

Study on energy conservation and carbon emission reduction design of timber structure building

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Abstract: Replacing traditional building materials with renewable and sustainable materials such as timber can control environmental pollution such as energy consumption and carbon emission in the whole life cycle of a building, which is conducive to energy conservation and environmental protection. How to design timber structure building better is the focus of this study. This study takes timber structure building as the research object, evaluates the building energy consumption and CO₂ emission with the whole life cycle concept. The comparative ecological advantages of timber structure building are obtained by comparing and analysing the brick-concrete structure building with equivalent thermal performance. Then by analysing the different spaces of timber structure building design, the design suggestions of energy saving and carbon reduction such as reducing the platform area appropriately and increasing the number of building floors are proposed when designing timber structure buildings.

1 Introduction

The construction industry plays a major role in global energy consumption and carbon emission. Building materials affect the whole life cycle of buildings. Through the study of forest and timber tracking management, timber is considered a green building material of energy saving and environmental protection [1]. The life cycle of timber products includes the flow of material and energy, and the design and construction of timber structure buildings also affect the climate environment of sustainably managed forests [2]. Timber is a negative carbon building material. The use of timber products helps to curb the growth of CO₂ content in the atmosphere and slow down the pace of climate change. In the whole life cycle evaluation [3], timber structure has the least adverse impact on the environment compared with concrete structure, brick-concrete structure, steel structure, and other architectural structure systems [4, 5], it is the only one of the analytical materials that can achieve sustainable environmental development [6]. Applying timber structure in residential buildings [7] and public buildings [8] has good environmental benefits. Building structure with timber can also achieve the goal of energy conservation and environmental protection, such as building exterior sunshade [9] and steel-timber composite floors and walls [10].

Researches on the whole life cycle or energy consumption and carbon emission of building materials of timber structure buildings are mostly concentrated on the whole building, while studies on the spatial decomposition and analysis and comparison of buildings are still lacking.

Timber structure design has been studied mostly in three aspects: structural system design, fire-fighting system design, and architectural system design. In the structural system design, some studies have been made on the stress [11–14] and seismic performance of timber structures [15, 16]. Some use timber to design new building structures to improve energy efficiency and reduce greenhouse gas emissions, such as a combination of glued laminated timber with steel stud and a combination of laminated veneer lumber with steel stud [17], timber–glass composite wall panels [18], and cross-laminated timber structures [19]. In the research of the fire-fighting system, the timber itself is flammable, so the research is mostly about the fire-fighting measures and ventilation and smoke extraction of timber structure buildings [20, 21].

The architectural system design of timber structure building mainly has two aspects, one is the case display of architectural design and the other is the thermal performance research of timber structure building. In the exhibition of architectural design cases, the form of a timber structure in the building and the complex internal ceiling was introduced in Churchill Meadows Community Centre case [22], and Norwegian Team showed the design of world's tallest timber building [23]. Debbie introduced the integration, construction, and operation of the timber structure with the landscape [24]. There are some studies in the thermal performance of timber structures. Hynek tested the dynamic thermal performance of building structures in experimental light weight timber-frame passive house to prove the favourable thermal performance [25]. Kalamees studied air leakage levels in timber frame building envelope joints and proposed air tightness improvement suggestions in the design of nearly zero-energy consumption timber buildings [26].

The research on design methods in the design of timber buildings mostly starts from the performance of buildings and puts forward design suggestions to reduce the energy consumption in the use stage of buildings. However, there is still a lack of research on the whole life cycle of buildings, the comprehensive energy consumption of building materials and carbon emission.

This study takes timber structure building as the research object, evaluates the building energy consumption and CO₂ emission (CE) with the whole life cycle concept. The comparative ecological advantages of timber structure building are obtained by comparing and analysing the brick-concrete structure building with equivalent thermal performance. Then the suggestions of timber structure building design are obtained by analysing the different spaces of the building.

2 Model description

2.1 Building description

This study took the timber structure building of the Garden Training Base of Zhejiang College of Construction as an example. The building has two floors, each of which has a part of the interior room and an outdoor platform. The construction area is 195 m², the first floor (F1) with the room area of 130 m², the second floor (F2) with the room area of 65 m². The area of the F1 with the platform is 106 m², and the area of the F2 with the platform is 105 m². The

building is constructed of a light timber structure with rock wool as thermal insulation material.

2.2 Control case

In order to analyse the ecological advantages of timber structure buildings, this study established a control case, i.e. the case building 'Timber Structure Building of Garden Practice Training Base of Zhejiang College of Construction', which used other structural systems like the control case. As the case building is a low-rise small size public building, and the light timber structure and the brick-concrete structure are wall load-bearing structures, the brick-concrete structure was adopted as the structural system of the control case building to calculate the list of construction quantities.

Rock wool is the thermal insulation material used in the timber structure case building, with the thermal conductivity of 0.048 W/(m K); expanded polystyrene (EPS) board is a common thermal insulation material in brick-concrete structures, with the thermal conductivity of 0.041 W/(m K). According to the simulation test, when the load is the same as that of timber structure building, the amount of insulation material is almost the same when rock wool or EPS is adopted as an energy saving method in brick-concrete structure building. The unit energy consumption of rock wool board is 3516 MJ/m³, and that of EPS is 1805 MJ/m³, and the unit CE of the two is similar. Therefore, the brick-concrete structure adopts a more energy saving method, i.e. EPS as the insulation material of the building as a control case.

2.3 Hypothesis

Assuming that the effective use time of the building is 10 years, through the calculation of energy consumption and carbon emission in the whole life cycle of the building, it is known that in the five stages of building production, transportation, construction, use and abandonment, energy consumption in the production stage accounts for the largest proportion (about 54%), and energy consumption in the use stage accounts for the second largest proportion (about 25%). The CE in the use stage accounts for the largest proportion (83%) and the CE in the production stage accounts for the second largest proportion (about 21%). In addition, this case lacks effective data in the construction stage and the abandonment stage. Therefore, this study takes the equivalent thermal performance of buildings, i.e. with the same energy consumption of timber structure and brick-concrete structure in the use stage as the premise, calculates the energy consumption and CE in the production stage and transportation stage of buildings, and conducts data analysis.

The case building has two floors, but the research results can be derived from a multi-storey building after the engineering quantity is divided in terms of the architectural space. According to the different quantities of engineering, the platform can be divided into two categories: the ground floor platform and the floor platform. Rooms can be divided into two categories: the typical floor rooms and the top floor rooms. For example, for a four-storey timber structure building, the calculation method and result of the ground floor platform (F1) should be similar to the F1 platform of the case building, the floor platform (F2, F3, F4) should be similar to the F2 platform of the case building. The calculation method and result of the typical floor room (F1, F2, F3) are similar to that of the F1 of the case building, while the top floor room (F4) is similar to that of the F2 of the case building.

3 Life cycle energy consumption and CE of the building

For the whole building, this work studies the energy consumption and CE data of the whole life cycle of building materials. The total

building energy consumption (EnC total) is the sum of the energy consumption in the building's production stage, transportation stage, construction stage, use stage, and demolition stage (EnC stage k), which is expressed with the formula

$$\text{EnC}_{\text{total}} = \sum \text{EnC}_{\text{stage } k} \quad (1)$$

The total CE of a building (CE total) is the sum of the CE in the building's production stage, transportation stage, construction stage, demolition stage (CE stage k), minus carbon sequestration (CS) of building materials, which is expressed with the formula

$$\text{CE}_{\text{total}} = \sum \text{CE}_{\text{stage } k} - \text{CS} \quad (2)$$

3.1 Building materials production stage

The production stage of building materials includes the exploitation and transportation of raw materials and the production of building materials. Materials used in timber structure buildings include dimensional lumber, pressure-treated lumber, oriented strand board (OSB), rock wool board, gypsum board, concrete, cement mortar etc. Materials used in brick-concrete structure buildings include concrete, fired perforated brick, steel bar, cement mortar, rock wool board etc.

During the exploitation and transportation of raw materials and the production and processing of building materials, energy sources such as fire brand, raw coal, crude oil, natural gas, gasoline, and electric power are consumed, and gases such as CO₂ will be emitted. Owing to the immature research on the whole life cycle database of dimensional lumber, pressure-treated lumber, and OSB, the calculation was carried out with reference to the original data. The energy data are from the literature [27]. Energy consumption per unit material is the sum of products of its energy consumption and energy consumption per unit material. The CE of dimensional lumber, pressure-treated lumber, and OSB is referred to the literature [28].

The database research of the whole life cycle of other major building materials is relatively mature, so this research takes energy consumption and CE data of materials such as concrete [29, 30], steel bar [31], plaster board [32], cement mortar [27, 33], rock wool board [34], and fired perforated brick [35] during the production stage as the material properties directly into computing, data was from the literature [36].

Energy consumption in the production stage (EnC production) of building materials is the sum of energy consumption of each material (EnC production material i). Energy consumption of each material is the product of unit energy consumption of building materials (EnC production-per material i) and its quantity (quantity material i) (see (3)).

CE in building material production stage (CE production) is the sum of CE of all materials (CE production material i). CE of each material is the product of CE per unit of building material (CE production per material i) and its quantity (see (4)).

3.2 Building materials transportation stage

Building materials transportation stage refers to the use of transportation means to transport building materials from the production and processing plant to the project construction site. The dimensional lumber, pressure-treated lumber, and OSB used in the case building were manufactured in British Columbia, Canada and transported to the site by sea and land. Other materials were purchased nearby and transported to the site by land. Concrete road transported with a cement mixer, measured by volume. Other materials transported by land with freight cars, measured by weight.

$$\begin{aligned} \text{EnC}_{\text{production}} &= \sum \text{EnC}_{\text{production material } i} \\ &= \sum \text{EnC}_{\text{production}} - \text{per material } i \times \text{quantity material } i \end{aligned} \quad (3)$$

$$\begin{aligned} \text{CE production} &= \sum \text{CE production material } i \\ &= \sum \text{CE production} - \text{per material } i \times \text{quantity material } i \end{aligned} \quad (4)$$

$$\begin{aligned} \text{EnC transportation} &= \sum \text{EnC transportation material } i \\ &\quad \times \text{Quantity material } i \times \text{distance material } i \end{aligned} \quad (5)$$

Calculation parameters: sea transport distance in the nautical mile (NM), 1 km = 1.852 NM; 1 kg diesel fuel consumption is 45.9 MJ; transportation of 1 kg of goods for 1 km consumes 0.0037 t of diesel oil; transporting 1 m³ of concrete for 1 km consumes 0.98 MJ of energy.

Energy consumption in the transportation stage of building materials (EnC transportation) refers to the sum of products of transportation energy consumption (EnC transportation material *i*), material quantity (quantity material *i*) and transportation distance (distance material) of each unit material (see (5)). CE in the transportation stage of building materials (CE transportation) refers to the CO₂ generated by the consumption of diesel during the transportation process and the CE factor of diesel is 0.0741 kg/MJ

$$\text{CE transportation} = \text{EnC transportation} \times 0.0741 \text{ kg/MJ} \quad (6)$$

3.3 Building construction stage

Owing to the lack of reliable actual measurement and literature data, this study refers to the estimation of brick-concrete buildings [37] for the energy consumption and CE during construction. Energy consumption during construction (EnC construction) is the product of the energy consumption (EC) per unit floor area (EC construction/area = 107.2 MJ/m²) and the building area (area)

$$\text{EnC construction} = 107.2 \text{ MJ/m}^2 \times \text{area} \quad (7)$$

CE during the construction stage (CE construction) is the product of the CE per unit building area (CE construction/area = 9 kg/m²) and the building area (area)

$$\text{CE construction} = 9 \text{ kg/m}^2 \times \text{area} \quad (8)$$

3.4 Building use stage

PBECA (software developed by China Academy of Building Research for Building Energy Conservation Analysis) building energy conservation analysis software can simulate the building environment and calculate the annual load of the building. Since the brick-concrete structure control case is a virtual building, this study adopts the software simulation method to analyse energy consumption. On the premise of the same energy consumption, this study compared the timber structure and brick-concrete structure in the whole life cycle and simulated the energy consumption with PBECA. Firstly, the annual cooling and heating load of timber building were calculated. Then, the annual cooling and heating load of brick-concrete structure building were calculated, and the simulation test of energy-saving measures was employed to make its load the same as the timber structure.

According to the parameters of the building, and the parameters provided by the Energy Conservation Design Standards for Public Buildings (DB33/1036–2007) [38] of Zhejiang Province, the annual cooling and heating load of the building were obtained. The functions of case building include classroom and conference room, and the life-cycle energy consumption and CEs are calculated according to 8 h use per day and 10 years lifetime. Wherein, CE coefficient per unit power generation is 0.78 kg/kWh

$$\text{EnC use} = 10 \text{ years} \times 3.6 \text{ MJ/kWh} \times \text{load} \quad (9)$$

$$\text{CE use} = 10 \text{ years} \times 0.78 \text{ kg/kWh} \times \text{load} \quad (10)$$

3.5 Building demolition stage

Owing to the lack of reliable actual measurement and literature data, this study refers to Wang Zhaoqing's research [39] and the estimation of multilayer brick-concrete buildings for the energy consumption and CE during building demolition.

Energy consumption of building demolition stage (EnC demolition) is the product of unit area energy consumption (EnC demolition/area = 1690.4 MJ/m²) and building area (area):

$$\text{EnC demolition} = 1690.4 \text{ MJ/m}^2 \times \text{area} \quad (11)$$

CE (CE demolition) of building demolition stage is the product of unit area CE (CE demolition/area = 141.7 kg/m²) and building area (area)

$$\text{CE demolition} = 141.7 \text{ kg/m}^2 \times \text{area} \quad (12)$$

3.6 CS ability of building materials

The dimensional lumber, pressure-treated lumber, and OSB used in the case building have the ability of CS. The raw material of the pressure-treated lumber is the same as the dimensional lumber, both of which are north American softwood. The carbon content rate is the average value of 51.2% taken from the Lamlom study [40]. CS of the building (CS) is represented by CE reduction. The molecular weight of CO₂ is 3.67 times that of carbon

$$\text{CE sequestration} = \sum \text{Quantity material } i \times 51.2\% \times 3.67 \quad (13)$$

4 Energy consumption and CE of building materials in each architectural space

The design of architectural space is the core of the architectural design. Based on the principle of architectural construction, the architectural space consists of structure constructions just like wall, floor, and ceiling. The constructions are composed of various building materials and their energy consumption and CE can be calculated.

4.1 Architectural space and materials

According to the architectural space, the case building can be divided into five parts: building foundation, F1 platform, F1 room, F2 platform, and F2 room. Each space consists of multiple constructs. The same materials of different constructions in one space are added to get the amount of each material in each space. For example, the dosage of dimensional lumber used in F1 room of timber structure building is the sum of dosage in exterior wall keel, window lintel of exterior wall door, interior wall keel, window lintel of interior wall door, floor slab combination beam, and floor slab wood joist.

4.1.1 Foundation: The foundation of the timber structure is general concrete structure [41]. The foundation of case building is foundation wall and concrete slab in both timber structure and brick-concrete structure.

4.1.2 F1 platform: F1 platform of timber building is a pressure-treated lumber platform built on the concrete foundation. F1 platform of the brick-concrete floor is to pour a concrete ground slab and daub cement mortar.

Table 1 Energy-saving measures for timber structure building

Building envelope	Energy-saving construction measures
slope roof (from top to bottom)	OSB (12.0 mm) + rock wool board (140.0 mm) + gypsum board (24.0 mm)
external walls (from outside to inside)	OSB (12.0 mm) + rock wool board (140.0 mm) + gypsum board (24.0 mm)
ground	cement mortar (38.0 mm) + reinforced concrete (120.0 mm) + compacted clay (150.0 mm)
exterior windows	plastic profile window frame $K \leq 2.7(W/(m^2K))$, with the frame area $\leq 25\%$ (6 mm transparent + 12 air + 6 transparent), and heat transfer coefficient of $2.80 W/m^2K$

Table 2 Annual heating and cooling load of timber building

Load type	Cooling and heating load value, kWh/year	Unit area load index, kWh/m ² /year
cooling load	30,073	154.22
heat load	15,703	80.53
cooling and heat load	45,776	234.75

Table 3 Energy-saving measures for brick-concrete structure building

Building envelope	Energy-saving construction measures
flat roof (from top to bottom)	cement mortar (20.0 mm) + EPS (140.0 mm) + cement mortar (20.0 mm) + reinforced concrete (120.0 mm)
slope roof (from top to bottom)	cement mortar (20.0 mm) + EPS (140.0 mm) + cement mortar (20.0 mm) + reinforced concrete (120.0 mm)
external walls (from outside to inside)	mortar (3.0 mm) + EPS (100.0 mm) + fired perforated bricks (240.0 mm) + cement mortar (20.0 mm)
ground	cement mortar (38.0 mm) + reinforced concrete (120.0 mm) + compacted clay (150.0 mm)
exterior windows	plastic profile window frame $K \leq 2.7(W/(m^2K))$, with the frame area $\leq 25\%$ (6 mm transparent + 12 air + 6 transparent), and heat transfer coefficient of $2.80 W/m^2K$

4.1.3 F1 room: F1 room is composed of walls, floors, beams, columns etc. The materials of timber structure are dimensional lumber, rock wool board, OSB, and gypsum board. The materials of the brick-concrete structure are concrete, fired perforated brick, cement mortar, EPS, and steel bar.

4.1.4 F2 platform: F2 platform of timber structure consists of bottom supporting columns, beams, floor slabs, and pressure-treated lumber platform; the materials are pressure-treated lumber and dimensional lumber. F2 platform of the brick-concrete structure consists of columns, beams, and floors, the materials are concrete, cement mortar, and steel bar.

4.1.5 F2 room: F2 room is composed of a wall, roof, beam column etc. The materials of timber structure are dimensional lumber, rock wool board, OSB, and gypsum board. The materials of the brick-concrete structure are concrete, fired perforated brick, cement mortar, EPS, and steel bar.

4.2 Property values of energy consumption and CE per unit of building materials

According to the whole life cycle study in Section 3, each building material has energy consumption and CE data in the production stage and transportation stage. Dimensional lumber, pressure-treated lumber, and OSB also have the ability of CS. These three sets of values were integrated to define the energy consumption per unit of building materials and the CE property values, which were used to calculate the spatial building envelope data. The data used in the construction stage, use stage, and demolition stage of the timber structure and the brick-concrete structure of the case building are the same, and as the data of the whole building, they cannot be divided into the property values of each material, which shall not be included in this part.

4.3 Calculation of space energy consumption and CE of buildings

Energy consumption for each space of the building (EnC space h) is the sum of the products of the property value of energy consumption per unit of building materials (EnC property material

i) and the amount of the same material in this space and different structures (quantity material $i_{\text{structure } j}$)

$$\text{EnC space } h = \sum \text{EnC property material } i \times \text{Quantity material } i_{\text{structure } j} \quad (14)$$

CE from each space of the building (CE space h) is the sum of products of the property value of energy consumption per unit of building materials (CE property material i) and the amount of the same material in this space and different structures (quantity material $i_{\text{structure } j}$)

$$\text{CE space } h = \sum \text{CE property material } i \times \text{quantity material } i_{\text{structure } j} \quad (15)$$

5 Results

5.1 Building energy conservation calculation

Modern timber structures use closely-spaced members of dimensional lumber and sheathing panels to form structural elements. Structural elements provide rigidity, support for interior finish and exterior cladding, and cavity for insulation. For exterior walls, batt-type and spray foam insulation are mostly used. Timber structure buildings are supported on concrete foundations, which is the same as the brick-concrete structure. Energy-saving measures for timber structure building are given in Table 1.

The annual cooling and heating load of timber building were calculated by PBECA and shown in Table 2.

According to the annual cooling and heating load of timber building, the design simulation test was carried out on the energy-saving measures for brick-concrete structure, so as to make the load value of both structures equal, thus obtaining the energy-saving construction measures for brick-concrete structure (Table 3).

5.2 Life cycle energy consumption and CE

5.2.1 Timber structure:

According to formulas (3) and (4), energy consumption and CE of dimensional lumber, OSB, and pressure-treated are as following (Table 4).

Energy consumption and CE of other main materials used in timber structure are shown in Table 5, and total in the production stage is shown in Table 6.

Table 4 Energy consumption and CE of dimensional lumber, OSB, and pressure-treated in the production stage

Material		Firebrand	Raw coal	Crude oil	Natural gas	Electricity power	Liquefied gas	Fuel oil	Gasoline	Total of energy	CE
dimensional lumber	consumption, kg/m ³	71.3	7.06	6.71	22.2 m ³ /m ³	124 kWh/m ³					
	energy consumption per unit, MJ/kg	20.9	26.2	45.5	54.4 MJ/m ³	3.6 MJ/kWh					
	total, MJ	1490.17	184.97	305.31	1207.68	446.4				2144.36	193.10 kg
OSB	consumption, kg/m ³	200.79			16.94 m ³ /m ³	206.76 kWh/m ³	1.5	0.75	0.03		
	energy consumption per unit, MJ/kg	20.9			54.4 MJ/m ³	3.6 MJ/kWh	54	45.5	45		
	total, MJ	4196.51			921.54	744.34	81	34.13	1.35	5978.86	695.37 kg
pressure-treated	consumption, kg/m ³	50.42	36.36	0.00115	8.08 m ³ /m ³	143 kWh/m ³					
	energy consumption per unit, MJ/kg	20.9	26.2	45.5	54.4 MJ/m ³	3.6 MJ/kWh					
	total, MJ	1053.86	952.67	0.05	439.55 T	514.8				2960.94	349 kg

Table 5 Energy consumption and CE of other main materials in the production stage

	Steel bar, kg ⁻¹	Concrete, m ⁻³	Plasterboard, m ⁻²	Cement mortar, kg ⁻¹	Rock wool board, m ⁻³	EPS, m ⁻³
energy consumption, MJ	33.91	2841.10	48	3.97	3516	1804.88
CE, kg	2.21	342.86	6.02	0.79	325.95	341.40

Table 6 Energy consumption and CE of building materials in the production stage

Material	Quantity, m ³	Energy consumption		CE	
		Unit energy consumption, MJ/m ³	Energy consumption, MJ	Unit CE, kg/m ³	CE, kg
dimensional lumber	32.00	2144.36	68,619.42	199.82	6394.24
OSB	7.65	5978.86	45,738.89	695.37	5319.62
pressure-treated lumber	12.56	2960.94	37,178.51	145.00	4382.16
rock wool board	71.63	3516.00	251,865.05	325.95	23,349.09
concrete	58.55	2841.10	166,346.64	342.86	20,074.45
plasterboard (m ²)	398.80	48.00	19,142.40	6.02	2400.78
cement mortar (kg)	10,079.12	3.97	40,034.26	0.79	7982.66
total			628,925.19		61,920.34

Table 7 Energy consumption and CE of building materials during transportation

Material	Quantity, t		Starting place–destination	Distance, km		Diesel consumption		Energy consumption, MJ	CE, kg
	Density, kg/m ³	Weight, t		Sea transportation distance, NM	Land transportation distance, km	Diesel oil weight, kg	Diesel oil volume, l		
dimensional lumber	529	16.93	B.C.-TAICANG PORT–College	5120	1010	657.17	782.34	30,163.95	2112.32
OSB	650	4.97	B.C.-TAICANG PORT–College	5120	1010	193.04	229.81	8860.60	620.49
pressure-treated lumber	587	7.37	B.C.-TAICANG PORT–College	5120	1010	286.13	340.64	13,133.59	919.72
rock wool board	150	10.75	factory–college		7	0.28	0.33	12.77	0.89
Concrete, m ³		58.55	factory–college		16	20.00	23.81	918.06	64.29
Plasterboard, m ²	10	4.42	factory–college		26	0.43	0.51	19.53	1.37
cement mortar, kg)		10.08	factory–college		16	0.60	0.71	27.39	1.92
total								53,135.91	3721.00

Table 8 Energy consumption and CE of building materials during the construction stage

	Electricity consumption, kWh	Energy consumption, MJ	CE, kg
building area, m ²	195	195	195
unit, m ⁻²	8.4	107.2	9.0
total	1638	20,904	1755

Table 9 Energy consumption and CE during the building use stage

	Cooling and heating load, kWh/m ²	Energy consumption, MJ	CO ₂ , kg
life cycle total	137,328.75	494,383.50	146,941.76

Table 10 Energy consumption and CE during the building demolition stage

	Energy consumption, MJ	CO ₂ , kg
building area, m ²	195	195
unit, m ⁻²	1690.4	141.7
total	329,628	27,631.5

Table 11 CS capacity of building materials

Material	Quantity, t	CS, kg
dimensional lumber	16.93	31,062.88
OSB	4.97	9124.54
pressure-treated lumber	7.37 (lumber weight 6.64)	12,188.62
total	—	52,376.04

Table 12 Life cycle energy consumption and CE of timber structure building

Life cycle stage	Energy consumption, MJ	CE, kg
production	628,925.19	61,920.34
transportation	53,135.91	3721.00
construction	20,904.00	1755.00
use	494,383.50	146,941.76
demolition	329,628.00	27,631.50
CS	—	-52,376.04
total	1,526,976.59	189,593.57

Table 13 Energy consumption and CE of building materials during the production stage

Material	Quantity, m ³	Energy consumption		CE	
		Unit energy consumption, MJ/m ³	Energy consumption, MJ	Unit CO ₂ , kg/m ³	CE, kg
fired perforated brick (thousand block)	30.97	4061.56	125,766.33	418.00	12,943.37
EPS	53.51	1804.88	96,581.62	341.40	18,268.79
concrete	126.54	2841.10	359,519.58	342.86	20,074.45
cement mortar, kg	88,755.53	3.97	352,536.96	0.79	1237.83
steel bar, kg	16,841.92	33.91	571,042.14	2.21	37,186.96
total			1,505,446.62		89,711.40

According to formulas (5) and (6), energy consumption and CE of building materials during the transportation are shown in Table 7.

According to formulas (7) and (8), energy consumption and CE of building materials during the construction stage are shown in Table 8.

According to formulas (9) and (10), energy consumption and CE of building materials during building use stage are shown in Table 9.

According to formulas (11) and (12), energy consumption and CE during the building demolition stage are shown in Table 10.

According to formula (13), CS ability of building materials is shown in Table 11.

According to formulas (1) and (2), life cycle energy consumption and CE of timber structure building are shown in Table 12.

5.2.2 Brick-concrete structure: According to formulas (3) and (4), energy consumption and CE of building materials during the production stage are shown in Table 13.

According to formulas (5) and (6), the transportation stage is shown in Table 14.

The data of construction and demolition stages refer to the literature and use stage accords to the energy saving calculation. The data of the three stages are the same with a timber structure.

In consideration of the various processes of the whole life cycle of the building as formulas (1) and (2), the energy consumption and

Table 14 Energy consumption and CE of building materials during the transportation stage

Material	Quantity, t		Distance, km		Diesel consumption		Energy consumption, MJ	CE, kg
	Density, kg/m ³	Weight, t	Starting place–destination	Land transportation distance, km	Diesel oil weight, kg	Diesel oil volume, l		
fired perforated brick (thousand block)	1400	43.35	factory–college	10	1.60	1.91	73.62	5.16
EPS	20.00	1.07	factory–college	7	0.03	0.03	1.27	0.09
concrete, m ³		126.54	factory–college	16	43.23	51.46	1984.18	138.95
cement mortar, kg	2000	88.76	factory–college	16	5.25	6.26	241.17	16.89
steel bar, kg		16.84	factory–college	35	2.18	2.60	100.11	7.01
total							2400.36	168.09

Table 15 Life cycle energy consumption and CE of brick-concrete structure building

Life cycle stage	Energy consumption, MJ	CE, kg
production	1,505,446.62	89,711.40
transportation	2400.36	168.09
construction	20,904.00	1755.00
use	494,383.50	146,941.76
demolition	329,628.00	27,631.50
total	2,352,762.48	266,207.75

Table 16 Energy consumption and CE of foundation

Material	Structural part	Unit	Quantity	Total quantity	Energy consumption		CE	
					Unit EnC, MJ/m ³	EnC, MJ	Unit CE, kg/m ³	CE, kg
concrete	foundation wall	m ³	41.87	58.55	2856.78	167,264.70	343.96	20,138.74
	concrete slab		16.68					

Table 17 Energy consumption and CE of the F1 platform of timber structure and brick-concrete structure building

	Material	Structural part	Unit	Quantity	Quantity subtotal	Energy consumption			CE		
						Unit EnC, MJ/m³	EnC, MJ	EnC subtotal, MJ	Unit CE, kg/m³	CE, kg	CE subtotal, kg
timber structure	pressure-treated lumber	P.T joist	m³	3.86	7.88	4005.74	31,568.04	31,901.12	−548.31	−4321.05	−4397.10
		P.T decking	m³	4.02							
	dimensional lumber	stair stringer	m³	0.11	0.11	3086.98	333.09		−704.89	−76.06	
brick-concrete structure	concrete	ground	m³	15.88	15.88	2841.10	45,358.59	78,673.08	343.96	5461.19	12,101.01
	cement mortar	ground	kg	8381.60	8381.60	3.97	33,314.49		0.79	6639.82	

P.T, pressured-treated lumber.

carbon balance capacity statistics were carried out, as shown in Table 15.

5.3 Energy consumption and CE of building space

In this case, the same foundation design was adopted in the timber structure and brick-concrete structure. Energy consumption and CE of the foundation are shown in Table 16.

F1 platform of timber building is composed of pressure-treated and dimensional lumber, and brick-concrete structure floor is composed of concrete and cement mortar. Energy consumption and CE of F1 platform are shown in Table 17.

F1 room is composed of walls, floors, beams, columns etc. The materials of timber structure are dimensional lumber, rock wool board, OSB, and gypsum board. The materials of brick-concrete structure are concrete, fired perforated brick, cement mortar, EPS, and steel bar. Energy consumption and CE of F1 room of timber structure and brick-concrete structure building are shown in Table 18.

F2 platform of timber structure consists of bottom supporting columns, beams, floor slabs, and pressure-treated lumber platform;

the materials are pressure-treated lumber and dimensional lumber. F2 platform of the brick-concrete structure consists of columns, beams, and floors, the materials are concrete, cement mortar, and steel bar.

Energy consumption and CE of F2 platform of timber structure and brick-concrete structure building are shown in Table 19.

F2 room is composed of walls, roof, beam column etc. The materials of timber structure are dimensional lumber, rock wool board, OSB, and gypsum board. The materials of brick-concrete structure are concrete, fired perforated brick, cement mortar, EPS, and steel bar.

Energy consumption and CE of F2 room of timber structure and brick-concrete structure building are shown in Table 20.

6 Discussion

6.1 Life cycle comparison

As can be seen from Fig. 1, with the brick-concrete structure as the standard, the total energy consumption of timber structure in the total life cycle (10 years) of the case building is 65% of that of brick-concrete structure. The energy consumption of building

Table 18 Energy consumption and CE of F1 room of timber structure and brick-concrete structure building

	Material	structure part	Unit	Quantity	Total quantity	Energy consumption			CE		
						Unit EnC, MJ/m ³	EnC, MJ	EnC subtotal, MJ	Unit CE, kg/m ³	CE, kg	CE subtotal, kg
timber structure	dimensional lumber	exterior wall studs	m ³	7.24	20.00	3086.98	61,742.56	62,138.09	-704.89	-14,098.37	-11,193.74
		exterior lintels	m ³	0.92							
		interior wall studs	m ³	0.73							
		interior lintels	m ³	0.02							
		floor-slab built up beams	m ³	2.95							
		floor-slab joist	m ³	8.14							
	rock wool board	exterior wall insulation	m ³	2.69	4.91	3516.37	17,265.65		325.98	1600.59	
		interior wall insulation	m ³	0.40							
		floor-slab insulation	m ³	1.82							
	OSB	exterior wall OSB	m ³	2.30	4.95	7137.19	35,308.58		-416.27	-2059.32	
		OSB sub floor	m ³	2.64							
	gypsum board	regular gypsum board for exterior wall	m ²	162.20	558.38	48.05	26,829.51		6.02	3363.36	
		regular gypsum board for interior wall	m ²	43.62							
		regular gypsum board	m ²	352.56							
brick-concrete structure	concrete (m ³)	column	m ³	4.56	31.40	2856.78	89,702.41	534,177.01	343.96	10,800.21	60,448.83
		beam		14.24							
		floor-slab		12.60							
	fired perforated brick (thousand block)	exterior wall	thousand	14.72	20.74	4063.29	84,258.27		418.10	8669.91	
		interior wall	block	6.02							
	cement mortar	floor	kg	5304.60	40,177.62	3.97	159,694.67		0.79	31,828.32	
		interior wall		21,286.40							
		exterior wall		12,573.02							
		column		1013.60							
	rock wool board (m ³)	wall	m ³	15.72	22.15	1804.93	39,985.44		341.41	7563.40	
		floor		0.89							
		plane roof		5.54							
	steel bar	column	kg	718.61	4733.91	33.91	160,536.21		2.21	1587.00	
		beam		1065.72							
		floor-slab		2949.58							

materials used in timber structure in the production stage is 42% of the brick-concrete structure. It follows that the timber structure is an energy-saving building.

With the brick-concrete structure as the standard, the total CE of timber structure during the life cycle of the case building was 70% of that of brick-concrete structure. The CE of building materials used in timber building in the production stage was 66% of that in brick-concrete structure (Fig. 2). It can be seen that the timber structure is a low-carbon building.

In the transportation stage of building materials, the energy consumption and CE of timber structure were 22.14 times than that of brick-concrete structure. The reason was that the building timbers were transported from British Columbia, Canada, which was a long journey. If the timbers grown domestically could be used, the energy saving and low carbon emission performance of timber structures would be better. Owing to the lack of field measurement data during construction and demolition, the literature statistics data was used. It was the precondition for

Table 19 Energy consumption and CE of F2 platform of timber structure and brick-concrete structure building

	Material	Structure part	Unit	Quantity	Total quantity	Energy consumption			CE		
						Unit EnC, MJ/m ³	EnC, MJ	EnC subtotal, MJ	Unit CE, kg/m ³	CE, kg	CE subtotal, kg
timber structure	pressure-treated lumber	P.T decking	m ³	4.23	4.23	4005.74	16,944.28	29,301.95	-548.31	-2319.34	-5141.11
		dimensional lumber	m ³	0.65	4.00	3086.98	12,357.67		-704.89	-2821.77	
		floor-slab joist		1.98							
		built up post		1.37							
brick-concrete structure	concrete	column	m ³	1.52	17.83	2856.78	50,949.78	172,790.25	343.96	6134.38	19,647.28
		beam	m ³	4.75							
		floor-slab	m ³	3.21							
		ground of decking	m ³	8.35							
	cement mortar	decking	kg	9445.60	10,459.20	3.97	41,572.36		0.79	8285.68	
		column	kg	1013.60							
	steel bar	column	kg	359.31	2366.96	33.91	80,268.11		2.21	5227.23	
		beam	kg	532.86							
		floor-slab	kg	1474.79							

comparing the timber structure and brick-concrete structure to make the heating and cooling load of the both same in the building use stage, so as to obtain the energy saving methods. CS of building materials is a characteristic performance of timber, which can store carbon in itself; therefore, timber structures can reduce carbon emission in building life cycle.

6.2 Comparison of building spaces

Taking brick-concrete structure as the benchmark, the energy consumption and CE of each building space of timber structure is compared with the brick-concrete structure to obtain the relative proportion of timber structure.

In the comparison of energy consumption in the whole life cycle of a building, the lowest proportion of timber structure is 42% in the production stage of building materials. In comparison with brick-concrete buildings, except for the same foundation, the energy consumption of spaces of timber structures accounts for <42%. The energy consumption of timber structure on the platforms of the F1 and F2 was relatively higher, which was 41 and 17% of that of brick-concrete structure, respectively. The energy consumption of timber structure in the rooms of the F1 and F2 was relatively lower, which was 12% of that of brick-concrete structure, respectively (Fig. 3). This result was mainly because the pressure-treated timber must be laid on the structural components of the outdoor platform of the timber structure, and the unit area of pressure-treated timber was high in energy consumption; therefore, from the perspective of energy consumption, the platform area should be controlled in the design of timber building.

In the comparison of CE in the whole life cycle of a building, the lowest proportion of timber structure is 66% in the production stage of building materials. In the comparison of CE in various spaces of the building, except that the foundation is the same with brick-concrete structure, the CS capacity of a timber structure in all other spaces is greater than CE capacity, far superior to the CE capacity of the whole building materials in production stage (Fig. 4). The reason is that the foundation of timber structure building is not made of timber and the area is too large, which increases the overall CE of the building. Therefore, timber structure buildings have advantages in CE reduction and are environment-friendly buildings.

In order to further study the design of timber structure buildings, energy consumption per unit area and CS capacity of timber structure buildings were calculated and compared according to different building spaces. The energy consumption per unit area (EnC/m²) of the first floor is 1.08 times that of the second floor, and the energy consumption per unit area of the first floor is 0.59

times that of the second floor. CS per unit area (CS/m²) of the platform on the first floor is 0.85 times that of the platform on the F2, and CS per unit area of the room on the F1 is 0.95 times that of the platform on the F2 (Fig. 5).

From the perspective of architectural design, the calculation results can be extended to buildings of general significance, i.e. the 'hypothesis' part divides the building into the ground floor platform, the floor platform, the typical floor room, and the top floor room.

For the design of the building outdoor platform, from the perspective of energy consumption, the floor platform is more energy-saving than the ground floor platform. In terms of CS capacity, the floor platform has a stronger CS capacity than the bottom platform. Therefore, in the design of timber structure building platform, the area of the ground floor platform can be reduced as far as possible, and the floor platform can be set appropriately.

For the design of the building interior room, from the perspective of energy consumption, the typical floor room is more energy-saving than the top floor room. In terms of CS capacity, the CS capacity of the typical floor room is stronger than that of the top floor room. Therefore, if the energy saving and emission reduction rate is considered from the unit area, the increase of floor numbers is a favourable measure in the design of timber structure building rooms.

7 Conclusion

In this study, the comparative study of timber structure building is carried out with brick-concrete structure building. From the whole life cycle evaluation, the energy consumption of timber structure is 65% of that of brick-concrete structure, and the CE of the timber structure is 70% of that of brick-concrete structure. Therefore, the timber structure is energy saving and low carbon emission building. The timber structure is more advantageous in the production stage of building materials but is inferior in the transportation stage. If the timber grown domestically can be used, energy saving and environmental protection performance of the timber structure buildings will be better.

This study also divides the building into five architectural spaces. Through the comparison between the timber structure and the brick-concrete structure, as well as the comparison between the different spaces of the timber structure, the suggestions of architectural design are proposed. In the comparison between the building platform and the room, the energy consumption of the building platform is relatively high, especially the ground floor platform. Therefore, when designing the timber structure building,

Table 20 Energy consumption and CE of F2 room of timber structure and brick-concrete structure building

	Material	Structure part	Unit	Quantity	Total quantity	Energy consumption			CE		
						Unit EnC, MJ/m ³	EnC, MJ	EnC subtotal, MJ	Unit CE, kg/m ³	CE, kg	CE subtotal, kg
timber structure	dimensional lumber	exterior wall studs	m ³	3.21	8.43	3086.98	26,028.35	52,953.66	-704.89	-5943.35	-5881.89
		exterior lintels	m ³	0.37							
		interior wall studs	m ³	0.45							
		interior lintels	m ³	0.02							
		roof built up beam	m ³	0.46							
		roof truss	m ³	3.06							
		roof joist	m ³	0.10							
		studs for dormer	m ³	0.77							
	rock wool board	exterior wall insulation	m ³	1.08	2.25	3516.37	7923.53		325.98	734.54	
		interior wall insulation	m ³	0.33							
		roof insulation	m ³	0.85							
	OSB	exterior wall OSB	m ³	0.93	2.66	7137.19	19,001.78		-416.27	-1108.25	
		OSB for dormer	m ³	0.05							
		roof OSB	m ³	1.69							
	gypsum board (m ²)	regular	m ²	55.09	72.24	48.05	3471.29		6.02	435.16	
		gypsum board for exterior wall									
		regular	m ²	17.16							
brick-concrete structure	concrete	column	m ³	1.83168	26.59	2856.78	75,962.86	440,718.39	343.96	9145.96	57,685.67
		beam	m ³	6.85							
		roof	m ³	14.00							
		overhanging eave	m ³	3.91							
	fired perforated brick (thousand block)	exterior wall	thousand block	8.52	10.23	4063.29	41,561.56		418.10	4276.55	
		interior wall	thousand block	1.71							
	cement mortar, kg	floor	kg	2372.00	30,365.20	3.97	120,693.08		0.79	24,055.01	
		pitched roof	kg	9657.60							
		interior wall	kg	10,480.80							
		exterior wall	kg	7366.40							
		column	kg	488.40							
	rock wool board	wall	m ³	9.21	31.36	1804.93	56,605.38		341.41	10,707.13	
		pitched roof	m ³	22.15							
	steel bar, kg	column	kg	319.28	4302.19	33.91	145,895.51		2.21	9501.02	
		beam	kg	752.88							
		floor-slab	kg	3230.03							

the platform area should be appropriately reduced, especially the area of the ground floor platform. In the comparison of energy consumption and CE of rooms in timber structure buildings, the performance of energy saving and emission reduction per unit area of rooms on the typical floor is better, while that on the top floor is worse. Therefore, when designing the interior room of timber structure building, the number of floors can be appropriately increased.

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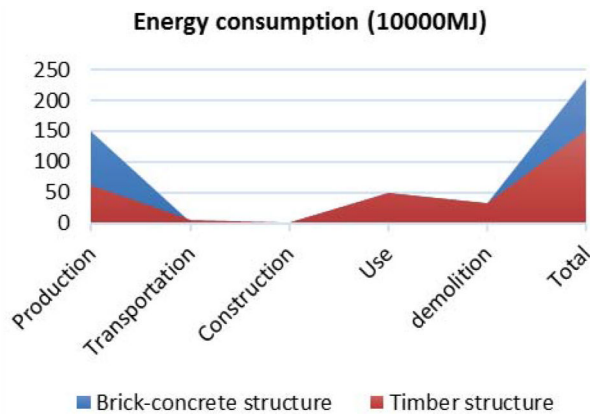


Fig. 1 Life cycle comparison of energy consumption

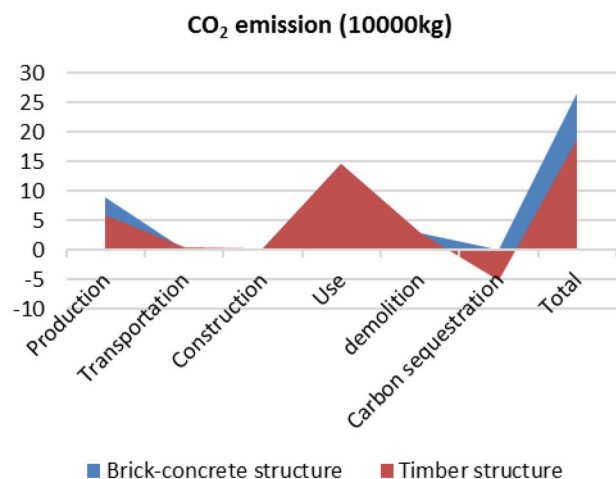


Fig. 2 Life cycle comparison of CE

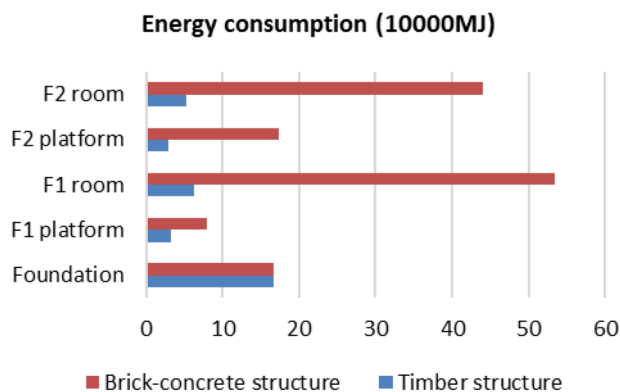


Fig. 3 Comparison of energy consumption of building spaces

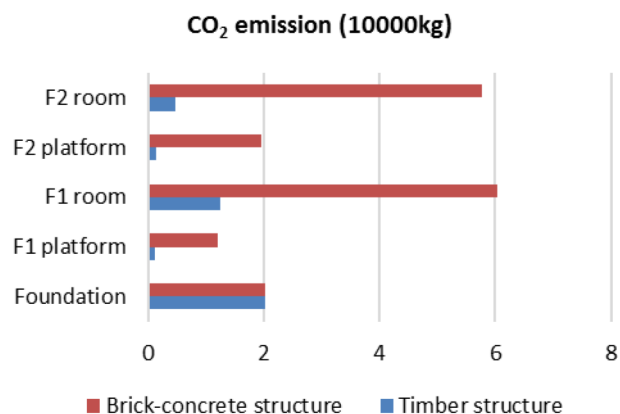


Fig. 4 Comparison of CE of building parts

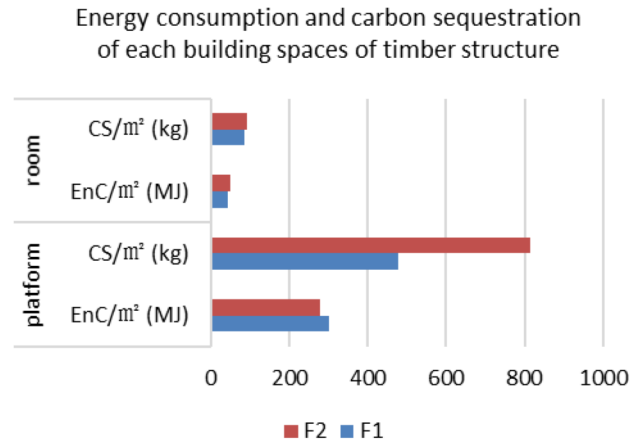


Fig. 5 Energy consumption and CS of each building spaces of the timber structure

9 References

- [1] Tonooka, Y., Takaguchi, H., Yasui, K., *et al.*: 'Life cycle assessment of a domestic natural materials wood house', *Energy Proc.*, 2014, **61**, pp. 1634–1637
- [2] Sathre, R., González-García, S.: 'Life cycle assessment (LCA) of wood-based building materials', in Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J. (Eds): 'Eco-efficient construction and building materials' (Woodhead Publishing Press, Sawston, 2014, 1st edn.), pp. 311–337, ISBN: 9780857097675
- [3] Liping, H., Yu, C.: 'Building with wood: the analysis of integrated environmental footprint on timber building', *Huazhong Archit.*, 2012, (2), pp. 175–177
- [4] Moncaster, A.M., Pomponi, F., Symons, K.E., *et al.*: 'Why method matters: temporal, spatial and physical variations in LCA and their impact on choice of structural system', *Energy Build.*, 2018, **173**, (8), pp. 389–398
- [5] Guardigli, L.: 'Comparing the environmental impact of reinforced concrete and wooden structures', in Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J. (Eds): 'Eco-efficient construction and building materials' (Woodhead Publishing Press, Sawston, 2014, 1st edn.), pp. 407–433, ISBN: 9780857097675
- [6] Pajchrowski, G., Noskowiak, A., Lewandowska, A., *et al.*: 'Wood as a building material in the light of environmental assessment of full life cycle of four buildings', *Constr. Build. Mater.*, 2014, **52**, (2), pp. 428–436
- [7] Thomas, D., Ding, G.: 'Comparing the performance of brick and timber in residential buildings—the case of Australia', *Energy Build.*, 2018, **159**, (15), pp. 136–147
- [8] Li, J., Rismanchi, B., Ngo, T.: 'Feasibility study to estimate the environmental benefits of utilising timber to construct high-rise buildings in Australia', *Build. Environ.*, 2019, **147**, pp. 108–120
- [9] Babaizadeh, H., Haghighi, N., Asadi, S., *et al.*: 'Life cycle assessment of exterior window shadings in residential buildings in different climate zones', *Build. Environ.*, 2015, **90**, (8), pp. 168–177
- [10] Chiniforush, A.A., Akbarnezhad, A., Valipour, H., *et al.*: 'Energy implications of using steel-timber composite (STC) elements in buildings', *Energy Build.*, 2018, **176**, pp. 203–215
- [11] William, W., Rupert, W., Deilia, G.: 'The capacity of shear-walls made with Caribbean timber species', *West Indian J. Eng.*, 2014, **37**, (1), pp. 4–9
- [12] Philipp, D., Stefa, W.: 'Structural failure in large-span timber structures: a comprehensive analysis of 230 cases', *Struct. Safety*, 2018, **71**, pp. 41–46
- [13] Philipp, D., Thomas, T.: 'Assessing the integrity of glued-laminated timber elements', *Constr. Build. Mater.*, 2015, **101**, pp. 1259–1270
- [14] Nabaei, S.S., Yves, W.: 'Geometrical description and structural analysis of a modular timber structure', *Int. J. Space Struct.*, 2011, **26**, (4), pp. 321–330
- [15] Sandhaas, C., Schädle, P., Ario, C.: 'Innovative timber building systems: comparative testing and modelling of earthquake behaviour', *Bull. Earthquake Eng.*, 2018, **16**, (5), pp. 1961–1985
- [16] Wuchuan, P., Changcheng, L., Hang, Z., *et al.*: 'Seismic control design for slip hysteretic timber structures based on tuning the equivalent stiffness', *Eng. Struct.*, 2016, **128**, pp. 199–214
- [17] Balasbaneh, A.T., Marsono, A.K.B.: 'Strategies for reducing greenhouse gas emissions from residential sector by proposing new building structures in hot and humid climatic conditions', *Build. Environ.*, 2017, **124**, pp. 357–368
- [18] Boštjan, B., Miroslav, P., Andrej, Š., *et al.*: 'Experimental investigations of timber-glass composite wall panels', *Constr. Build. Mater.*, 2014, **66**, pp. 235–246
- [19] Havel, G.: 'Cross-laminated timber structures', *Fire Eng.*, 2016, **159**, (1), pp. 48–53
- [20] Fontana, M., Frangi, A.: 'Fire safety of multistorey timber buildings', *Struct. Build.*, 2010, **163**, (4), pp. 213–226
- [21] Dårmon, R., Suci, M.: 'Smoke ventilation strategy for a timber structure building', *Procedia Manuf.*, 2018, **22**, pp. 249–255
- [22] Mississauga, O.: 'Churchill meadows community centre', *Can. Architect*, 2017, **62**, (12), pp. 44–45
- [23] Reid Robert, L.: 'Norwegian team designs world's tallest timber building', *Civil Eng.*, 2010, **80**, (8), pp. 26–28
- [24] James, D.: 'Timber building proves best solution for layer expansion and environment', *Poultry World*, 2011, **165**, (2), pp. 32–32

- [25] Hynek, L., Iveta, S.: 'Dynamic thermal performance of building structures in experimental lightweight timber-frame passive house'. Proc. Int. Multidisciplinary Scientific GeoConf. SGEM. 2013, Albena, Bulgaria, June 2013, pp. 403–410
- [26] Kalamees, T., Alev, Ü., Pärnalaas, M.: 'Air leakage levels in timber frame building envelope joints', *Build. Environ.*, 2017, **116**, pp. 121–129
- [27] Department of Energy Statistics, National Bureau of Statistics, People's Republic of China: '*China energy statistical yearbook 2016*' (China Statistics Press, Beijing, 2016)
- [28] Eggleston, H.S., Buendia, L., Miwa, K., *et al.* (Eds.): '*2006 IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme*' (IGES, Japan, 2006)
- [29] Wang, C., Ding, G.H.: 'Preliminary study on life cycle assessment of concrete containing fly ash', *Ind. Safety Dust Control*, 2007, **33**, (1), pp. 39–42
- [30] Liu, S.N.: 'Study on the environmental impact assessment and improvement of cement & concrete system', PhD thesis, Wuhan University of Technology, 2002
- [31] Su, X., Zhang, X., Sun, Y.Q.: 'Detailed life cycle inventory analysis of building components in steel-construction residential buildings', *J. Tongji Univ., Nat. Sci.*, 2011, **39**, (12), pp. 1784–1788
- [32] JCT 523–2010.: 'Norm of energy consumption per unit quantity for gypsum plasterboard', 2010
- [33] GB175–2007.: 'Common portland cement', 2007
- [34] Ling, W.: 'Study on external wall structure of rural houses in severe cold region based on life cycle ecological footprint theory', PhD thesis, Harbin Institute of Technology, 2012
- [35] Yang, Q.M.: 'Quantificational life cycle assessment of environmental impact of construction productions', PhD thesis, Tianjin University, 2009
- [36] GB/T2589–2008.: 'General principles for calculation of total production energy consumption', 2008
- [37] Yan, Y.: 'Research of energy consumption and CO₂ emission of buildings in zhejiang province based on life cycle assessment', MD thesis, Zhejiang University, 2011
- [38] DB331038–2007.: 'Zhejiang design standard for energy efficiency of public buildings', 2007
- [39] Wang, S.Q., Wang, W., Zhang, X.: 'Calculation and analysis on energy consumption of residential buildings in severe cold region based on life cycle theory', *Build. Sci.*, 2008, **24**, (4), pp. 58–61
- [40] Lamtom, S.H., Savidge, R.A.: 'A reassessment of carbon content in wood: variation within and between 41 North American species', *Biomass Bioenergy*, 2003, **25**, (4), pp. 381–388
- [41] GB50006–2003.: 'Code for design of timber structures', 2003