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Tubular veneer timber: structural testing and flat pack self-shaping for ultra-light, cylindrical wood components

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ABSTRACT: Traditional solid wood structural elements often suffer from inefficiencies in material usage and transportation, while hollow-section structural components are commonly fabricated from carbon-intensive materials such as steel, aluminum, and concrete. Tubular Veneer Timber (TVT) seeks to present a more sustainable alternative by utilizing wood's hygroscopic properties as a shaping mechanism to create super-thin-walled, hollow cylindrical members. TVT is constructed from multiple layers of peeled, thin veneer sheets that are laminated together and programmed to self-shape into tubes as they dry which may significantly reduce material waste and transportation volume comparatively.

This research investigates the structural performance of Tubular Veneer Timber, with a focus on its compressive strength and the consistency of its ability to hygromorphically self-shape. Manufacturing methods include vacuum and hydraulic pressing techniques to laminate veneer layers, followed by controlled air-drying to achieve a targeted cylindrical geometry. Compression testing evaluates the load-bearing capabilities of TVT to assess its viability for structural applications. Initial findings indicate that TVT exhibits a high strength-to-weight ratio while offering substantial material and logistical efficiencies. This study contributes to the growing body of research on bio-based, responsive materials and highlights TVT's potential for reducing the carbon footprint of the construction industry.

KEYWORDS: cross laminated, hygroscopic, material programming, structural testing, wood bilayers

1 – INTRODUCTION

The construction industry is a major contributor to global carbon emissions, with cement accounting for a significant share of embodied carbon in buildings and infrastructure [1]. In response to this situation, the architecture, engineering, and construction industry has responded with several initiatives to challenge designers to reduce embodied carbon and greenhouse gas emissions such as Architecture 2030 and SE 2050 [2], [3]. Among these alternatives, wood has shown strong potential due to its renewability, carbon sequestration potential, and ability to be sourced sustainably.

Tubular Veneer Timber (TVT) utilizes the hygroscopic properties of wood to form self-shaping, lightweight, and structurally viable cylindrical elements. A key enabling aspect of TVT is its use of peeled veneer rather than sawn boards, distinguishing it from other self-shaping wood research. The peeling process allows for the efficient use of smaller logs, making it a more sustainable approach to wood utilization. While veneer-based products often require more adhesives, TVT mitigates this by using only two layers which reduces adhesive consumption. By leveraging a renewable resource in wood, TVT can potentially reduce reliance on materials with carbon-intensive processes.

To explore the use of TVT further, this research aims to advance the understanding of TVT, particularly its hygroscopic self-shaping, manufacturing process, and compressive capacity. The results of this research will enable researchers to determine the initial viability of TVT for load-bearing applications and the potential of

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TVT to reduce carbon emissions associated with material transport, as it may be able to be packed flat and shape on site.

The scope of this investigation includes the consistency of TVT manufacturing, reliability in actuation, and the compressive capacity of TVT. By addressing these factors, this research contributes to the broader efforts of integrating sustainable, high-performance materials into the built environment.

2 – BACKGROUND

Self-shaping materials have been explored for their potential to create dynamic, responsive structures. Solid structural elements, while widely used, can be less efficient compared to hollow structures in terms of material use and load-bearing capacity. Research in lightweight structural optimization suggests that hollow geometries, such as tubes, can offer superior strength-to-weight ratios while reducing material consumption [4], [5]. This efficient volume is commonly observed in both engineered and natural structures, where tubular configurations allow for increased stability with minimal material use [4], [5], [6].

Hygroscopically actuated wood bilayers have been extensively studied for their ability to undergo shape transformations based on moisture fluctuations [7], [8], [9], [10], [11]. This self-shaping behaviour has been leveraged to create passive responsive elements for architectural applications [13], [14], [15], [16]. Research on programmable wood veneer structures has demonstrated the viability of using differential swelling properties to achieve complex curvatures without using force during the actuation process [9], [14], [17], [18]. Such studies lay the foundation for utilizing self-shaping wood in structural applications, particularly in semi and full cylindrical forms.

Tubular structures have long been recognized for their ability to efficiently distribute loads while minimizing weight. Hollow cylindrical forms, commonly used in materials like steel and concrete, provide high strength-to-weight ratios and resistance to bending and torsion [4], [6], [16]. The principles of tubular strength have been applied across various disciplines, from aerospace engineering to architecture.

Investigating the feasibility of tubular wood structures involves rigorous experimental testing. Studies have examined how wood's mechanical properties change when formed into cylindrical shapes and subjected to different environmental conditions [6], [8], [15]. Computational and physical testing of self-shaping wood gridshells and veneer laminates have provided insight into their load-bearing capacities and deformation behaviours [7], [15], [19]. These studies focus on two primary configurations: fast-responding thin veneer bilayers that achieve high curvature with radii ranging approximately from 0.4 to 1.5mm [7], [8], and larger bilayers constructed from thicker boards or lamellae, which attain curvature radii in the range of 1 to 2 meters [15]. The studies found that self-shaping wood structures can achieve complex, controlled deformations under specific conditions that requires careful moisture control for long term stability. These results were achieved through digital modelling and some physical testing wood species such as Beech and Spruce to predict deformation. These studies did not provide specific data on the compression capacities of these materials or explicitly assess their viability as structural components. However, such research is critical supporting evidence when analysing the structural viability of Tubular Veneer Timber (TVT) and similar forms.

Efforts to produce hollow wooden tubes have been attempted with research demonstrating the potential of veneer-based timber circular hollow section (CHS) beams as efficient load-bearing elements [6]. The study demonstrated that CHS beams exhibit predictable failure modes, such as local buckling, and can be optimized by considering cross-sectional slenderness and material properties. These findings support the continued exploration of tubular timber structures for lightweight and sustainable architectural applications.

Architect Shigeru Ban has demonstrated the architectural potential of tubular materials through his work with paper tubes. His projects, such as the Paper Dome and emergency shelters, highlight how cylindrical forms can be structurally efficient and more sustainable than their steel and concrete counterparts [10], [12], [18], [19], [23]. Studies on paper tube construction and load-bearing capabilities provide valuable parallels for exploring similar concepts in wood veneer [19], [22], [23].

The current research landscape surrounding hygroscopic self-shaping wood structures includes studies on material properties, computational modelling, and full-scale applications [13], [15], [17], [24]. Investigations into climate-responsive envelopes and adaptive architectural systems further contextualize the potential of self-shaping wood for structural innovation [9], [13], [14], [15], [17], [18]. As sustainable material solutions gain prominence, understanding how self-shaping wood can contribute to efficient structural systems remains an essential area of study.

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3 – PROJECT DESCRIPTION

This research investigates the consistency in manufacturing, hygroscopic responses, and compressive strength of TVT columns. The study aims to quantify the reliability of member actuation and the variability of compressive material strength of TVT. By analysing these factors, the authors seek to further the reliability and applicability of TVT in architectural and structural applications.

Research Questions:

1. What is the variability in curvature across samples?
2. What is the compressive strength of TVT and what is the variability of this strength, and how do they compare to conventional cylindrical wood structures in load-bearing applications?

4 – EXPERIMENTAL

The study utilized 1/16" furniture grade maple veneer sheets sourced for their favorable density and consistent high quality. Veneer layers were cross-laminated to promote self-shaping behavior and structural integrity. Henkel Loctite HBX 602 polyurethane adhesive was used in cross-lamination to maintain flexibility while ensuring sufficient bonding strength between layers of veneer (Figure 1).

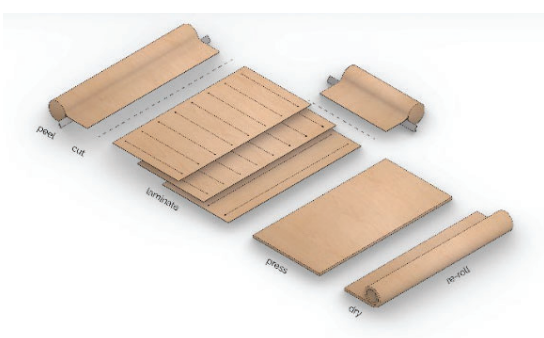

Figure 1. Diagram shows process of cutting veneer, layup and assembly, pressing and actuation.

Production was conducted in collaboration with the University of Oregon and Oregon State University through the Tallwood Design Institute. The fabrication process included two primary lamination techniques:

1. Vacuum Pressing: Used for the production of specimens in experimental set 1. Limited veneer to 4-feet in length.
2. Hydraulic Pressing: Conducted using a Minda TimberPress X 225 to apply controlled pressure for improved adhesion and uniformity for specimens in experimental set 2. This change in lamination techniques allowed for upscaling to 8-foot veneer laminations which is similar to construction-sized structural components.

Aside from differing lamination techniques, experimental sets 1 and 2 remained consistent in the type of adhesive used, application of adhesive, sourcing of veneer layers, and time allowed for samples to actuate before testing.

Following fabrication, samples were tested for compressive strength using a Forney testing machine per ASTM C39 [25]. The testing process measured load-bearing capacity and failure modes under compression. Data collected from these tests were further analyzed to evaluate variability in the data.

Future research will focus on establishing Douglas fir as a viable material for TVT, given its widespread use in the construction industry. Testing will begin by analyzing its adhesion and actuation quality. By refining fabrication techniques, this research aims to adapt TVT for broader application in mass timber construction.

5 – RESULTS

Compressive strength testing was conducted on both experimental set 1 and experimental set 2. Specimens from experimental set 1, which were fabricated in late 2023 and tested in February 2024, exhibited an average stress at break of 36.05 MPa with a standard deviation of 3.06 MPa (Figure 2). These results were calculated by taking the maximum stresses each specimen withstood, adjusted for its top and bottom surface area.

Maximum Compressive Stresses of Specimen in Experimental Set 1	
Specimen in Experimental Set 1	***Maximum Stress (MPa)***
Specimen 1	37.12
Specimen 2	30.40
Specimen 3	36.21
Specimen 4	36.82
Specimen 5	39.72
Average	*36.05*

Figure 2. Table shows compressive strength results from experimental set 1, showing average stress at break of 36.05 MPa and a standard deviation of 3.06 MPa.

In contrast, experimental set 2, which was produced between July and August of 2024 and tested in August of 2024, had a slightly lower average compressive stress of 35.06 MPa and a higher standard deviation of 5.90 MPa (Figure 3). The increased variability in experimental set

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2 suggests that external factors, such as seasonal humidity variations or minor deviations in the lamination process, may have influenced the compressive properties.

Maximum Compressive Stresses of Specimen in Experimental Set 2	
Specimen in Experimental Set 2	*Maximum Stress (MPa)*
Specimen 1	40.07
Specimen 2	39.83
Specimen 3	27.82
Specimen 4	38.04
Specimen 5	25.78
Specimen 6	38.80
Average	*35.06*

Figure 3. Table shows compressive strength results from experimental set 2, showing a slightly lower average stress at break of 35.06 MPa as well as an increased standard deviation of 5.90 MPa.

Compression testing of the TVT specimens revealed consistent failure patterns, primarily characterized by delamination along the edge face in contact with bottom teel retainer used to hold the cylinder in place within the Forney testing machine. This separation occurred at the adhesive interface, indicating a potential weakness in bond strength under compressive stress. Additionally, cracks propagated through both the inner and outer veneer layers which may suggest localized stress concentrations (Figure 4 & Figure 5). Several specimens also exhibited buckling, particularly in areas where veneer grain alignment may have influenced deformation behavior (Figure 4 & Figure 5). These failure modes highlight key considerations for refining the lamination process and improving the structural integrity of TVT under compressive loads.

Figure 4. Experimental Set 1 specimen 4 shows buckling, cracking and delamination after testing.

Figure 4b. Experimental Set 2 specimen 1 shows buckling, cracking and delamination after testing.

The results indicate that TVT maintains a high compressive strength-to-weight ratio of 64.7 MPa/kg across experimental sets 1 and 2, which reinforces its potential as a viable structural component. However, the increase in standard deviation in experimental set 2 suggests that factors such as fabrication seasonality, veneer grain direction, and pressing conditions may impact the consistency of mechanical properties. While the average stress at break remained comparable between the two sets, the higher variability in experimental set 2 warrants further investigation into process standardization to improve reliability.

The ability to predictably self-shape into cylindrical forms is a critical factor to test in understanding the viability of TVT as a structural system. The curvature of specimens was evaluated, and the curves were compared against an idealized curve with a 101.6mm diameter, one of the required diameters of the tubes per ASTM C39 (Figure 6). Across experimental set 2, the standard deviation of curvature measurements ranged from 6.00 mm to 7.98 mm looking at a given point, indicating moderate variability in the self-shaping process (Figure 7). The percentage error in curvature measurements was between 21% and 24%, suggesting that while TVT exhibits a reliable tendency to form tubes, there are inconsistencies in the final geometry.

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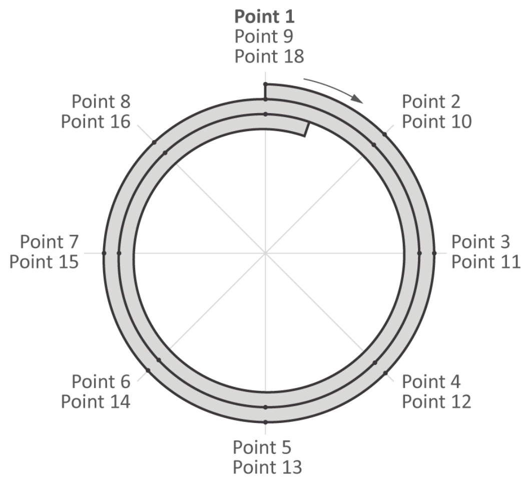

Figure 6. Diagram of curvature evaluation method, showing how points were taken along the spiralling edge of a specimen. Points were collected clockwise from the outermost edge to the interior of the spiral, working their way to the inside.

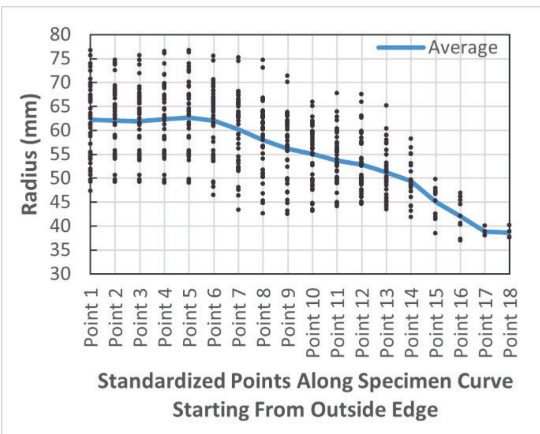

Figure 7. Scatter plot showing variation in curvature post-actuation in TVT specimens from experimental set 2. The blue line shows average curvature decreasing from the outer edge of the specimen to the inner edge of the spiral shape. The standard deviation of radii ranges from 6.00mm to 7.98mm point to point.

Several factors may have contributed to the variability in curvature, including differences in veneer grain direction, adhesion inconsistencies between veneer layers, and slight variations in lamination pressure. Additionally, specimens exhibited a degree of flexibility post-drying, which allowed for curvature adjustments using straps and clamps as restrictive devices. This suggests that while self-shaping is a key feature of TVT, some degree of post-processing or a strict quality control procedure may be necessary to achieve precise geometric tolerances for structural applications.

Due to the natural variability in self-shaping, 14 of the 20 specimens in experimental set 2 exceeded the 101.6 mm diameter constraint and could not be tested in the Forney testing machine. Six specimens from experimental set 2 met the dimensional requirements and were subjected to compression testing.

Additionally, the curvature inconsistencies and size constraints identified in this study suggest the need for tighter manufacturing controls or potential adaptations in structural testing methodologies. Future research should explore ways to refine the self-shaping process to achieve more consistent tube diameters, thereby expanding the range of specimens that can be subjected to standardized testing.

6 – CONCLUSION

The results of this study highlight both the potential and challenges of Tubular Veneer Timber (TVT) as a self-shaping structural system. The curvature analysis demonstrated moderate variability in actuation, with standard deviations ranging between 6.00 mm and 7.98 mm point to point and a percent error of 21% to 24% in experimental set 2. This suggests that while the self-shaping process is functional, additional refinement is needed to improve consistency. External factors such as veneer moisture content, pressing conditions, and seasonal fabrication differences likely contributed to the observed variation in final tube diameters.

Compressive strength testing yielded promising results, with average stress at break ranging from 35.06 MPa to 36.05 MPa. While experimental set 2 showed increased variability compared to set 1, the overall compressive performance indicates that TVT could serve as a viable structural component. The specimens were produced with the intention of fitting within the 101.6 mm diameter constraints of the Forney testing machine; however, this is not the average diameter that these maple TVT samples actuated to. Many specimens had finalized diameters that were too large to fit in the testing machine which resulted in specimens that went untested.

The failure patterns observed in compression testing such as consistent delamination, cracking in both inner and outer veneer layers, and buckling, demonstrate areas for further refinement in the TVT lamination process. These results suggest that improving bond strength or pressing quality could enhance structural performance under compressive loads. Addressing these challenges will be critical for advancing TVT as a reliable material for structural applications.

One of TVT's most compelling advantages is its ability to significantly reduce transportation volume through the flat-packing of its members during storage and transport. The transformation from a flat panel to a tubular form enables up to a 90% reduction in transport volume when comparing flat-packed TVT members to actuated TVT members. This could be particularly valuable for applications requiring lightweight, deployable structures, such as modular buildings or emergency shelters.

TVT shows strong potential as a lightweight, deployable, and more sustainable alternative to traditional hollow-section materials. Its use of two peeled veneer layers enhances material efficiency while reducing adhesive consumption. This method allows for the utilization of smaller logs and minimizes waste, making TVT a more sustainable alternative to sawn board-based options. Future research should focus on refining the self-shaping process to improve dimensional accuracy, exploring alternative testing methods and equipment for larger specimens, and investigating additional applications beyond compressive load-bearing structures. Potential use cases include temporary structures, scaffolding, and modular construction systems where rapid deployment and sustainable materials are key considerations.

Future research will focus on developing wider-radius TVT while maintaining its status as an ultra-lightweight building component using Douglas Fir, given its broader acceptance in the construction industry in the Pacific Northwest (Figure 8). Investigating how this material performs under compression and refining the lamination process to work effectively with veneer exhibiting greater natural variation will be key to enhancing its structural viability. This direction focuses on expanding the real-world applications of TVT to establish it as a practical solution for mass timber construction.

Figure 8. Photo shows an eight foot long 10.8kg Douglas Fir TVT prototype being held up by one person. The specimen has an approximate radius of 230mm with a total wall thickness of 7.14mm. Future work aims to demonstrate the viability of Douglas Fir TVT through analysis of its variability in actuation, and through specimen performance testing.

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