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DESIGN AND CRADLE-TO-GRAVE LIFE-CYCLE ASSESSMENT: FULL-SCALE SIX-STORY SHAKE-TABLE TEST BUILDING LATERAL SYSTEMS

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ABSTRACT: This paper describes the lateral force resisting system (LFRS) design in a full-scale six-story shake-table test building and presents a comparative cradle-to-grave life-cycle assessment of alternative LFRSs. The test building features the reuse of material from a ten-story shake-table structure comprised of engineered mass timber (MT) products. These include MT floors (cross-, glue-, nail-, and dowel-laminated timber [CLT], [GLT], [NLT], [DLT]); MT post-tensioned rocking walls (CLT and mass ply panels [MPP]); and a gravity system consisting of laminated-veneer lumber (LVL) beams and columns. Shake-table testing will benchmark innovative, low-damage design solutions for the LFRSs. To supplement this test, the environmental impact of a MT LFRS is determined relative to design alternatives that use conventional materials. The Athena Impact Estimator for Buildings was used to perform a comparative, cradle-to-grave life-cycle assessment (LCA) of the prototype MT LFRS with respect to an alternative, functionally equivalent reinforced concrete (RC) shear wall design. The LCA results showed reduced environmental impacts across some impact metrics, with a significant reduction in Global Warming Potential for the MT LFRS when accounting for biogenic carbon.

KEYWORDS: Engineered wood products; Life-cycle assessment; Rocking wall; Seismic Design; Shake-table test

1 INTRODUCTION

The rapid development of MT engineered wood products has resulted in a suite of new design opportunities for architects and engineers. As many building types using these MT products have not yet been codified, liberty in their use has fuelled the development of new engineering design solutions that strive to meet both resilience and sustainability criteria. These innovative designs would benefit from experimental benchmarking to accelerate acceptance from various regulatory jurisdictions and agencies for design code adoption.

A full-scale six-story MT building testing program will be implemented at the National Hazards Engineering Research Infrastructure outdoor shake-table testing facility at University of California San Diego (NHERI@UCSD) by the Converging Design Project team [1]. The testing program is intended to benchmark low-damage MT LFRS design solutions, provide data for numerical models employing MT, and inform design methodologies and life-cycle analyses.

This paper summarizes the designs of the shake-table specimen LFRS and provides insight into the relative environmental sustainability of these design choices. A cradle-to-grave LCA was used to investigate the

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environmental impact of the MT LFRS, as compared to a functionally equivalent RC design solution.

2 SPECIMEN REUSE AND SHAKE-TABLE TESTING

This study highlights a six-story MT test building, which will feature the reuse of a ten-story MT test building from the NHERI TallWood test program [2]. The top four stories and non-structural elements of the original ten-story building will be deconstructed to form the new six-story specimen that will consist of various engineered MT products, as shown in Figure 1.

The ten-story building was designed to feature post-tensioned (PT) MT rocking walls with U-shaped flexural plates (UFPs) as energy dissipators. The four rocking walls are connected to the timber diaphragm through a shear key connection designed for the transfer of horizontal shear forces while allowing for wall rotation and vertical displacement relative to the diaphragm. Self-centering capabilities are included through a series of four PT high-strength steel rods located near the center of the wall section and spanning across the entire wall height. Figure 2 shows the UFP-wall configuration, illustrating key components such as PT rods and shear keys for lateral force transfer.

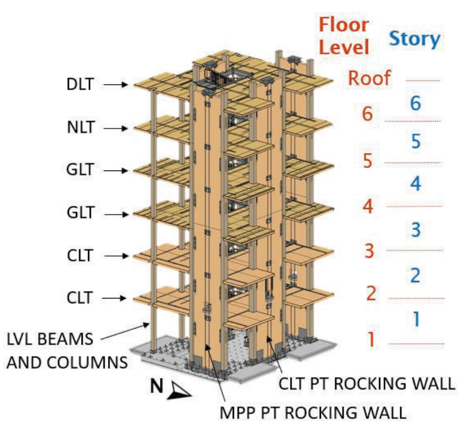

Figure 1: *Six-story MT test building*

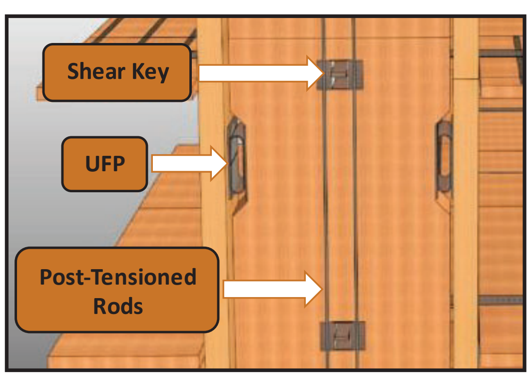

Figure 2: *PT rocking wall with UFPs*

Following deconstruction and inspection for any damage that may have resulted from the ten-story testing program, the new six-story building specimen will consist of three phases, in which three different LFRSs will be tested.

In the first phase of the six-story testing, the inherited shear wall panels in both directions will be cut to size and reused. A new UFP-wall configuration will then be installed, along with a new PT rod setup, based on the Direct Displacement-Based Seismic Design (DDBD) method. This methodology has been proposed as an alternative design procedure that allows the designer to achieve strain-limit- or drift-limit-based performance objectives [3,4]. The UFPs were designed as the main component that will behave in the inelastic range, in which its displacement was defined as the performance objective. The panels and post-tensioned rods are designed and expected to remain essentially elastic. Wall system design limit states and performance objectives are described in more detail in section 3.2.3.

The plan for the second phase of testing involves the replacement of the two MPP walls resisting lateral forces in the N-S direction. In their place, a new LFRS will be installed featuring MPP panels with buckling-restrained braces (BRBs) whose design is informed by LFRS prototype testing at Oregon State University (OSU) [5,6]. The BRBs are installed at the wall boundaries in the first story, acting as high-ductility hold-downs, while the MPP walls are designed to remain essentially elastic above the base [7]. The proposed lateral system takes inspiration from previous research on steel elastic frames, and concrete and mass timber walls employing buckling-restrained columns as energy dissipators [8–10]. The BRBs are bolted at both ends to gusset plates. The top gusset plate is ultimately connected to the MPP wall through steel side plates and 45-deg inclined, fully threaded screws. The design detail takes advantage of the high strength and stiffness of inclined screws in tension [11,12], while compressive forces are transferred through bearing of the MPP on top of the timber to BRB connection.

The planned final phase of testing involves the removal of the LFRS installed in the second phase of testing and installation of a new LFRS design that is still under development.

3 LIFE-CYCLE ASSESSMENT

3.1 BACKGROUND

One of the many aspects driving the innovation and development of new MT design solutions is the potential for enhanced building system sustainability through environmental impact reduction. This relative environmental utility can be quantified and analyzed using a cradle-to-grave LCA – a systematic method for compilation of lifetime product system inputs and outputs, and their potential environmental impacts [13].

Several studies [14–17], using an established LCA framework [13] have investigated the environmental performance of MT building systems with respect to functionally equivalent reinforced concrete and steel design alternatives. Findings from the various studies indicate significant environmental impact savings associated with the use of MT structural systems.

3.2 METHODS

3.2.1 Goal and scope

The objective of this study is to contribute to the existing body of research contrasting the environmental impacts of MT and conventional design alternatives using the LCA framework developed in ISO 14040 [13]. The study scope involves a comparative LCA focusing specifically on the MT LFRS presented for the phase I design (UFP-wall configuration) in contrast with a functionally equivalent RC shear wall design. For this study, functional equivalence is defined as a wall design with a lateral force-resisting ability in compliance with seismic provisions specified in relevant building codes and standards [18,19]. The defined functional unit is a LFRS for a six-story building with approximately 500 square meters of usable space, designed to resist a Risk-Targeted Maximum Considered Earthquake (MCE_R) in Seattle, Washington, USA. This study follows the LCA framework developed in ISO 21930 [20], which defines four life-cycle stages: Production, Construction, Use, and End-of-Life. In addition, the framework includes an option to add Beyond Building Life (BBL) net benefits sourced from reuse, recycling, energy recovery, and carbon sequestration occurring outside the system boundary.

The system boundary defined for this analysis is cradle-to-grave; thus, environmental impacts are tracked from the point of raw material extraction to their end-of-life, with consideration given to BBL net credits from the timber and steel material after departing the defined system boundary. The Use stage is omitted from this analysis, as it relates to building operation. This aspect is not relevant to this study, which focuses solely on the LFRS. Figure 3 summarizes the four life-cycle stages, the modules within each stage, and the study system boundary with the Use stage omitted.

3.2.2 Seismic design parameters

The alternative RC walls were designed to achieve functional equivalence with the MT rocking walls and, therefore, used the same seismic parameters in design, as summarized in Figure 3.

3.2.3 MT phase 1 wall design

As previously described, the MT LFRS used in phase 1 is comprised of four MT rocking walls. A pair of stacked, 9-ply (314 mm) CLT panels [21] resist forces in the E-W direction, while a pair of thinner (233 mm), stacked 9-ply MPP panels [22] resist lateral forces in the N-S direction. For each wall, two UFPs are provided at each level along the height to provide energy dissipation and increase system ductility. The MPP walls include a double UFP configuration at the first story. Four post-tensioned rods are also included for each MT wall to provide recentering capability. These wall systems were designed using the DDBD, considering limit states that enable enhanced resilience performance objectives. Table 2 provides a summary of the considered limit states and performance objectives.

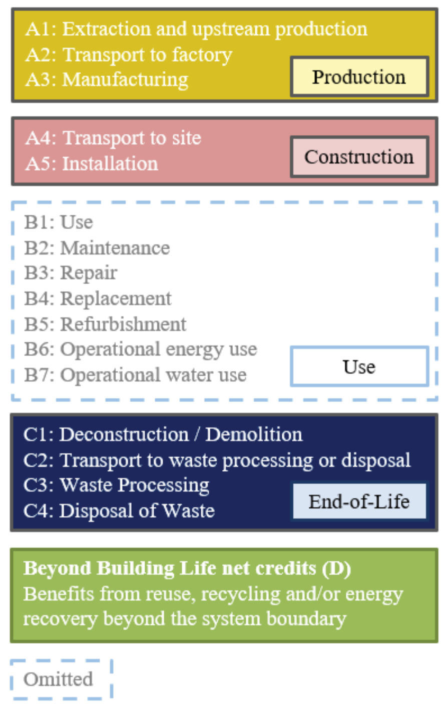

Figure 3: *ISO 21930 life-cycle stages and study system boundary*

Table 1: *Seismic design parameters*

Location	Seattle, Washington (USA)	
Risk Category	II	
Site Class	C	
Importance Factor	1.0	
Seismic Design Ctgy.	D	
MCE_R Hazard Level	S_S = 1.378	S_1 = 0.48
	F_a = 1.2	F_v = 1.2
	S_{MS} = 1.378	S_{M1} = 0.48

3.2.4 RC shear wall design

To perform the comparative assessment, a functionally equivalent RC shear wall was designed consistent with the previously described functional unit. A design software tool, ETABS [23], was used to determine the required steel reinforcement. Relevant US building codes and standards were followed, including ACI 318-19 [18] and ASCE 7-16 [19]. The wall was designed with 34.4 MPa (5000 psi) concrete and includes special reinforced

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boundary elements in the first two stories in accordance with code provisions [18]. Table 3 provides a summary of seismic design coefficients and factors used for a special reinforced concrete shear wall per [19].

Table 2. MT wall seismic design criteria

Limit states	
UFPs	Yielding at SLE, UFP ultimate displacement at MCE_R
PT Rods	Yielding at MCE_R
Walls	Yielding at DE; crushing at MCE_R
Global level performance objectives	
SLE	0.5% roof drift ratio
DE	2% roof drift ratio
MCE_R	4% roof drift ratio*

* Beyond 3% drift limit specified in ASCE 7-16

Table 3: *RC wall design coefficients and factors*

Response Mod. Coeff.	R = 6
Overstrength Factor	$\Omega_0 = 2.5$
Deflection Amp. Factor	$C_d = 5$

Figure 4 shows the rebar detailing along the height of the N-S RC shear walls. Wall detailing is similar for N-S and E-W walls, with the exception that the N-S walls are 2980 mm (9'-9") and E-W walls 2675 mm (8'-9") in width. All dimensioning and rebar sizing was calculated according to US standards, which are converted to SI units for approximate dimensions, and "soft metric" rebar sizes.

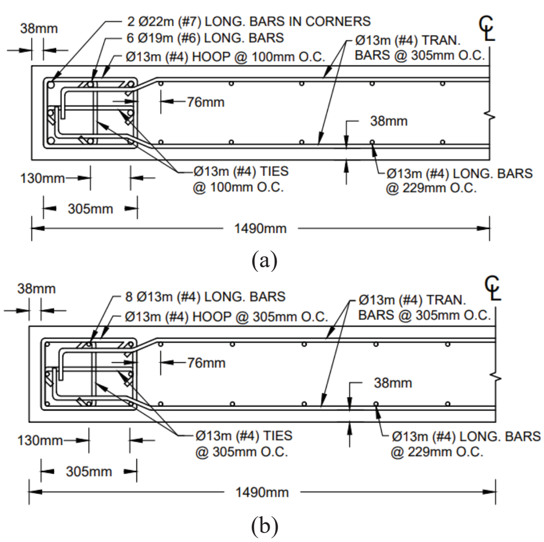

Figure 4: *RC N-S wall steel reinforcement detail (a) Level 1 – 3; (b) Level 3-7*

3.2.5 Bill of materials

Upon design completion, a bill of materials (BOM) was assembled from the RC wall and phase I MT rocking wall designs. Note, although the MT LFRS to be tested in Phase I will contain a steel foundation beam for enhanced compatibility with the shake-table surface, the MT LFRS will be redesigned with a RC foundation, as this is the planned foundation system for future implementation of these LFRSs. Table 4 provides a high-level summary of the timber, steel, and concrete materials and material quantities present in the MT and RC design alternatives.

Table 4: *MT and RC wall BOM summary*

MT rocking wall			
Element	**Mat.**	**Unit**	**Qty**
N-S Rocking Wall	CLT	m^3	37.6
E-W Rocking Wall	MPP	m^3	24.9
Bounding Columns	LVL	m^3	23.3
Out-of-Plane Bracing	Steel	kg	1494
Splice Connections	Steel	kg	2673
Shear Trans. (Found./Wall)	Steel	kg	2793
Shear Trans. (Wall/Dia.)	Steel	kg	4715
Recentering Mechanism	Steel	kg	5657
Damping System	Steel	kg	5583
Wall Foundation	Concrete	m^3	3.1
Wall Foundation	Steel	kg	211
Column Base Connection	Steel	kg	836
Fasteners	Steel	kg	1811
RC shear wall			
Shear Walls	Concrete	m^3	72.6
Shear Wall Reinforcement	Steel	kg	5454
Shear Trans. (Wall/Dia.)	Steel	kg	2560
Wall Foundation	Concrete	m^3	5.2
Wall Foundation	Steel	kg	228
Fasteners	Steel	kg	86.2

3.2.6 LCA tools

The comparative cradle-to-grave LCA framework was applied using the Athena Impact Estimator for Buildings (IE4B). This IE4B tool draws upon a highly developed, proprietary life-cycle inventory (LCI) database that complies with the framework used in [13]. The environmental impacts associated with LCI outputs are aggregated following procedures developed in the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) [24] methodology in accordance with ISO 21930 [20].

IE4B also provides data for energy use, transportation, construction, maintenance, demolition, and other processes in addition to the data developed for building materials [25]. To account for material waste in construction, transport to disposal, and other processes, IE4B also attributes material specific waste factors. At the End-of-Life stage, IE4B assumes that the current practices of material disposal will be the same as in the future. For steel, a "closed material loop recycling methodology" is

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followed, where percentages of material recycled are tabulated per [26], and the avoided burdens of steel manufacturing are added to the BBL stage in accordance with [13]. For timber materials, the End-of-Life pathway assumption is 80% landfill, 10% combustion, and 10% recycling, where 77% of the biogenic carbon in the MT sent to landfill remains permanently sequestered, and 23% decomposes and is released back into the atmosphere. This accounting system results in 61.6% of the total initial biogenic carbon being permanently sequestered. IE4B assigns net credits from biogenic carbon sequestration in the BBL stage in agreement with international standards, including [27–29]. In this way, IE4B attempts to capture the holistic environmental impact.

3.2.7 Study limitations

While the IE4B tool can help users get a general sense of the environmental impacts associated with different design alternatives, the results may lack precision due to the assumptions and simplifications inherent within the tool and present in any LCA calculation. Some of these uncertainties arise from the method IE4B uses for determining LCI results, which involves averaging regional data for emissions associated with the modules listed in Figure 3, as well as other simplifications assumed for construction and deconstruction energy. To account for this, the IE4B tool suggests that LCA results be viewed with a 15% margin of error, where alternative designs within this margin can be considered close to equal in terms of environmental impact [25].

Other study limitations involve the simplified design of the RC shear wall in contrast with the MT rocking wall design. This RC design does not include many of the design features that help the MT design achieve enhanced resilience performance objectives. These features include recentering and energy dissipation mechanisms that assist in reducing residual displacements and limiting damage. Lacking these elements, the RC wall does not achieve 100% functional equivalence in design objectives and may provide a conservative environmental impact estimate.

3.3 RESULTS AND DISCUSSION

The environmental impacts of the MT and RC design alternatives were tabulated by way of importing the assembled BOM into the IE4B software program. Data for several evaluation metrics were produced, including global warming potential (GWP), acidification potential (AP), human health particulate (HHP), eutrophication potential (EP), ozone depletion potential (ODP), smog potential (SP), and total primary energy (TPE). While all metrics are important, this study will highlight the associated carbon footprint of each design alternative, best represented by the GWP metric (CO_2 equivalent mass over a 100-year time horizon). Figure 5 presents the comparative life-cycle environmental impacts of the two design alternatives without beyond building life (BBL) net credits added for carbon sequestration and metal recycling. The data was normalized by the greater of the two impacts for ease in comparison.

A mixed result can be observed from the seven environmental metrics analyzed. Note again, a significant amount of steel was added to the MT rocking wall system to meet performance objectives (energy dissipation, recentering, etc.), while the RC wall was designed to be similar to traditional shear wall systems that do not include these elements. Ultimately, without considering BBL net credits, the GWP associated with each wall design is similar. However, when including the BBL net credits in the LCA, the GWP disparity between the two designs grows substantially.

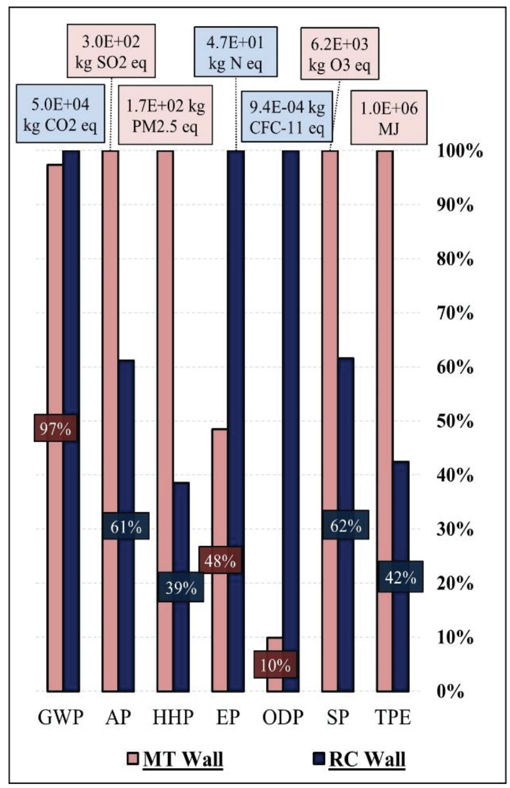

Figure 5: *Normalized impact metrics for MT and RC walls without BBL net credits*

Figure 6 shows the comparative environmental impacts with BBL net credits included. It can be observed that the MT shear wall design has only 42% of the GWP that is associated with the RC design when BBL net credits are included. This decrease in total GWP for the MT design is expected per the IE4B methodology, as described in section 3.2.6., considering permanent carbon sequestration and steel recycling. While knowing the total impact of the seven environmental metrics is important, any steps toward impact mitigation will require a more refined analysis of how each life-cycle stage contributes to the LCA.

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Figure 7 shows a comparative breakdown of the GWP impacts from each life-cycle stage. It can be observed that the GWP associated with the Production, Construction, and End-of-Life phases were relatively similar for both designs. However, BBL net credits reduced the total impact of the MT design and increased the total impact of the RC design.

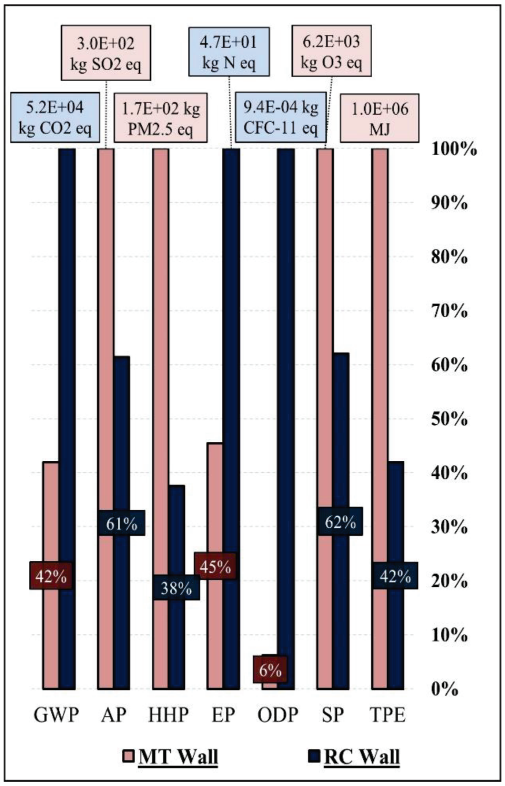

Figure 6: *Normalized impact metrics for MT and RC walls with BBL net credits*

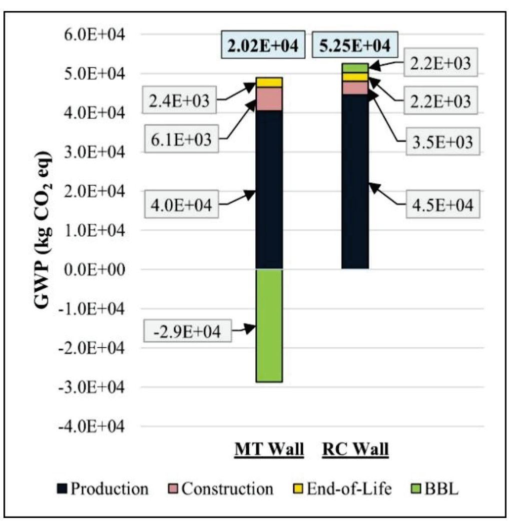

Figure 7: *GWP by life-cycle stage for MT and RC walls*

Figure 8 shows a breakdown of the cradle-to-grave GWP contribution including BBL net credits of each element grouping as described in Table 4. When considering environmental impacts (particularly GWP) associated with the MT wall design, examining how each element grouping contributes to the total GWP can be insightful. The data presented in Figure 8 shows that while the timber elements are associated with a net negative GWP, the large amount of steel in the system significantly increases the total GWP.

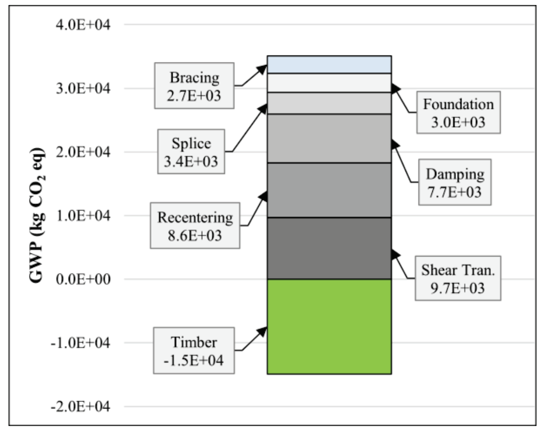

Figure 8: *MT wall: GWP by element grouping*

Beyond the environmental impact metrics discussed in Figure 5 to Figure 8, it is important to interpret LCA results within the proper context. While consideration of environmental sustainability is a growing factor for architects and engineers during the preliminary design stage, it is certainly not the only evaluation criteria, and, most times, not the most important in accordance with current practice. When performing a holistic review of design alternatives, it is not uncommon for sustainability goals to be overshadowed by economic, perception, and logistical design criteria. Thus, while MT designs can be associated with reduced environmental impacts, particularly GWP, it is critical to understand that there are other important design criteria that must also be carefully considered, balanced, and factored into the final design choices.

3.4 FUTURE WORK

The presented cradle-to-grave analysis compares environmental impacts of RC and MT lateral systems using Athena IE4B to give high-level insight into the sustainability of the two design alternatives. The environmental impact metrics were mixed across designs, while the GWP associated with the timber design decreased from 97% to 42% of the RC design when accounting for permanently sequestered carbon and recycled steel.

However, opportunity exists to broaden the study scope and calculate environmental impact metrics with increased precision. Subsequent work will expand the shake-table specimen case study to include a Whole Building Life-Cycle Assessment (WBLCA) for the six and original ten-story shake-table test building. This study will develop a higher resolution analysis, where opportunities for population of all WBLCA modules will be explored using a mixture of primary and secondary data.

Additionally, the short lifespan of the shake-table test building will be leveraged for insight into the End-of-Life stage for MT construction. Prior to testing, a variety of End-of-Life scenarios for the building material will be examined to determine the most practical and sustainable End-of-Life pathways. Following completion of testing, empirical data will be collected throughout deconstruction, e.g., deconstruction time, labor requirements, specialized equipment needs, transportation, waste generated, and potential material reuse opportunities. Based on the data collected, the LCA will be revisited, and the impact of the information collected evaluated. These efforts will highlight logistical challenges and opportunities associated with various MT End-of-Life pathways, with particular emphasis on the feasibility of MT reuse in the context of circular economy [30, 31].

Ultimately, understanding the relative cradle-to-grave environmental impacts on design choices within building systems has become progressively more relevant for practicing architects and engineers and may become increasingly so as monetary implications of low embodied carbon designs gain traction. In the past several years, many governmental regulatory programs, such as cap and trade [32], have surged in popularity. A primary objective, among many, of these programs has been to assign dollar values to environmental impacts to help provide a business incentive for impact reduction. When applied to the building sector, the usage of renewable, low-impact materials, such as the engineered MT products herein, stand to benefit. Future studies will further explore the convergence of economic and environmental criteria into a singular design methodology.

4 CONCLUSIONS

Shake-table testing of a full-scale six-story MT structure will be conducted to benchmark the design of three LFRSs. All design phases feature PT CLT rocking walls resisting forces in the E-W direction, while three independent LFRSs will be tested for lateral force resistance in the N-S direction for each phase. For these LFRSs, the phase I design will feature MPP walls with UFPs, phase II will consist of new MPP walls with BRBs, and phase III design is still under development.

The LFRS designed in phase I was compared with a functionally equivalent RC design to contrast cradle-to-grave environmental impacts of the two design alternatives. The Athena IE4B tool was employed to tabulate impact metrics and showed a mixed comparative performance between the MT and RC designs, with significant GWP advantage given to the MT solution when accounting for BBL net credits. Examining the GWP at each life-cycle stage, it was observed that the Production, Construction, and End-of-Life stages were similar between design alternatives, with a major disparity in accounted BBL net credits. Considering each element group in the MT wall system, it was shown that the timber elements have a net negative GWP contribution, while the other steel elements contribute significantly to the total GWP.

Overall, this research examines the comparative environmental sustainability of MT design solutions, while also investigating their structural performance in seismic regions.

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