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STRUCTURAL PERFORMANCE, ECONOMIC BENEFITS, AND ENVIRONMENTAL IMPACT BETWEEN STEEL STRUCTURE, STEEL - TIMBER HYBRID STRUCTURE, AND TIMBER STRUCTURE IN HIGH SEISMIC ZONE

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ABSTRACT: Globally, the construction industry is a major source of carbon emissions. Studies show that using low-carbon engineered wood in building sector help reducing environmental impact. However, hybrid structures system may be an efficiency and economical solutions comparing with full timber structures in high seismic zone. In this study, an existing building was adopted and hybrid structure system was proposed by replacing parts of the structure components into wood, including steel structure system, hybrid steel-timber structure system, and timber structure system. A comparative analysis of environmental and economic benefits was conducted, including construction cost, carbon content in materials and so on. The results show that the steel-timber hybrid structure system can reduce structural weight by 51%, while the timber structure can reduce it by 60%, comparing with steel structure. In terms of total embodied carbon, the steel structure system, steel-timber hybrid structure system, and timber structure system account for 1024.4 tons, 692.6 tons, and 551.9 tons of CO_2e, respectively. Incorporating partial timber structures in hybrid structure system help reducing costs and achieve better environmental benefits.

KEYWORDS: steel-timber hybrid structure, structural performance, construction cost, embodied carbon emission

1 – INTRODUCTION

The speed of global warming makes sustainability issues more important than ever. Policies aimed at achieving net-zero carbon emissions by 2050 are released by many countries, with the goal of minimizing greenhouse gas emissions, through negative carbon technologies and forest carbon sinks. The construction industry is one of the largest sources of carbon emissions globally. Engineered wood in building sector help reducing environmental impact. However, hybrid structures system may be an efficiency and economical solutions comparing with full timber structures in high seismic zone. In this study, an existing building was adopted and hybrid structure system was proposed by replacing parts of the structure components into wood, including steel structure system, hybrid steel-timber structure system, and timber structure system. A comparative analysis of environmental and economic benefits was conducted, including construction cost, carbon content in materials and so on. Previous research replaced traditional RC structures with RC-timber hybrid structures in residential buildings to study their structural stability and environmental impact in high-seismic zones. The findings indicated approximately 52% decrease in carbon emissions with the RC-timber hybrid structure. Taiwan is located on the Pacific Ring of Fire, making it one of the regions with frequent and intense earthquakes. In this study, steel-timber hybrid structures, simulating and comparing multiple configurations to assess their structural feasibility in high-seismic zones are investigated. 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. The results in this study provides an approximate calculation of carbon emissions, building costs, aiming to offer a preliminary exploration of the advantages and outcomes of these configurations to support further research.

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2 – METHOD AND MODELING

2.1 Method

The target building is an existing 10-story apartment complex, approximately 3.5 m in each floor, plus a rooftop projection, with total height of 38.5 m. This study redesigned the above-ground part of an existing building in Taiwan into three structural systems, conducting a series of comparative analyses on different structural configurations, including:

- Type 1: Steel structure system
- Type 2: Steel-timber hybrid structure system
- Type 3: Timber structure system

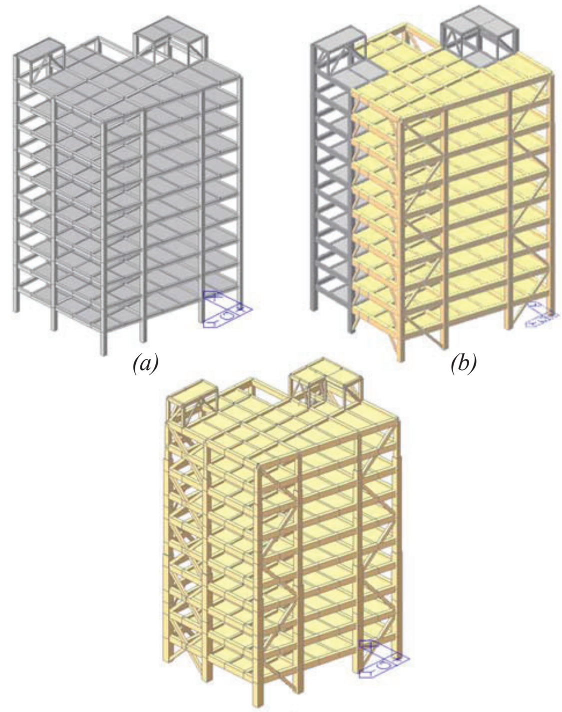
Figure 1 illustrated the proposed three structural systems. The steel-timber hybrid structure system retains the steel stair cores, with deck slabs poured with reinforced concrete (RC). The other beams and columns are replaced with glued-laminated timber (GLT) and the floors with cross-laminated timber (CLT). GLT braces are added to the timber structure for stability. The seismic simulation follows Taiwan's standards, located in the high-seismic Pacific Ring of Fire. All floors include assumed loads, and the story drift ratio is controlled with no structural failures. The structural performance of these three structure systems was assessed to clarify the efficiency of material utilization in order to determine the cradle-to-site embodied carbon. Additionally, structure material and construction costs were collected to calculate the structural cost and conduct a comparative economic analysis of these three systems.

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. Table 1 and Figure 2 show the distribution of the material combinations used for the different types in this research.

2.3 Modeling Setting

Taiwan specifications (2011) is used in this study to analyzes static seismic loads, and the location factor of Taipei Basin II is assumed in this case. The coefficients for the approximate period were determined according to the materials used for each type of structure systems. The steel strength is selected as SS490, and the reinforced concrete (RC) strength is chosen as 4000 psi. The modulus of elasticity for the wood is set to 90,000 kgf/cm², and density is 500 kgf/m³. The floor load settings are dead load of 300 kgf/m² and live load of 200 kgf/m² for each type of structure systems, while the roof has dead load of 300 kgf/m² and live load of 150 kgf/m². The boundary conditions are set based on material properties, fixed connection for both steel column-to-beam connections and for RC slab-to-beam connections, and pin connection for timber structures. The timber



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

Fig. 1. (a) Steel structure; (b) steel-timber structure; (c) timber structure.

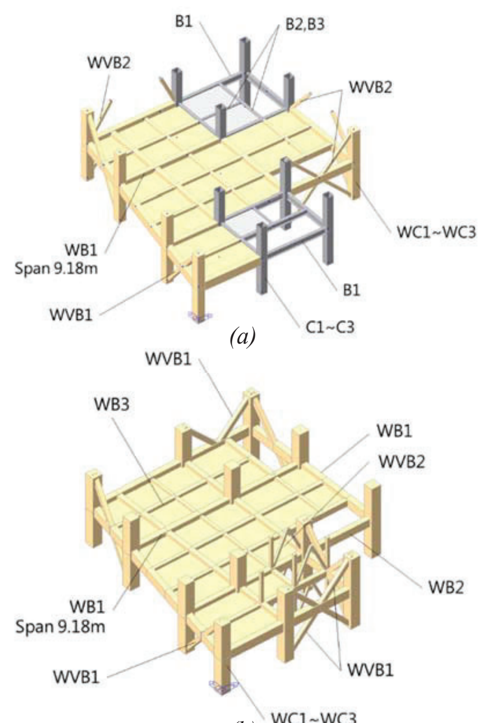


Fig. 2. (a) Steel-timber hybrid structure; (b) timber structure.

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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" in Taiwan. Douglas fir with grade E105-F345 is selected as the timber material. Additionally, both long-term and short-term allowable stresses were checked to ensure compliance with design requirements.

2.4 Carbon Emission

The “Life Cycle Assessment” (LCA) concept is referred in this study, 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. The carbon emissions are calculated based on material sources using "Taiwan’s Low Carbon Building Assessment Manual" in this study, and partial data of the embodied carbon is referred to "A Brief Guide to Calculating Embodied Carbon" (The Structural Engineer, July 2020) published by British Institution of Structural Engineers.

Since this study have designated imported Douglas fir from North American, the calculations of shipping embodied carbon are based on the suggested carbon factor from "A Brief Guide to Calculating Embodied Carbon", and the calculation of the domestic transportation within Taiwan will be presented locally.

Table 1. Material Combination for Each Type.

Type								
Type 1		**Columns**				**Brace**		
	Steel	C1	C2	C3	C4	VB1		
	Section (mm)	650×650×30	600×600×28	550×550×25	200×200×8/12	244×175×7/11		
		Beams					**Floor Slab**	
	Steel	B1	B2	B3	B4	B5	RC	
	Section (mm)	700×300×13/24	588×300×12/20	488×300×12/20	400×200×8/13	350×175×7/11	180	
Type 2		**Columns**				**Brace**		
	Steel	C1	C2	C3	C4	VB1		
	Section (mm)	650×650×30	600×600×28	550×550×25	200×200×8/12	244×175×7/11		
	GLT	WC1	WC2	WC3	WVB1	WVB2		
	Section (mm)	650×650	550×550	450×450	330×330	270×270		
		Beams				**Floor Slab**		
	Steel	B2	B3	B4	B5	RC		
	Section (mm)	588×300×12/20	488×300×12/20	400×200×8/13	350×175×7/11	180		
	GLT	WB1	WB2	WB3	WB4	CLT		
	Section (mm)	500×850	450×750	400×550	300×500	180		
Type 3		**Columns**					**Brace**	
	GLT	WC1	WC2	WC3	WC4	WC5	WVB 1	WVB 2	WVB 3
	Section (mm)	850×850	700×700	550×550	400×400	300×300	400×400	300×300	270×270
		Beams				**Floor Slab**		
	GLT	WB1	WB2	WB3	WB4	CLT		
	Section (mm)	500×850	450×750	400×550	300×500	180		

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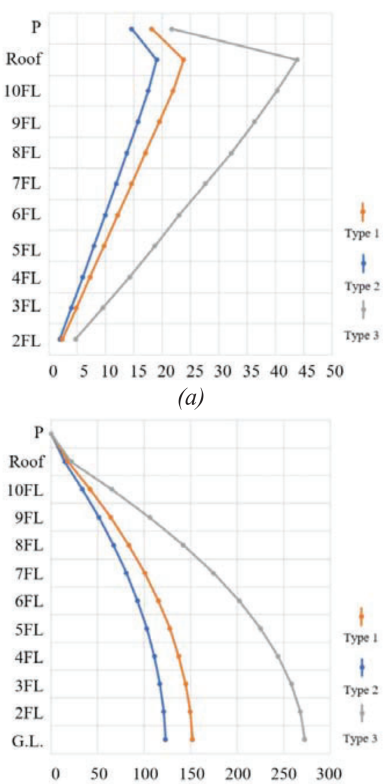
3 – RESULTS AND DISCUSSIONS

3.1 Building Performance

The comparison of story force and story shear in different types of modeling are illustrated in Figure 3, representing the lateral force acting on each floor across four types. Type 3, which is the timber structure, obtain the highest story and shear force due to the setting of lower ductility ratio R suggested by local regulation, while resulting in highest story and shear force. However, the maximum inter-story drift and their corresponding floors for each type are 4.54 cm, 4.64 cm and 10.28 cm on the top floor for Type 1, Type 2 and Type 3 respectively. According to the Building Technical Regulations in Taiwan, the allowable inter-story drift is limited to 0.5%, and all structures comply with this requirement.

Figure 4 shows the material weight for each type. The total weight of Type 1 - Steel structure is the largest, while Type 2 – Steel-Timber hybrid structure is the second largest, accounting for 51% of building weight of Type 1. Types 3, which replaced materials with timber, significantly reduced the weight, with a reduction of 60% of the building weight of Type 1.



(a)

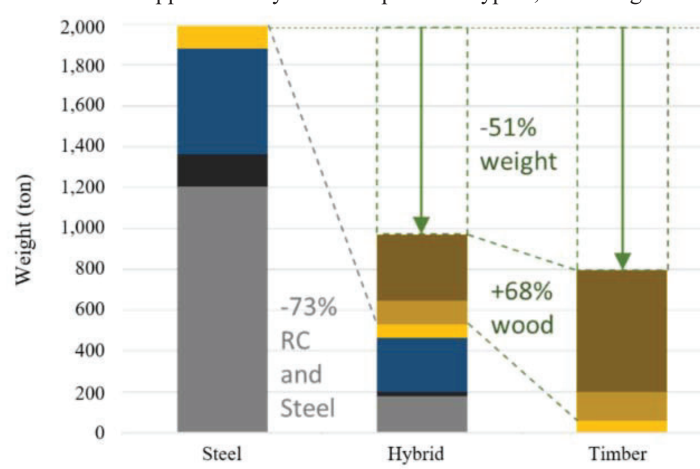
(b)

Fig. 3. (a) story force; (b) story shear. (tonf)

3.2 Carbon Emission

This study has designated imported Douglas fir from North American, with a road transport distance of 630 km within Canada and a sea transport distance of 10,214 km from Canada to Taiwan. Table 2 and table 3 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.

Figure 5 shows the calculation results of carbon emissions, including the timber, concrete, rebar, and steel components for each type, which are 1024.4 tons, 692.6 tons, and 551.9 tons, respectively. A comparative analysis indicated that Type 3, which is timber structure, resulted in lower emissions compared to Type 1 and Type 2, which are steel structure and steel-timber hybrid structure. Type 3, which is timber structure, demonstrated the lowest emissions, reducing emissions by 46% compared to Type 1. Meanwhile, type 3, which is steel-timber hybrid structure, reduce emissions by approximately 30% compared to Type 1, indicating that



	Steel	Hybrid	Timber
GLT C&B	0.0	321.0	598.7
CLT roof slab	0.0	116.9	136.9
Deck / remainder	111.9	67.3	59.9
Steel frame	516.8	263.7	0.0
Rebar	157.5	23.0	0.0
Concrete	1,204.0	176.1	0.0
Total (ton)	1,990.2	968.0	795.5

Fig. 4. Weight of building in different types (tons)

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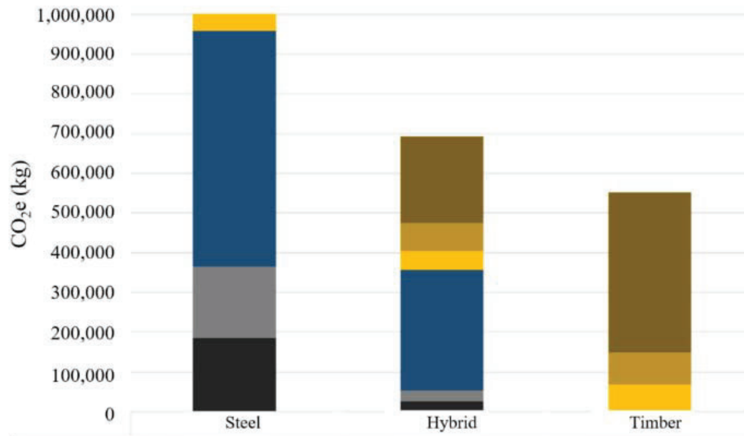
Table 2. Timber carbon emission factor. ($kgCO_2$/kg)

	A1-A3	A4	A5
GLT	0.512	0.232	0.009
CLT	0.437	0.232	0.008

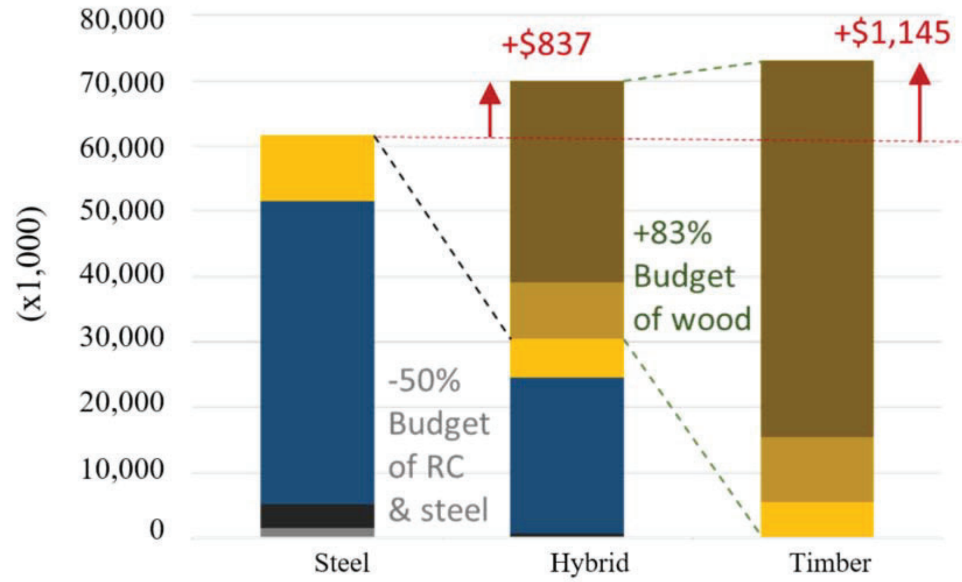
Table 3. Concrete, rebar, and steel carbon emissions factors.

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



	Steel	Hybrid	Timber
GLT C&B	0.0	218,601.0	402,326.4
CLT roof slab	0.0	69,789.3	81,729.3
Deck / remainder	65,160.9	47,616.0	67,824.7
Steel frame	594,320.0	303,255.0	0.0
Concrete	179,550.0	27,119.4	0.0
Rebar	185,416.0	26,220.0	0.0

Fig. 5. Embodied carbon in different types (kg-CO_2e)



	Steel	Hybrid	Timber
GLT C&B	$ 0	$ 30,922.0	$ 57,672.9
CLT roof slab	$ 0	$ 8,579.8	$ 10,047.7
Deck / remainder	$ 10,069.2	$ 6,054.8	$ 5,388.3
Steel frame	$ 46,512.0	$ 23,733.0	$ 0
Rebar	$3,622.5	$ 529.0	$ 0
Concrete	$ 1,454.8	$ 212.8	$ 0
Total (x1,000)	$ 61,658.5	$ 70,031.4	$ 73,108.9

Fig. 6. Construction cost in different types.

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the steel-timber hybrid structure system exhibit the competitive performance in carbon reduction.

3.3 Construction Cost

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

- Steel: 90,000 NTD /ton
- RC: 2,900 NTD /m^3
- Rebar: 23,000 NTD /ton
- CLT: 40,000 NTD /m^3
- GLT: 52,500 NTD /m^3

Figure 6 shows the cost for these types, from Type 1 to Type 3, are 61.7 million NTD, 70 million NTD, 73.1 million NTD, respectively. Steel structure (Type 1) is the cheapest in terms of total cost. Timber stricture (Type 3) has the highest price, even though the weight of Steel is relatively close, Type 2 is lower than Type 3 by approximately 3.1 million NTD. The prices of Type 2 and Type 3 are relatively close. Although the total weight of Type 2 is higher than Type 3, the construction cost of Type 2 is more economically acceptable. 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.

4 – CONCLUSION

In this study, different combinations of building materials is simulated to determine whether carbon emissions can be reduced, as well as calculating the construction costs. Below are the conclusions. In conclusion, steel-timber hybrid structures effectively reduce carbon emissions while maintaining the same structural performance comparing with steel structure. The cost of hybrid timber structures is higher compared to timber structure by approximately 3.1 million NTD, which presents a competitive structure system in term of structure performance, material efficiency, and construction cost in high seismic zone. 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 North American to conduct simulations at higher standards, exploring its feasibility in Taiwan.

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