Slash Storage: Carbon Vaults to Help Mitigate Near Term Wildfire and Climate Change Pressure

JANA VANDERGOOT
Yale University &
University of Maryland

SINEAD CROTTY
Yale University

JUSTIN FREIBERG
Yale University

OLIVER LEITNER
Yale University

ANASTASIA O'ROURKE
Yale University

DEAN TAKAHASHI
Yale University

HAO WANG
Yale University

QIAN HUANG
Yale University

JUN SHI
Yale University

SILAS NEWMAN
Yale University

FUAD KHAZAM
Yale University

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Over the past century, fire suppression and increased human settlement at the Wildland-Urban Interface (WUI) have led to dramatic increases in the risk and impact of catastrophic wildfires.[1] Climate change contributes to the problem by increasing temperatures and aridity, and by reducing precipitation in fire prone regions.[2] A 2016 study found that climate change doubled the cumulative forest fire area in the American West since 1984.[3] The direct and indirect costs of wildfire include emergency firefighting costs, property losses, impairment to air and water quality, injuries and fatalities, healthcare costs, infrastructure shutdowns, and lost revenues.

Architects working near the WUI are required by law to specify construction materials and create site plans with fire suppression and life safety in the context of severe wildfires in mind. Working successfully in the WUI demands that designers have a deeper understanding of the carbon cycling, land management practices, and funding obstacles connected to forest systems. This paper discusses the work of Yale University's Carbon Containment Lab (CC Lab) to develop a building typology called the Carbon Vault, a low-cost, nature-based structure for storing carbon in woody biomass. Carbon vaults address the need to reduce and contain wood fuel in forests that are prone to severe wildfire. A fire-resistant form of Dowel Laminated Timber (DLT) mass timber, called Residual DLT, is presented in this paper as a construction material for carbon vaults in the WUI. Residual DLT addresses the wood waste of forest land management practices, especially those in forests prone to severe fire, by creating an opportunity to engage carbon offset markets.

INTRODUCTION: IMPACTS OF SEVERE WILDFIRE ON FOREST CARBON CYCLING

High-intensity wildfires lead to tree mortality, damage to soils and hydrology, and result in decreased capacity for forests to fix and store carbon.[4] It is estimated that U.S. forests store 58.7 billion metric tonnes of carbon and sequester 211 million metric tons of carbon every year.[5] According to the Congressional Research Service and data from the EPA, 5% of all U.S. forest carbon is stored in deadwood material, an estimated 2,777 million metric tons of carbon. Without intervention, severe wildfires in the U.S. may reduce the carbon sequestration potential of forests by >50%.[6] Even the most conservative estimates suggest that western U.S. forest fires emitted 851 ± 228 million metric tonnes of CO_2 between 2000 and 2016.[7]

LAND MANAGEMENT OPTIONS

Land and fire management practices have exacerbated fire hazards by promoting a build-up of wood biomass fuel in forests. [8] Forest restoration interventions can better manage woody biomass in forests to reduce fuel for wildfires, prevent this carbon from being released into the atmosphere during wildfire events, and help to mitigate wildfire risk and improve the carbon sequestration potential of U.S. forests.[9]

Forest managers use mechanical thinning and prescribed burning and allow low and moderate-intensity fires to burn (when appropriate and safe to do so) to preemptively reduce the woody biomass fuel loads and reduce wildfire severity. These actions garner a carbon benefit by reducing carbon emissions from wildfire, and by promoting greater tree survivorship in the event of a fire.[10] However, the carbon emissions from prescribed wood burning, especially larger wood waste piles, need to be considered carefully.

Thinning beneath the forest canopy to remove small diameter "ladder fuel" trees and to reduce surface fuel decreases the likelihood that a fire will burn at a high intensity.[11] To provide perspective on the enormity of the treatment needed, on federal land alone, estimates say that approximately 60 million acres are at risk of unnaturally severe fires.[12] To treat this land would require a doubling of the pace and scale of annual treatments. Policy at the state level has begun to support thinning projects. California signed into law SB 904 which requires the state to double forest fuel removal. It is estimated that mechanical thinning could enable profitable management of 800,000 acres of forest land per year. Thinning on such scale is economically feasible and would substantially reduce wildfire intensity in California.[13]

Figure 1. Image caption: *Disposing of thinned woody biomass "slash" through controlled burning*. Image credit: L. Asherin, U.S. Forest Service, https://www.fs.usda.gov/rmrs/slash-past-rehabilitating-pile-burn-scars-0, Accessed November 09, 2022.

Where mechanical thinning generates excess, non-merchantable biomass, land managers have several opportunities. The carbon in thinned woody biomass can be stored in-situ, using techniques such as weatherproof enclosures or burial to arrest decomposition in forests. Woody biomass can also be removed from the forest and brought closer to construction material logistics hubs. At these hubs, wood can be more easily converted to end uses like biochar soil additives, or be used in negative emissions technologies, such as biomass energy carbon capture and storage (BECCS).[14]

SLASH STORAGE IN CARBON VAULTS

In 1995, fire suppression comprised 16% of the Forest Service budget; by 2015, that figure surpassed 50% — owing to an overall decline in budget, combined with increased fire suppression costs.[15] The result was dwindling funding for preventative fuel mitigation treatments. Potential revenues from carbon offset markets could help defray the costs of forest restoration, and the Inflation Reduction Act will also incentivize action. For example, annual carbon gathering treatments on 500,000 acres in Oregon and Washington could potentially remove ~10 million metric tons of CO2 equivalent (MTCO2e) and yield $500 million at $50 per MTCO2e.

The Yale CC Lab carbon vault project targets carbon in waste wood leftover from forest thinning and logging operations. This pre-commerical wood often remains in forests in the form of large slash piles because it is not economically feasible to sell as woodchips, pulpwood or firewood. Rather than leaving waste wood to decay naturally in forest stands where it can contribute to the health of forest soils and wildlife habitat, land managers often gather and burn wood residuals in a low-cost effort to prevent serious catastrophic wild fires.

The carbon vault project assumes the practice of slash burning as a baseline from which to work. Pile burning releases carbon into the atmosphere and has generated some concern from the scientific community because of lasting changes in soil pH, decreased soil fungi colonization, and poor tree seedling performance in persistent burn scars on the land.[16] Public perception and the air quality problems due to excess wood smoke is also a significant concern related to burning slash.

Another assumption used as a starting point for vault design was some level of future engagment with technologies like the proposed green hydrogen-generating processes that captures CO2 and could be employed with low-cost wood waste biomass and geologic storage. Development-stage bio-energy carbon

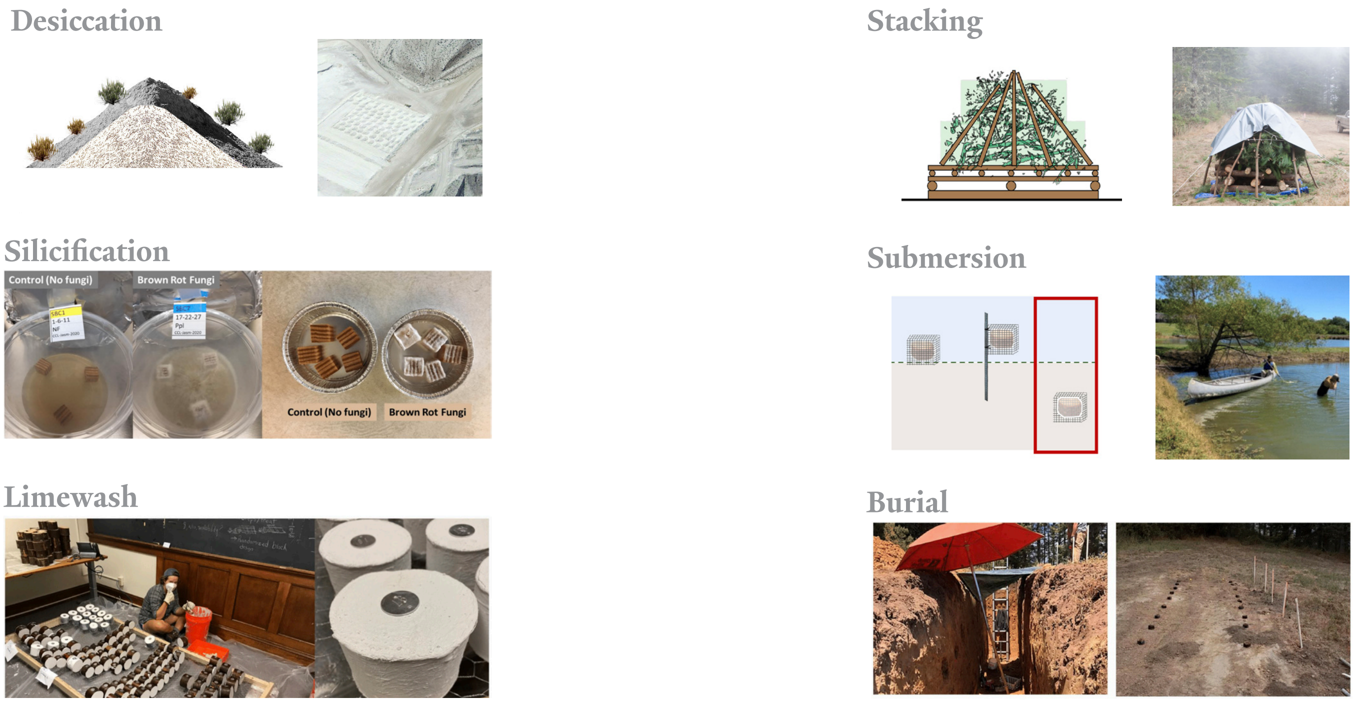

Figure 2. Image caption: *Woody Biomass Delayed Decomposition Treatments* Image credit: Yale University CC Lab, 2022

capture and storage (BECCS) systems have demonstrated the feasibility of generating green hydrogen and capturing concentrated streams of CO2 from wood waste, but not yet at scale.[17] These technologies require longer time horizons for development, whereas the need for forest thinning and containment of carbon in woody biomass is urgent. Temporary (five to ten-year) storage of wood in carbon vaults addresses this time gap and provides a potential guaranteed source of feedstock for future BECCS systems. On the other hand, carbon vaults, especially the underground vaults, can also be designed for more long-term (one-hundred-year) containment and take advantage of potential revenue sources, such as federal, state and/or voluntary carbon offset incentives resulting from carbon removal and negative emissions. As a nature-based climate solution, potentially in combination with BECCS systems, carbon vaults address challenges including community resistance to more energy intensive and expensive carbon capture technologies as well as the lengthy and often unsuccessful federal planning processes, and the need for coordinated treatments across multiple ownerships.[18]

The carbon vaults designs are a kit of parts solution, rather than one size fits all. The kit of parts options can be nimbly employed to address the range of forest environments, land management approaches, stakeholders, and social pressures. The kit of parts unfolded alongside small-scale trials that exploring wood treatments. The CC Lab explored wood desiccation, wood silicification, limewashing wood and submersion of wood in water in addition to wood burial and strategically stacking and covering wood aboveground in configurations that allowed maximum air flow and minimum ground contact.

Following the trials, the CC Lab teamed with community and institutional partners and private land managers to design three vault types that could be built to full-scale as pilot projects. In 2022, the CC Lab will help to construct belowground vaults, aboveground vaults, and mass timber vaults. This paper briefly describes all three vault types and concentrates on mass timber vaults.

BELOWGROUND VAULTS

Burial of wood biomass for carbon containment in belowground vaults shows promise in both dry, arid climates as well as wet, temperate climates.[19] The advantage of vaults that store woody biomass belowground in very low oxygen environments is the opportunity to store vast amounts of wood. Burial also has the potential to meet the durability expectation of one-hundred-years seen in many carbon offset markets. The most successful potential sites for wood burial have dry, arid climates where subsurface hydrology has minimal impact on the air seal of the burial chamber. Potential drawbacks of wood burial include high costs for equipment, fuel, and the labor required to process and transport wood residuals along forest logging roads to vault sites. Another drawback concerns the ability and ease of gaining access to the wood for future use once it is buried.

The CC Lab team has identified burial sites, including superfund sites and mine reclamation pits, that provide the ideal climate

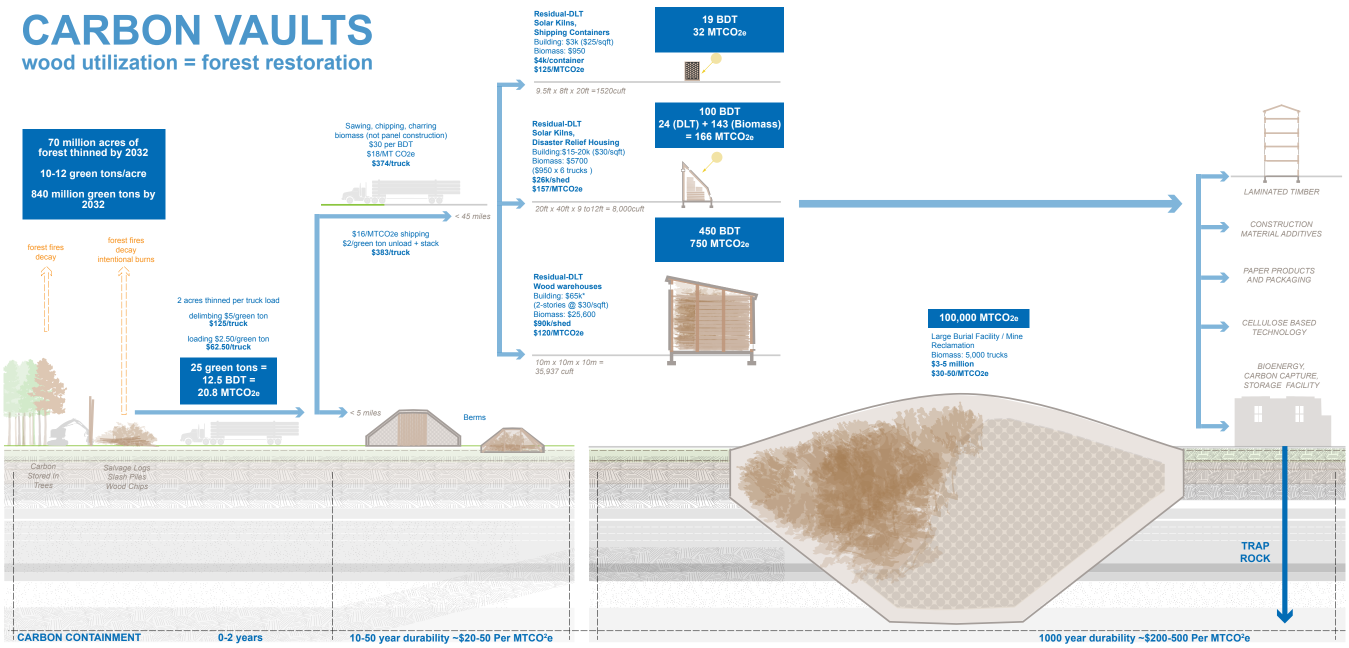

Figure 3.Image caption: *Carbon Vault Kit of Parts* Image credit: Jana VanderGoot, Yale University CC Lab, 2022

and site conditions at a short distance from planned forest thinning. The pilot projects are designed to measure decay by insect pests or microorganisms in different types of chambers. Some are enclosed by a natural soil cover only and others are lined with synthetic material.

ABOVEGROUND VAULTS

Aboveground vaults offer a flexible solution where ground water is a concern or where the ability to excavate pits for burial is limited. Log landings, slash pile burn scars, and centrally located sawmills are places where accumulated woody biomass does not travel far from the location where it was removed from the forest. Synced cut-to-length harvesters and log processors as well as the automation of logging machinery drastically reduces the number of times wood residue would have to be handled to find its way inside an aboveground vault. Retrieving the wood from an aboveground vault for future use in BECCS systems can be made simple with an enclosure system that is easy to disassemble.

Aboveground vaults do not provide the anoxic conditions that underground vaults can inherently provide. Addressing the rate of wood decay due to microorganisms in aboveground vaults is essential. A 2014 study of decay in downed woody debris found that 50% of the biomass of conifers left exposed in forests remained after twenty years.[20] With a ten-year-storage goal, the primary challenge of aboveground vaults is to provide a weather and fire-resistant enclosure system that keeps stored wood off the ground and discourages insect pests.

Construction materials like wood ash cement, hardened soil from slash pile burning, mycelium, and pine needle-reinforced earth plaster can achieve net-zero carbon footprints as part of aboveground vault enclosure systems. These materials are often present or can be produced in fire prone forests. Ash, charred wood, and clay soils are also by nature fire and insect resistant. Factoring the sequencing of aboveground vault construction into the normal activities of log harvesting and processing equipment can ease the construction time and the burden of building aboveground vaults for wood storage.

MASS TIMBER CARBON VAULTS IN THE WILDLAND-URBAN INTERFACE (WUI)

Building with mass timber is a viable strategy for containing carbon in woody biomass. The CC Lab worked with students from Yale School of Architecture (YSOA) in the summer of 2022 to develop two innovative types of mechanically fastened mass timber panels composed of wood waste that could become a legitimate commercial construction product for enclosing carbon vaults. Cross-stacked Residual-Dowel Laminated Timber (DLT) and Braced Residual-DLT are innovative because they employ small-wood (2-6" diameter residual logs from thinning operations), logs with beetle or fire-damage, and wood that remains as the byproduct of sawing logs for dimensional lumber.

The Residual DLT panels are a modified version of standard DLT, which connects stacked softwood strips called "lamellae" with hardwood dowels that stay in place because of the surface tension created between the softwood lamellae and hardwood dowels. The dowels are dried to 5-6% moisture content so that

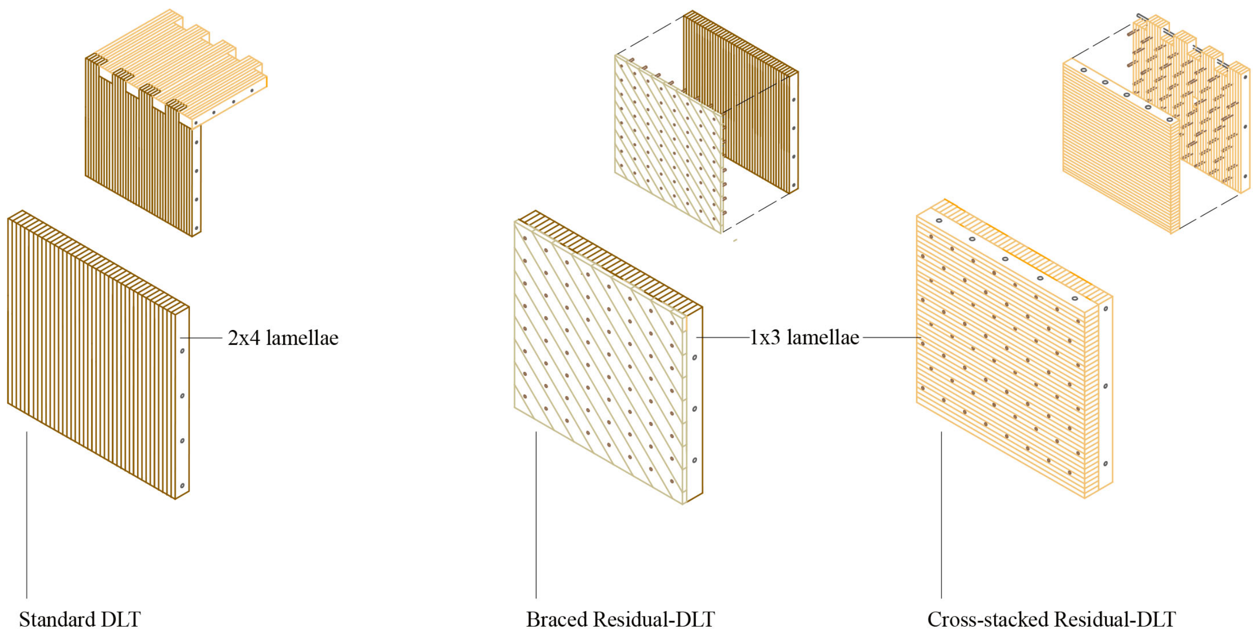

Figure 4. Image caption. *Wood dowel connections and layering systems for Residual-DLT panels*. Image credit: CC Lab, 2022

they expand once they are placed in softwood panels dried to 12-19% moisture content.

The diagonal layers of the Braced Residual-DLT and the cross-stacked wood of the Cross-stacked Residual-DLT make them more structurally stable than a standard single layer DLT panel that can only span in one direction. If designed and installed properly, braced and cross-stacked panels are strong in two directions and can potentially function as structural diaphragms to resist lateral loads from wind and seismic activity. Residual DLT panels utilize lower quality wood and, as a result, they have lower structural performance. This lower quality is not necessarily a problem if the panels are designated as a cover for unoccupied, low rise carbon vaults.

FIRE PROTECTION

The 2021 International Wildland-Urban Interface Code provides ignition-resistant construction regulations to protect against fire spread. DLT mass timber is a relatively fire-resistant construction system for low rise buildings and can achieve two-hour fire-resistant rating.[21] Code officials look to WUI and International Building Code (IBC) guidelines for fire ratings based on construction type. DLT falls under the guidelines for Type IV Heavy Timber construction.

The CC Lab is exploring options for improving fire ratings of carbon vault enclosures. Fire test trials were conducted with ash-cob plaster composed of a mix of waste ash from industrial incinerators and clay-soil. The panels tested included a cross-stacked DLT with no plaster coating, a panel with 1/8" thick ash-mud plaster sandwiched between two layers of wood lamellae, and a panel with the 1/2" thick ash-cob plaster applied to the top of the wood.

Significant charring occurred on the layers of wood lamellae that were exposed directly to the fire source. Less charring occurred on the layer of lamellae where the 1/8" thick layer of ash-cob provided a fire protection barrier.

Color changes occurred on the 1/2" thick layer of ash-cob applied to the top of a DLT panel when the ash-cob was exposed to fire, however, it offered significant fire protection to wood beneath it. The DLT panel with 1/2"of ash-cob never caught on fire. Charring occurred on the wood around the edges of the panel that were more exposed to the fire source, but the structural integrity of the wood is intact.

The DLT panel with no plaster applied combusted and was almost completely consumed by fire before it smoldered and extinguished. The remaining wood is heavily damaged.

Next steps involve third-party testing for fire rating with the ASTM E84-20 Standard Method for Surface Burning could be used to test this hybrid panel system with the goal of achieving a Class A or B rating.

THE HUMAN DIMENSION OF CARBON VAULTS

A critical part of the carbon vaults conversation has to do with the human dimension of the project. Residual-DLT panels do not require specialized labor forces or expensive equipment.

They can be easily constructed in small to medium sized mills. Butt joints can extend panel length and box joints can join corners. These types of joints are created by simply staggering the lamellae, and running a dowel through the joint. Long dowels running perpendicular to the grain of the lamellae and short dowels running through the grain fasten the lamellae in the Braced Residual-DLT and the Cross-stacked Residual-DLT panels. These examples emphasize the need for familiarity and buy-in a significant component of the success and value of wood storage vaults in the suite of carbon containment projects.

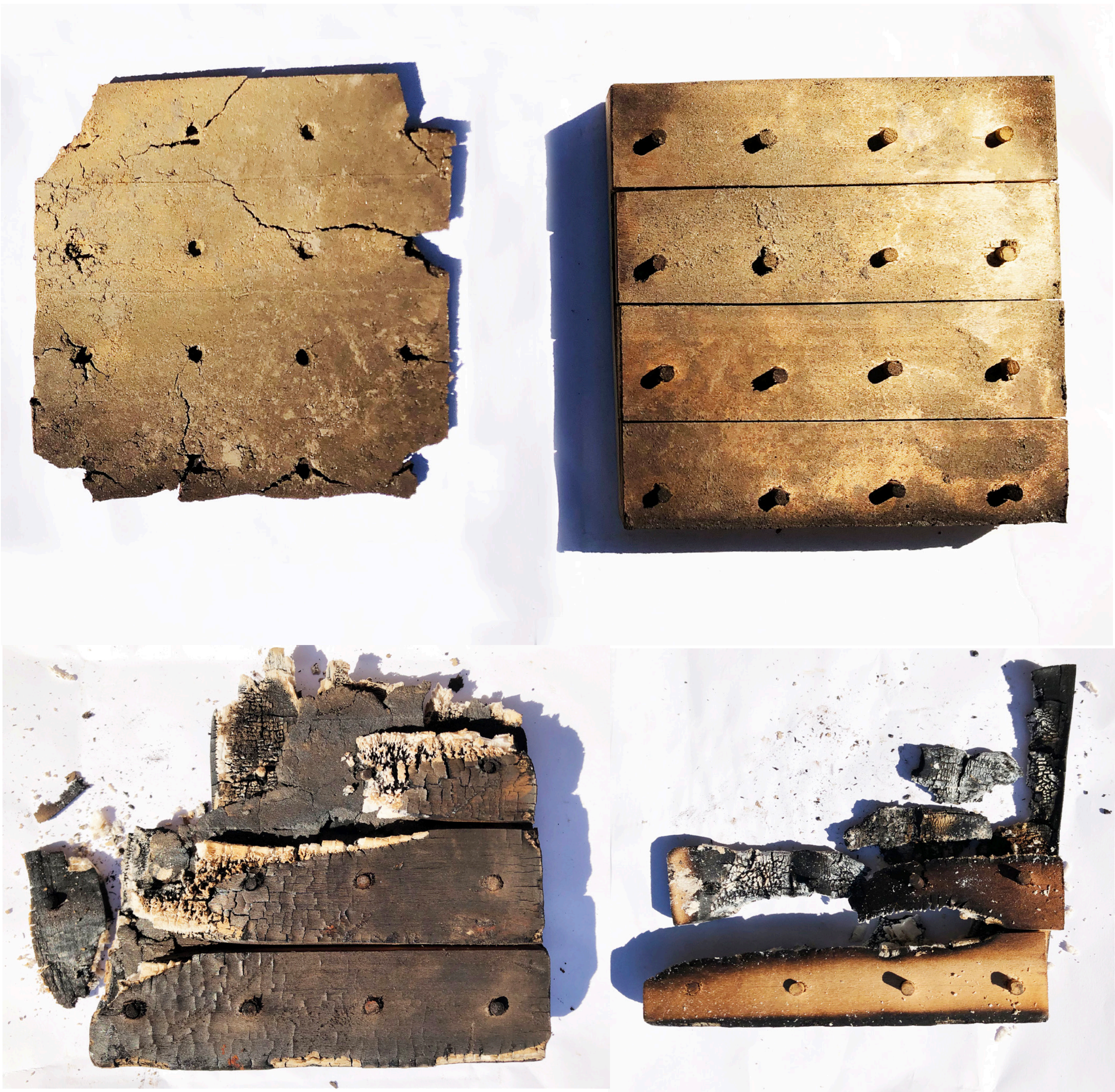

Figure 5. Image caption. *Fire Tests in Residual-DLT panels with ash-cob coating. Above: 1/2" coating on top. Bottom Left: 1/8" coating sandwiched between lamellae. Bottom Right: no coating* . Image credit: CC Lab, 2022

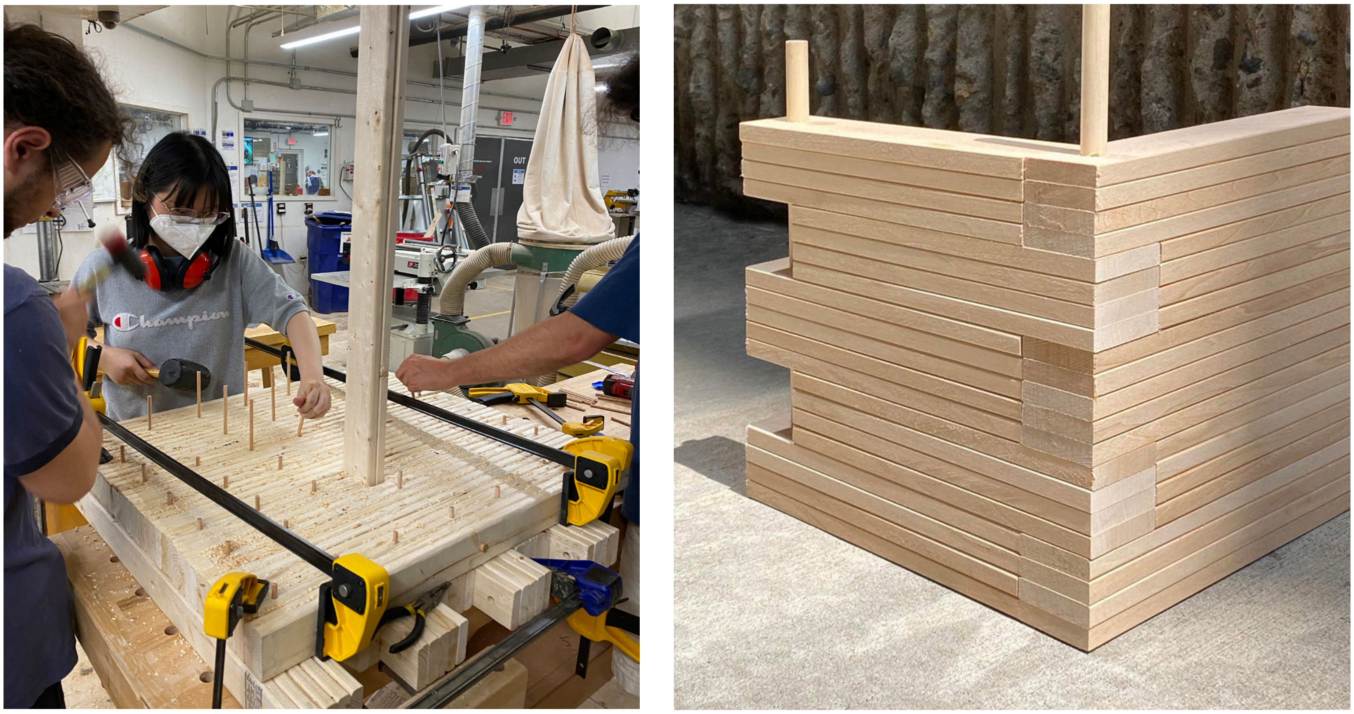

Figure 6. Image caption. *Inserting dowels into Cross-stacked Residual DLT* and corner butt joint. Image credit: CC Lab, 2022

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