CASE STUDY AND COMPARISON OF EMBODIED CARBON AND CONSTRUCTION COST BY ADOPTING ALTERNATIVE TIMBER-BASED HYBRID STRUCTURE SYSTEM

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(Received: September 06, 2024; Revised: November 01, 2024; Accepted: November 03, 2024)

DOI: 10.31130/ud-jst.2024.516E

Abstract - The rise in global temperatures, driven by carbon dioxide emissions, has spurred the construction industry to seek carbon reduction strategies. This study evaluates the environmental benefits of using wood materials in construction by redesigning an existing reinforced concrete (RC) residential building in New Taipei City, Taiwan. Four structural combinations were developed, replacing concrete with timber and steel. Numerical simulations confirmed the feasibility of these systems, and comparisons of embodied carbon, costs, and construction periods were conducted. The proposed hybrid models, which extensively replace concrete with timber and steel for the core, reduced initial embodied carbon by 25.6% compared to the original RC building, though costs increased by 3.9 times. These findings underscore the potential of hybrid timber systems as a sustainable alternative in construction, offering significant carbon reduction benefits for Taiwan while aligning with environmental goals.

Key words - Hybrid structure; mass timber materials; sustainable construction.

1. Introduction

The speed of global warming is rapidly increasing, making sustainability issues more important than ever. Many countries have proposed policies aimed at achieving net-zero carbon emissions by 2050, with the goal of minimizing anthropogenic greenhouse gas emissions and offsetting them through negative carbon technologies and forest carbon sinks. In the construction sector, which is one of the highest contributors to carbon emissions, reducing carbon output is a crucial direction.

To achieve this goal, this study introduces an innovative approach in construction by transforming traditional reinforced concrete (RC) residential buildings into hybrid structures that primarily use timber and steel. Timber is renewable and can sequester carbon during its growth, and its carbon emissions during construction are lower compared to RC and steel structures. Steel has high structural efficiency, making it a suitable choice alongside timber to replace RC residential buildings. This alternative not only enhances structural performance but also reduces overall carbon emissions [1].

The experiment of replacing traditional RC structures with RC-timber hybrid structures in residential buildings to study their structural stability and environmental impact in high-seismic zones [2, 3]. Their findings showed an approximately 52% decrease in carbon emissions with the RC-timber hybrid structure. Given that steel structures are among the most stable in terms of strength, the goal of this study is to partially replace a high-rise residential building with timber and steel structures. Midas software is used to simulate the structural behavior of different material combinations. Taiwan is located on the Pacific Ring of Fire, making it one of the regions with frequent and intense earthquakes. This study investigates steel-timber hybrid structures, simulating and comparing multiple configurations to assess their structural feasibility in high-seismic zones. It provides an approximate calculation of carbon emissions, costs, and carbon taxes, aiming to offer a preliminary exploration of the advantages and outcomes of these configurations to support further research.

2. Method and modeling

2.1. Method

The case analyzed in this study is a high-rise residential building in New Taipei City, Taiwan.

(a) *(b)*

Figure 1. *(a) The typical residential floor plan, (b) 3D modeling perspective of study building*

The original design is an RC frame with three column spans and plan dimension is 12.5 m x 29.2 m. With one ground floor and fourteen residential floors, the building height is 54.8 m. Figure 1 presents the typical floor plans and a 3D modeling perspective of the building. The study conducted a series of comparative analyses on different structural configurations, including:

Type 1: Fully RC structure;

Type 2: Fully steel structure;

Type 3: A steel structure incorporating timber slabs and braces;

Type 4: A steel core structure with timber structures on both sides, featuring timber slabs.

The technology for wood processing is now quite mature, with the two main types of glued forms being Cross-Laminated Timber and Glued Laminated Timber.

(1) Cross-Laminated Timber (CLT): is made from layers of lumber boards stacked crosswise and glued together, providing excellent structural stability and resistance to deformation. It is suitable for walls, floors, and roofs.

(2) Glued Laminated Timber (GLT): consists of bonded layers of dimensional lumber, allowing for structural components in various shapes and sizes. GLT is valued for its high strength and lightweight properties, making it ideal for large-span applications like beams and arches.

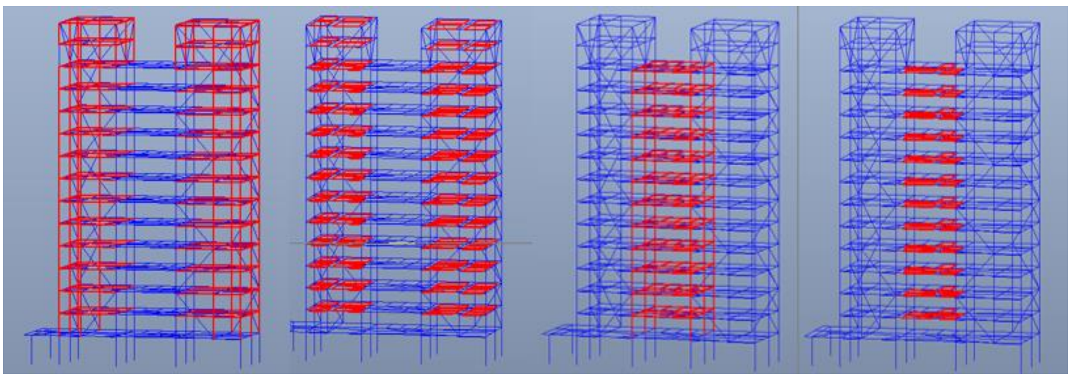
The study used Midas Gen to simulate structural behavior through static analysis, applying the Finite Element Method (FEM) to divide complex structures into smaller elements.

2.2. Building material

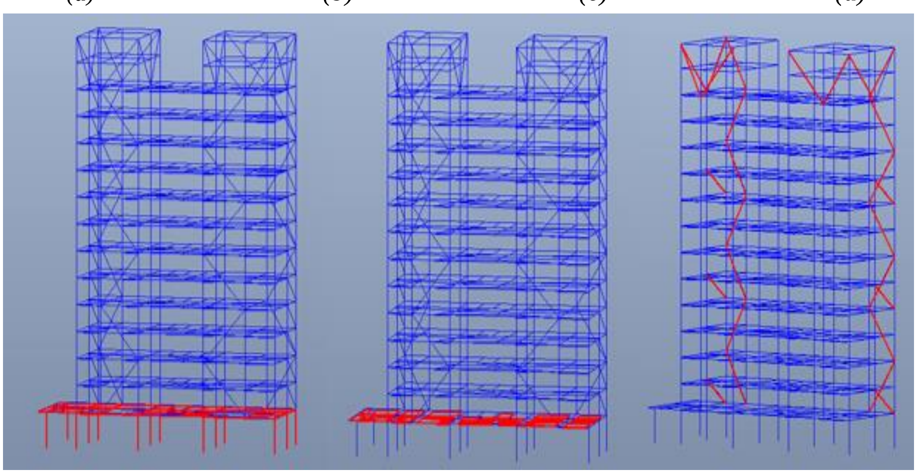
In the process of designing the hybrid structural model, this study utilized Midas simulation, considering seismic forces, dead load, and live load, and evaluated the forces on the members. This study achieves similar structural performance across the four types by controlling the cross-sections of the members.

Figure 2 and Table 1 shows distribution of the material combinations used for the different types in this research. Among them, the RC structure does not include the diagonal bracing shown in Figure 2(a). Type 1 is the original all-RC residential model. To minimize variables, Type 2 is configured with a steel frame and RC plates. In Type 3, the RC plates are replaced with CLT while maintaining a steel frame, as in Type 2. Type 4 replaces the building structure with CLT and plates with GLT; based on typical replacement methods, the service core is designed with steel to enhance core rigidity and seismic resistance, with diagonal bracing added to reinforce the timber structures on both sides. These four model types clearly illustrate the differences resulting from each replacement.

Table 2 show the section dimensions and material of components for each type in this study.



(a) *(b)* *(c)* *(d)*



(e) *(f)* *(g)*

Figure 2. *Material combination table for each type*

Table 1. *Material combination table for each type*

Area	a	b	c	d	e	f	g
Component	structure	plate	structure	plate	structure	plate	bracing
Type 1	RC	RC	RC	RC	RC	RC	none
Type 2	Steel	Steel	RC	Steel	RC	Steel	Steel
Type 3	Steel	CLT	Steel	CLT	Steel	RC	GLT
Type 4	GLT	CLT	Steel	CLT	Steel	RC	GLT

Table 2. *Section dimensions and material of components*

Type 1	Main columns	Secondary columns	Beams	Joists	Plates
Materials	RC	RC	RC	RC	RC
Section and thickness (mm)	950*1250	700*900	700*900	400*750	150

Type 2	Main columns	Secondary columns	Beams	Joists	Bracings	Plates
Materials	Steel	Steel	Steel	Steel	Steel	RC
Section and thickness (mm)			442*400*22*36			150

Type 3	Main columns	Secondary columns	Beams	Joists	Bracings	Plates	1F Plates
Materials	Steel	Steel	Steel	Steel	GLT	CLT	RC
Section and thickness (mm)	400*550*4	442*400*22*36	442*400*22*36	442*400*22*36	500*240	150	150

Type 4		Columns	Secondary columns	Beams	Joists	Bracings	Plates	
Materials	core and 1F	Steel	none	Steel	Steel	none	Core	1F
Section and thickness		500*750*40		492*500*22*36	442*400*22*36		CLT	RC
(mm)							150	150
Materials	Both side	GLT	GLT	GLT	GLT	GLT	CLT	
Section and thickness (mm)		1100*800	700*500	700*500	600*450	700*500	150	

2.3. Modeling setting

This study used Taiwan (2011) specifications to analyze static seismic loads in Midas, selecting the Taipei Basin II based on the case location [4]. The coefficients for the approximate period were determined according to the materials used for each structural type. The steel strength is selected as SS490, and the reinforced concrete (RC) strength is chosen as C420. The modulus of elasticity for the wood is set to 90000kgf/cm^2, and weight density is 500 kgf/m^3. The floor load settings are the same across the different combinations: each floor has a dead load of 300 kgf/m^2 and a live load of 200 kgf/m^2, while the roof has a dead load of 300 kgf/m^2 and a live load of 150 kgf/m^2. The boundary conditions are set based on material properties: for steel structures, it is fixed; and for RC, it is fixed. Timber structures often use steel connectors; however, with wear and tear, the connections become looser over time, so we set them as pin for timber structures [5].

The timber structures in this study cannot be verified using Midas software, unlike RC and steel structures. Instead, they were assessed through a different process. Force data for GLT members were obtained from Midas, and subsequent calculations were conducted to ensure that the bending stress and shear stress remained within the specified limits according to the "Design and Construction Specifications of Wood Construction for Buildings. "Douglas fir was selected as the timber material and classified as a Grade III structural material per relevant standards. Additionally, both long-term and short-term allowable stresses were checked to ensure compliance with design requirements.

2.4. Carbon emission

This study refers the “Life Cycle Assessment” (LCA) concept, specifically stages A1 to A5, also known as "cradle to grave”, it refers to the lifecycle of a product from production and use to disposal or recycling. In Building Life Cycle Assessment, A1-A3 covers material production to processing, A4 refers to material transportation, and A5 involves the construction process [6].

This study calculate carbon emissions based on material sources using "Taiwan’s Low Carbon Building Assessment Manual" and "A Brief Guide to Calculating Embodied Carbon" (The Structural Engineer, July 2020).

The first part is to calculate the carbon emissions from the timber. Since this study have designated imported Douglas fir from Canada, the calculations are based on the European specifications-"A Brief Guide to Calculating Embodied Carbon" [7]. The calculation of the domestic transportation process within Taiwan will be presented in the next section.

The calculation formula is as follows:

$$Carbon\ emissions(kgCO_2e) = Weight \times FactorA1{\sim}A3 + Weight \times FactorA4 + Weight \times FactorA5 \quad (1)$$

These factors were derived from "A Brief Guide to Calculating Embodied Carbon", and the weight refers to the weight of the timber.

The next part is to calculate carbon emission of concrete, rebar, steel, and timber transportation in Taiwan. The factors of these three materials already include stages A1 to A5, and the transportation factors follow the table of “Fuel Costs and Dynamic Carbon Emission Factors for Road Vehicles”, as declared by Taiwan's Ministry of Transportation and Communications.

The calculation formula is as follows:

$$Carbon\ emissions(\ kgCO_2e) = Weight \times Factor(concrete/rebar/steel) + Distance(Taiwan\ transport\ of\ timber) \times Factor \quad (2)$$

These factors were derived from "Taiwan’s Low Carbon Building Assessment Manual", and the weight refers to the weight of the concrete, rebar and steel.

3. Results

3.1. Assessment material weight

Table 3 shows the material weight for each type. The total weight of Type 1 is the largest, while Type 2 is the second largest, accounting for 38% of Type 1's weight. Types 3 and 4, which replaced some materials with wood, significantly reduced the weight, with a reduction of 80% and 78% compared to Type 1, respectively.

Table 3. *Material weight for each type*

	Supplier	Type 1	Type 2	Type 3	Type 4
Steel	0	1,364,834	1,339,009	658,838	Steel
RC	7,890,049	1,767,931	146,090	146,090	RC
CLT	0	0	337,883	337,883	CLT
GLT	0	0	12,510	579,032	GLT
Total weight (kg)		8,414,049	3,250,065	1,731,543	1,845,192

3.2. Story Shear and Story Drift Ratios

Figure 3 shows the story force, representing the lateral force acting on each floor across four types, with the 15th floor having the highest story force, and Type 1 exhibiting the highest values on each floor. Figure 4 shows the story shear of four types, which is the cumulative force of story forces from top to bottom on each floor. The story shear for Type 1 is significantly higher than that of the other types. The story shear on the ground floor of Type 2, Type 3 and Type 4 is approximately 33%, 21% and 25% of that of Type 1, respectively. Among them, the shear story of Type 3, Type 4, which are hybrid structures, are also lower than that of Type 2. Because these two types replaced some materials with timber, the reduced weight led to a decrease in story shear.

The maximum inter-story drift and their corresponding floors for the four types are 0.23% on the 15th floor, 0.29% on the 15th floor, 0.21% on the 15th floor, and 0.30% on the 14th floor, respectively. According to the Building Technical Regulations in Taiwan, the allowable inter-story drift is limited to 5/1000, and all structures comply with this requirement.

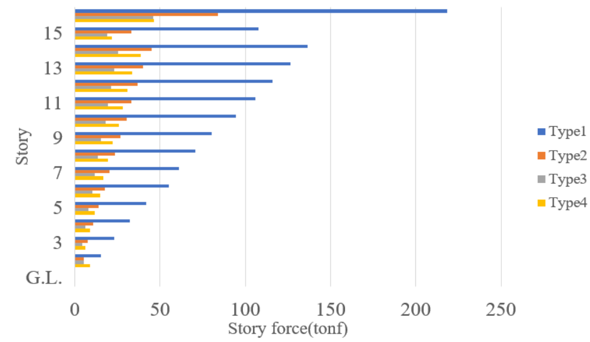


Figure 3. *The story force of model*

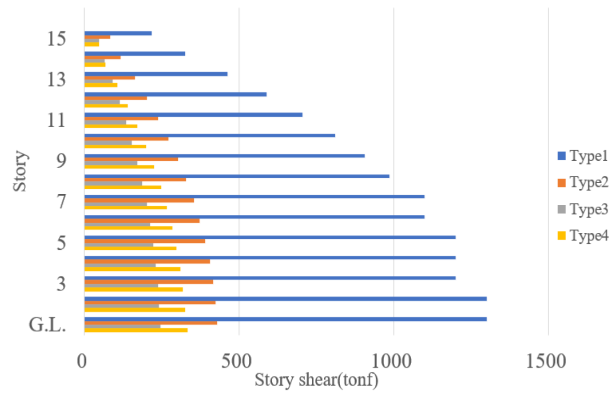


Figure 4. *The story shear of model*

3.3. Carbon emissions calculating

This study has designated imported Douglas fir from Canada, with a road transport distance of 630 km within Canada and a sea transport distance of 10,214 km from Canada to Taiwan. Table 4 shows the factors about timber carbon emissions. In this study, factors A1-A3 were derived from the corresponding lookup tables. Factor A4 is calculated based on road transportation distance and sea transportation distance, using the corresponding lookup table coefficients. The calculations in this part did not include the transportation of timber within Taiwan. Factor A5 is calculated based on factor A1-A3, and A4.

(a) The formula for transport factor is as follows:

$$Road\ transport\ factor = 0.0001065\left(\frac{\frac{kgCO_2}{kg}}{km}\right) \times Canada\ road\ transport\ distance(km)$$
$$= 0.0001065 \times 630 = 0.067(kgCO_2/\text{kg}) \quad (3)$$

$$Sea\ transport\ factor = 0.0001614\left(\frac{\frac{kgCO_2}{kg}}{km}\right) \times Sea\ transport\ distance(km)$$
$$= 0.0001614 \times 10214 = 0.165(kgCO_2/\text{kg}) \quad (4)$$

(b) The formula for A4 and A5 factor is as follows:

$$Factor\ A4 = road\ transport\ factor + Sea\ transport\ factor = 0.067 + 0.165 = 0.232(kgCO_2/\text{kg}) \quad (5)$$

$$Factor\ A5 = 0.01 \times (A1{\sim}A3 - 1.64 + A4 + 0.005 + 1.77) \quad (6)$$

Table 4. *Timber carbon emission factor*

	Factor A1-A3 ($kgCO_2$/kg)	Factor A4 ($kgCO_2$/kg)	Factor A5 ($kgCO_2$/kg)
GLT	0.512	0.232	0.009
CLT	0.437	0.232	0.008

Table 5 shows the factors about concrete, rebar, steel materials carbon emissions and timber transportation in Taiwan. The RC density is calculated as 2300 kg/m³ in this study. In this study, factors A1-A5 were derived from the corresponding lookup tables.

The formula for transport carbon emissions is as follows:

$$\begin{aligned} &\mathit{Taiwan\ road\ transport\ carbon\ emissions} \\ &= 0.000529\left(\frac{\frac{kgCO_2}{\text{kg}}}{\text{km}}\right) \\ &\qquad \times \text{Taiwan road transport distance(km)} \\ &= 0.000529 \times 360 = 0.067(kgCO_2) \qquad (7) \end{aligned}$$

Table 5. *Concrete, rebar, and steel carbon emissions factors*

Material	Factor A1-A5
Concrete	497.15 $kgCO_2/m^3$
Rebar	1.15 $kgCO_2$/kg
Steel	1.16 $kgCO_2$/kg

Figure 5 shows the calculation results of carbon emissions, including the timber, concrete, rebar, and steel components for the four types, which are 2159 ton, 2773 ton, 1831 ton, and 1607 ton, respectively. A comparative analysis indicated that Type 3 and Type 4, which are hybrid structures incorporating wood, resulted in lower emissions compared to Type 1 and Type 2, which are traditional RC and steel constructions. Notably, Type 4, which incorporates more wood, demonstrated the lowest emissions, reducing emissions by 26% compared to Type 1. This underscores the effectiveness of hybrid constructions in reducing carbon emissions while maintaining structural strength.

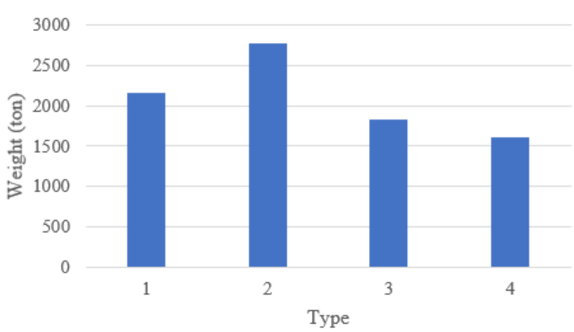


Figure 5. *The A1~A5 carbon emissions of the four types*

3.4. Material Cost and Carbon Tax Potential

To determine material costs, compute the prices for steel bars, RC, CLT, and GLT used in the four structural configurations examined in this study, based on the following market prices:

Steel: 2,880 USD /ton;

RC: 92.8 USD /m^3 (with an assumed density of 2,300 kg/m³);

Rebar: 736 USD /ton;

CLT: 1,280 USD /m^3;

GLT: 1,680 USD /m^3 (European import prices).

The cost for these four types, from Type 1 to Type 4, are 1,607 thousand, 4,291 thousand, 4,642 thousand, and 4,269 thousand, respectively. Full RC Type 1 is the cheapest in terms of total cost. Type 3 has the highest price, even though the weight of Steel is relatively close, Type 2 is lower than Type 3 in overall price. The prices of Type 2 and Type 4 are relatively close. Although the total weight of Type 2 is higher than Type 4, the main material (RC) of Type 2 is more economical in price, so that the overall cost will not be too high. The wood in Type 4 is more expensive, but its use is relatively small, which may keep the total price from being too high. Type 3 has a slight advantage in weight, but Type 4 is more economical in terms of price. Although the steel weight of Type 4 is 50% of Type 3, the final price is comparable. The reason is that Type 3 uses GLT, which accounts for 2% of the weight of Type 4.

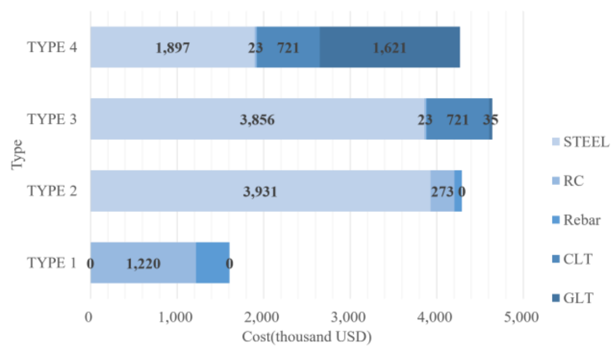


Figure 6. *Material cost consumption for each type*

Subsequently, compare the weight and cost of each construction method across the various combinations. The observed differences in costs can provide valuable insights for future construction practices.

3.5. Assessment Carbon tax potential

For assessing carbon tax implications, reference to the World Bank's 2023 Carbon Pricing Status and Trends Report, given that Taiwan has yet to establish its own carbon pricing framework [8, 9]. In the absence of a national standard, utilize the carbon pricing data provided by the London School of Economics and Political Science, as commissioned by the Environmental Protection Agency in 2020. Convert and compare the carbon tax rates for the four structural combinations using the following national rates:

Uruguay: 141.87 USD/ton CO_2 eq;

Sweden: 134.62 USD/ton CO_2 eq;

Canada: 41.42 USD/ton CO_2 eq;

Ireland: 38.31–46.6 USD/ton CO_2 eq;

Singapore: 3.86–19.31 USD/ton CO_2 eq;

Japan: 2.07 USD/ton CO_2 eq.

For Taiwan, the carbon pricing is set at 9.6 USD per ton. These calculations will allow for a comparison of the carbon tax costs associated with each structural combination, providing a basis for evaluating future construction cost considerations.

Taking the World Bank's 2023 Carbon Pricing Status and Trends Report as a reference. Asia, which has only begun to levy carbon taxes in recent years, has lower carbon tax prices than Europe and America.

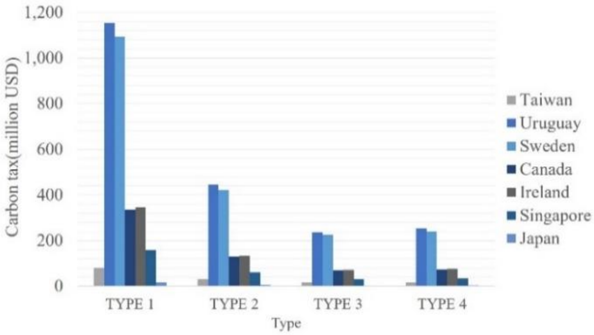


Figure 7. *Carbon tax comparison over countries and potential in Taiwan*

Comparing carbon tax prices for four combinations as one of the trends considered in future construction costs. Type1 has the highest total value among all types. The values of Type 3 and Type 4 are significantly lower than the other two. This indicates that carbon tax policies under these two types may be looser or less comprehensive.

4. Conclusions

This study simulated different combinations of building materials to determine whether they can reduce carbon emissions, while also calculating the costs and construction duration after incorporating carbon taxes. The study supplements by noting that they did not investigate steel-wood hybrid structures and discusses the differences among steel, RC, and the two hybrid structures. Below are our conclusions.

(1) Story Shear and Inter Story Displacement:

Type 3, which is the lightest of the four types, exhibits the lowest story shear, indicating that replacing RC plates with timber while using steel in structure frames can reduce story shear under the same displacement conditions.

(2) Carbon emission

Type 4, which incorporates the most timber components, has the lowest carbon emissions. This indicates that using hybrid structures with timber effectively reduces carbon emissions.

(3) Cost and Carbon Tax

Although hybrid timber buildings require a higher initial investment, they significantly reduce carbon emissions over the building's lifecycle. In accordance with European regulations, the potential for carbon tax reductions highlights a key advantage of hybrid timber construction.

In conclusion, hybrid timber structures effectively reduce carbon emissions while maintaining the same structural performance. The cost of hybrid timber structures is higher compared to other materials, which presents a challenge at this stage. However, as carbon taxes become more prevalent in the coming years, timber construction will have advantages in this regard. Thus, with the growing emphasis on environmental sustainability, timber emerges as a highly promising material. This study makes efforts to advance carbon reduction practices in the construction field, using high seismic zones as a case study and importing timber from Canada to conduct simulations at higher standards, exploring its feasibility in Taiwan.

Acknowledgments: The authors acknowledge the financial support of National Science and Technology Council, Taiwan under grant no. NSTC 113-2221-E-011 -044 -MY2, and the National Taiwan University of Science and Technology for their support of this project.

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