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MODULAR CONSTRUCTION WITH LOW-GRADE HARDWOOD CROSS-LAMINATED TIMBER

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ABSTRACT: In this paper the author evaluates the results of a design-build project that employed the use of prefabricated, modular construction with cross-laminated timber (CLT) panels custom-developed from local, low-grade hardwood (Yellow Poplar, Liriodendron tulipifera). The American Institute of Architects award-winning project is the first permanent building in the United States to be granted a building permit for, and complete construction with, hardwood CLT. The paper presents and evaluates the attainment of each of the following research objectives in the design-build process and includes a review of the mechanical and structural testing underpinning panel performance. The project's research objectives included: (1) the development of locally-sourced, pressed, and utilized hardwood CLT that mechanically outperforms commercially available softwood CLT; (2) the development of low-carbon project logistics that allowed for all design and construction steps – from wood harvesting to CLT layup and utilization – to occur within a 3-hour driving radius of the project site; and (3) the development of prefabricated, modular construction workflows for the project's structural, exterior-exposed hardwood CLT. The 10-meter-tall hardwood CLT project was completed, passed all inspections, and opened to the public in 2021.

KEYWORDS: Hardwood cross-laminated timber, Modular timber construction, Local-species CLT development

1 INTRODUCTION

1.1 PROJECT BACKGROUND

The following paper presents the material development process of Yellow Poplar (Liriodendron tulipifera) hardwood cross-laminated timber (HCLT) and a built structure resulting from the HCLT's application in the public realm. The author focuses specifically on the development and testing of the HCLT product as it relates to the modular construction methods employed for the construction of the built structure, the New River Train Observation Tower in Radford, Virginia. The handicap-accessible train viewing tower is the first permanent building in the United States to be granted a building permit for, and complete construction with, hardwood CLT.

The author of this paper was approached in Fall 2017 by a colleague at Virginia Tech to help co-lead a new design-build project funded by the nearby City of Radford, Virginia. The city sought to build a train observation tower to provide public, handicap access to views over the New River and a historic railway line adjacent to the city's history museum. Over the following two-and-a-half-year period, the author and Professor Kay Edge led the development of full-size, 5 foot by 10 foot, structural, exterior exposed HCLT panels created from locally-sourced, low-grade Yellow Poplar. The panels were subsequently assembled off-site into two prefabricated modules joined by a heavy timber base frame, transported to the site, and attached by crane to a steel and helical pile substructure. The project was completed in 2021. The project has won local, state, national, and international design awards.

1.2 COURSE ORGANIZATION

1.2.1 Course Types

Upon the launch of the design project for the New River Train Observation Tower in Spring 2018, the two faculty leaders co-taught a graduate-level design studio, as well as co-taught a seminar course that paired students from the Department of Sustainable Biomaterials at Virginia Tech with graduate architecture students.

Figure 1: *View from railroad of completed tower*

Faculty from Wood Science, Timber Engineering, and Forestry were also involved in joint teaching sessions. The multi-disciplinary teams presented numerous design schemes to the City of Radford and received feedback. Over the forthcoming semesters, students across the

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undergraduate and graduate curriculum were engaged in various aspects of the project. Third-year undergraduate students developed façade studies while graduate design-build students designed technical details for construction, for example. The faculty led the design development project phase and a graduate student assumed project and construction management responsibilities, as well as late-stage project design work for his M.Arch thesis project.

1.2.2 Concept and Schematic Design

The project site is located adjacent to Norfolk Southern rail lines, an industrial tar storage site, and an industrial access road. The site descends from the road level approximately 16 feet to the base of the structure, and subsequently another 20-25 feet to the rail lines. The students began conceptual design with the idea that the building should showcase the structural potential of softwood cross-laminated timber (CLT), as well as its warm aesthetic, by exposing the material on the interior and exterior of the structure. Following numerous design iterations over a multi-month period, the students created a design whereby the difficult site conditions could be managed through off-site prefabrication of timber modules. Two modules were to be constructed with CLT and were each approximately ten by fifteen by ten feet. The modules were to be placed atop both a steel (Module A) and concrete (Module B) substructure per site conditions. The modules were then designed to be bisected by a pedestrian bridge such that the bridge would serve as a structural datum tying the entire building together while also helping to minimize pendulum vibrations from foot traffic. Module A was designed to be 18 feet above grade and closest to the railroad tracks while Module B was designed to be two feet above grade and closest to the access road (see Figure 2). Both modules were to be built entirely of CLT. To reduce the potential for structural degradation over time, Module A was adapted such that it would be primarily supported by a heavy timber frame atop a steel, hollow tube substructure. If damage were to occur over time to the CLT, a new module could easily be installed to replace it.

Figure 2: *Site Plan*

As the team moved closer to construction, it became apparent that softwood CLT would not be available regionally as wait times for production and delivery were significant. Additionally, CLT sourced from Canada, Europe, or the Pacific Northwest of the Unites States had such a high carbon cost for transport that it did not meet the sustainability goals of the design.

1.3 YELLOW POPLAR CLT DEVELOPMENT

1.3.1 Lab Testing Background

Due to the lack of softwood CLT availability, the project team consulted with faculty from the Department of Sustainable Biomaterials at Virginia Tech who had been intimately engaged with hardwood CLT research during prior years using locally-sourced Yellow or Tulip Poplar. Sustainable Biomaterial faculty had worked with the product at a lab-sample size and had not yet produced full size panels. A decision was made by the project team to develop full-size panels and apply them to the project based upon the lab-scale testing that the Sustainable Biomaterial faculty had undertaken. Their knowledge of the product was well developed. By 2018, Virginia Tech timber researchers in coordination with West Virginia University had published more articles on hardwood CLT than any other university unit globally for both Beech and Yellow Poplar based products. Their work focused specifically on the mechanical properties and yield analysis of Yellow Poplar CLT [1]. Even with that research background, when the author first began working on hardwood CLT with the Sustainable Biomaterial faculty, including Dr. Daniel Hindman and Dr. Henry Quesada, testing had only recently been completed at West Virginia University regarding Yellow Poplar CLT delamination and other key mechanical properties.

1.3.2 Mechanical and Structural Literature

Dr. Omar Espinoza and Dr. Urs Buehlmann have written about the "technical and economic feasibility" of hardwood CLT in the United States. They provide an overview of current applications of HCLT, including projects by Hasslacher Norica, Waugh Thistleton, and IDK [2]. Additional projects by Alison Brooks Architects and DRMM in the UK, in association with the American Hardwood Export Council (AHEC), have increased public attention on hardwood cross-laminated timber (HCLT) products. The Journal of Contemporary Wood Engineering article "The Quality Assurance of Tulipwood Cross Laminated Timber (CLT) for Multi-Ply" directly addresses AHEC's work with American hardwood in a British context [3]. Other recent research had been completed on the mechanical and structural performance of Yellow Poplar CLTs before the Virginia Tech project team attempted the production of a full-scale panel [4, 5].

Mechanical and structural testing by Dr. Daniel Hindman was key to the project team's product development work. The report "Mechanical Performance of Yellow-Poplar Cross Laminated Timber" (2015) by Milad Mohamadzadeh and Dr. Hindman was particularly useful as the purpose of the research was to "evaluate mechanical performance of yellow-poplar CLT as an alternative for standard CLT made of softwood species" [6].

Mohamadzadeh and Hindman tested "mechanical properties such as bending strength and stiffness as well as bond line shear strength and face delamination of three layered yellow-poplar CLT" to determine the product's feasibility for structural engineering applications [7]. They concluded that the "bending stiffness, bending strength and interlaminar shear capacity were significantly greater than specified values for Grades V1 and V2 in PRG 320" per ANSI/APA guidelines in 2012 [8]. Bending strength, bondline shear strength, face delamination, wood failure, and interlaminar shear capacity were deemed appropriate for HCLT structural applications, while the authors recommended further long-span testing and noted that relatively high glue failure was likely the result of the HCLT's uniquely high shear strength per the wood type, Yellow Poplar [9].

Notably, AHEC's "Tulipwood CLT Properties and Manufacturing Requirements" document, published September 2019, was created after the Virginia Tech project team had already settled on a product development path using Dr. Hindman's aforementioned research. AHEC's document, produced in coordination with the Centre for Offsite Construction + Innovative Structures at Edinburgh Napier University, the Construction Scotland Innovation Centre, and others, provides a thorough overview of the key considerations of Yellow Poplar CLT including sourcing, fabrication, and application. From procurement, pre-processing of lamellae, assembly, and post-processing, AHEC's document focuses on the production process in the UK in coordination with European Standard (EN) regulations. For the Radford project, many of the same production steps were followed. The manual would have been used by the project team if it would have been available at the appropriate time.

2 RESEARCH OBJECTIVES

2.1 DEVELOPMENT OF LOCALLY-SOURCED HCLT

Due to the availability of Yellow Poplar CLT manufacturing knowledge and the logistical difficulty to access softwood CLT, the project team chose to develop our own HCLT product using locally-sourced, low-grade wood. The project was an attempt to illustrate the economic potential for an overlooked and underutilized forest resource, low-grade Yellow Poplar, and also an opportunity to showcase the upcycling potential of under-valued local resources. The Virginia Tech team partnered with the Southern Virginia Higher Education Center (SVHEC) to produce the panels on the same equipment where the lab-sample panels had earlier been produced for structural testing. SVHEC's manufacturing facility was the only facility within a 300-mile radius of Virginia Tech's campus capable of pressing full-size HCLT panels. The facility had modified an industrial plywood press such that it was capable of achieving the required pressure to press the HCLT. Wood was sourced from multiple regional sawmills and refined on site at SVHEC. The boards were planed and aligned before gluing and pressing. After pressing, the rough-edge panels were cut on an industrial CNC. Unlike the Scottish production process for Multi-Ply's HCLT panels as outlined in the AHEC manufacturing document, SVHEC used a hydraulic press rather than a vacuum press.

Figure 3: *Advantage EP-950A glue application by student during assembly.*

While the panels looked factory finished after manufacture, the project team noticed 1/16" or less hairline gaps at the panel edges between lamellae. At the time, the project team assumed that there may have been a glue distribution error or a lack of hydraulic press pressure within two-inches of the panel edge. The latter was determined to be the issue and this gap later led to minor delamination of the product in south-facing, vertical applications. The HCLT panels were noticeably heavier and denser in comparison to a softwood CLT panel made of Southern Yellow Pine or Spruce-Pine-Fir. As such, project team needed to develop our own internal workflows to handle the panel finishing and assembly for panels with such unique properties, as well as work with our project engineer to make sure that the heavy panels were suitable for the modular construction methods that we planned to use per the difficult project site.

2.2 LOW-CARBON PROJECT LOGISTICS

Through the project partnership with the SVHEC, the project team was able to source local materials, use a locally-upcycled press, assemble panels within a 15-mile radius of the project site, and efficiently deliver and construct the tower. This highly-localized process can be compared to the primary alternative which would have entailed shipping panels hundreds or even thousands of miles to the project site while local, low-grade Yellow Poplar resources remained unused. The SVHEC manufacturing facility is housed in a former tobacco warehouse that was adaptively reused, thereby also lowering tangential carbon emissions compared to a workflow that used facilities with high-embodied carbon. In fact, the SVHEC facility will be prioritized for future projects simply because it aligns with the low-carbon, circular economy mission of the project and supports the

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overarching goal of lowering carbon emissions holistically across the entire project ecosystem. The bullet points below list the 'project strategies' (PS) that saved operational and embodied carbon versus the 'typical alternative' (TA) to the relevant issue as shown below:

Radford Train Tower Carbon-Smart Strategies
PS1: Upcycling of tracked, local, low-grade timber
TA: Variable; Non-specific material approach
PS2: Layup conducted in low-embodied carbon facility
TA: Support of high embodied carbon facilities via use
PS3: High-efficiency, low waste, offsite assembly
TA: Low-efficiency, high waste, on site assembly
PS4: Design for replacement and disassembly
TA: Disassembled and discarded after useful life

Despite the successes of a highly localized material sourcing, upcycling, shipping, assembly, and delivery process, the project's carbon ecosystem could have been improved via the following 'strategies' (S):

S1: All-wood structure with replaceable foundations
S2: Use of hardwood-nail or dowel-laminated timber
S3: Use of a carbon-tracking digital management system
S4: Holistic use of renewable energy (saws, delivery vehicles, computers, etc.)

Underpinning all of the carbon strategies in the project is the modular approach to construction. If the project were site built, the project team estimates that even with all the realized and unrealized carbon-saving strategies aforementioned effectively implemented, the project would still be carbon positive simply due to the inefficiency of on-site construction. Tangential carbon emitting sources such as finishing materials (e.g., EDPM, adhesives, waxes, etc.) plus the inefficiency of labor (e.g., additional food costs, wear on vehicles from excessive trips to the site, etc) would offset the carbon saved for a project of this scale.

The project effectively accomplished multiple key carbon-reducing strategies, but there are also improvements that can be made. Through offsite manufacturing and descriptive material-IDs affiliated with each building product used, the entire construction process could be tracked and carbon inefficiencies reduced – see restado.de and Concular, as well as Madaster digital carbon management systems [10,11].

2.3 MODULAR CONSTRUCTION WORKFLOWS

2.3.1 Panel Preparation

Following the arrival of the HCLT panels at Virginia Tech's Research and Demonstration Facilty (RDF), each panel underwent a three-step process: (1) hard wax was applied to lamellae end grain; (2) pilot holes were drilled for the forthcoming 12" timber screws; and (3) certain panel faces were treated with a base coat of linseed-oil-pine-tar mix. As some panel end grain would be concealed by other panel faces after assembly, the end grain of exposed lamellae was treated in advance. The project team was concerned about water absorption through the end grain if the panel was immersed in standing water after construction on site. Pilot holes were drilled into each panel in a staggered manner so as to avoid the timber screws splitting the wood when installed. The pilot holes were drilled multiple inches away from the panel's edge and in a manner that would allow them to align with the adjacent lamella, as opposed to a glue joint.

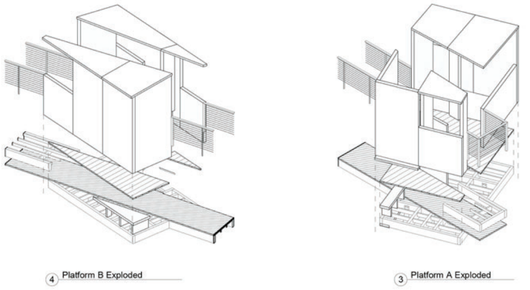

Figure 4: *Structural drawing of Module A*

Drawing upon the history of Virginia as a tar-producing state and the aesthetic and smell of the adjacent railroad tracks, the project team chose pine tar as the protective coating for the exterior of the HCLT. A 50% pine tar and 50% linseed oil mix was used to maximize the tar's penetration into the wood grain for maximum protection. Both the linseed oil and pine tar are natural products. The linseed oil significantly slowed the drying time of the pine tar application, but allowed for a deep grain penetration. The pine-tar-linseed-oil mix took approximately one week to dry per coat. The base coat was applied at the RDF facility and quickly soaked into the HCLT, forming a dark low-mess coating. Subsequent onsite applications were significantly slower to dry and were generally more messy to apply.

Figure 5: *Module A and B bisected by bridge*

2.3.2 Modular Construction

The modular assembly of HCLT panels occurred at RDF following panel preparation. The base of Module A was designed as a heavy timber structure for the following reasons: (1) a concern that the HCLT should not be the primary substructure due to its exposure to the elements and potential to delaminate over time; (2) the structural need to support cantilevering elements of the module off the hollow-core steel substructure; and (3) the ease of structural attachment that heavy timber provided over a more thin, panelized timber product. The module assembly team was primarily composed of two people, a forklift operator and a labourer whose primary role was to stabilize the panel in place, fine tune its location with a rubber hammer, and screw the HCLT panel in place via the pilot holes. The HCLT was exceptionally heavy due to its density and therefore special consideration in regard to the forklift movement and driving surface needed to be considered. Due to the HCLT's eventual exposure to the elements, all timber screws were coated with liquid wax before being driven into the pilot holes. The project team took this unusual step to avoid water being sucked into each screw hole due to capillary action, thus leading to wood rot. By impregnating each hole with liquid wax, the project team sought to keep the screw holes free of water. A staggered screw placement allowed the HCLT panels to have an enhanced moment resistance when attached to the thick heavy timber beams. Each screw was determined by the engineer to carry 200 pounds of load and the screws were spaced approximately every twelve inches across the HCLT-to-HCLT and HCLT-to-timber joints.

Figure 6: *Wax application by student during assembly*

2.4 TRANSPORTATION AND ON-SITE LOGISTICS

Each timber module weighed in excess of 2,000 pounds. Module A was assembled offsite at RDF and transported via an industrial forklift and low-boy trailer to the construction site. Module B was partially assembled offsite before being transported to the site flat packed and assembled on site. It was determined that Module A was structurally robust enough for full prefabrication, transport, and crane assembly due to its 90-degree corner joints and HCLT interior columns. Module B was less rigid and prefabrication was determined to be detrimental to the assembly process.

Figure 5: *Industrial forklift transporting Module A*

3 POST-CONSTRUCTION VISUAL INSPECTION

3.1 OVERVIEW

The New River Train Observation Tower opened to the public in 2021. The author conducted a limited visual inspection in February 2023 to assess potential deterioration of exterior exposed HCLT, as well as any general aesthetic changes due to sunlight, freeze-thaw cycles, and insects. The project's modular design allows for the replacement of HCLT components. As such, regular visual inspections should be conducted to determine if any exterior-exposed HCLT elements need to be repaired or replaced. This visual inspection did not address the current structural condition of the tower as its primary objective was to denote the aesthetic changes that have taken place since construction completion.

3.2 DISCOLORATION

Despite the HCLT modules being protected with a pine-tar-linseed-oil finish on one face and a clear ASTM-D4446-rated sealant on the other, some discoloration of the wood product and finishes has occurred. The discoloration that has occurred is not unexpected for UV-exposed surfaces. The sharp black pine-tar-linseed-oil treatment has dulled to a dark gray or soft matte black finish. Multiple coats of the mixture were originally applied to exterior-facing elevations of the HCLT product and the treated surfaces held their color for the first year. It is recommended that the wood surfaces be re-coated every two years in the project's maintenance manual and it seems unlikely that such a re-coat has occurred. The faces coated with a clear wood sealer have maintained their warm, natural wood color, minus a slight dulling of the color from a soft brown to a warm gray or tan.

3.3 DELAMINATION

Perhaps the most serious visual change in the project observed during the visual inspection was the partial delamination of the outermost lamellae on south-facing HCLT panels wherein the outmost layer of lamellae is oriented vertically. Per prior text, the project team was concerned during the manufacturing process that the

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custom-engineered press was not able to achieve the proper pressure on the outer two inches of each 5 foot by 10-foot panel. The project team hypothesizes that south facing HCLT panels receive a greater thermal load than other panels in the module and therefor the improper pressing process has led to micro delamination or cracking. The cracking has then allowed water to infiltrate and through freeze thaw cycles and has exacerbated the delamination. An alternate hypothesis is that the panels were already deaminating in a minor way when installed. Freeze-thaw cycles have therfore simply exacerbated cracks that were already present during manufacture. While the delaminating lamellae only have a maximum separation of .25 inches or less, maintenance will need to be performed before any additional separation occurs. The HCLT modules were prefabricated such that panels were oriented vertically as a means to align the strongest axis of the product with the highest tensile forces resulting from module transportation, each panel needing to be strong enough to support its own self-weight. Thus, the vertical panel orientation is better than a horizontal panel orientation at channelling rainwater away from the exterior seams of the lamellae, but there is still significant water exposure for the panel.

3.4 INSECTS

The author did not observe any modifications to the panels' physical integrity due to insect activity. The author was concerned about termite damage to the exterior exposed HCLT panels, but no evidence was present of any insect activity.

4 CONCLUSIONS

Through the achievement of the project's research objectives, the author and project partners were able to establish workflows for future projects that seek to utilize Yellow Poplar cross-laminated timber for modular, offsite construction. The built project illustrates the architectural and structural potentials for HCLT use in modular assembly workflows and confirms certain architectural and spatial potentials for the product, notably its free-span potential at a relatively thin cross-sectional thickness. Certain project decisions, including the use of a laminated product for an exterior application were justified due to the experimental nature of the structure and use of the structure as a prototype. However, the application of the HCLT product in a long-term or permanent use case wherein it is exposed to water, and thus freeze-thaw cycles, is not recommended, even with high-performance surface treatments. This follows common guidance on the use of structural, engineered wood products in exposed settings. The procedural decision to pre-drill pilot holes in the HCLT for wood screws to prevent cracking, as well as to impregnate the holes with a liquid wax, has proven to be a workable approach as confirmed by the two-year visual inspection. Lastly, but perhaps most importantly, the author recommends a highly-controlled fabrication/pressing process for any HCLT product that is produced in smaller factory setting less accustomed to industrial CLT standards and workflows. The production process can use AHEC's manufacturing requirements document as a guide. Quality control during a distributed manufacturing process is difficult to achieve, but necessary to ensure product quality and safety.

Figure 7: *Yellow Poplar CLT panels before surface treatment*

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