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ASSESSING THE REUSE POTENTIAL OF MASS TIMBER CONSTRUCTION USING A TEN-STORY SHAKE TABLE CASE STUDY

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ABSTRACT: The continual growth in mass timber construction has stimulated discussion about how mass timber products can drive sustainability through the end-of-life stage, shifting the building sector towards a circular economy that reduces the overall demand on virgin forest resources. Moreover, the potential for mass timber buildings to function as effective carbon sinks depends on extending the service life of mass timber members via reuse. Through a collaborative effort between the University of Oregon and Oregon State University faculty, working together in the TallWood Design Institute, this study developed a framework for the reuse potential of mass timber members using the Natural Hazards Engineering Research Infrastructure (NHERI) ten-story shake-table specimen for seismic testing at the University of California San Diego. The test structure was analyzed using a digital model to determine mass timber reuse efficiency across panel type and scenarios that span a range of material reprocessing intensity, incorporating fully engineered and modeled connections as an additional parameter to reuse constraints. Finally, this project quantified reuse material efficiencies based on selected strategy and highlighted the opportunities and challenges of reuse.

KEYWORDS: End-of-Life, Mass Timber, Reuse, Life-cycle Analysis

1 – INTRODUCTION

Mass timber buildings can have lower embodied carbon than reinforced concrete and steel counterparts; however, the end-of-life stage is a major contributing factor to this net carbon advantage [1,2]. Extending the life of wood-based building materials through reuse can allow longer forest crop rotation, increasing the efficiency of forest carbon sequestration and storage in building materials [3].

The reuse of materials from mass timber buildings is thought to have the advantage that demolition can be avoided, and instead structural members can be disassembled using a similar process as when they were constructed; and that those individual elements can undergo reprocessing and be reused in other buildings, contributing to a circular economy [4]. This is considered environmentally preferred over other end-of-life scenarios and a “waste hierarchy” prioritization structure has been developed around minimizing waste and carbon footprint and has been as applied to mass timber buildings [5]. In order of prioritization in this hierarchy: (1) waste is prevented altogether, (2) a product is reused, (3) is recycled, (4) is used for energy recovery, and avoided when possible, (5) placed in a landfill.

Due to the very limited stock of mass timber buildings that have reached their end-of-life stage, case studies on planning for disassembly and potential reuse scenarios of various mass timber components are limited. One such example, however, is a temporary market hall constructed in Stockholm, Sweden and in use from 2016 – 2020 while the existing permanent facility underwent renovations. Because of the temporary initial use case of the structure, it was designed for deconstruction (DfD) by the architecture firm Tengbom. The entire post and beam structure was later reassembled in Mölnlycke, Sweden near Gothenburg to be used as a sports facility. Among many positive findings from this reuse case study, and even though the structure was able to be reused without reprocessing of mass timber components, the change in program meant some columns needed to be repositioned and additional steel was needed to accommodate this [6]. Additionally, the change of site came with different wind load design requirements that resulted in necessary modifications to some members at the exterior wall condition.

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Shake-table test specimens are a periodically available source of deconstructed mass timber and available to study for reuse in this context because these structures typically have a very short relative lifespan. These structures are not primarily designed for reuse, so likely require reprocessing of mass timber components, and a design process that is able to implement the reused material resource available.

Passarelli (2018) described the process and impact of reusing a portion of the material from a five-story shake-table specimen after testing at the Three-Dimensional Full-Scale Earthquake Testing Facility or "E-Defense" in Japan [7]. When the material was repurposed in the construction of a café, an analysis examined the global warming potential (GWP) impacts under various scenarios based on percentage of reused material employed in lieu of sourcing virgin material and disposal of the shake-table test specimen. Overall GWP decreased as the reuse percentage of mass timber increased.

Vamza et al. (2021) proposed that the possible percentage of mass timber suitable for reuse can be extended through reprocessing technology focused on the recombination of smaller off-cut sections and/or irregularly shaped sections that couldn't be reused as is [8]. Using CLT panel off-cuts from a single-family housing project design, 70% of initial waste was found suitable to be reprocessed and repurposed into new CLT panels. This material recovery process, within the framework of substituting panels fabricated from virgin stock while also displacing off-cuts that would otherwise be disposed of, prioritizes higher grade mass timber reuse pathways over lower grade waste streams.

Developing a framework for repurposing end-of-life mass timber building components will broaden understanding of potential future reuse streams, which may in turn improve modern design for deconstruction efforts in today's new construction. Investigation of reprocessing, regrading, and reuse potential can also contribute to establishing a certification system for deconstructed mass timber.

2 – PROJECT DESCRIPTION

This project develops a roadmap for mass timber reuse as a conceptual case study utilizing available design and construction documentation for a realized ten-story shake-table test specimen, which at the time of testing was the world's tallest structure tested on a shake-table. This test structure has an inherently short service lifespan; however, consideration was given toward future mass timber building deconstruction and end-of-life pathways if this structure, built with today's materials, methods and technology, was considered for reuse many years in the future. This assessment evaluates feasibility for reuse, recovery, recycling, transport, processing, and waste disposal assuming a reasonably large mass timber building stock in the future, where there is an established market for reuse, if not an industry focused on reusing deconstructed mass timber building components.

2.1 CASE STUDY STRUCTURE

The ten-story shake-table test specimen was constructed and tested at the Natural Hazards Engineering Research Infrastructure at the University of California, San Diego (NHERI@UCSD) shake-table facility [9]. Several mass timber products and systems were incorporated in the structure including rocking walls with U-shaped flexural plates to dissipate energy and post-tensioned rods for re-centering. The design was intended to be damage-free at design earthquake (DE) level, and sustain only minor and repairable damage at maximum considered earthquake (MCE_R) level. The ten-story test specimen was subjected to 88 earthquakes on the shake-table, and was found to have no damage to the structural system at the completion of testing.

The top four stories were then deconstructed, and a six-story test specimen was used for further testing by the NHERI Converging Design program [10]. After this additional testing was complete, the entire structure was completely deconstructed.

Life-cycle assessments for these structures are covered in detail elsewhere [11,12], as is the deconstruction process and actual reuse of mass timber elements [13]. Some key findings from the deconstruction phase are relevant to this case study regarding workflows for reprocessing and regrading of structural members. (1) Due to budget constraints, the most time efficient methods were employed, resulting in some elements such as column and wall panels spanning multiple floor levels being cut and lifted out in smaller pieces, losing some reuse potential they would otherwise retain as larger members. (2) Some sections were removed from the structure as modular units with beams and columns attached to floor diaphragms, again for efficiency, requiring additional staging and processing once on the ground or at a later stage. (3) New holes were drilled as lifting pick points, and was done at the discretion of the contractor, resulting in a lack of as-built documentation locating these penetrations in the disassembled members. (4) Long screws that broke when attempting removal had the screw heads cut off with the shank of the screw remaining in one member which would require locating and removing them at a later stage, depending on the reuse case for that member.

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2.2 CASE STUDY MODEL

The ten-story test structure utilized for this study is composed of various types of mass timber products, including cross-laminated timber (CLT), glue-laminated timber (GLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), veneer-laminated timber (VLT) panel, mass plywood panel (MPP), and laminated veneer lumber (LVL) columns and beams. The location each material type is used in the structure along with dimensional characteristics are shown in Table 1.

Several types of steel connections are used in the test structure as listed in Table 2, including for the gravity system and rocking wall system, but also as diaphragm splice and load distribution elements.

Table 1: Ten-story shake-table test specimen mass timber components material characteristics

Member Type & Location	Material Type	Depth (m)	Area (m^2)	Volume (m^3)
Level 2 & 3 Diaphragm	CLT	0.18	168	30.3
Level 4 & 5 Diaphragm	GLT	0.16	151	23.5
Level 6 Diaphragm	NLT	0.14	83	11.3
Level 7 Diaphragm	DLT	0.14	83	11.3
Level 8 - 11 Diaphragm	VLT	0.16	345	53.8
All Beams	LVL	-	-	37.0
All Columns	LVL	-	-	56.7
N - S Rocking Wall	CLT	-	-	61.6
E - W Rocking Wall	MPP	-	-	40.9
Total Mass Timber Volume				**326.4**

Table 2: Ten-story shake-table test specimen steel connection components material characteristics

Steel Connection Type	Weight (kN)
Beam Connection	20.5
Column Connection	12.5
U-shaped Flexural Plate Configuration	112.0
Post-Tensioned Rod	2.7
Wall Saddle	16.0
Wind Saddle	12.5
Wall Splice	44.9
Shear Key Configuration	81.0
Shear Collector	24.5
Tie Strap	4.5
Spline Strap	6.7
Total Steel Weight	**337.8**

Steel diaphragm connections vary in layout by floor level and mass timber panel material type, and some of these differences can be seen in the rendered three-dimensional model of the ten-story test specimen shown in Fig. 1. The level of detailed documentation extends to fastener characteristics by placement, including fastener depth (reaching above or below the panel centerline or through penetrations) and insertion angle. This level of detail is drawn upon to inform and optimize the reprocessing and regrading potential of each member as represented conceptually in Fig. 2.

Figure 1. Model of ten-story shake-table test specimen with mass timber structural members and steel connections shown. Positioning and layout of floor diaphragm steel connections varies by mass timber material type used at each level.

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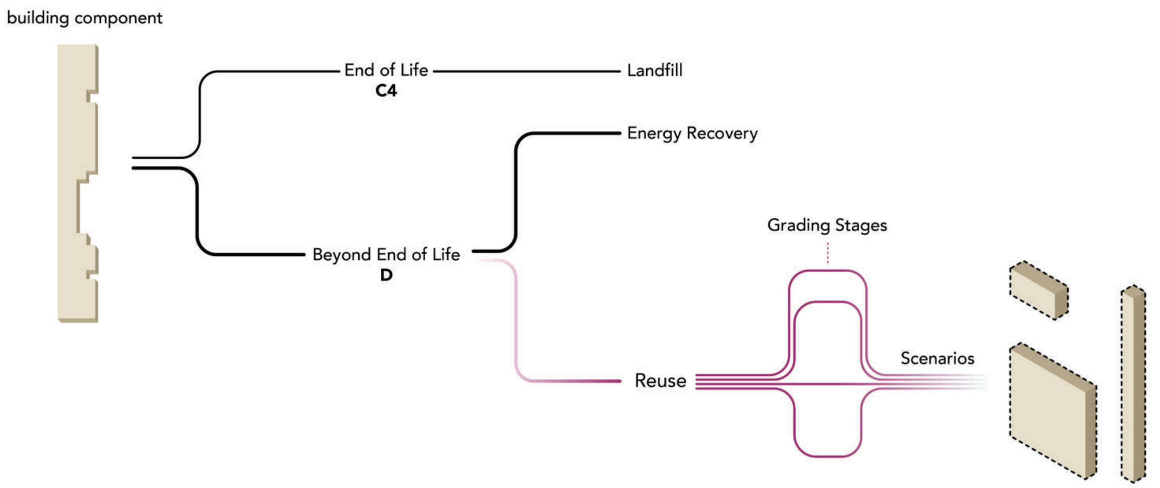

Figure 2. Conceptual reuse process with pathway from building component to reprocessed and regraded standardized product outputs.

3 – DESIGN PROCESS

When considering potential reuse efficiency of structural elements by member type, columns and beams would ideally be reused at their full dimensions or with as little downsizing as necessary, and rocking walls are long simple rectangular panels that could hopefully be reused again as long rectangular panels. However, particularly in the case of this structure, floor diaphragm panels are irregularly shaped with multiple zones where various types of steel connections are made and would require the most intensive optimization effort and reprocessing phase to efficiently reuse the maximum percentage possible.

To accomplish this, two basic optimization strategies are proposed based on potential reuse output products. The first is to regrade sections of a panel removed from a structure by how its material properties allow it to be reused from an aesthetic "visual" or "non-visual" categorization, and at the same time from a "structural" or "non-structural" reuse potential categorization. The grading stages that will guide how a panel will be reprocessed are described in Table 3, with each successive stage being more limiting in how fastener penetrations are addressed.

The second optimization strategy proposes standardized commodity output products and sizes. If a new building can be designed to incorporate elements of one or more existing buildings before they are deconstructed, this may offer the greatest material reuse efficiency through defining design constraints based on specific material resources available. Though possible, several barriers exist to one deconstructed structure successfully and immediately being repurposed into another [14]. Standardized sizing of mass timber reuse products would allow panels to be processed when deconstructed, transported, stored and sold via a market for like-sized mass timber elements. Designers of new construction using reused materials would have a standard catalog of parts at their disposal. This reuse pathway would likely lead to a greater percentage of mass timber material being reused from irregularly shaped panels. Seven scenarios for reuse products are described in Fig. 3, each could have multiple standard incremental sizes, much like the system already in place for dimensional lumber.

Steel connections and fasteners are a significant factor in reuse of mass timber when buildings become taller, and when they are sited within seismically active zones. With mass timber material type and steel connection type varying by location and structural system use case in the test specimen, analyzing panels at the point of installed condition was identified early on as being the necessary first step in the process to accurately begin an optimization framework for reuse. This was done manually by referencing two-dimensional drawings and referenced details describing fastener conditions and adding that information to a preexisting three-dimensional model that could be used as input for the

Table 3: Regrading categories for visual and structural material characteristics.

Regrading Stage	Reuse Grading Category	Panel Processing Criteria Description
0	As Is	No modifications, no processing
1	Non-Visual & Non-Structural	Include all areas with fastener penetrations
2	Non-Visual & Structural	Remove areas where fasteners extended beyond panel centerline
3	Visual & Structural	Remove all areas with fastener penetrations

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partially automated optimization workflow. Relevant metadata beyond panel dimensions alone could vary by building, but in this case includes overlaying the location and coverage area of steel connections, as well as size, orientation and depth of fastener penetrations. All of which implicate if and how these zones of panels might be reused and is dependent on desired output product characteristics as much as input material characteristics.

The next step in the workflow is shown in Fig. 4, where a deconstructed panel from the building and one or more desired reuse output products are optimization model inputs, while quantities of each output product and the

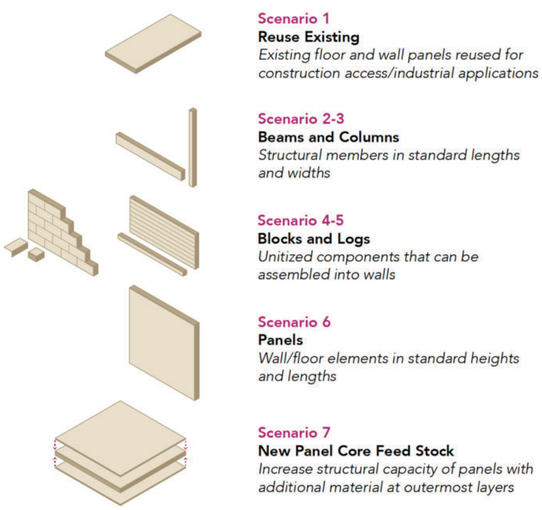

Figure 3. Potential standardized commodity product scenarios.

material reuse efficiency are the model outputs. The direction of the first cut toward making rectangular subpanels, which will in turn be cut down to desired commodity product unit sizes, has an impact on the overall reuse percentage, as does the product orientation when laid out on the panel. Thus, multiple processing pathway configurations are analyzed and ranked by both reuse efficiency and unitized output quantities.

The digital tool takes a building Revit model into Rhinoceros 3D as panel components and uses Grasshopper to calculate parametric results of reuse output scenario combinations which are exported as CSV data files that are aggregated and analyzed using a spreadsheet.

4 – OUTCOMES AND REFLECTIONS

A reuse optimization process was developed focusing on irregular floor plate geometry and fastener criteria from the case study structure, but the system can be applied to any mass timber element under consideration for reprocessing. The floor plates alone account for 40% of the wood fiber used in this structure and minimizing waste from potential reuse is more nuanced with these members than for columns and beams, for example.

Each panel was assessed for dimensional optimization with consideration for existing material irregularities that could affect reprocessing. Reuse scenarios were developed to achieve commodity product standardization with visual and structural grading requirements based on available material inflow characteristics, degree of

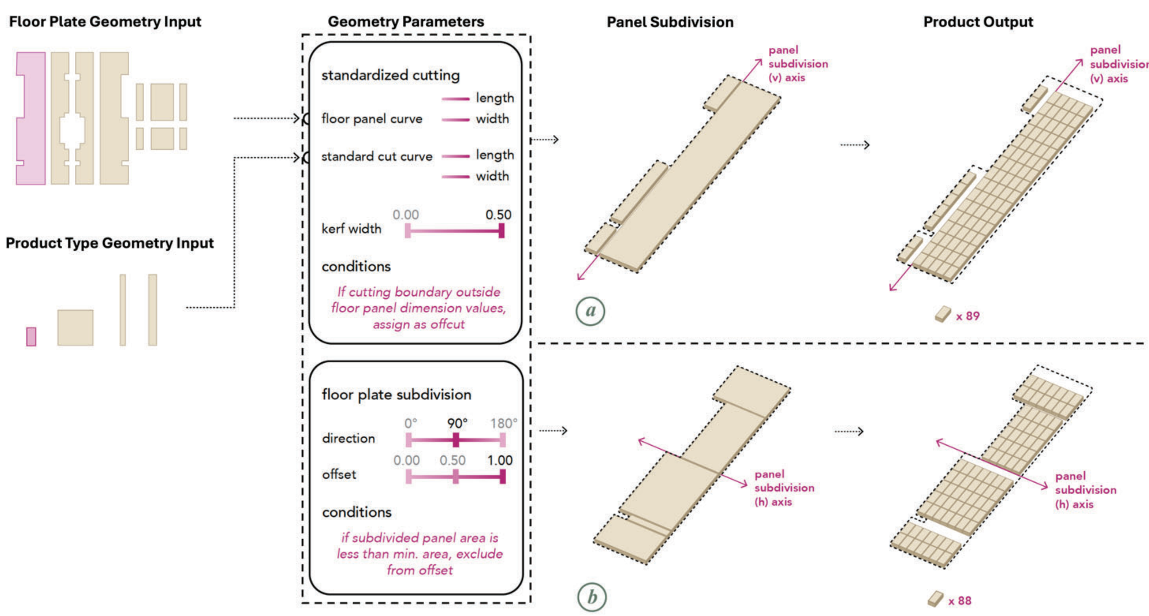

Figure 4. Parametric optimization workflow with resultant output quantities and overall reuse percentage dependent on initial panel subdivision cuts occurring along (a) panel long axis, or (b) panel short axis.

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processing required, and outflow product use case criteria. From this parametric analysis, volumetric recovery and reuse material efficiency was calculated after offcut, saw kerf, and additional processing waste were factored in. This framework provides one set of metrics for evaluating potential reuse and continued carbon sequestration for the ten-story specimen structure.

Fig. 5 shows the usable material remaining as rectangular subpanels from a CLT floor plate after cuts are made 102 mm (4 in.) outside of fastener zones defined by grading stage criteria, and off-cuts less than 305 mm (12 in.) in either dimension is also removed. The percent remaining at this reprocessing step is shown in Table 4 and ranges from 94% for non-visual and non-structural grade stage 1 to 42% for visual and structural grade stage 3.

Table 4 also shows an overall reuse percentage for each stage after optimized output for the smallest product scenario of 610 mm x 305 mm (24 in. x 12 in.) blocks, and with a second successive pass at remaining material to cut 305 mm x 305 mm (12 in. x 12 in.) half blocks. The blocks had the highest reuse efficiency among the product scenarios analyzed at up to 74% due to their size.

Recombining material into larger segments or with new material was not analyzed in this way and would depend on the sizing and grading requirements for a given recombination processing step. Proposed scenario seven, where reused panels could become core material for new panels with new outer lamella top and bottom is an intriguing concept to potentially increase reuse efficiency if structural performance values could be validated or if it could be applied in a non-structural use case.

Fig. 6 represents a comparison of three different palletized commodity products as possible output from one floor panel of the case study structure.

Table 4: Reuse percentage of entire CLT floor plate at three reprocessing steps and for each of four regrading options using the smallest sized output product scenario of blocks and half blocks.

CLT Diaphragm Reuse Percentage					
	Reprocessing Step	**Grade Stage 0**	**Grade Stage 1**	**Grade Stage 2**	**Grade Stage 3**
1	Rectangular subpanels cut from building CLT floor panels	100%	94%	61%	42%
2	610 mm x 305 mm blocks, optimize layout and cut from subpanels	-	67%	42%	26%
3	305 mm x 305 mm half blocks, optimize layout and cut from subpanel remainder	-	74%	46%	32%

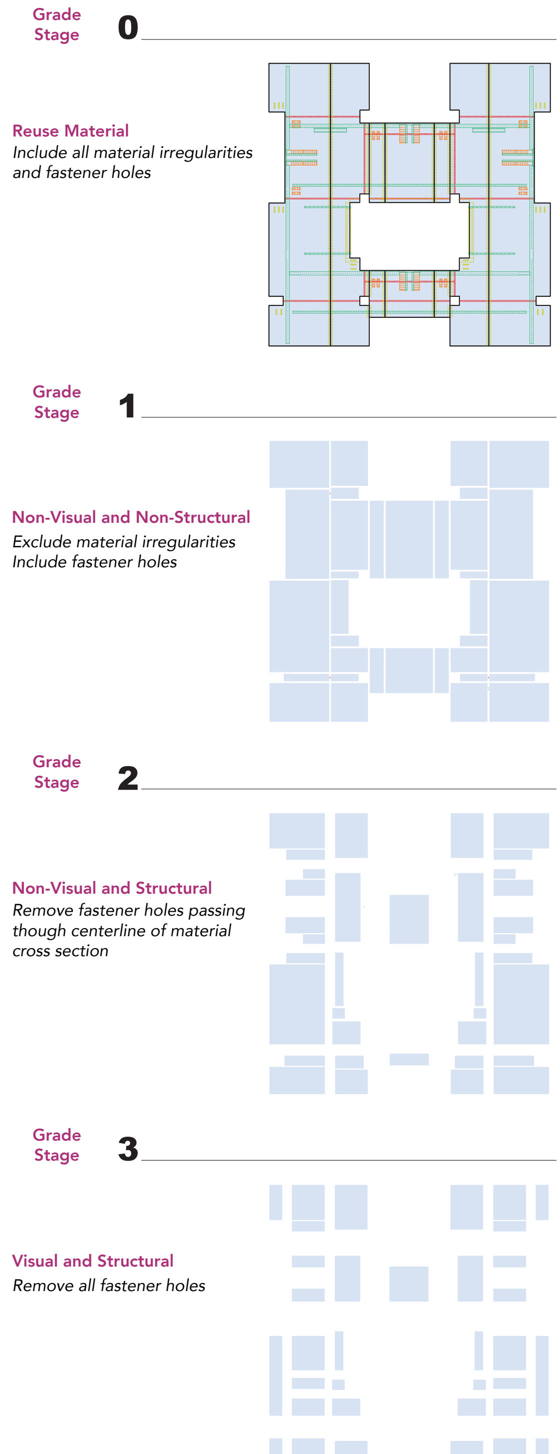

Figure 5. Plan view of one CLT floor diaphragm with four regrading stage options showing subpanel areas remaining after applying visual and structural inclusion/exclusion criteria.

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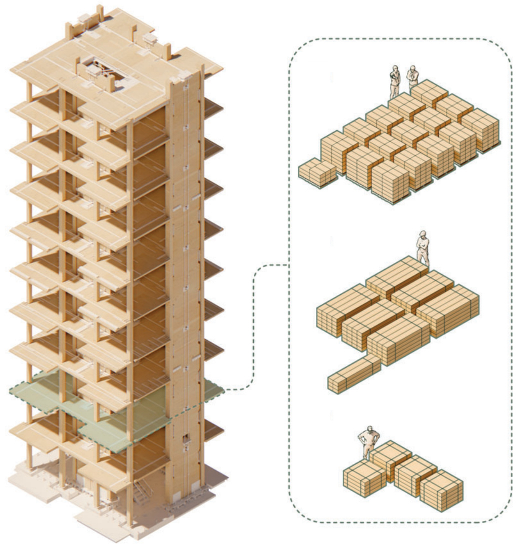

Figure 6. Model of ten-story shake-table specimen with three potential standardized commodity reuse products shown with relative quantities attained from reprocessing one floor diaphragm at grade stage 1.

5 – CONCLUSIONS AND RECOMMENDATIONS

Focusing on the methods in which a range of mass timber panel types can be deconstructed and reprocessed, this project developed a matrix of material reuse options and evaluation considerations with the intent of quantifying material reuse efficiency and maximizing continued carbon sequestration for deconstructed mass timber panels. Efforts in this area can reduce the future reliance on virgin material stock and expand the wood salvage and fabrication workforce. The development of scenarios that capture how fastener penetrations and member design irregularities affect reuse efficiency may inform current mass timber building design strategies that can better optimize the deconstruction process and reuse potential for the end-of-life stage of mass timber buildings beyond estimates found in this case study.

Buildings designed for deconstruction can improve future reuse scenarios and adoption. Barriers to reuse include the lack of reprocessing, staging and storage facilities, current financial incentives, and lack of an accepted method for structural regrading. In addition to market incentives, systems that provide ease of access to standardized inventories of reusable building material, reuse composites, structural recertification, and address other challenges associated with reuse including transportation and reprocessing of large, heavy members at partner facilities, are crucial to ensuring the adoption of mass timber reuse. Future phases of this project should focus on the substitution benefits from using one of the developed reuse scenarios compared to using new mass timber, steel, and concrete.

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