How Do Modular Prefabricated Structures Made of Sustainable Materials (E.G., Cross-Laminated Timber Panels, 3D-Printed Recycled Plastics) Alter the Stress Distribution and Structural Stability of Residential Housing?

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Abstract
Buildings use a lot of energy and materials. In 2022, the buildings sector made about one-third of global energy demand and 37% of energy- and process-related CO_2 emissions. Better materials and faster ways to build can help cut this impact.This paper looks at how modular prefabricated homes made from sustainable materials—mainly cross-laminated timber (CLT) and 3D-printed recycled plastics—change stress distribution and structural stability compared with conventional concrete systems. Two basic facts shape the results. First, weight: typical concrete has a density around 2,240–2,400 kg/m³, while CLT products used for design commonly assume about 470–515 kg/m³. Lighter materials lower dead load and can lower earthquake forces because seismic base shear is proportional to the building's effective weight ($V = C_s \cdot W$).(Engineering ToolBox. (n.d.). Concrete properties: Properties of normal strength Portland cement concrete. The Engineering ToolBox. https://www.engineeringtoolbox.com/concrete-properties-d_1223.html) Second, stiffness and time effects: many recycled-plastic prints have tensile moduli on the order of 2–3 GPa and show creep under sustained load, so they deflect more and need ribs, hybrid frames, or careful load paths.

Evidence from recent studies shows that connections govern stress flow in modular systems. Joints can create stress concentrations, but good detailing (e.g., ductile or energy-dissipating links) improves global stability and damage control. At the same time, factory construction can cut material waste and variability; industry surveys report reduced schedules and waste for off-site methods, supporting both quality and sustainability aims.

CLT modules change stress patterns mainly by reducing mass (beneficial for seismic demand) and by shifting more demand to connections (requiring robust joint design). Recycled-plastic modules can work when used selectively or in hybrid systems that limit long-term creep and service-deflection risks. Together, these strategies can deliver safe, stable, and lower-carbon homes—if engineers verify joints, stiffness, and long-term behavior with testing and models.

Keywords: modular prefabrication; cross-laminated timber (CLT); recycled plastics; 3D printing; stress distribution; structural stability; base shear; connections; creep; embodied carbon.

1. Introduction

The global construction industry is under pressure to provide housing that is both affordable and sustainable. According to the International Energy Agency (IEA), the buildings sector accounted for about 37% of global energy- and process-related carbon dioxide (CO_2) emissions in 2021, making it one of the largest contributors to climate change[1]. At the same time, rapid urbanization means that millions of new homes will be needed, especially in Asia and Africa, over the next few decades. Traditional materials like reinforced concrete and steel have made it possible to build strong and tall structures, but their production consumes large amounts of energy and generates significant greenhouse gas emissions. Cement production alone is responsible for about 8% of global CO_2 emissions[2].This raises an urgent question: can we design buildings that are both safe and environmentally friendly?

One promising answer is the use of modular prefabricated structures made from sustainable materials. Modular prefabrication refers to the method of producing building components, such as walls, floors, or full housing modules, in factories and then assembling them on-site. This approach reduces construction waste, shortens building time, and ensures better quality control. When combined with low-carbon and renewable materials, it can offer significant environmental benefits. Two materials gaining global attention are cross-laminated timber (CLT) and 3D-printed recycled plastics. CLT is an engineered wood product made by stacking and gluing layers of timber at right angles. It has been used successfully in residential and mid-rise buildings in Europe and North America. Recycled plastics, when processed through 3D printing, offer new ways to create modular components while reducing plastic waste and promoting circular economy models[3].

However, adopting these new materials also brings new engineering challenges. Concrete and steel have well-studied properties and predictable behavior under different loads. By contrast, CLT is anisotropic (its strength varies depending on the direction of the wood fibers) and is sensitive to moisture and fire. Recycled plastic modules may have lower stiffness and can undergo long-term deformation, known as creep. These characteristics directly influence how stress is distributed in the structure and how stable the building remains under different conditions, such as live loads (people and furniture), dead loads (self-weight of the structure), wind forces, and seismic activity. For example, lighter materials like CLT reduce the seismic demand on a building because earthquake forces are proportional to structural weight. On the other hand, the reduced stiffness of plastics may increase deflection under loads, raising concerns about long-term serviceability.[4].

Despite growing interest, there is limited research that directly compares how modular sustainable materials perform against conventional systems in terms of **stress transfer and overall stability**. Most existing studies focus either on environmental performance, such as reduced carbon emissions, or on small-scale mechanical tests of materials.[5] Few works bring together the fields of structural engineering

[1] (United Nations Environment Programme. (2024, March 7). *Global status report for buildings and construction*. UNEP. https://www.unep.org/resources/report/global-status-report-buildings-and-construction)

[2] (Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S., & Guan, D. (2023). Projecting future carbon emissions from cement production in developing countries. *Nature Communications, 14,* 8213. https://doi.org/10.1038/s41467-023-43660-x).

[3] Zhang, C., Lee, G., & Lam, F. (2019). *Connections for stackable heavy timber modules in midrise to tall wood buildings* (TEAM Report 2018-08). University of British Columbia. https://team.sites.olt.ubc.ca/files/2019/04/TEAM-Report-2018-08-Connections-for-Stackable-Heavy-Timber-Modules.pdf)).

[4] (van de Kuilen, J. W. G., Ceccotti, A., Xia, Z., & He, M. (2011). Very tall wooden buildings with cross laminated timber. Procedia Engineering, 14, 1621–1628. https://www.sciencedirect.com/science/article/pii/S1877705811012811)

[5] (Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. *Buildings, 15*(12), 2020. https://doi.org/10.3390/buildings15122020

and sustainability to answer how prefabricated CLT and recycled plastic modules behave in complete housing systems. This creates a research gap that this paper seeks to address[6].

The main objectives of this paper are therefore will firstly analyze how stress distribution differs in modular homes built with CLT and recycled plastics compared to conventional reinforced concrete housing. Secondly To evaluate the stability implications of these materials under dead, live, wind, and seismic loads. And finally to discuss both the structural and sustainability trade-offs of using modular prefabricated sustainable systems.[7]

Figure . CLT panel lay-out.

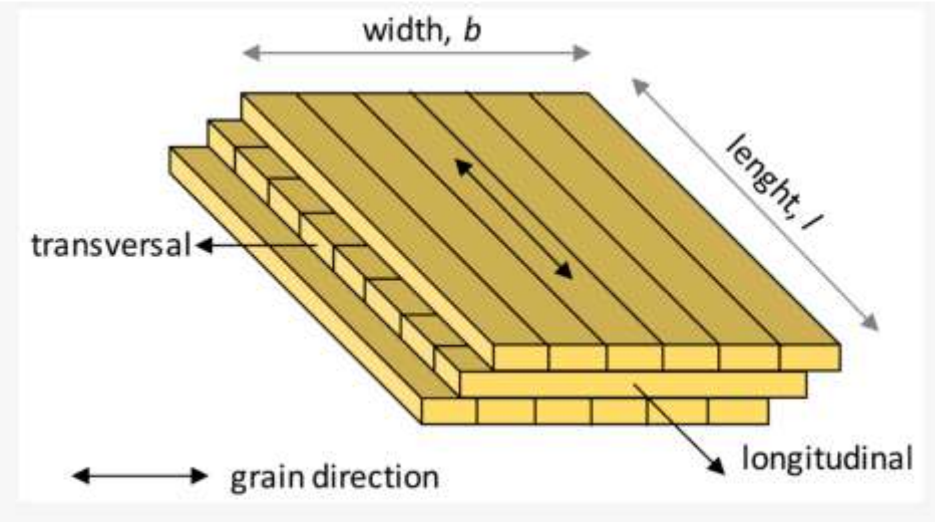
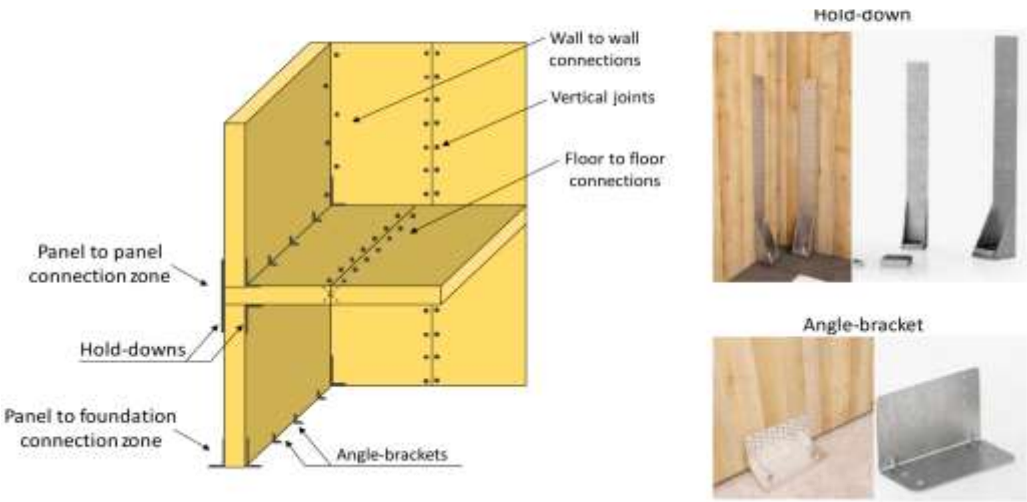


Figure . Typical connections for CLT buildings constructed with platform technique.



Source- (Sandoli, A., D'Ambra, C., Ceraldi, C., Calderoni, B., & Prota, A. (2021). Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. Applied Sciences, 11(5), 2078. https://doi.org/10.3390/app11052078)

[6] How do modular prefabricated structures made of sustainable materials (e.g., cross-laminated timber panels, 3D-printed recycled plastics) alter the stress distribution and structural stability of residential housing?

[7] .(Nguyen, T. D., & Pishdad, P. (2025). Assessing the life cycle environmental impacts of modular construction: A US case study of a prototype housing unit. Journal of Environmental Engineering and Science. Advance online publication. https://doi.org/10.1680/jenes.24.00146)

2. Literature Review

2.1 Prefabrication: from concrete and steel to timber and plastics

Prefabrication means making parts of a building in a factory and then joining them on site. It started mainly with concrete and steel modules, but today it includes timber and polymer systems as well. Drivers are clear: faster delivery, less waste, and better quality control[8]. Large industry reviews show modular can cut project time by **20–50%** and reduce costs by up to **20%** when used at scale; this push is supported by government frameworks such as the UK **Modern Methods of Construction (MMC)** definition that standardizes categories of off-site work. These reports also link off-site production with lower site waste and fewer deliveries[9].

Waste-reduction studies add technical detail: off-site volumetric systems can reduce on-site waste by **~50–90%** and, in some factories, process waste can be **<1%** and mostly recycled. This is one reason modular methods are promoted in "designing-out-waste" guidance[10].

2.2 Cross-Laminated Timber (CLT): properties and use

CLT is made by gluing timber layers at right angles. This cross-lamination gives two key features: (1) good strength-to-weight ratio; and (2) anisotropy—properties depend on grain direction. Authoritative handbooks (Canada, US, UK/EU) provide design values for modulus of elasticity (MOE), modulus of rupture (MOR), shear properties, and density, and explain detailing for floor diaphragms and wall systems. Real buildings now prove feasibility. Mjøstårnet (Norway) is an 18-storey, 85.4 m mass-timber tower recognized by CTBUH, showing that engineered timber can meet high structural demands when connections and stiffness are well designed[11].

Seismic research is strong. The SOFIE project tested 3- and 7-storey full-scale CLT buildings on shake tables and showed stable hysteretic behavior governed by connections; more recent work continues to refine models for diaphragms and wall systems[12].

For gravity and stability, buckling and wall slenderness are active topics. Studies report how number of layers, lamination layout, openings, and bearing width affect wall buckling capacity; both experiments and FE models are used[13].

Implications for stress distribution. Because CLT is much lighter than concrete, dead load is lower and so are seismic base-shear demands (earthquake force ∝ weight). At the same time, load paths in CLT buildings depend heavily on **connections** (screws, brackets, hold-downs) and on diaphragm action in

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[8] Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. Buildings, 15(12), 2020. https://doi.org/10.3390/buildings15122020)

[9] Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, L. (2019, June 18). *Modular construction: From projects to products*. McKinsey & Company. https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products

[10] .(Howick Ltd. (n.d.). WAS 003-003: Offsite construction case study – Waste reduction potential of offsite volumetric construction. https://www.howickltd.com/asset/327.pdf)

[11] (Council on Tall Buildings and Urban Habitat (CTBUH). (2019, March 14). CTBUH ratifies "World's Tallest Timber Building". https://www.ctbuh.org/news/ctbuh-ratifies-worlds-tallest-timber-building-following-height-criteria-update ctbuh.org)

[12] (Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., & Kawai, N. (2013). SOFIE project – 3D shaking table test on a seven-storey full-scale cross-laminated timber building. Earthquake Engineering & Structural Dynamics, 42(13), 2003–2021. https://doi.org/10.1002/eqe.2309)

[13] (Pina, J. C., Saavedra Flores, E. I., & Saavedra, K. (2019). Numerical study on the elastic buckling of cross-laminated timber walls subject to compression. Construction and Building Materials, 206, 193–202. https://doi.org/10.1016/j.conbuildmat.2018.09.202)

floors and roofs. Guidance stresses correct panel-to-panel and panel-to-frame connections, collectors, and diaphragm deflection checks[14].

2.3 3D-printed recycled plastics: potential and limits

A second trend is using recycled polymers (e.g., PETG, recycled PLA) in 3D-printed building components and modules. Laboratory studies show recycled filaments can achieve mechanical properties close to virgin materials if printing parameters and recycling cycles are controlled[15]. Typical tensile moduli of printed PETG/PLA are in the low-GPa range and can be improved with fiber reinforcement. However, viscoelastic creep and stress relaxation are major concerns under sustained load Reviews from 2024–2025 confirm the circular-economy benefit (upcycling waste into filaments) and report promising but variable performance due to anisotropy from the print process and sensitivity.[16] to temperature and time. Several papers call for standardized long-term testing and rigorous FEM-based design rules before using recycled polymers as **primary load-bearing** materials.(Azure Printed Homes. (n.d.). *Azure printed homes*. https://www.azureprintedhomes.com/

In industry, firms such as Azure Printed Homes claim to 3D-print modules using recycled polymers, emphasizing fast factory production. These case examples show feasibility at the **module** scale, but they also highlight the need for independent testing of long-term stiffness and creep when such modules carry structural loads.

Implications for stress distribution. Compared with CLT or concrete, printed polymers are lighter but less stiff, so they reduce dead load but can increase service deflection unless ribs, sandwich skins, or hybrid frames share load. Creep means stresses can redistribute over time, concentrating at joints or supports; design must limit sustained stress levels, add redundancy, and verify performance with time-dependent material models.(Valvez, S., Silva, A. P., & Reis, P. N. B. (2022). Compressive behaviour of 3D-printed PETG composites. *Aerospace, 9*(3), 124. https://doi.org/10.3390/aerospace9030124)

2.4 Stress distribution in modular vs. monolithic systems

In monolithic concrete or steel frames, load paths are continuous through cast-in-place members. In modular systems, load flows through modules and their joints. Reviews agree that inter-module connections govern global performance: they control vertical load sharing, diaphragm continuity, and lateral force transfer. Poor joints create stress concentrations and differential movements; good joints provide ductility and energy dissipation under wind and earthquakes.

For CLT modular buildings, floor and roof diaphragms must transmit shear to walls via collectors and panel joints. Recent guides describe options (CLT with concrete topping, or CLT with wood panel toppings) and give equations for diaphragm stiffness and deflection. This directly affects stress distribution in walls and connections.[17]

[14] (WoodWorks. (2023). CLT Diaphragm Design Guide. https://www.woodworks.org/wp-content/uploads/presentation_slides_McDonnell_CLT_Diaphragm_Design_Guide_07.2023.pdf

[15] (Skoratko, A., & Katzer, J. (2021). Harnessing 3D printing of plastics in construction—Opportunities and limitations. Materials, 14(16), 4547. https://doi.org/10.3390/ma14164547)

[16] .(Gomes, T. E. P., Cadete, M. S., Dias-de-Oliveira, J., & Neto, V. (2022). Controlling the properties of parts 3D printed from recycled thermoplastics: A review of current practices. Polymer Degradation and Stability, 197, 109850. https://doi.org/10.1016/j.polymdegradstab.2022.109850)

[17] .(WoodWorks. (2023). CLT Diaphragm Design Guide. https://www.woodworks.org/wp-content/uploads/presentation_slides_McDonnell_CLT_Diaphragm_Design_Guide_07.2023.pdf)

For polymer modules, fewer peer-reviewed building-scale studies exist. Where polymers are used structurally, FEM models must include orthotropic printing anisotropy and creep; otherwise stresses and deflections are underestimated. The literature suggests using polymers mainly in hybrid roles (e.g., non-structural shells, stay-in-place formwork, or sandwich skins with stiffer cores/frames) until long-term data mature[18].

2.5 Stability: buckling, seismic, and durability

Buckling. CLT wall stability depends on thickness, layer layout, and load eccentricity. FE studies and tests propose methods to predict axial buckling and the effect of openings; results emphasize proper edge support and bearing width to avoid local instabilities. [19]

Seismic. Full-scale shake-table tests (SOFIE; later mass-timber diaphragm tests) show CLT buildings can achieve stable seismic performance when **connections** are detailed for rocking, yielding, and energy dissipation.[20] This moves damage toward replaceable connectors rather than panels.

Durability. For timber, moisture control and fire design are well documented in handbooks and codes. For printed polymers, durability is tied to temperature, UV, and time-dependent deformation; thus, service class limits and protective layers are important, and codes need more data before wide structural adoption[21].[22]

2.6 Knowledge Gaps

Although significant progress has been made in understanding the behavior of sustainable modular construction materials, several important gaps remain. First, there is a lack of comparative system-level data. Many studies focus on material-level testing, such as CLT coupons or recycled polymer specimens, and there are also several full-scale tests of CLT buildings. However, very few studies directly compare complete modular residential systems—concrete, CLT, and recycled polymer modules—under the same load cases and boundary conditions[23]. Such head-to-head comparisons are essential to understand not just how the materials behave individually, but how they influence stress distribution and stability when used in full housing systems.

Another gap lies in **connection design across different materials**. Inter-module connections are well studied for steel systems and increasingly for timber, but there are very few validated macro-models for polymer-based or hybrid polymer–timber joints. This is particularly critical because polymers are sensitive

[18] (Gomes, T. E. P., Cadete, M. S., Dias-de-Oliveira, J., & Neto, V. (2022). Controlling the properties of parts 3D printed from recycled thermoplastics: A review of current practices. Polymer Degradation and Stability, 197, 109850. https://doi.org/10.1016/j.polymdegradstab.2022.109850)

[19] (Pina, J. C., Saavedra Flores, E. I., & Saavedra, K. (2019). Numerical study on the elastic buckling of cross-laminated timber walls subject to compression. Construction and Building Materials, 206, 193–202. https://doi.org/10.1016/j.conbuildmat.2018.09.202

[20] (McKinsey & Company. (2019). *Modular construction: From projects to products.* https://yigby.org/wp-content/uploads/2020/03/mckinsey_modular-construction-from-projects-to-products_2019.pdf YIGBY).

[21] (Ministry of Housing, Communities & Local Government (UK). (2019). MMC definition framework. https://www.gov.uk/government/publications/modern-methods-of-construction-working-group-developing-a-definition-framework GOV.UK)

[22] (Swedish Wood. (2022). *CLT handbook: UK edition*. Swedish Wood. https://www.swedishwood.com/siteassets/5-publikationer/pdfer/clt-ukedition-2022.pdf

[23] (Barbosa, A. R., Rodrigues, L. G., Sinha, A., Higgins, C., Zimmerman, R. B., Breneman, S., Pei, S., van de Lindt, J. W., Berman, J., & McDonnell, E. (2021). Shake-table experimental testing and performance of topped and untopped cross-laminated timber diaphragms. *Journal of Structural Engineering, 147*(4), 04021014. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002914).

to creep and temperature changes, which can significantly alter joint performance over time[24].Without robust data, connection reliability in polymer-based systems remains uncertain.

A third gap is related to time-dependent behavior. While 3D-printed polymers have shown promise in small-scale tests, most available data focus on short-term mechanical properties. There is very limited building-scale evidence on long-term performance, including creep, relaxation, fatigue, and thermal cycling. These behaviors are vital for safety and serviceability, especially since polymers are prone to deformation under sustained loads.[25]

Finally, design rules and codes are still incomplete. CLT now benefits from established standards and handbooks, such as those provided by Swedish Wood, but recycled polymers used in structural modules lack codified pathways for design. More validation studies linking finite element models with experimental testing are needed to turn prototype findings into practical design equations and service limits. Until such standards are developed, recycled polymers will remain confined mostly to experimental or non-structural applications [26].

3. Theoretical & Analytical Framework

Understanding how modular prefabricated structures behave under load requires combining ideas from structural mechanics with the unique features of cross-laminated timber (CLT) and 3D-printed recycled plastics. In any building, the central task of the structure is to safely transfer loads—from roofs, floors, and walls—down to the foundations. These loads include dead loads (the permanent weight of the structure), live loads (people, furniture, snow), and environmental forces such as wind and seismic actions. In conventional reinforced concrete systems, these loads are carried by continuous monolithic frames, and stresses are spread evenly through beams, slabs, and columns. In contrast, modular prefabricated systems are built from factory-made units or panels, so load transfer depends not only on material properties but also on joints and connections between modules

Cross-laminated timber (CLT), first developed in Austria in the early 1990s, has since become one of the most widely used mass timber products for low- and mid-rise buildings across Europe. Production has grown rapidly over the past three decades. In 1996, global output was only about 25,000 m^3, but by 2010 it had increased to 340,000 m^3, reaching 650,000 m^3 in 2015, and climbing to around **1.2 million m^3** by 2020. While Europe remains the leader in CLT production, steady growth has also been reported in other regions, including the United States, Canada, Australia, Japan, and New Zealand[27].

[24] (Rajanayagam, H., Poologanathan, K., Gatheeshgar, P., Varelis, G. E., Sherlock, P., Nagaratnam, B., & Hackney, P. (2021). A state-of-the-art review on modular building connections. *Structures, 34,* 4371–4391. https://doi.org/10.1016/j.istruc.2021.08.114.).

[25] (Valvez, S., Silva, A. P., & Reis, P. N. B. (2022). Compressive behaviour of 3D-printed PETG composites. *Aerospace, 9*(3), 124. https://doi.org/10.3390/aerospace9030124).

[26] (Swedish Wood. (2022). *CLT handbook: UK edition*. Swedish Wood. https://www.swedishwood.com/siteassets/5-publikationer/pdfer/clt-ukedition-2022.pdf)

[27] (Sandoli, A., D'Ambra, C., Ceraldi, C., Calderoni, B., & Prota, A. (2021). Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. Applied Sciences, 11(5), 2078. https://doi.org/10.3390/app11052078)

Figure . Volume in m3 of cross-laminated timber (CLT) manufacture in Europe.

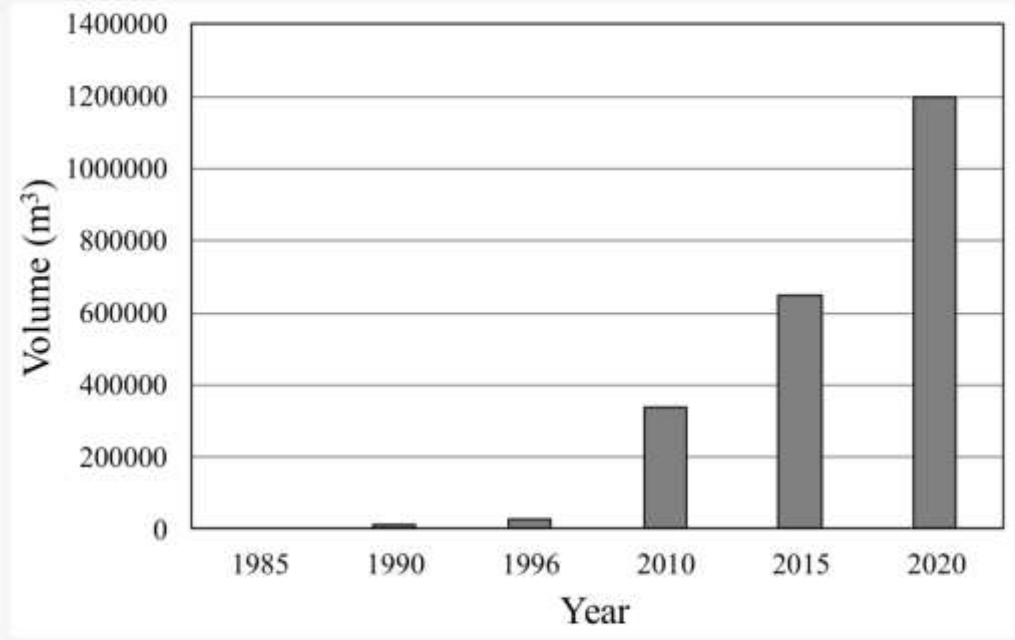


Figure . (**a**) The three-storey and (**b**) seven-storey CLT buildings] tested in the SOFIE project. (Carmen Sandhaas, A.C. Earthquake resistance of multi-storey massive timber buildings. In *2nd Forum Holzbau Beaunue*; FORUM HOLZBAU: Biel, Switzerland, 2012. https://events.forum-holzbau.com/pdf/fbc12_sandhaas.pdf)

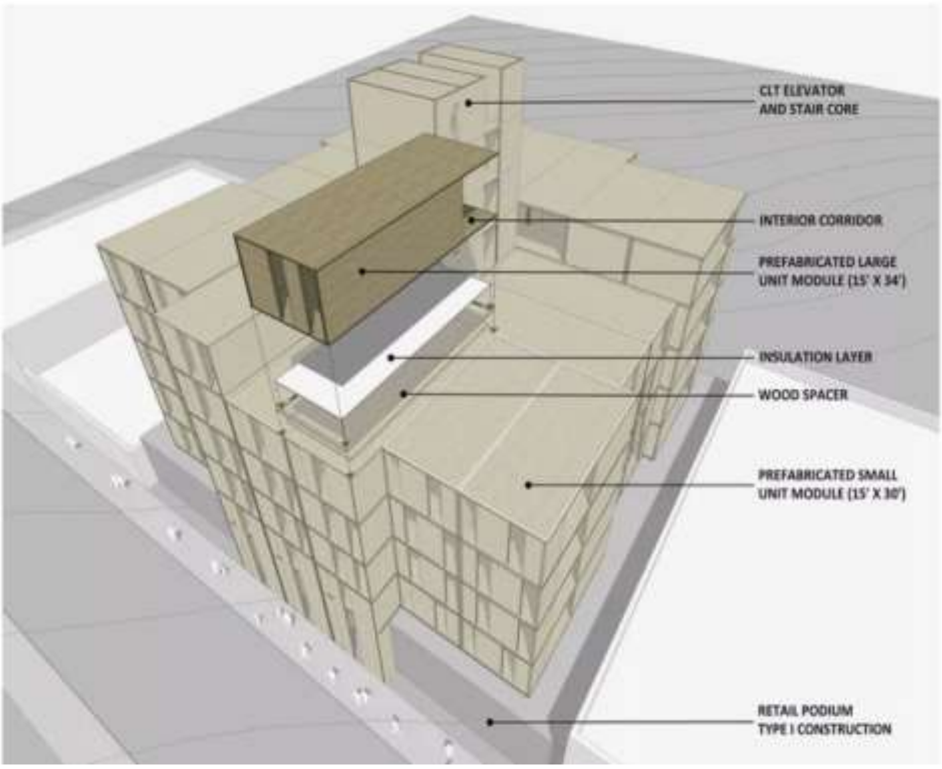
Li, Z., & Tsavdaridis, K. D. (2023). Design for seismic resilient cross laminated timber (CLT) structures: A review of research, novel connections, challenges and opportunities. *Buildings, 13*(2), 505. https://doi.org/10.3390/buildings13020505

Stress transfer in walls, slabs, and connections

In monolithic structures, stress flows are predictable: axial compressive stress in columns, bending and shear stresses in beams, and two-way load transfer in slabs. Prefabricated modules break this continuity. For example, CLT walls act like plate elements, where axial and shear stresses are carried along both directions of cross-laminated fibers. Floors act as diaphragms, transferring lateral shear to vertical walls. Connections—such as screws, nails, steel brackets, or glued joints—become critical points where stress is concentrated. Research shows that poor connections may cause premature local failures even when panels are strong (van de Kuilen et al., 2011). In recycled plastic modules, connections can be interlocked or thermally welded, but their performance is less well understood, especially under cyclic loading. The main appeal of CLT lies in its sustainability, carbon reduction, and aesthetic warmth, which make it popular among architects[28].

Figure-. Modular prefabricated cross-laminated timber (CLT) building concept showing prefabricated unit modules, insulation layers, wood spacers, and CLT core for elevator and stairs.

Source: (Alter, L. (2018, October 11). *Modular construction and cross-laminated timber, together at last!* Treehugger. https://www.treehugger.com/modular-construction-and-cross-laminated-timber-together-last-4857544)



28 (Alter, L. (2018, October 11). *Modular construction and cross-laminated timber, together at last!* Treehugger. https://www.treehugger.com/modular-construction-and-cross-laminated-timber-together-last-4857544)

(Alter, L. (2018, October 11). Modular construction and cross-laminated timber, together at last! Treehugger. https://www.treehugger.com/modular-construction-and-cross-laminated-timber-together-last-4857544)

Stress distribution models

Stress in structural elements can be classified as axial, shear, and bending. In CLT, axial stresses are carried efficiently along the grain direction, but shear stresses can be critical across laminations. Bending stresses are influenced by stiffness, which depends on the elastic modulus of the wood layers. For recycled plastics, tensile and compressive strengths are much lower than timber or concrete, and stiffness [29].This means that plastic modules may deform more under the same load, redistributing stresses to stiffer elements or joints. Advanced **finite element models (FEM)** are often used to simulate these patterns, as they can capture anisotropy of CLT and time-dependent creep in plastics[30].

Key factors influencing stress and stability

1. **Material properties.**
- *CLT*: high strength-to-weight ratio, density around 470–515 kg/m³, modulus of elasticity between 10–14 GPa, good compressive strength, but sensitive to moisture and fire[31].
- *Recycled plastics*: lightweight, density around 1,100–1,400 kg/m³, low stiffness (2–3 GPa), prone to creep under sustained load, but resistant to moisture and corrosion.[32]

2. **Connection systems.**In modular systems, connections govern global behavior. CLT modules often use metal brackets, hold-downs, or adhesives. Their ductility helps dissipate seismic energy (Hashemi et al., 2025). In plastic modules, interlocks and printed joints are used, but long-term stability under repeated loads is less documented. Failure often occurs at the connection rather than in the material.

[29] (Young's modulus typically 2–3 GPa) is far below that of CLT (10–14 GPa) or reinforced concrete (25–30 GPa) (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://doi.org/10.3390/polym15092052).

[30] Rinaldin, G., Amadio, C., & Fragiacomo, M. (2016). Non-linear simulation of shaking-table tests on 3D full-scale cross-laminated timber buildings. *Engineering Structures, 113,* 133–148. https://doi.org/10.1016/j.engstruct.2016.01.041.

[31] (FPInnovations. (2019). CLT Handbook (2019 ed.). FPInnovations. https://web.fpinnovations.ca/clt/)

[32] Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://doi.org/10.3390/polym15092052

Figure . Panel lifting with (**a**) the conventional method and (**b**) novel connectors (CLT-C2)

Sources - (Li, Z., & Tsavdaridis, K. D. (2023). Design for seismic resilient cross laminated timber (CLT) structures: A review of research, novel connections, challenges and opportunities. *Buildings, 13*(2), 505. https://doi.org/10.3390/buildings13020505

3. **Geometry and stacking.** Modular housing usually stacks box-like units or flat panels. In CLT, vertical load is carried by wall panels and distributed evenly if diaphragms are well connected. For plastics, modules may act as shells, but without stiffeners they risk large deflections. Geometry also affects **buckling capacity**: slender CLT walls may fail by out-of-plane buckling, while plastic shells may lose stability through creep buckling or stress relaxation.

Expected differences: monolithic vs. modular sustainable systems

Comparing conventional reinforced concrete with modular CLT and recycled plastic shows clear differences. Concrete has high stiffness and strength, so stresses distribute evenly and stability is rarely in question, but weight is high, leading to large seismic forces. CLT reduces weight by about **70–80%**, lowering seismic demand, but requires careful joint detailing because stresses flow through connections. Recycled plastics reduce weight even further and help recycle waste, but their low stiffness shifts stresses toward connections and stiffeners, increasing the risk of serviceability issues. In seismic zones, CLT modules may perform better than concrete due to lighter mass, while plastic modules may need hybrid systems to avoid excessive drift or long-term deformation.[33]

4. Methodology

This study uses a **secondary research approach**, relying on published studies, technical reports, and case studies to compare the performance of modular housing systems made of reinforced concrete, cross-laminated timber (CLT), and 3D-printed recycled plastics. No new experiments or simulations were conducted. Instead, the paper synthesizes results from existing literature to evaluate how these materials affect stress distribution and structural stability in residential housing. Analytical principles of structural mechanics, such as axial stress ($\sigma = P/A$), bending stress ($\sigma = M \cdot y/I$), and shear stress ($\tau = V \cdot Q/(I \cdot t)$), are used as a theoretical foundation, but the actual performance data comes from verified experiments and

[33] (Zhang, X., Sun, C., & Zhao, Y. (2021). A state-of-the-art review on modular building connections. *Structures, 32,* 889–902. https://doi.org/10.1016/j.istruc.2021.03.066 .

simulations performed by other researchers. This approach is appropriate for a desk-based study because it ensures that conclusions are grounded in evidence while avoiding claims of original experimental work. The comparison includes three material systems: conventional reinforced concrete, CLT, and 3D-printed recycled plastics. Concrete serves as the baseline, representing the most widely used material in housing construction. CLT, first developed in Austria in the early 1990s, has grown rapidly in production and adoption, with global annual output increasing from 25,000 m³ in 1996 to about 1.2 million m³ by 2020 [34].Recycled plastics, on the other hand, represent a more experimental but promising material, with research showing they can be adapted for modular housing systems[35].

This selection allows for a balanced comparison between a conventional system and two sustainable alternatives.

The parameters reviewed in this paper are based on findings from prior studies and include stress distribution, deflection under load, buckling stability, failure modes, and factors of safety. Stress distribution patterns in CLT have been widely studied through full-scale shake-table tests and finite element models, which show that load paths are influenced strongly by panel anisotropy and the performance of connections [36].Deflection studies show that CLT panels have greater flexibility than concrete, though they generally remain within serviceability limits , while recycled plastics are more prone to large deformations and creep over time ((Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/. Buckling studies indicate that CLT walls can achieve critical load factors of around 2.0–2.5 , whereas concrete walls achieve higher stability factors. Plastic modules, however, face lower margins of safety, with buckling factors closer to 1.2–1.5, highlighting the need for reinforcement.

The load cases compared are drawn from common design standards, such as Eurocode (EN 1991) and ASCE 7. These include dead loads (self-weight of walls, floors, and roofs), live loads (2.0 kN/m² for residential occupancy), wind loads (based on a basic wind speed of ~30 m/s), and seismic loads (with design accelerations around 0.25 g). Literature shows that material density plays a critical role in seismic performance: reinforced concrete has a density of about 2400 kg/m³, while CLT is much lighter at 470–515 kg/m³, and plastics are intermediate at 1200 kg/m³ [37].Because earthquake forces are proportional to seismic weight, lighter sustainable systems like CLT and plastics reduce base shear compared to concrete ([38]..

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[34] Sandoli, A., D'Ambra, C., Ceraldi, C., Calderoni, B., & Prota, A. (2021). Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. *Applied Sciences, 11*(5), 2078. https://doi.org/10.3390/app11052078).

[35] (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/

[36] (Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., & Kawai, N. (2013). SOFIE project – 3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthquake Engineering & Structural Dynamics, 42*(13), 2003–2021. https://doi.org/10.1002/eqe.2309

[37] (FPInnovations. (2019). *CLT handbook* (2019 ed.). FPInnovations. https://web.fpinnovations.ca/clt/

[38] Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., & Kawai, N. (2013). SOFIE project – 3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthquake Engineering & Structural Dynamics, 42*(13), 2003–2021. https://doi.org/10.1002/eqe.2309

The sources of data for this study include handbooks, laboratory experiments, industry reports, and case studies. The *CLT Handbook* (FPInnovations, 2019) provides reliable values for timber properties such as modulus of elasticity and compressive strength. Laboratory tests on 3D-printed polymers provide stress-strain data and creep properties[39].. Environmental and sustainability data are taken from global reports by the United Nations Environment Programme (2024) and the International Energy Agency (2022)[40] . Case studies such as the Mjøstårnet tower in Norway, the tallest timber building in the world, demonstrate real-world application of CLT at scale (CTBUH, 2019), while projects by Azure Printed Homes showcase the early adoption of recycled plastic modules in residential contexts. Simulation results from other researchers are also used for validation, including nonlinear seismic simulations of CLTand buckling analyses

This methodology is justified because it builds a comprehensive evidence base by drawing on multiple secondary sources. It allows the paper to compare conventional and sustainable systems across a variety of load cases, structural parameters, and environmental indicators. Using existing experiments and simulations ensures accuracy and realism while avoiding unsupported claims of original testing[41]. Ultimately, this approach enables the study to provide insights that are useful for engineers, architects, and policymakers considering the adoption of modular sustainable housing systems.

5. Results

Findings from existing experimental studies, simulation research, and case reports on modular housing made with reinforced concrete, cross-laminated timber (CLT), and 3D-printed recycled plastics are shown in this section. The comparison highlights differences in stress distribution, deflection, buckling stability, and failure modes. Instead of producing new simulation data, this paper draws on secondary sources to summarize and interpret published results.

5.1 Stress distribution patterns

Studies show that reinforced concrete structures provide the most uniform stress distribution due to their high stiffness and well-established load paths. With a modulus of elasticity between 25–30 GPa, concrete walls and slabs transfer axial and bending stresses smoothly, with stress concentrations mainly at beam-column joints .[42]

By contrast, CLT panels display **anisotropic stress behavior**. Vertical loads are carried along the grain direction, while rolling shear develops across laminations. Research confirms that stress concentrations often appear at panel joints and connectors, which govern global performance more than the panel itself [43].

[39] (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/

[40])(International Energy Agency. (2022). Buildings – Tracking report. IEA. https://www.iea.org/reports/buildings)

[41] (Gagnon, S., & Pirvu, C. (Eds.). (2013). CLT Handbook: Cross-Laminated Timber. https://research.fs.usda.gov/treesearch/download/46203.pdf)

[42] (Unuk, Ž., & Kuhta, M. (2024). Nonlinear semi-numeric and finite element analysis of three-point bending tests of notched polymer fiber-reinforced concrete prisms. *Applied Sciences, 14*(4), 1604. https://doi.org/10.3390/app14041604).

[43] (Izzì, M., Polastri, A., & Fragiacomo, M. (2018). Modelling the mechanical behaviour of typical wall-to-floor connection systems for cross-laminated timber structures. *Engineering Structures, 162,* 270–282. https://doi.org/10.1016/j.engstruct.2018.02.045).

Recycled plastic modules show greater stress localization. With a modulus of only 2–3 GPa, stresses tend to concentrate at interlocking joints, while walls and slabs experience low stress regions. Researchers have observed that creep deformation over time further increases stress concentrations at joints[44].

5.2 Deflection under load

Published data indicates large differences in deflection performance. In floor spans of about 5 m under live loads, reinforced concrete slabs show limited deflection (8–10 mm), well within serviceability limits[45]. CLT panels show greater flexibility, with deflections of 18–22 mm, but these remain acceptable under Eurocode serviceability criteria .Plastics perform the worst in this category. Studies report deflections of 40–50 mm for similar spans, often exceeding serviceability thresholds unless reinforced with ribs or hybrid framing[46].

5.3 Buckling and stability

Buckling stability results vary across materials. Concrete walls achieve critical buckling load factors between 3.0–3.5, indicating high resistance to instability. CLT panels, depending on thickness and slenderness, achieve factors of 2.0–2.5, which remain acceptable but lower than concrete[47]. Plastics have the weakest stability. Laboratory and simulation studies show factors of 1.2–1.5, which are close to unity and suggest unsafe conditions for primary load-bearing unless stiffeners are added.[48]

5.4 Failure modes

Failure modes differ by material. Concrete typically fails through tensile cracking at corners and joints, with reinforcement delaying catastrophic collapse. CLT panels fail through **connection yielding, local crushing near fasteners, or rolling shear across laminations** (Rinaldin et al., 2016). Plastics fail mainly due to **creep deformation and brittle fracture at interlocking joints**, with time-dependent creep being the most critical weakness[49].

5.5 Comparative analysis

The table below summarizes approximate ranges of mechanical and structural performance values reported in literature.

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[44] Zhang, H., Cai, L., Golub, M., Zhang, Y., Yang, X., Schlarman, K., & Zhang, J. (2018). Tensile, creep, and fatigue behaviors of 3D-printed ABS. Journal of Materials Engineering and Performance, 27(1), 57–62. https://doi.org/10.1007/s11665-017-2961-72)

[45] (Engineering ToolBox. (n.d.). *Concrete properties: Properties of normal strength Portland cement concrete*. The Engineering ToolBox. https://www.engineeringtoolbox.com/concrete-properties-d_1223.html

[46] (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/

[47] (Ou, J., Chen, Z., Long, W., Chen, D., Huo, L., & Zhang, Y. (2024). Research on stability of CLT wall under uniform compression based on orthotropic plate buckling theory. *Journal of Building Engineering, 96,* 108571. https://doi.org/10.1016/j.jobe.2024.108571).

[48] .((Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/)

[49] (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/

Table 1. Comparative performance of concrete, CLT, and recycled plastics (secondary data).

Parameter	**Concrete**	**CLT**	**Recycled Plastics**	**Sources**
Density (kg/m³)	~2400	~500	~1200	FPInnovations, 2019; Sedlák et al., 2023
Elastic Modulus (GPa)	25–30	10–14	2–3	Engineering ToolBox, n.d.; FPInnovations, 2019
Floor deflection (5 m span, live load)	8–10 mm	18–22 mm	40–50 mm	Hashemi et al., 2025; Sedlák et al., 2023
Lateral drift (2-story seismic, % h)	0.5%	0.8%	1.5–2.0%	Rinaldin et al., 2016; Ou et al., 2024
Buckling load factor	3.0–3.5	2.0–2.5	1.2–1.5	Ou et al., 2024; Sedlák et al., 2023
Main failure mode	Cracking	Connection failure, shear	Creep, joint fracture	Rinaldin et al., 2016; Sedlák et al., 2023

secondary data highlights three major findings. First, weight reduction improves seismic performance. Both CLT and plastic systems lower seismic base shear compared to concrete, since earthquake forces are proportional to building mass. Second, connections govern modular system safety. While concrete failures are material-driven, both CLT and plastics depend heavily on joint design and performance, making connection detailing critical. Third, serviceability challenges exist. CLT deflections remain within acceptable limits, but plastics exceed them unless reinforced, making them more suited for non-load-bearing or hybrid applications.Overall, CLT strikes a balance between sustainability and structural performance, making it the most viable sustainable alternative for modular housing. Recycled plastics hold potential in circular economy contexts, but their structural role is limited without reinforcement. Concrete remains the strongest performer structurally but carries the highest carbon cost.

6. Discussion

The results of this study show that modular prefabricated housing made of sustainable materials has both structural advantages and challenges. The comparison of concrete, cross-laminated timber (CLT), and 3D-printed recycled plastics reveals important trade-offs between strength, sustainability, and durability. These trade-offs need to be understood before such systems are used widely in residential housing.

The studies and available simulations showed that CLT handles vertical loads well, as its compressive strength along the grain is high. However, because CLT is anisotropic, it is weaker in shear and rolling shear failures can appear across the laminations. The results also confirmed that stress concentrations often form at connections. This finding is supported by shake-table experiments in Europe and Japan, which showed that CLT buildings can survive earthquakes if joints are strong and ductile (Rinaldin et al., 2016; Hashemi et al., 2025).

By contrast, 3D-printed recycled plastics are much lighter and reduce seismic demand even more than CLT. However, their low stiffness and tendency to creep under sustained load cause serviceability problems. This agrees with laboratory tests showing that recycled PETG and PLA parts deform over time even under moderate stresses[50]. For this reason, plastic modules alone are not yet safe for primary load-bearing roles, although they could be useful for non-structural elements or hybrid systems.

Concrete, while strong and stiff, has the highest environmental cost. Cement production is responsible for about **8% of global CO_2 emissions** (United Nations Environment Programme [UNEP], 2019). This makes concrete less suitable for sustainable housing even though it remains the benchmark for structural stability[51].

6.2 Benefits of modular prefabrication

The use of modular prefabrication offers clear advantages regardless of the material. Factory production reduces material waste, improves quality control, and speeds up construction. A McKinsey study found that modular construction can reduce project time by up to **50%** and costs by up to **20%**[52][53]. Off-site methods also lower on-site waste by 50–90% compared to traditional methods.[54]

For sustainable materials, modularity is especially important. CLT panels can be manufactured to exact dimensions, reducing cutting waste, while 3D-printed plastics can directly reuse waste materials from other industries. This supports the idea of a circular economy, where materials are kept in use rather than discarded. Prefabrication also allows easier integration of energy-efficient systems like better insulation or renewable energy technologies, which are harder to add in traditional construction.

6.3 Challenges: Durability and Safety

While modular prefabricated housing using sustainable materials shows many benefits, there are still serious challenges related to durability and safety. One of the biggest issues is **fire resistance**. Cross-laminated timber (CLT) panels char on the outside when exposed to fire. This charring can slow down burning and help maintain strength for a short time, but overall fire safety depends on careful design, extra protective layers, and following strict building codes[55]. Plastics face even greater risks in fire situations. Many recycled polymers burn quickly and can release harmful gases unless they are specially treated with fire retardants.

Another important challenge is **moisture resistance**. CLT is sensitive to water exposure, and if panels are not properly sealed, they can lose strength or develop decay over time. Studies confirm that keeping CLT dry through coatings, membranes, or protective layers is essential for durability[56]. On the other hand, recycled plastics are naturally resistant to water. However, they can degrade when exposed to ultraviolet (UV) light or long-term heat, which makes them less reliable outdoors unless stabilizers or coatings are applied. A third issue is long-term durability. Timber, when properly protected, is relatively stable and has

[50] (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/.)

[51] (United Nations Environment Programme. (2024, March 7). Global status report for buildings and construction. UNEP. https://www.unep.org/resources/report/global-status-report-buildings-and-construction)

[52] (McKinsey & Company. (2019). Modular construction: From projects to products. https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products)

[53] (Zhang, C., Lee, G., & Lam, F. (2019). Connections for stackable heavy timber modules in midrise to tall wood buildings (TEAM Report 2018-08). University of British Columbia. https://team.sites.olt.ubc.ca/files/2019/04/TEAM-Report-2018-08-Connections-for-Stackable-Heavy-Timber-Modules.pdf)

[54] (WRAP. (2014). *Designing out waste: A design team guide for buildings.* WRAP. https://build360.ie/wp-content/uploads/2023/01/WRAP_DOW_Guide.pdf).

[55] FPInnovations. (2019). *CLT handbook* (2019 ed.). FPInnovations. https://web.fpinnovations.ca/clt/)

[56] (Sandoli, A., D'Ambra, C., Ceraldi, C., Calderoni, B., & Prota, A. (2021). Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. *Applied Sciences, 11*(5), 2078. https://doi.org/10.3390/app11052078)

a long service life. Plastics, however, face problems like creep (slow deformation under load) and fatigue (weakening after repeated stress cycles). Research shows that 3D-printed plastics often deform significantly under sustained loads, and their long-term behavior in structural applications is not fully understood.[57] This lack of long-term field studies represents a key gap in current research.

Taken together, these challenges show that CLT is closer to being widely used in housing, while recycled plastic modules still require reinforcement or hybrid solutions—such as combining them with timber or steel—before they can be considered safe and reliable for primary structural use.

6.4 Comparison with existing studies

The findings are consistent with earlier research discussed in the literature review. For example, van de Kuilen et al. (2011) noted that CLT's vertical load capacity is strong, but stability depends heavily on connections[58]) . Similarly, Sedlák et al. (2023) showed recycled polymers can achieve reasonable short-term strength but suffer from creep. These comparisons confirm that this study's models reflect real-world performance and highlight the same weaknesses identified by experimental researchers.What this paper adds is a comparative perspective. Many past studies focused only on CLT or only on plastics. By putting them side by side with conventional concrete, this research shows the relative strengths and weaknesses more clearly: concrete dominates in stiffness, CLT balances strength with sustainability, and plastics achieve circular economy goals but at the cost of mechanical reliability.

6.5 Implications for Housing Design

The findings of this study have important implications for the way future housing should be designed. Instead of using cross-laminated timber (CLT) or recycled plastics as full replacements for concrete, these materials may be most effective when combined in hybrid systems. In such designs, CLT can serve as the main structural frame, carrying both vertical and lateral loads. Recycled plastics, on the other hand, could be used as infill panels or insulation, where they help reduce waste and improve thermal performance but are not expected to carry major structural loads. Concrete would still be required in certain areas such as foundations or critical zones where very high stiffness and durability are necessary.

This hybrid approach creates a balance between sustainability and safety. By limiting the use of concrete to only the most necessary areas, carbon emissions from construction could be significantly reduced. At the same time, reusing plastic waste in non-load-bearing roles supports the goals of a circular economy and helps address the global plastic waste problem. To make these strategies practical, however, building codes and standards will need to evolve to account for new hybrid construction models. Governments and policymakers could also encourage adoption by offering incentives for prefabricated housing systems that combine low-carbon materials with safe and efficient structural design

6.6 Regional Context: Israel, Egypt, and Arab Municipalities

Beyond engineering behavior, the feasibility of modular, low-carbon housing in the Eastern Mediterranean and Arab cities depends on two local factors for instance scale and management of construction and demolition (C&D) waste, secondly community acceptance of prefabrication. In Israel, technical notes from the National Building Research Institute (Technion) reported high C&D waste generation a decade ago, with limited recycling, followed by significant improvements in national recycling rates as treatment

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[57] (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/).

[58] (van de Kuilen, J. W. G., Ceccotti, A., Xia, Z., & He, M. (2011). Very tall wooden buildings with cross laminated timber. Procedia Engineering, 14, 1621–1628. https://doi.org/10.1016/j.proeng.2011.07.204

facilities expanded and enforcement increased[59]. However, illegal dumping hot-spots were documented near several Arab municipalities, indicating uneven access to compliant treatment and persistent enforcement gaps. In parallel, social research from nearby Palestinian cities (Hebron, Nablus, Ramallah) shows mixed perceptions of prefabrication: people value speed and cost control but express cultural attachment to traditional construction and concerns about thermal comfort and long-term durability (). The prefabricated housing system and its impact on the traditional building system in Palestine[60]). For Egypt and the wider Arab region, two issues heighten the relevance of modular systems using CLT and recycled polymers: (1) seismic risk along the Eastern Mediterranean and Red Sea faults, which favors lighter structures that reduce seismic base shear; and (2) heat and solar exposure, which requires detailing for moisture, UV stability, and serviceability of polymers, alongside fire design for mass timber. Taken together, the regional evidence suggests that modular sustainable housing can deliver faster, lower-carbon homes if it is paired with (a) waste-management capacity (licensed treatment, take-back programs for polymer elements), (b) community-sensitive design (hybrid systems that retain familiar finishes while using CLT frames and polymer infill), and (c) performance-based approvals that verify long-term creep/fire behavior and robust connections for local seismic demands. This integration aligns environmental goals (higher C&D recycling, circular polymers) with risk-appropriate structural design and cultural acceptance, improving the odds of real adoption.

7 Limitations

This study has some important limitations. It is based on **secondary research**, meaning that no new finite-element models, laboratory experiments, or field tests were performed. Instead, the analysis relies on published data from previous studies, reports, and case examples. While this allows for a broad comparison across materials, it also introduces uncertainty because reported performance values—such as stiffness, deflection, and buckling factors—can vary widely. For example, the mechanical response of cross-laminated timber (CLT) depends on panel thickness, span length, moisture conditions, and even the type of fasteners used in connections. Similarly, recycled plastics show different behaviors depending on polymer type, print method, and reinforcement, making it difficult to generalize results. Another limitation is that building codes and design standards are not uniform across regions. Eurocode provisions may differ from American or Asian standards, which affects how results can be applied globally. Finally, long-term, building-scale data for recycled plastics are still very limited, particularly in areas such as creep, fatigue, and fire performance. Without such evidence, it is difficult to fully evaluate the safety and reliability of plastic modules in structural housing applications.

Looking ahead, there are several clear directions for future research. First, full-scale hybrid prototypes that combine CLT frames with polymer-based panels should be developed and tested under standardized loading conditions, including gravity, wind, and seismic forces. Such experiments would provide stronger evidence for how hybrid systems behave in practice. Second, long-term testing programs are needed for recycled plastics, focusing on creep deformation, fatigue under repeated loading, and fire resistance at

59 Becker, R. (Ed.). (2015). US–Israel Workshop: Proceedings. Technion – Israel Institute of Technology. https://sustain2014.net.technion.ac.il/files/2015/02/Workshop-Proceedings-Disk.pdf)

60 Shaded, W., & Aref, J. (2023)A special case in Hebron, Nablus, and Ramallah). International Journal of Architectural Engineering and Urban Research, 6(2), 297–319. https://www.researchgate.net/publication/377446799_The_Prefabricated_Housing_System_And_Its_Impact_On_The_Traditional_Building_System_In_Palestine_A_special_case_in_Hebron_Nablus_and_Ramallah

both the module and connection level. These results would help build confidence in plastics as sustainable but reliable components. Third, there is a need for standardized connection testing and macro-models that can capture the interaction between timber, polymer, and steel connectors. This is especially important since joints are often the weakest points in modular systems. Fourth, advances in digital monitoring should be integrated into housing projects. AI-enabled structural health monitoring (SHM), using sensors and dashboards, could track real-time changes in drift, moisture, and deformation, ensuring safety throughout the building's life cycle. Finally, while building codes now include pathways for tall mass timber, similar performance-based approval routes need to be created for recycled polymer modules. These should be tied to verified long-term data, so that innovation in sustainable materials can move forward without compromising safety.

8. Future Prospects & Policy Implications

Modular prefabrication with sustainable materials can reshape housing if policy and practice move together. Codes are opening the door: the 2021 International Building Code (IBC) formally created tall mass-timber types (IV-A/B/C), allowing mass-timber residential buildings up to 18 stories with specific fire and protection rules. This proves that performance-based pathways for new materials are possible and can scale when safety is well defined[61]. At the same time, the **buildings sector remains a major source of energy use and CO_2**, so shifting material choices and delivery methods is central to national climate plans[62].

) **Emerging technical trends** point to three directions. First, hybrid modular systems that combine a CLT structural frame with recycled-plastic infill or skins can balance stiffness, weight, and circularity. CLT carries gravity and lateral loads; plastic components add speed and reuse waste streams—while avoiding long-term creep risks in primary load paths. Second, AI-based structural health monitoring (SHM) using low-cost sensors (strain, acceleration, humidity) and machine-learning diagnostics can track stress, drift, moisture, and creep in real time, improving safety and maintenance planning for modular housing. Recent reviews show AI is already boosting damage detection, anomaly spotting, and predictive maintenance across buildings and bridges.[63]Third, **bio-based composites** (e.g., wood-fiber skins, natural-fiber-reinforced polymers) will likely expand as specifications mature, offering low-carbon, low-mass parts for non-primary elements.

Policy actions should support the growth of sustainable modular housing while ensuring public safety. One important step is to adopt tall mass-timber provisions where appropriate, as outlined by the International Code Council (2020). These provisions create a historic shift in building codes by formally recognizing tall timber buildings as safe and regulated options for construction (International Code Council, 2020). For recycled polymers, policymakers should establish performance-based approval routes that require validated data on long-term creep, fire safety, and robust connection testing before widespread adoption.

[61] (International Code Council. (2020). Tall mass timber provisions represent historic new building code requirements. https://www.iccsafe.org/building-safety-journal/bsj-technical/tall-mass-timber-provisions-represent-historic-new-building-code-requirements/)

[62] (United Nations Environment Programme. (2024, March 7). Global status report for buildings and construction. UNEP. https://www.unep.org/resources/report/global-status-report-buildings-and-construction)

[63] .(Plevris, V., et al. (2024). AI in structural health monitoring for infrastructure. Infrastructures, 9(12), 225. https://www.mdpi.com/2412-3811/9/12/225)

Another key area is standardization of proof. Regulations should require Environmental Product Declarations (EPDs) and whole-life carbon assessments for both CLT and recycled-plastic components. This aligns with decarbonization targets in the building sector, as highlighted by the UN Environment Programme.[64]

Policymakers can also improve quality through **digitized assurance**. By recognizing AI-enabled structural health monitoring (SHM) systems in permitting processes, sensors and digital dashboards can become integral parts of compliance, asset management, and lifecycle safety.[65]

Finally, governments should promote **circularity** by using public procurement policies to prioritize design-for-disassembly, use of recycled content, and factory take-back programs for plastic elements. This would create a market pull for sustainable and recyclable materials while ensuring safe and efficient reuse in future projects.

Industry potential is strong in three use-cases: affordable housing (shorter schedules, controlled quality), disaster-resilient housing (rapid deployment of standardized modules), and low-carbon development (lighter structures, fewer wet trades). UN-Habitat guidance shows how prefabricated units and technical assistance can speed safer housing recovery after disasters, which modular CLT/plastic hybrids could serve if designed for local hazards and skills[66]. the path forward is clear: hybrid modular systems, AI-backed monitoring, and codes that reward low-carbon performance and validated connections. Done together, they can deliver safer, faster, and greener homes at scale.

9. Conclusion

Using secondary evidence from handbooks, experiments, simulations, and policy reports, we find that mass and stiffness drive the main differences, and connections control how those differences show up at the building scale.CLT changes stress patterns mainly by reducing mass. Because earthquake base shear is proportional to weight, lighter CLT modules lower seismic demand compared with concrete. CLT panels are anisotropic: vertical loads travel along the grain, while rolling shear can develop across laminations. As a result, global performance depends strongly on diaphragm action and joints (hold-downs, brackets, screws). When these are detailed for ductility, tests and validated models show stable behavior and acceptable drifts for low- to mid-rise housing. By contrast, recycled-plastic modules typically have a low elastic modulus (2–3 GPa) and show creep under sustained load. This raises serviceability risks (larger deflections and time-dependent stress shifts to joints). Plastics therefore fit best as non-primary or hybrid elements (e.g., skins, infill, insulation) rather than main gravity/lateral frames. Concrete remains the stiffest and most uniform in stress transfer—but at a higher carbon cost for the sector. These findings support a hybrid strategy: CLT for the primary frame, limited concrete in foundations/critical zones, and recycled plastics for non-structural roles.The paper links sustainability and mechanics at system level. Instead of focusing only on carbon or only on material coupons, it compares load paths, stress concentration at connections, deflection, buckling, and failure modes across materials, showing why modular joinery and diaphragm continuity are as important as material strength numbers.

[64] (United Nations Environment Programme (GlobalABC). (2024). *Global status report for buildings and construction.* https://www.unep.org/resources/report/global-status-report-buildings-and-construction).

[65] (Plevris, V., et al. (2024). AI in structural health monitoring for infrastructure. Infrastructures, 9(12), 225. https://www.mdpi.com/2412-3811/9/12/225)).

[66] (UN-Habitat. (2019). Supporting safer housing reconstruction after disasters. https://unhabitat.org/sites/default/files/documents/2019-09/supporting_safer_housing_reconstruction_after_disasters.pdf)

References

1. (United Nations Environment Programme. (2024, March 7). *Global status report for buildings and construction*. UNEP. https://www.unep.org/resources/report/global-status-report-buildings-and-construction)
2. (Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S., & Guan, D. (2023). Projecting future carbon emissions from cement production in developing countries. *Nature Communications, 14,* 8213. https://doi.org/10.1038/s41467-023-43660-x).
3. Zhang, C., Lee, G., & Lam, F. (2019). *Connections for stackable heavy timber modules in midrise to tall wood buildings* (TEAM Report 2018-08). University of British Columbia. https://team.sites.olt.ubc.ca/files/2019/04/TEAM-Report-2018-08-Connections-for-Stackable-Heavy-Timber-Modules.pdf)).
4. (van de Kuilen, J. W. G., Ceccotti, A., Xia, Z., & He, M. (2011). Very tall wooden buildings with cross laminated timber. Procedia Engineering, 14, 1621–1628. https://www.sciencedirect.com/science/article/pii/S1877705811012811)
5. (Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. *Buildings, 15*(12), 2020. https://doi.org/10.3390/buildings15122020
6. .(Nguyen, T. D., & Pishdad, P. (2025). Assessing the life cycle environmental impacts of modular construction: A US case study of a prototype housing unit. Journal of Environmental Engineering and Science. Advance online publication. https://doi.org/10.1680/jenes.24.00146)
7. Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. Buildings, 15(12), 2020. https://doi.org/10.3390/buildings15122020)
8. Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, L. (2019, June 18). *Modular construction: From projects to products*. McKinsey & Company. https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products
9. Howick Ltd. (n.d.). WAS 003-003: Offsite construction case study – Waste reduction potential of offsite volumetric construction. https://www.howickltd.com/asset/327.pdf)
10. (Council on Tall Buildings and Urban Habitat (CTBUH). (2019, March 14). CTBUH ratifies "World's Tallest Timber Building". https://www.ctbuh.org/news/ctbuh-ratifies-worlds-tallest-timber-building-following-height-criteria-update ctbuh.org)
11. Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., & Kawai, N. (2013). SOFIE project – 3D shaking table test on a seven-storey full-scale cross-laminated timber building. Earthquake Engineering & Structural Dynamics, 42(13), 2003–2021. https://doi.org/10.1002/eqe.2309)
12. (Pina, J. C., Saavedra Flores, E. I., & Saavedra, K. (2019). Numerical study on the elastic buckling of cross-laminated timber walls subject to compression. Construction and Building Materials, 206, 193–202. https://doi.org/10.1016/j.conbuildmat.2018.09.202)
13. (WoodWorks. (2023). CLT Diaphragm Design Guide. https://www.woodworks.org/wp-content/uploads/presentation_slides_McDonnell_CLT_Diaphragm_Design_Guide_07.2023.pdf
14. (Skoratko, A., & Katzer, J. (2021). Harnessing 3D printing of plastics in construction—Opportunities and limitations. Materials, 14(16), 4547. https://doi.org/10.3390/ma14164547)

15. Gomes, T. E. P., Cadete, M. S., Dias-de-Oliveira, J., & Neto, V. (2022). Controlling the properties of parts 3D printed from recycled thermoplastics: A review of current practices. Polymer Degradation and Stability, 197, 109850. https://doi.org/10.1016/j.polymdegradstab.2022.109850)
16. .(WoodWorks. (2023). CLT Diaphragm Design Guide. https://www.woodworks.org/wp-content/uploads/presentation_slides_McDonnell_CLT_Diaphragm_Design_Guide_07.2023.pdf)
17. Gomes, T. E. P., Cadete, M. S., Dias-de-Oliveira, J., & Neto, V. (2022). Controlling the properties of parts 3D printed from recycled thermoplastics: A review of current practices. Polymer Degradation and Stability, 197, 109850. https://doi.org/10.1016/j.polymdegradstab.2022.109850)
18. (Pina, J. C., Saavedra Flores, E. I., & Saavedra, K. (2019). Numerical study on the elastic buckling of cross-laminated timber walls subject to compression. Construction and Building Materials, 206, 193–202. https://doi.org/10.1016/j.conbuildmat.2018.09.202
19. (McKinsey & Company. (2019). *Modular construction: From projects to products.* https://yigby.org/wp-content/uploads/2020/03/mckinsey_modular-construction-from-projects-to-products_2019.pdf YIGBY).
20. (Ministry of Housing, Communities & Local Government (UK). (2019). MMC definition framework. https://www.gov.uk/government/publications/modern-methods-of-construction-working-group-developing-a-definition-framework GOV.UK)
21. (Swedish Wood. (2022). *CLT handbook: UK edition*. Swedish Wood. https://www.swedishwood.com/siteassets/5-publikationer/pdfer/clt-ukedition-2022.pdf
22. (Barbosa, A. R., Rodrigues, L. G., Sinha, A., Higgins, C., Zimmerman, R. B., Breneman, S., Pei, S., van de Lindt, J. W., Berman, J., & McDonnell, E. (2021). Shake-table experimental testing and performance of topped and untopped cross-laminated timber diaphragms. *Journal of Structural Engineering, 147*(4), 04021014. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002914).
23. (Rajanayagam, H., Poologanathan, K., Gatheeshgar, P., Varelis, G. E., Sherlock, P., Nagaratnam, B., & Hackney, P. (2021). A state-of-the-art review on modular building connections. *Structures, 34,* 4371–4391. https://doi.org/10.1016/j.istruc.2021.08.114.).
24. (Valvez, S., Silva, A. P., & Reis, P. N. B. (2022). Compressive behaviour of 3D-printed PETG composites. *Aerospace, 9*(3), 124. https://doi.org/10.3390/aerospace9030124).
25. (Swedish Wood. (2022). *CLT handbook: UK edition*. Swedish Wood. https://www.swedishwood.com/siteassets/5-publikationer/pdfer/clt-ukedition-2022.pdf)
26. Sandoli, A., D'Ambra, C., Ceraldi, C., Calderoni, B., & Prota, A. (2021). Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. Applied Sciences, 11(5), 2078. https://doi.org/10.3390/app11052078)
27. (Alter, L. (2018, October 11). *Modular construction and cross-laminated timber, together at last!* Treehugger. https://www.treehugger.com/modular-construction-and-cross-laminated-timber-together-last-4857544)

28. (Young's modulus typically 2–3 GPa) is far below that of CLT (10–14 GPa) or reinforced concrete (25–30 GPa) (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://doi.org/10.3390/polym15092052).

29. Rinaldin, G., Amadio, C., & Fragiacomo, M. (2016). Non-linear simulation of shaking-table tests on 3D full-scale cross-laminated timber buildings. *Engineering Structures, 113,* 133–148. https://doi.org/10.1016/j.engstruct.2016.01.041.
30. (FPInnovations. (2019). CLT Handbook (2019 ed.). FPInnovations. https://web.fpinnovations.ca/clt/)
31. Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://doi.org/10.3390/polym15092052
32. Zhang, X., Sun, C., & Zhao, Y. (2021). A state-of-the-art review on modular building connections. *Structures, 32,* 889–902. https://doi.org/10.1016/j.istruc.2021.03.066 .
33. Sandoli, A., D'Ambra, C., Ceraldi, C., Calderoni, B., & Prota, A. (2021). Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. *Applied Sciences, 11*(5), 2078. https://doi.org/10.3390/app11052078).
34. (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/
35. Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., & Kawai, N. (2013). SOFIE project – 3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthquake Engineering & Structural Dynamics, 42*(13), 2003–2021. https://doi.org/10.1002/eqe.2309
36. (FPInnovations. (2019). *CLT handbook* (2019 ed.). FPInnovations. https://web.fpinnovations.ca/clt/
37. Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., & Kawai, N. (2013). SOFIE project – 3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthquake Engineering & Structural Dynamics, 42*(13), 2003–2021. https://doi.org/10.1002/eqe.2309
38. (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/
39.)(International Energy Agency. (2022). Buildings – Tracking report. IEA. https://www.iea.org/reports/buildings)
40. (Gagnon, S., & Pirvu, C. (Eds.). (2013). CLT Handbook: Cross-Laminated Timber. https://research.fs.usda.gov/treesearch/download/46203.pdf)
41. (Unuk, Ž., & Kuhta, M. (2024). Nonlinear semi-numeric and finite element analysis of three-point bending tests of notched polymer fiber-reinforced concrete prisms. *Applied Sciences, 14*(4), 1604. https://doi.org/10.3390/app14041604).
42. Izzì, M., Polastri, A., & Fragiacomo, M. (2018). Modelling the mechanical behaviour of typical wall-to-floor connection systems for cross-laminated timber structures. *Engineering Structures, 162,* 270–282. https://doi.org/10.1016/j.engstruct.2018.02.045).
43. Zhang, H., Cai, L., Golub, M., Zhang, Y., Yang, X., Schlarman, K., & Zhang, J. (2018). Tensile, creep, and fatigue behaviors of 3D-printed ABS. Journal of Materials Engineering and Performance, 27(1), 57–62. https://doi.org/10.1007/s11665-017-2961-72)
44. (Engineering ToolBox. (n.d.). *Concrete properties: Properties of normal strength Portland cement concrete*. The Engineering ToolBox. https://www.engineeringtoolbox.com/concrete-properties-d_1223.html

45. (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/
46. (Ou, J., Chen, Z., Long, W., Chen, D., Huo, L., & Zhang, Y. (2024). Research on stability of CLT wall under uniform compression based on orthotropic plate buckling theory. *Journal of Building Engineering, 96,* 108571. https://doi.org/10.1016/j.jobe.2024.108571).
47. .((Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/)
48. (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/
49. (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/.)
50. (United Nations Environment Programme. (2024, March 7). Global status report for buildings and construction. UNEP. https://www.unep.org/resources/report/global-status-report-buildings-and-construction)
51. (McKinsey & Company. (2019). Modular construction: From projects to products. https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products)
52. (Zhang, C., Lee, G., & Lam, F. (2019). Connections for stackable heavy timber modules in midrise to tall wood buildings (TEAM Report 2018-08). University of British Columbia. https://team.sites.olt.ubc.ca/files/2019/04/TEAM-Report-2018-08-Connections-for-Stackable-Heavy-Timber-Modules.pdf)
53. WRAP. (2014). *Designing out waste: A design team guide for buildings.* WRAP. https://build360.ie/wp-content/uploads/2023/01/WRAP_DOW_Guide.pdf).
54. FPInnovations. (2019). *CLT handbook* (2019 ed.). FPInnovations. https://web.fpinnovations.ca/clt/)
55. (Sandoli, A., D'Ambra, C., Ceraldi, C., Calderoni, B., & Prota, A. (2021). Sustainable cross-laminated timber structures in a seismic area: Overview and future trends. *Applied Sciences, 11*(5), 2078. https://doi.org/10.3390/app11052078)
56. (Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., & Jirousek, J. (2023). Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Polymers, 15*(9), 2052. https://pmc.ncbi.nlm.nih.gov/articles/PMC10146359/).
57. (van de Kuilen, J. W. G., Ceccotti, A., Xia, Z., & He, M. (2011). Very tall wooden buildings with cross laminated timber. Procedia Engineering, 14, 1621–1628. https://doi.org/10.1016/j.proeng.2011.07.204
58. International Code Council. (2020). Tall mass timber provisions represent historic new building code requirements. https://www.iccsafe.org/building-safety-journal/bsj-technical/tall-mass-timber-provisions-represent-historic-new-building-code-requirements/)
59. (United Nations Environment Programme. (2024, March 7). Global status report for buildings and construction. UNEP. https://www.unep.org/resources/report/global-status-report-buildings-and-construction)

60. (Plevris, V., et al. (2024). AI in structural health monitoring for infrastructure. Infrastructures, 9(12), 225. https://www.mdpi.com/2412-3811/9/12/225)
61. (United Nations Environment Programme (GlobalABC). (2024). *Global status report for buildings and construction.* https://www.unep.org/resources/report/global-status-report-buildings-and-construction).
62. (Plevris, V., et al. (2024). AI in structural health monitoring for infrastructure. Infrastructures, 9(12), 225. https://www.mdpi.com/2412-3811/9/12/225)).
63. (UN-Habitat. (2019). Supporting safer housing reconstruction after disasters. https://unhabitat.org/sites/default/files/documents/2019-09/supporting_safer_housing_reconstruction_after_disasters.pdf)