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COMPARISON OF ENERGY EFFICIENCY BETWEEN WOODEN-BASED HYBRID STRUCTURE SYSTEM AND RC STRUCTURE SYSTEM IN SUBTROPICAL AND TROPICAL AREA

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ABSTRACT: In response to the environmental problems of global warming, the need to save energy and carbon emissions, the energy usage in building sector accounts for 40% of global energy consumption, and its greenhouse gas emissions account for more than three-thirds of its global emissions. It is the largest source of emissions in most countries. However, previous research has mostly focused on comparing the energy-saving efficiency between wooden and RC structures in high-latitude regions, energy-saving efficiency between wooden and RC structures in low-latitude regions, especially in sub-tropical or tropical area in Asia, has not been focused. In this study, in order to examine the energy consumption differences in sub-tropic and tropic area, the energy consumptions in Taipei, Kaohsiung, Hochimin City and Singapore were compared. Moreover, considering the common-used construction materials in buildings in the selected Asian cities, hybrid structure system comprises RC beams/columns and various floors and walls system such as brick, wood and so on was used for the comparison. Simulation method was used to compare the energy efficiency of the four-story and ten-story wooden structures, RC structures, and other types of hybrid system focusing on the usage phase of the building in this study. The research method is to establish a simulation model based on the literature review to set the basic building parameters for analysis. The software called Green Building Studio in Revit was used to simulate the energy consumption in different types of buildings. The carbon emission was calculated to compare the difference in energy efficiency between different structures. Moreover, the combination of different wooden based structural system which was influenced by the energy consumption was evaluated as well, in order to understand the advantage of applying wooden components. The results of the study show that, the use of CLT in four-story and ten-story buildings has a common energy-saving trend in the energy consumption. For the hybrid structural system, the average energy saving are up to 7.49% to 8.12%, depending on the different types of wooden based hybrid system, when the numbers of the original RC buildings were replaced by wooden buildings.

KEYWORDS: Wood structure, RC structure, building energy use, building energy simulation

1 INTRODUCTION

Due to the environmental problems caused by global warming, energy consumption and carbon emissions must be reduced. The building density in an area rapidly increases with increasing population. A report of the United Nations Environment Program indicates that the energy consumption of the construction sector accounts for 40% of the global energy consumption. In addition, the greenhouse gas emissions of the construction sector account for over 33% of the total global emissions, and the construction sector is considered the largest emission source. Consequently, to reduce their environmental impact, construction-related industries should aim to reduce their energy consumption and carbon dioxide emissions in the usage stage of the building life cycle.

Wood construction is becoming increasingly popular internationally, and various new types of wooden building materials and wood construction methods are constantly emerging. From the environmental perspective, wooden structures are favorable insulators that are suitable for carbon fixation. The thermal conductivity of concrete is 1.4 w/m·k, which is 10 times the conductivity of wood. In this study, in order to examine the energy consumption differences in sub-tropic and tropic area, the energy consumptions in Taipei, Kaohsiung, Hochimin City and Singapore were compared. Moreover, considering the common-used construction materials in buildings in the selected Asian cities, hybrid structure system comprises RC beams/columns and various floors and walls system such as brick, wood and so on was used for the comparison. The amounts of the carbon emission was calculated to compare the difference in energy efficiency between different structure systems. Moreover, the power reserve capacity (rate) in the power station which was influenced by the energy consumption was evaluated as well, in order to understand the advantage of applying wooden components in to the wooden-based hybrid structure system in tropical and subtropical area.

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2 METHODOLOGY

2.1 ASSESSMENT OF ENERGY CONSUMPTION

Autodesk Green Building-rating System (GBS) was used for simulating the structure energy consumption in this study. GBS can be used as an independent cloud-service-based program or a plug-in component of the Revit program for energy analysis. GBS comprises the DOE-2.2 analysis core and can provide extremely detailed analysis. As a cloud-based tool, GBS can facilitate rapid computation on the Autodesk server. In general, the DOE-2.2 analysis core requires extremely detailed information on the building envelope and electromechanical system for computation. However, GBS presets numerous building envelope and electromechanical system parameters according to the ASHRAE standard. Thus, architects can focus more on the design factors that have decisive influences on the overall energy consumption of buildings and can ignore technical details. In addition to the building energy consumption, electricity consumption, and annual carbon emissions, GBS can calculate the Energy Star score of buildings. It can also evaluate the glass property and water usage efficiency scores according to the LEED evaluation system published by the U.S. Green Building Council. GBS can even determine the solar energy usage potential.

2.2 ASSESSMENT OF CO2 EMISSION

The Guidelines for National Greenhouse Gas Inventories published by the Intergovernmental Panel on Climate Change were used for the assessment of carbon dioxide emissions. In this study, the calculation method for the emissions of carbon dioxide, methane, and nitrous oxide was adopted to calculate the carbon emissions of different countries. GBS calculates the energy consumption of buildings according to two major parameters: electricity consumption and fuel consumption. The calculated carbon emission of electricity consumption differs according to the electricity carbon emission coefficients of different countries. The carbon emissions can be calculated using equation (1). The emission coefficients of different countries are listed in Table 1. For calculating the carbon emission of fuel consumption, the fuel volume (m3) is first converted into energy units. An energy of 38 MJ or 10.6 kWh can be generated by burning 1 m3 of natural gas. The carbon emission of fuel consumption can then be calculated using equation 2. The carbon emissions coefficient of fuel is listed in Table 2, and all the compared countries have the same carbon emissions coefficient of fuel. The carbon emissions of the total energy consumption of a building can be obtained by summing the carbon emissions of electricity and fuel.

(A) Electricity consumption is converted into carbon emissions by using the following formula:

Electricity usage (kWh) × electricity emissions coefficient (kg CO_2e/kWh) = carbon dioxide emissions(kg) (1)

(B) Fuel consumption is converted into carbon emissions by using the following equation:

Fuel usage (m^3) × natural gas emissions coefficient (kg CO_2e/m^3) = carbon dioxide emissions (kg) (2)

(C) The carbon emission of total energy consumption is calculated as follows:

Carbon emission of total energy consumption (kg) = equation (1) + (2) (3)

3 SIMULATION MODELING

To determine the energy usage efficiencies under different conditions, the energy consumption and carbon emission were compared for different numbers of stories (4 and 10), different construction materials (RC and CLT), and cities with different latitudes (from north to south, Taipei, Kaohsiung, Hochimin City and Singapore). The related structure usage situations and air admission timing of the air-conditioning system were set. In addition, the energy simulation was only conducted for the daily usage stage in the structure life cycle. When GBS was used for structure energy simulation, the basic settings, simulation parameters, weather data, electromechanical system, indoor load, and operation schedules had to be input in the simulation process. The basic parameters and settings of this study are as follows:

1. According to the descriptions on the official website of Autodesk, the data on weather stations were obtained from the World Meteorological Organization.
2. For concrete materials, the pre-existing data in the program were used. The parameters of CLT walls were obtained from relevant research.
3. For the electromechanical system and indoor load, detailed data were required from the DOE-2.2 analysis core to the electromechanical system for the operation. However, the building envelope and electromechanical system parameters were preset in GBS according to the ASHRAE standards. Different air-conditioning systems are used in different countries. The preset parameters were used for the mechanical system and indoor load in this study. The preset parameters of heating, ventilation, and air-conditioning (HVAC) systems were a central variable air volume system, hot-water heating, a performance coefficient of 5.96 for the freezer, and a boiler efficiency of 84.5.

Because this study was a preliminary study, a 24/7 operation schedule was set. Thus, simulations were conducted 7 days a week and 24 hours a day. Then, GBS was used to analyze the simulated building energy consumption. In the comparison of the energy consumptions of different building materials (RC and CLT) in cities at different latitudes, only the energy consumption in the operation stage was considered. In

addition, the following assumptions were made in the simulation process for the energy consumption:
(1) The window positions remained the same when switching from an RC structure to a CLT structure; thus, the illumination demands remained the same.
(2) Except for the balcony, the indoor temperatures of all the rooms were controlled between 18 and 26 °C.
(3) No heating or cooling was conducted in the stair areas.
(4) Electricity was used for the air-conditioning system and illumination, and fuel was used for heating.

3.1 TARGET BUILDING

To determine the energy usage efficiencies for different numbers of stories and different weather conditions, the standard floor of social housing in Taipei City was used as the standard floor in this study. The layouts and basic information of a four-story building and a 10-story building are listed in Table 3.

3.2 BUILDING MATERIALS

The influence of the floor height on the energy-saving efficiency was examined. In addition, the energy consumption efficiencies of the RC and wooden-based hybrid structures were compared. In this study, only the energy consumption in the daily life stage of the building was examined. The simulated building was an RC structure with fixed floor plans on different floors, the building height, building direction, total area, and opening such as windows and doors were fixed for the building simulation. The layout and the structure of the other types of buildings follow the RC structure, which was the target building, however, the material of structures floors and walls, was replaced with wooden components. The building types are illustrated and as shown in Fig 2.

Table 1. Electricity carbon emission coefficients of different countries.

Country	Electricity carbon emission coefficient (kg CO2e/kWh)
Taiwan (Taipei/Kaohisung)	0.53
Vietnam (Hochumin City)	0.57
Singapore	0.41

The physical properties of RC and CLT, including their heat transfer coefficient, specific heat, and density, were also determine for complete analysis. As presented in Table 4, RC has a higher heat transfer coefficient, specific heat, and density than CLT does. Thermal resistance and heat loss are inversely correlated. Thus, an increase in the thermal resistance of the wall material between the interior and exterior of a building can reduce the heat loss of the building (equation 4). As presented in Table 4, CLT walls have a higher thermal resistance than RC walls do. The thermal resistance of a 300-mm-thick external CLT wall is up to 3.3 m2·K/W. The thermal resistance of a 300-mm-thick RC external wall is only 0.25 m2·K/W, which is approximately 1/13th the thermal resistance of a 300-mm-thick CLT external wall. Table 5 lists the physical properties of RC and CLT walls of different thicknesses. Fig. 2 displays the models of numerical analysis. Four- and Ten-story CLT and RC buildings were constructed for comparing the energy consumptions in their daily life stages.

$$\text{Heat loss}=(A/R)\times(T_{indoor}-T_{outdoor}) \quad (4)$$

A : external surface area of the building
R : thermal resistance (R value)
T_{indoor}: indoor air temperature
$T_{outdoor}$: outdoor air temperature

Table 2. Fuel carbon emission coefficient.

Item	Carbon emission coefficient (CO2e/m3)
Natural gas	1.88

Table 3. Basic information on the target buildings.

Building type	4F	10F
Single-story floor area	192.8 m²	702.6 m²
Total floor area	771.2 m²	7026.0 m²
Total surface area	1161.2 m²	3906.6 m²
Exterior window ratio	16.4%	19.9%
User number per unit area	3 people/100 m²	3 people/100 m²
Total user number	23 people	211 people
Average illumination power	6.6 W/m²	6.6 W/m²

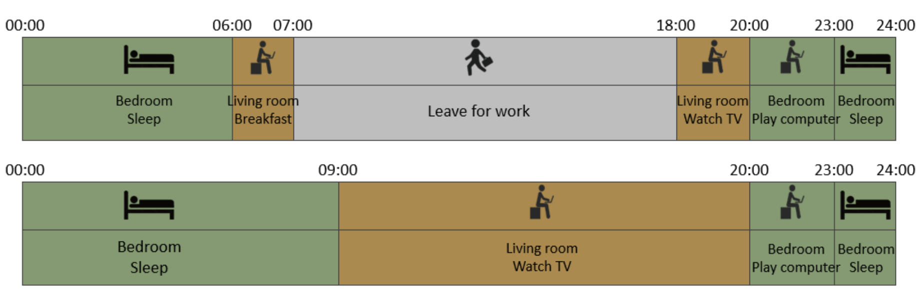

Fig. 1. Life trajectory for simulation

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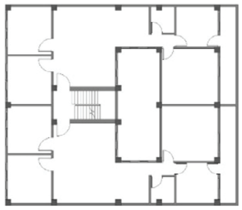
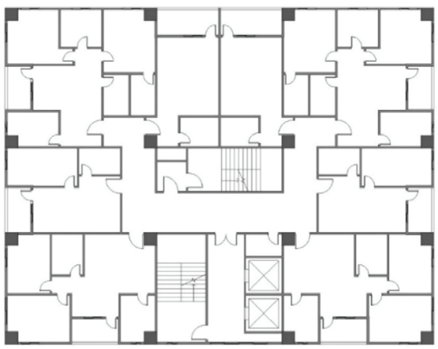
3.3 CITIES IN SUB- AND TROPICAL AREA

Cities at different latitudes have different climates, which influence the energy consumption of buildings. The climate includes the highest and lowest outdoor temperatures and humidity.

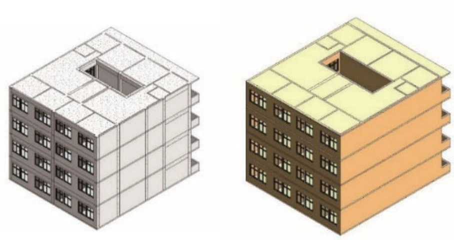


(a) 4-story building

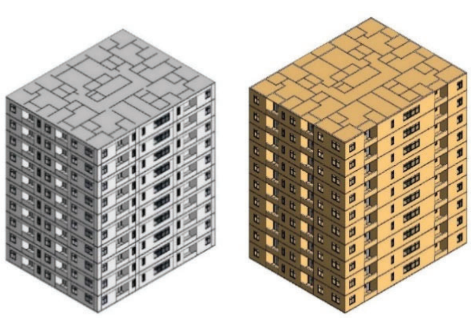


(a) 10-story building

Fig. 2. Standard floor plans of the target buildings



(a) Analysis models of the 4-story RC and CLT structures.



(b) Analysis models of the 10-story RC and CLT structures.

Fig. 3. Simulation modelling.

In this study, the energy consumptions of buildings in cities at different latitudes were also simulated to determine how the overall energy usage efficiency varied with the latitude. The latitude of Taipei was selected as the standard. The other cities selected for comparison were Tokyo and Harbin, which are located to the north of Taipei, as well as Singapore, which is located close to the equator and to the south of Taipei. These cities were selected for comparing the energy-saving efficiencies of RC and CLT buildings of different heights in different environmental conditions. The monthly average temperatures of the aforementioned cities in 2021 are presented in Fig. 4. The lowest monthly average temperature in Taipei, which is located at a high latitude of subtropical zone, was 17.7 °C in January, and the highest monthly average temperature in Taipei was 30.6 °C in July. Thus, the largest monthly average temperature difference was approximately13 °C in Taipei. The lowest monthly average temperatures in Singapore, which is located at a low latitude, near Equator, were 27 °C in December, and the highest monthly average temperatures in Singapore were 29 °C in August and September, respectively. The highest monthly average temperature difference in Singapore was only 2 °C. The highest monthly average temperatures of Kaohisung and Hochimin City, which are located inbetween the tropical zone, were 28.6 °C in August and 30.6 °C in April, respectively. These temperatures were comparable to the high temperatures in Singapore, which is located in the tropics as shown in Fig. 4 and Fig. 5.

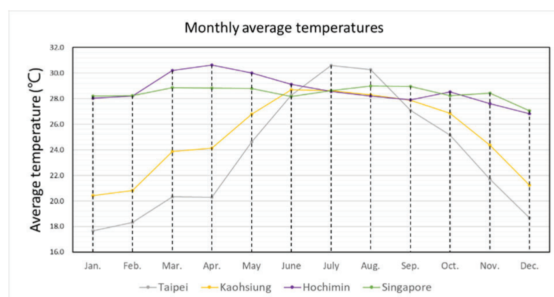


Fig. 4. Monthly average temperatures of the cities.

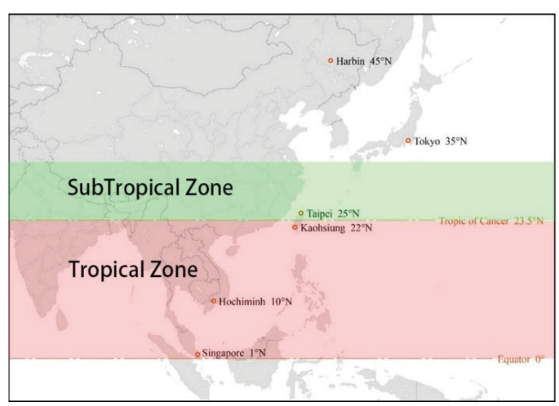
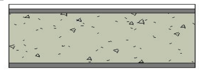
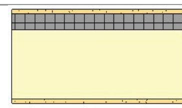
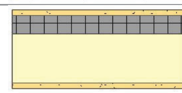
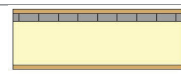


Fig. 5. Cities in Sub- and Tropical Zone

Table 5. Interior materials of different wall types.

Wall material	Wall purpose	Total thickness (mm)	Wall schematic	Interior material	Thickness (mm)
RC	Exterior wall	150		Ceramic tile	10
				Cement mortar	10
				Concrete	120
				Cement mortar	10
	Interior wall	120		Cement mortar	10
				Concrete	100
				Cement mortar	10
CLT	Exterior wall (10F)	300		Plasterboard	15
				Rigid insulation wall	50
				CLT	220
				Plasterboard	15
	Exterior wall (4F)	215		Plasterboard	15
				Rigid insulation wall	50
				CLT	135
				Plasterboard	15
	Interior wall	150		Plywood	10
				Rigid insulation wall	20
				CLT	110
				Plywood	10

4 RESULT AND DISCUSSION

4.1 ENERGY CONSUMPTION

In the simulation, electricity was used by the HVAC system, illumination equipment, and other equipment. Fuel was used by the HVAC and domestic water heating systems. Table 6 presents the simulation results for the 4- and 10-story building made of different building materials and located in cities at different latitudes.

Taking10-story building in Taipei for example, which is located at the highest latitude among the considered cities, the annual electricity consumptions of the RC and CLT structures were 157 and 151 kWh/m^2, respectively. For Singapore, which is at the lowest latitude, the annual electricity consumptions of the RC and CLT buildings were 202 and 190 kWh/m^2, respectively. For both 4- and 10-story building, the simulation results indicated that the electricity consumption of RC buildings was considerably higher than that of CLT structures at higher and lower latitudes. However, at low latitudes, the difference in the electricity consumptions of RC and CLT buildings was relatively higher. The different trend was observed for the fuel energy usage though. Overall, the energy-saving efficiencies of CLT buildings were higher than those of RC structures. The differences in the energy-saving efficiencies considering both electricity and fuel of CLT and RC buildings were higher at higher latitudes.

A comparison of the total energy consumptions of RC and CLT buildings is presented in Table 6 as well. For four-story buildings, the total energy consumptions of the CLT buildings were approximately 98.7%, 99.6%, and 98.7% those of the RC buildings in Kaohsiung, Hochimin City, and Singapore, respectively. No significant difference was observed in the total energy consumptions of the four-story CLT and RC buildings in these cities. Greater difference of the total energy consumptions of RC and CLT buildings is observed in Taipei, which is approximately 89.6% difference. For 10-story buildings, the total energy consumptions of the CLT buildings were approximately 95.9%, 97.3%, and 96.1% those of the RC buildings in Kaohsiung, Hochimin City, and Singapore, respectively. For Taipei, the difference between the total energy consumptions of the 10-story CLT Buildings and RC buildings was marginally higher than that of the four-story CLT and RC structures, which is 88.8% of the difference.

4.2 CO2 EMISSION

Table 7 presents the carbon dioxide emissions per unit area for 4- and 10-story RC and CLT structures in cities at different latitudes. The carbon emissions of electricity energy consumption mainly originate from air-conditioning systems, illumination systems, and basic facilities of the structure. The carbon emissions of fuel energy consumption mainly originate from the use of heating systems. Electricity carbon emissions were calculated according to the electricity emission coefficients of the countries in which the considered cities are located (Tables 1 and 2). Thus, the carbon emissions from the same electricity energy consumption were different in different countries.

The electricity carbon emissions of four-story RC and CLT buildings were 95 and 93 kg/m^2·yr, respectively, in Taipei; thus, the difference in the electricity carbon emissions of the two types of four-story structures was only 2 kg/m^2·yr in Taipei. In Singapore, the electricity carbon emissions of four-story RC and CLT buildings were 157 and 153 kg/m^2·yr, respectively, which represents an electricity carbon emission difference of 4 kg/m^2·yr. The difference in carbon emissions was small because the monthly average temperature in every month

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in Singapore was higher than 26 °C, which was the temperature set in this study for the air-conditioning system to be turned on. The air-conditioning system demands were high. Thus, the demands for carbon emissions from electricity energy consumption were high for both RC and CLT buildings. For Taipei, in addition to the air-conditioning system demands, the heating system demands were slightly high. The carbon emissions of fuel energy consumption for four-story RC and CLT buildings in Taipei were 38 and 30 kg/m^2·yr, respectively, which represents a fuel carbon emission difference of 8 kg/m^2·yr. In Singapore, the fuel carbon emissions of four-story RC and CLT buildings were both 19 kg/m^2·yr. In cities at higher latitudes, the heating system needs were higher. Thus, the fuel carbon emissions and fuel carbon emission differences increased considerably with the latitude. Table 7 indicate that the 10-story buildings had better carbon emission reduction effects to those of the four-story buildings for electricity and fuel energy consumption. For regions at higher latitudes (Taipei), the differences in electricity carbon emissions of 10- and 4-story structures were not significant. However, the carbon emissions reduction efficiencies of buildings with more stories could be shown in the differences of fuel carbon emissions. Thus, greater differences were observed in the carbon emissions of total energy consumption for RC and CLT buildings in Taipei and Singapore for 10 story building.

4.3 HYBRID BUILDING SYSTEM

The results of this study indicate that CLT buildings have higher energy-saving and carbon reduction efficiencies than RC buildings do at different latitudes. These efficiencies increase with the number of floors. Moreover, the differences in the energy consumption efficiencies of CLT and RC buildings increase with the latitude. All the East Asian cities selected in this study have high degrees of urbanization and concentrated high-rise buildings. The existing high-rise buildings in these cites face the problem of aging. For example, in Taipei, most buildings are RC structures that are approximately 30–50 years old. These structures are still usable; however, their overall energy consumption is high because of the RC building material. Consequently, in this study, few strategies are proposed for the renewal of these buildings in the future. The proposed strategy involves preserving existing RC beam structures and renewing the floors and walls with CLT for renovation type 1. Replacing the top 4 floors of the building with wooden system is the renovation type 2 in this study. For renovation type 3, the original service core with RC as major construction material is preserved, while the rest of the living space is replaced by wooden construction. On the basis of this concept, three wooden based hybrid building systems are defined, and the analysis model was established in this study. Fig. 6 illustrates the models of preserving the RC beam structures and replacing the floors and walls with CLT, replacing the top 4 floors of the building with wooden system, and the original service core with RC as major construction material is preserved. The energy consumptions of CLT and RC structures of the same size were also compared. The analysis and simulation conditions were the same as stated previously as shown in Section 3. The simulation results are concluded and as shown in the next section.

Table 6. Energy consumption comparison of structures with different heights in different cities.

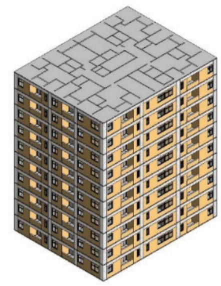
		Taipei		Kaohsiung		Hochimin City		Singapore	
		RC	CLT	RC	CLT	RC	CLT	RC	CLT
(A)Electricity (kWh/m²/yr)	4 storys	175	179	210	211	222	221	232	227
	10 storys	157	151	188	178	193	184	202	190
(B)Electricity (MJ/m²/yr)	4 storys	631	644	756	761	799	795	833	818
	10 storys	566	543	675	641	695	662	726	682
(C)Fuel (MJ/m²/yr)	4 storys	761	603	481	460	415	414	390	389
	10 storys	701	583	461	449	407	410	382	382
Sum (B)+(C) (MJ/m²/yr)	4 storys	1392	1247	1237	1221	1214	1209	1223	1207
	10 storys	1267	1126	1136	1090	1102	1072	1108	1064

Table 7. Carbon emissions comparison of structures with different heights in different cities.

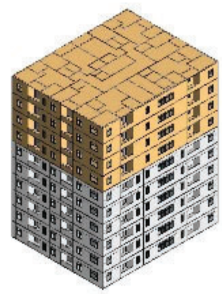
		Taipei		Kaohsiung		Hochimin City		Singapore	
		RC	CLT	RC	CLT	RC	CLT	RC	CLT
(A)Electricity (kg/m²/yr)	4 storys	95	93	113	112	127	126	157	153
	10 storys	84	81	100	95	110	105	136	128
(C)Fuel (Kg/m²/yr)	4 storys	38	30	24	23	21	21	19	19
	10 storys	35	29	23	22	20	20	19	19
Sum (A)+(B) (Kg/m²/yr)	4 storys	133	123	137	135	148	147	176	172
	10 storys	119	110	123	117	130	125	155	147

4.4 SIMULATION RESULTS FOR HYBRID BUILDING SYSTEMS

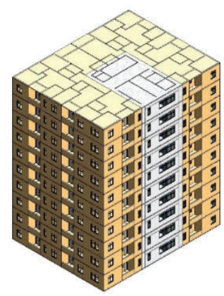
The analysis results presented in Table 8 indicate that 3 types of different hybrid buildings have better electricity energy consumption performance to the RC structure. The electricity energy consumption performance of the hybrid buildings is only marginally worse (3%–7% lower) than that of the CLT buildings. Thus, the proposed hybrid buildings are close to the CLT buildings in terms of electricity energy consumption. For fuel energy consumption, no significant difference was observed between the different building in Singapore and Hochimin City and Kaohsiung, which is located at a lower latitude. In Taipei, which are located at relatively higher latitudes, the fuel energy consumption of the hybrid buildings is higher than that of the RC buildings and not significantly different from that of the CLT buildings. The CLT and wooden based hybrid buildings exhibited no significant difference in their total energy consumptions. The aforementioned buildings exhibited lower total energy consumptions than the RC buildings did. The energy-saving efficiency of the proposed wooden hybrid structure system, which comprises RC beam structures and CLT floors and walls for hybrid type 1, replacing the top 4 floors of the building with wooden system for hybrid type 2, and original service core with RC as major construction material preserved for hybrid type 3, are close to that of CLT buildings. The advantage of the hybrid building system is obvious if the weight of the material is compared. The total building weight is potentially reduced if part of the building material is replaced from reinforced concrete to wood, due to the light weight property for wood comparing to concrete. In the region with high frequent earthquake, especially in Taipei or Kaohsiung, the reduction of building weight means the seismic force can be potentially reduced, improving the resilience of the building.



(a) Hybrid Type 1: models of preserving the RC beam structures and replacing the floors and walls with CLT



(b) Hybrid Type 2: models of replacing the top 4 floors of the building with wooden system



(b) Hybrid Type 3: models of original service core with RC as major construction material preserved

Fig. 6. Models of different hybrid building systems

Table 8. Energy consumption of hybrid buildings with RC and CLT structures.

Taipei					
	RC	CLT	Hybrid Type 1	Hybrid Type 2	Hybrid Type 3
(A) Electricity	566	543	549	549	540
(B) Fuel	701	583	570	638	576
Sum (A)+(B) (MJ/m²/yr)	1267	1126	1119	1187	1116
Kaohsiung					
	RC	CLT	Hybrid 1	Hybrid 2	Hybrid 3
(A) Electricity	675	641	649	654	642
(B) Fuel	461	449	440	442	440
Sum (A)+(B) (MJ/m²/yr)	1136	1090	1089	1096	1082
Hochimin City					
	RC	CLT	Hybrid 1	Hybrid 2	Hybrid 3
(A) Electricity	695	662	673	675	666
(B) Fuel	407	410	407	392	407
Sum (A)+(B) (MJ/m²/yr)	1102	1072	1080	1067	1073
Singapore					
	RC	CLT	Hybrid 1	Hybrid 2	Hybrid 3
(A) Electricity	726	682	692	700	685
(B) Fuel	382	382	382	368	382
Sum (A)+(B) (MJ/m²/yr)	1108	1064	1074	1068	1067

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5 CONCLUSIONS

In this study, the differences of energy consumption and carbon emission at sub-tropical and tropical area such as Taipei, Kaohsiung, Hochimin City and Singapore, were compared. The preliminary study clarified that the energy-saving efficiency is higher in the cities in the higher latitude when the construction materials are substituted from RC structure to CLT structure. Generally, the performance of wooden buildings is better than RC buildings and the following results are conclude.

(1) For 10-story buildings, the total energy consumptions of the CLT buildings were approximately 95.9%, 97.3%, and 96.1% those of the RC buildings in Kaohsiung, Hochimin City, and Singapore, respectively. For Taipei, the difference between the total energy consumptions of the 10-story CLT Buildings and RC buildings was marginally higher than that of the four-story CLT and RC structures, which is 88.8% of the difference. For cities located in Subtropical area such as Taipei, archiving a better energy consumption efficiency than the cities located in tropical cities, such as Kaohsiung, Hochimin City, or Singapore.

(2) The greater differences were observed in the carbon emissions of total energy consumption for RC and CLT buildings in Taipei and Singapore for 10 story building, indicating that the 10-story buildings had better carbon emission reduction effects to those of the 4-story buildings for electricity and fuel energy consumption.

(3) The electricity energy consumption performance of the hybrid buildings is only marginally worse (3%–7% lower) than that of the CLT buildings, indicating the energy-saving efficiency of the proposed wooden hybrid structure system, which comprises RC beam structures and CLT floors and walls for hybrid type 1, replacing the top 4 floors of the building with wooden system for hybrid type 2, and original service core with RC as major construction material preserved for hybrid type 3, are close to that of CLT buildings. Thus, it is understood that the proposed hybrid buildings are close to the CLT buildings in terms of total energy consumption.

In conclusion, the proposed hybrid building system, which comprises RC beams, columns and CLT floors and walls, replacing the top 4 floors of the building with wooden system, and original service core with RC as major construction material preserved have less building weight compared to the original RC building, and less energy required for the manufacturing of building materials in the renovation of the aged building, has an energy-saving efficiency close to that of a CLT building. For the cities selected in this study, the proposed hybrid building systems can be effectively used for old building renewal.

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