture.

A chapel composed of splitting A-sectioned rafters sandwiched with transparent material (D):

Figure 11 (a–c) illustrates a chapel constructed using splitting A-shaped beams (Figure 4, D), with transparent material (sheet glass) inserted at the ridge joints of the wood section. The beams are slightly offset from each other, forming a diamond-shaped volume. The slits serve as lighting inlets, creating an impressive glowing effect within the interior space, resembled the experience of natural light filtering through fractures in wood, producing diffused light nodules.

A drugstore with a roof with asymmetric Y-shape beams (E):

Figure 12 (a–c) presents a drugstore featuring asymmetrical Y-shaped beams (Figure 4, E) which facilitate the integration of top lights and support solar panels. The structure beneath the roof follows a Japanese conventional frame construction system, onto which the beams are set. To mitigate excessive shearing stress concentration, the beams are supported at the intersections by double girders on each side. This proposal aimed to demonstrate the applicability of the new building element within conventional constructions practices.

A canteen with a roof combining Y- and H-shaped beams (F):

Figure 13 (a–c) showcases a canteen building with a roof structure that integrates Y-shaped and H-shaped beams (Figure 4, F) providing water girders and top lighting. This design proposal sought to explore further architectural possibilities by combining beams of different sections. The beams extends far beyond the building's spatial profile, emphasizing horizontality and ensuring ample coverage of the interior space.

5 – RESULTS

Figure 14 provides an overview of the feasibilities and challenges discussed thus far. Several technical advancements are required to realize the ideal of plant-mimetic architecture. One significant are of development is "Combined Material" (bottom left) and the associated advancements in "Manufacturing Method" (top left), which aim to maximize the exposure of timber members as primary structural elements. Another key focus is accumulating technical trials related to "Integrated Function" (top right) to uncover advanced design feasibility. It is evident that a series of structural experiments will be necessary to address the challenges identified in the "Structural" domain (bottom right).

6 – CONCLUSION

As depicted in Figure 14, the feasibility of prepared synthetic wood, one potential path toward plant-mimetic timber architecture, can only be achieved through interdisciplinary advancements. This process aligns with the principles of "technical ecology," requiring continuous and steady evolution.

With this evolution, the perception of architecture will also shift. The high-tech approaches, which precise control over confined interior environment, may give way to a more natural and organic vision, one that embraces subtle, non-intrusive modifications to the natural environment to enhance humanized cultural

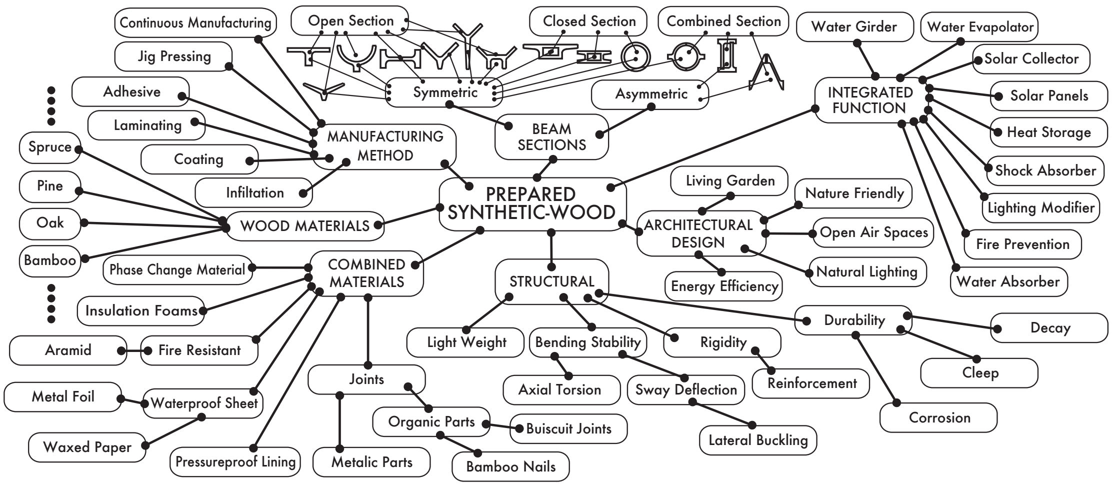

Figure 14. Research agenda conceptually mapped around prepared synthetic wood

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living. This concept is not entirely unfamiliar; many traditional architectural practices have yielded sophisticated and sustainable outcomes, offering valuable lessons and insights.

The map illustrates a diverse intellectual landscape shaped by independent yet interconnected research interests. To achieve tangible outcomes, coordinated and cross-disciplinary collaboration will be essential.

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