Engineered Science
DOI: https://dx.doi.org/10.30919/es8d845

Evaluation and Analysis of the Architectural Environment of Traditional Folk Houses in Tibetan Plateau, China

Luxi Lu,[1,2] Tianke Zhang,[3] Xiaoliang Wang,[1,4] Yu Han,[1,4] Deepak Sridhar,[5] Handong Li,[6] Ben Bin Xu,[7] Kuzin Victor Fedorovich[8] and Xianmin Mai[1,*]

Abstract

The climate adaptation strategies employed by traditional folk houses provide a theoretical basis and experience for the development of sustainable architecture. This study aimed to perform a quantitative analysis of the traditional Muya folk houses in the Tibetan plateau, China. To understand the indoor building environment characteristics, variation rules, and residents' thermal comfort in winter, a field investigation of traditional Muya folk houses was conducted, and its building environment was evaluated by measuring indoor and outdoor environmental parameters. To evaluate the building performance and environmental level for the whole year, this study also used software such as Ecotect, Grasshopper, Phoenics, and TRNSYS to conduct numerical simulations on the model of the Muya folk house. The results show that the Muya folk houses adapt to the local environment well, and the overall energy consumption of the traditional Muya folk houses was lower than that of the modern construction techniques and materials. The research results provide theoretical support for the design of vernacular architecture and new rural houses on the Tibetan plateau.

Keywords: Tibetan plateau; Muya folk house; Indoor environment; Sustainable architecture.
Received: 03 January 2023; Revised: 12 March 2023; Accepted: 19 March 2023.
Article type: Research article.

1. Introduction

Energy consumption has been rising globally,[1] a large part of which is related to the construction field.[2] Extensive studies have confirmed that the energy consumption of building materials and buildings in the production and construction process accounts for a large proportion of global energy consumption. At the same time, greenhouse gas emsissions are also extremely high.[3] To alleviate problems such as energy consumption, environmental pollution, and climate warming caused by excessive greenhouse gas emissions, scholars have tried to use renewable and sustainable energy in buildings. Passive solar building design plays an important role in lowering costs and reducing energy consumption without affecting modern living standards.[4].

Traditional folk houses are distributed around the world and exhibit local architectural characteristics. They represent a building type based on the needs of residents, using traditional and local materials and construction methods. Traditional folk houses fully exploit local building materials and climate conditions, with good indoor thermal stability, warmth in winter and coolness in summer, and low energy consumption being typical climate-adaptive building characteristics.[5] In some areas, this low-energy passive building design strategy has always been an indispensable part of local buildings. Passive buildings save energy and achieve sustainable development.[6,7] However, with urbanization and the rapid development of construction technology, the natural adjustment of traditional residential buildings and the construction wisdom contained in them, such as climate adaptation technology, have been gradually ignored.[8] At the same time, the energy cost per unit area of rural housing in

[1] *School of Architecture, Southwest Minzu University, Chengdu, 610041, Sichuan, China.*
[2] *School of Architecture and Urban Planning, Shenzhen University, 518060, Shenzhen, Guangdong, China.*
[3] *Administrative Committee of Eastern New District of Baise, Baise, 533000, Guangxi, China.*
[4] *China-Portugal Joint Laboratory of Cultural Heritage Conservation Science supported by the Belt and Road Initiative, Southwest Minzu University, Chengdu, 610041, Sichuan, China.*
[5] *Zentek Ltd. 24 Corporate Crt, Guelph, Ontario, N1G 5G5, Canada.*

China has gradually increased by 3.4 times in past decades.[9] In October 2021, the Communist Party of China (CPC) Central Committee issued the Opinions of the CPC Central Committee and the State Council on Fully, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon emissions peak and Carbon Neutrality, calling for the need to vigorously develop energy-saving and low-carbon buildings and accelerate the large-scale development of ultra-low energy consumption, near-zero energy consumption, and low-carbon buildings. The aim of the opinions was to comprehensively promote green low-carbon building materials, promote the recycling of building materials, and develop green rural residential housing.[10]

Environmental adaptation methods are important for sustainable architectural design. Firstly, architectural design should adapt to the climate and culture. The ecological wisdom and passive design concepts used in traditional local buildings need to be inherited and applied to modern buildings. Secondly, how to carry out low-carbon and energy-saving architectural design is closely related to thermal adaptation. To save energy used for heating and cooling, we can extend the free operation mode (neither heating nor cooling).[11]

Therefore, from the perspective of sustainable development, energy conservation, and environmental protection, reducing building energy consumption is of great significance to achieving the goal of carbon emissions peak and carbon neutrality. Protecting traditional folk houses as well as learning and inheriting the green ecological wisdom and climate adaptation technology contained in traditional folk houses are effective ways to realize building energy conservation and carry forward traditional architectural culture.

To explore the green ecological wisdom and climate adaptation strategies contained in traditional folk houses, many researchers have focused on performing thermal environment monitoring and numerical simulation.[12-21] At the same time, scholars have summarized the thermal comfort zone and thermal neutral temperature of different countries and regions through research on thermal performance simulation and building design technology. Their aim has been to reduce building energy consumption and put forward a local adaptive coefficient.[22–26] and put forward appropriate building technology and optimization suggestions.[27,28]

As a typical representative of the dwellings in the Tibetan Plateau, Muya folk houses have unique cultural and architectural features. They are mainly distributed at the southeastern margin of the Tibetan Plateau, with an altitude of 1900–4000 m (averaged at 3100 m) and an average annual temperature of 7.29°C. Solar radiation is strong throughout the year with an intensity of ~6650 MJ/m^2 and the annual average sunshine duration is about 2600 hours. Under such unique geographical and climatic conditions, Muya folk houses reflect thousands of years of construction skills. As passive buildings, these houses do not use mechanical heating or refrigeration. However, until now, the research on Tibetan folk houses has mainly focused on culture and structure, and the research and actual measurement related to the thermal environment of Tibetan folk houses have been mostly carried out in the Tibet Autonomous Region, Gannan region, and Jiarong Tibetan region.[29–35] Research on Muya folk houses has been relatively scarce, and most of the existing research has focused on the cultural color, architectural space, and architectural characteristics of villages.[36-40] There has been a lack of systematic research on the quantitative evaluation of the local residential building environment and its ecological wisdom.

To better understand the building performance and ecological adaptability of Muya folk houses, which has inconvenient transportation, energy shortages, and unique geographical and climatic conditions, how the local wood and stone building technology can adapt to the local environmental conditions should be analyzed. In this study, four typical self-built Muya folk houses were selected as the research objects. The building environment of Muya folk houses was evaluated by measuring the environmental parameters that characterize the building environment. At the same time, simulation software such as Ecotect, Grasshopper, Phoenics, and TRNSYS was used to evaluate the annual energy consumption and ventilation of Muya folk houses. In addition, considering the utilization of sustainable building technology, we also propose the idea of using local traditional green building technology as a plan to improve the building environment of folk houses. The results of this study are conducive to a better understanding of the ecological adaptability of such buildings in high-altitude areas and can provide effective suggestions for the energy-saving design of new residential buildings.

2. Materials and methods

[6] *Mechanical and Construction Engineering, Northumbria University, Newcastle Upon Tyne, NE1 8ST, UK.*
[7] *Mechanical and Construction Engineering, Faculty of Engineering and Environment, Northumbria University, Newcastle Upon Tyne, NE1 8ST, UK.*
[8] *Section of Geology, Mining, and Processing of Minerals, Russian Academy of Engineering, Moscow 125009, Russia.*
**Email:* maixianmin@foxmail.com (X. Mai)

2.1 Overview of Muya folk houses

Muya folk houses have a history of one thousand years, and they are generally three-story buildings. To adapt to the cold climate in winter and maintain strong defense and load-bearing properties, Muya folk houses often use relatively thick external walls, usually about 600–1200 mm. The layout of the houses is relatively simple. Most of the house plans are rectangular (Fig. 1(a)) and L-shaped (Fig. 1(b)). The "L" shape is more common, and the rectangular layout is mostly used for some old folk houses with narrow land. The beam and column systems of Muya folk houses are evenly and symmetrically arranged. The overall elevation is trapezoidal in width from bottom to top. In the functional layout, there are permanent livestock pens and storage rooms on the ground floor of the building, which are generally not used for daily living. The second floor has a permanent reception room, bedroom, and kitchen, and the third floor has a scripture hall. In the "L" shaped plane layout, the scripture hall is often set on one side of the "L"-shaped plane, which separates the scripture hall and the living space from each other and takes into account the unique position of the scripture hall.

The building materials of Muya folk houses are mainly stone and wood, with mud and grass as auxiliary materials. One of the typical characteristics is the use of different filling materials. Muya folk houses usually contain mud and lonicera rupicola above the floor and roof slabs (Fig. 2). This strategy not only reduces energy consumption and costs but also affords a good thermal insulation effect and improves the indoor thermal environment.

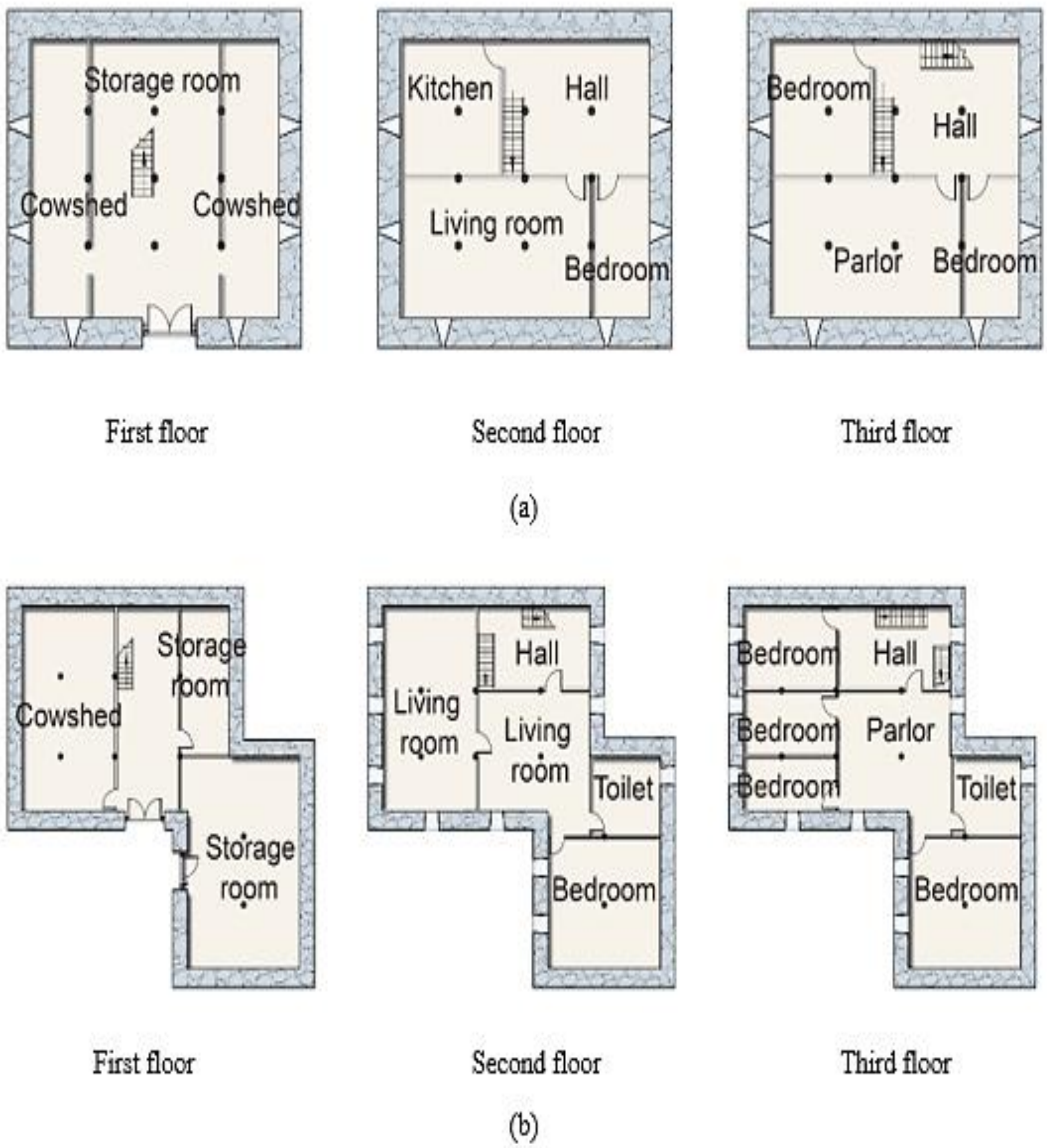
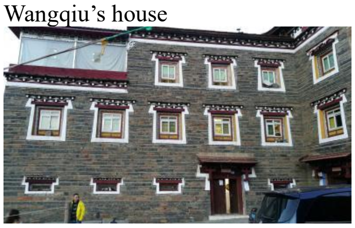


Fig. 1 Schematic diagram of layouts: (a) rectangular plane; (b)"L"-shaped plane layout.

Table 1. Overview of measurement objects.

Folk house name	Floor area (m^2)	Floor space (m^2)	Number of floors	Orientation	Year of construction
 Luozhu's old house	520	143	4F	Southeast	800 AD
 Niumai's old house	842	224	4F	Southeast	1200 AD
 Wangqiu's house	777	284	3F	Southeast	1992
 Niumai's new house	661	231	3F	Southeast	2010

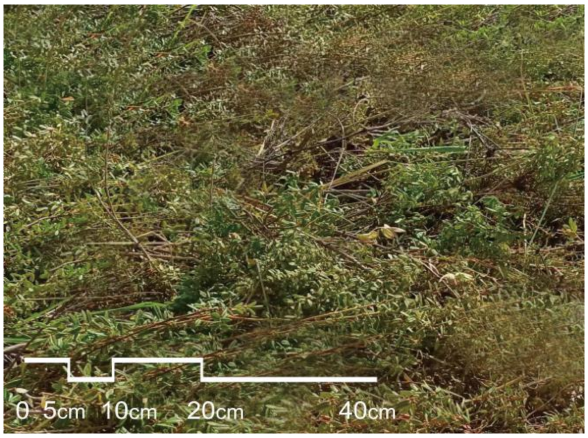


Fig. 2 Characteristic filling materials of Muya folk house, Lonicera Rupicola.

2.2 Building environment measurement

2.2.1 Measurement object

In this study, four typical Muya folk houses were selected for testing, two of which have a history of more than 800–1200 years and represent the old Muya folk houses. The other two residential buildings, built in the past 30 years, are representative of the newly built Muya folk houses. The corresponding profiles and parameters of the research objects are shown in Table 1.

2.2.2 Measuring materials and methods

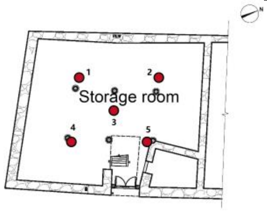
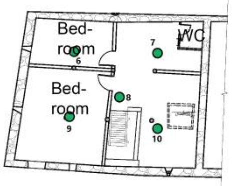
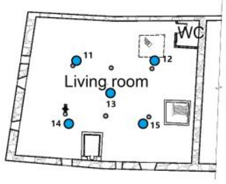
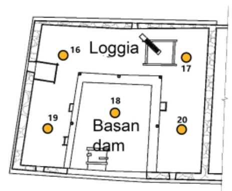
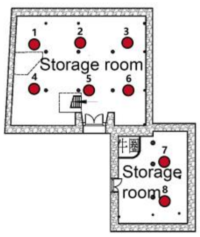
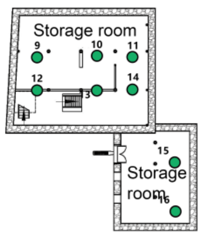
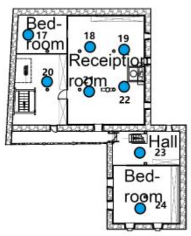
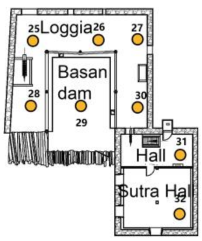
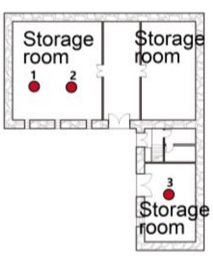
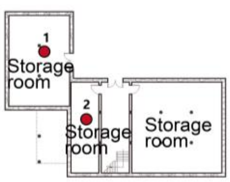
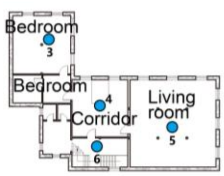
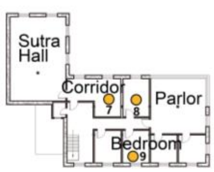
In this study, field surveys of indoor environmental quality in winter and summer were conducted on the measuring objects in January and July 2021, respectively. The objective measurement aimed to quantitatively evaluate and analyze the environmental conditions of the measured object. The measurement parameters include the indoor and outdoor air temperature, and relative humidity, which were acquired by a self-recording instrument.

To measure the environmental indexes of different rooms, in the new folk houses, the actual measurement of the new house was conducted for different functional rooms such as the bedroom, living room, and kitchen. The measuring points are shown in Table 2. As the partition walls of the old houses have been partially demolished, the measurement of the old residential buildings in this study was carried out through the uniform distribution of points. During the field measurement, multiple measuring points were set on each floor to improve the accuracy of the measurement. When setting the measuring points, we first used the mutually perpendicular auxiliary lines to divide the plan equally and marked the staggered points with the numbers 1, 2, and 3... N. During the test, we took the position 1.1m high in the vertical floor direction above each measuring point for measurement. This height represents the forehead height under the average sitting posture of Chinese residents,[41] and the measuring points on each floor correspond to each other.

2.3 Building performance simulation

The building performance simulation used computer mathematical models created based on basic physical principles and reasonable engineering practices to replicate various aspects of building performance.[42] In addition to the field measurement of the four research objects, we used the method of building performance simulation to simulate the thermal, and wind environment to supplement the field measurement and enrich the research content. At the same time, the building performance simulation complied with relevant standards such as the Standard for Green Performance Calculation of Civil Buildings (JGJ / T 449) and the previous studies of other scholars.[43,44]

Table 2. Distribution of measuring points.

Location of measuring points	1F	2F	3F	4F
Luozhu's old house				
Niumai's old house				
Wangqiu's house				
Niumai's new house				

2.3.1 Parameter setting

(1) Environmental conditions

To simulate the thermal environment of residential buildings, it is necessary to use climatic parameters such as the outdoor temperature and humidity of the local area. In this study, the meteorological data detected by meteorological stations in China and meteorological parameters in the meteorological parameter standard for building energy conservation were used for setting the outdoor parameters.[45]

(2) Enclosure parameters

After the model had been established, the structural parameters of exterior walls, interior walls, roofs, floors, windows, and other enclosure structures were set in the software. We set them according to the structural levels of each enclosure structure in the simulation object. Among them, the structural practices of the two old houses and the two new houses were different. The structural practices of the new and old houses were compared as follows (Fig. 3). Table 3 shows the structural levels and corresponding thermal parameters of the enclosure structure.

(3) Indoor parameter setting

In addition to setting the parameters of the environment and the enclosure structure, we also set the indoor environment according to the actual situation. In fact, each house above corresponds to a family, and each family has five permanent members. Based on the local daily life and sleep habits, the residents have the largest number of people at 8:00–9:30 in the morning, 12:00–13:30 in the afternoon, and 18:00–19:30 in the evening, and the minimum number of people at other times was 0. For each person with mild activity, the heat release was set to 75 W, and the lights were turned on during 7:00–8:00 in the morning and during 18:00–23:00 in the evening. In addition, the working time and power of other equipment were subject to the actual situation. At the same time, the following assumptions were also made during parameter setting:

a. The density, specific heat capacity, and heat transfer

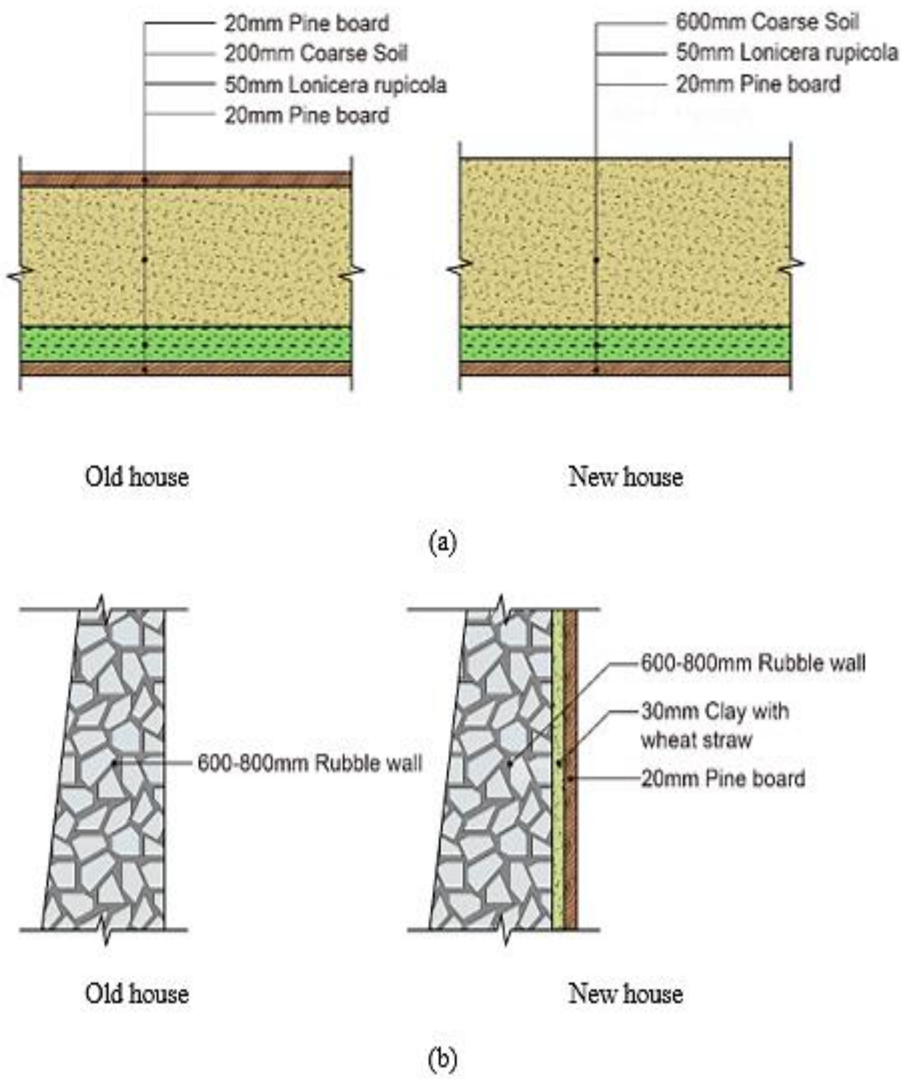


Fig. 3 Comparison of construction practices between old and new Muya folk houses: (a) Roofs; (b) Walls.

Table 3. Structural levels and parameters of enclosure structure.

Room name	Construction	The thickness of structural layer (mm)	Material (Inside-Out/Bottom-Up)	Dry density ρ_0 (kg/m³)	Thermal conductivity λ[W/ (m·K)]	Specific heat capacity C[kJ (kg·K)]
Storage room	Exterior wall	800	Stone Wall	2800	3.49	0.92
	Floor	1000	Compaction of clay	2000	1.16	1.01
		20	Pine board	500	0.14	2.51
		60	Lonicera rupicola	216	0.041	2.01
	Floor slab	30	Dirt	1800	0.93	1.01
		20	Pine board	500	0.14	2.51
Bedroom	Exterior wall	800	Stone Wall	2800	3.49	0.92
		20	Pine board	500	0.14	2.51
		20	Pine board	500	0.14	2.51
		60	Lonicera rupicola	216	0.041	2.01
	Floor slab	30	Dirt	1200	0.47	1.01
		20	Pine board	500	0.14	2.51
	Interior wall	20	Pine board	500	0.14	2.51
Bathroom	Exterior wall	800	Stone Wall	2800	3.49	0.92
		20	Pine board	500	0.14	2.51
	Floor slab	60	Dirt	1800	0.93	1.01
		20	Pine board	500	0.14	2.51
	Interior wall	370	Brick wall	1900	1.10	1.05
		20	Pine board	500	0.14	2.51
Living room	Exterior wall	800	Stone Wall	2800	3.49	0.92
		20	Pine board	500	0.14	2.51
		20	Pine board	500	0.14	2.51
		60	Lonicera rupicola	216	0.041	2.01
	Floor slab	30	Dirt	1200	0.47	0.93
		20	Pine board	500	0.14	2.51
	Interior wall	20	Pine board	500	0.14	2.51
Parlor	Exterior wall	800	Stone Wall	2800	3.49	0.92
		20	Pine board	500	0.14	2.51
		20	Pine board	500	0.14	2.51
		60	Lonicera rupicola	100	0.047	2.01
	Floor slab	30	Dirt	1200	0.47	0.93
		20	Pine board	500	0.14	2.51
	Interior wall	370	Brick wall	1900	1.10	1.05
		20	Pine board	500	0.14	2.51
		20	Pine board	500	0.14	2.51
	The roof	60	Lonicera rupicola	100	0.041	2.01
		600	Dirt	7850	58.2	0.48

coefficient of the enclosure were regarded as constants.
b. Walls, window glass, and floors were considered uniform and isotropic.
c. The temperature of the vertical enclosure structure was considered uniform along the vertical direction.
d. The influence of the thermal bridge of the model was ignored in the simulation.

2.3.2 Thermal environment simulation

Over the past 60 years, researchers have developed various energy simulation models, such as mono-zone models, multi-room models, zonal models, computational fluid dynamics (CFD) models, and multi-zone models to reduce the building energy consumption through a whole-building simulation program. Energy simulation software, such as EnergyPlus, Espr, and Transient System Simulation Tool (TRNSYS), are powerful tools that can be used to predict the energy performances of buildings (e.g., heating, cooling, and artificial lighting).[46] TRNSYS is an open-source, menu-driven simulation program developed by the University of

Wisconsin–Madison, which includes an extensive material library compared to other similar building simulation tools.[47] The extensive material library and detailed scheduling capabilities of TRNSYS make it possible to model new and complex building technologies located in any part of the world that cannot be modeled by other whole-building energy simulation programs.[48,49] At the same time, many scholars have studied the performance of TRNSYS and determined that it has excellent accuracy in simulating building energy consumption, its calculation times are shorter than those of most other software, and it is easy to use.[50,51]

In terms of thermal environment simulation, Grasshopper and TRNSYS software were used to establish the simulation models (Fig. 4) and simulate Muya folk houses built in different construction methods, mainly to simulate their indoor thermal comfort and thermal load, and to compare and analyze the results. Among them, Grasshopper analyzes indoor thermal comfort through the indicators of the predicted mean vote (PMV) value and indoor dissatisfaction percentage. TRNSYS analyzes the energy consumption of different practices and different houses by simulating the heat load consumed by the rooms for 8,760 hours of the year.

2.3.3 Indoor ventilation simulation

Phoenics was mainly used to simulate indoor ventilation status. From the perspective of fluid mechanics, the speed, direction, and state of the indoor airflow were expressed through the airflow. According to the indoor conditions of the residential buildings, the indoor ventilation environment was established and simulated in the software.

2.3.4 Model verification

To verify the building environment simulation model, before the simulation analysis, the measured data was selected in winter to compare with the simulated data. The comparison between the simulated data and the measured data is shown in Fig. 5. The normalized mean deviation error (NMBE) and the coefficient of variation (CV) of the root mean square deviation error (RMSE) were used to evaluate the agreement of the NMBE. The NMBE value indicates the presence of systematic error or bias, while CV (RMSE) is a strong indicator of simulation accuracy.[52] NMBE and CV (RMSE) are defined as follows:

$$NMBE(\%) = \frac{\sum_{i=1}^{n}(t_{ip}-t_{im})}{n-1} \times \frac{1}{t_m} \times 100 \tag{1}$$

$$CV(RMSE)(\%) = \sqrt{\frac{\sum_{i=1}^{n}(t_{ip}-t_{im})^2}{n-1}} \times \frac{1}{t_m} \times 100 \tag{2}$$

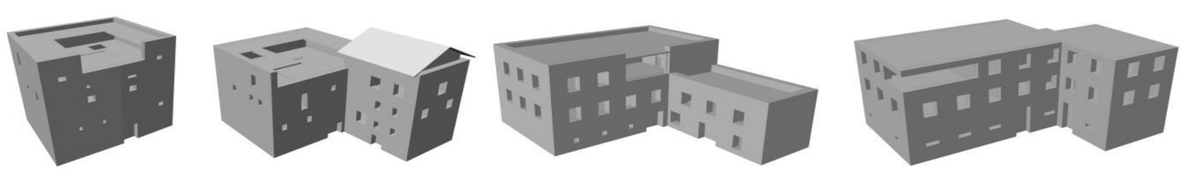
where the t_{ip} is the calculated temperature at the time of node i, t_{im} is the measured temperature of node i, t_m is the arithmetic mean of m measurement data point samples, and n is the number of measured data points during the monitoring period. According to the above formula, the NMBE and CV (RMSE) values were lower than the specified maximum value (25%). Therefore, the NMBE and CV (RMSE) parameters verify the effectiveness of the model in calculating the thermal and humidity characteristics of Muya folk houses, indicating that the model can accurately reflect the thermal and humidity environment of Muya folk houses in the natural state. Through this model, we could analyze and discuss the thermal environment optimization design of Muya folk houses in the next step.

3. Results and discussion

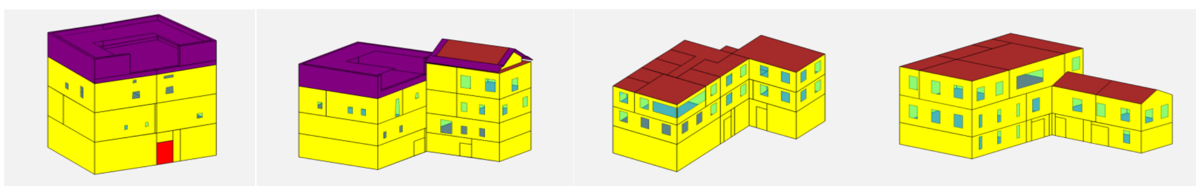
3.1 Analysis of measured results

3.1.1 Analysis of measured temperature

According to the test data, we drew the temperature change curves of each measuring point during the test (Fig. 6). The average temperature (T_{av}), the maximum temperature (T_{max}), the minimum temperature (T_{min}), the maximum temperature difference (T_d), and the data variance (D) of each floor or room



(a)



(b)

Fig. 4 Muya folk houses: (a) original building model; (b) building simulation model.

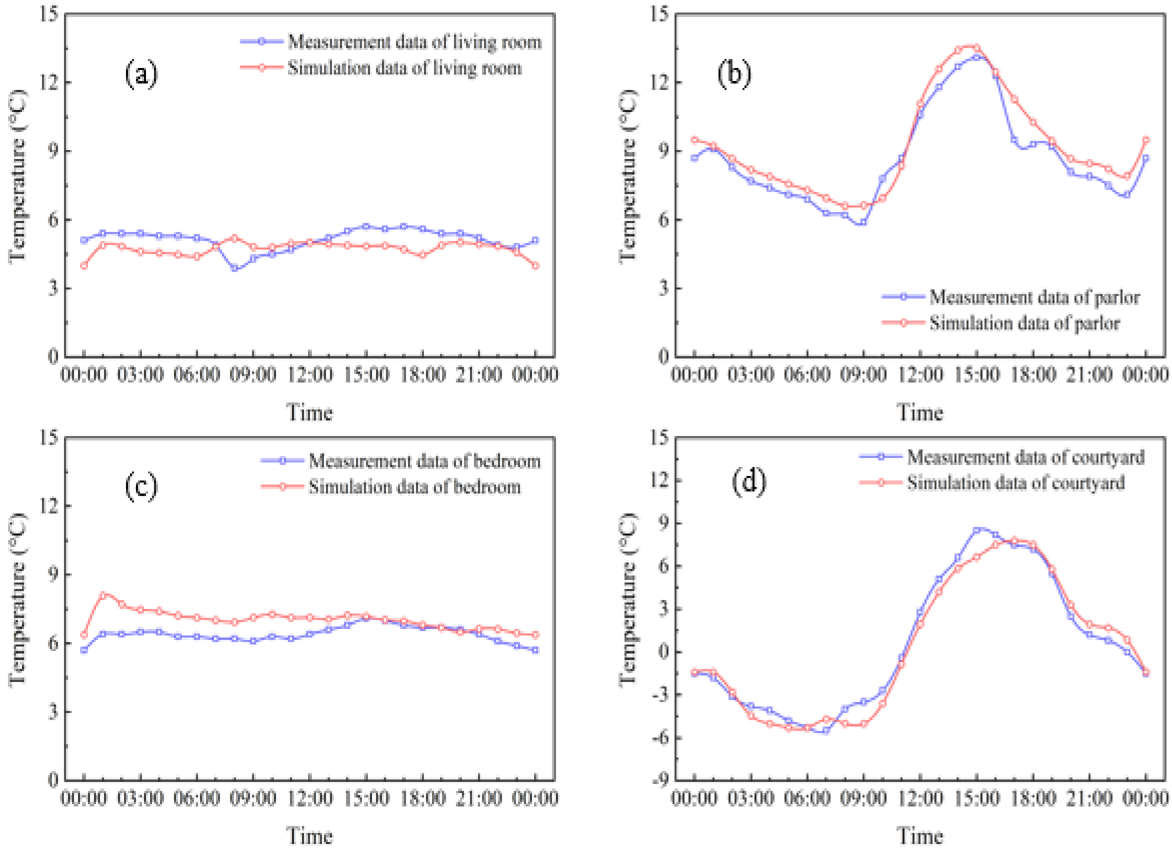


Fig. 5 Comparative analysis of measured data and simulated data: (a) Living room; (b) Parlor; (c) Courtyard; (d) Bedroom.

of the four residential buildings were calculated (Table 4). From the test results, the average outdoor temperature is 1.2°C, and the minimum temperature is −8.8°C, which occurs around 8:00–9:00 in the morning; The maximum temperature is 16.5°C, which occurs around 15:00–16:00 in the afternoon. The temperature difference between day and night is large, and the daily temperature fluctuation range is 25.3°C. The average temperature of each room in the two old residential buildings is 4.9°C and 6.2°C, respectively, and the average temperature of each room in the two new residential buildings is 6.2°C and 7.1°C, respectively.

According to the outdoor temperature statistics above, the temperature changes greatly during the day and at night, the temperature is high during the day, and the temperature drops sharply at night.

From the temperature change comparison curves, the internal thermal environment of each residential building is affected by the outdoor temperature and has a positive correlation with the temperature change of the external environment, but the degree of change is different. From the range of temperature fluctuation, the indoor temperature of the old residential buildings is more affected by the outdoor temperature than that of the new residential buildings, and the indoor temperature of the old residential buildings is lower than that of the new residential buildings.

Table 4. Temperatures of measuring points in Muya folk houses (°C).

Measured object	Measured position	T_{max}	T_{min}	T_{av}	T_d	D
Luozhu's old house	Floor 1	8	1.9	4.8	6.1	1.9
	Floor 2	7.1	2.5	4.7	4.6	1.3
	Floor 3	8.6	2.9	5.1	5.8	1.7
	Floor 4	10.5	−4.1	1.6	14.6	5.5
Niumai's old house	Floor 1	11.4	3.2	7.1	8.2	2.8
	Floor 2	9.8	1.2	5.5	8.6	2.7
	Floor 3	10.4	1.7	6.1	8.7	3.1
	Floor 4	12.1	−6.8	0.9	18.9	7.0
Wangqiu's house	Living room	5.7	3.9	5.1	1.8	0.5
	Kitchen	15.7	3.3	9.6	12.4	4.5
	Living room	10.6	5.3	7.9	5.3	1.7
	Bedroom	6.8	5.7	6.4	1.1	0.3
	Yard	16.5	−8.8	1.2	25.3	9.2
Niumai's new house	Living room	6.3	4	5.3	2.3	0.8
	Living room	8.6	4.3	6.3	4.3	1.4
	Kitchen	15.8	3.6	9.5	12.2	4.7
	Bedroom	7.3	4.7	5.8	2.6	0.8

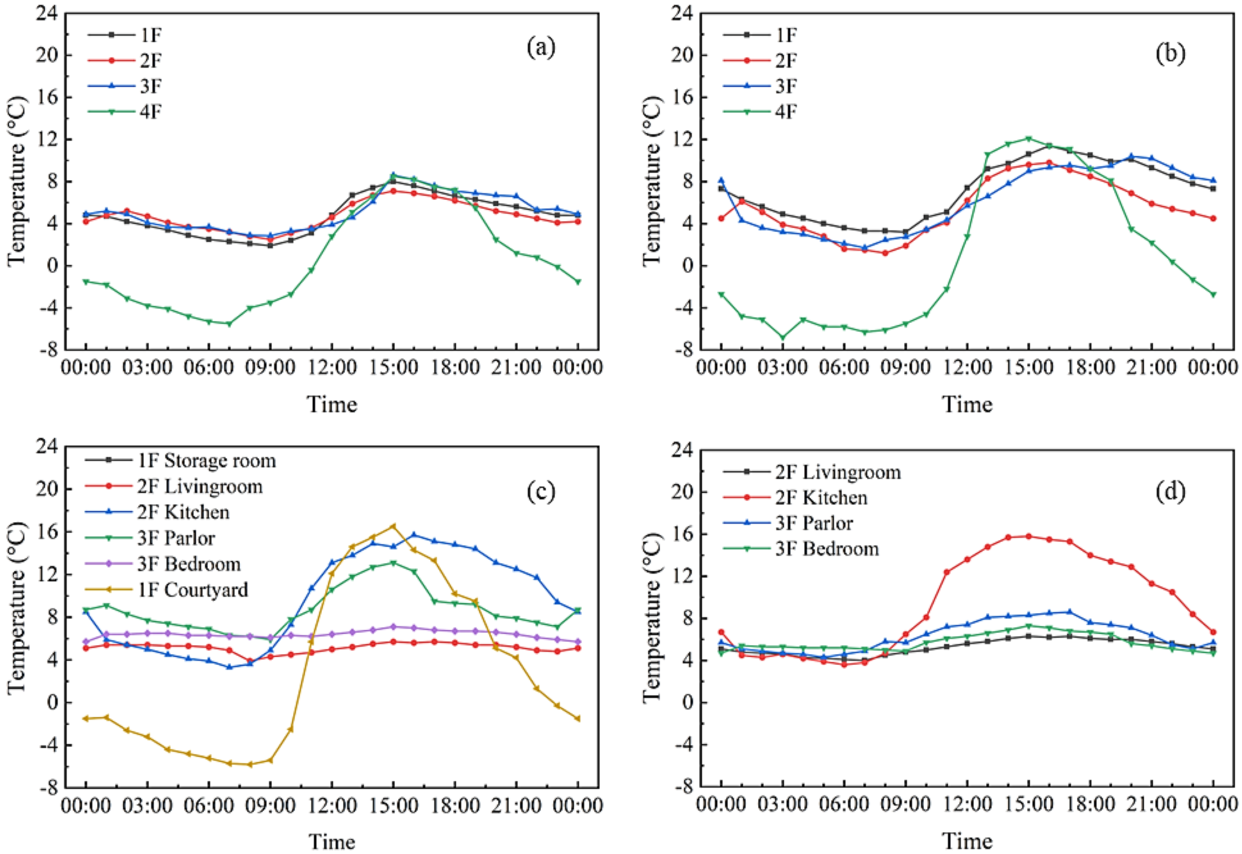


Fig. 6 Temperature change of measuring points: (a) Luozhu's old house; (b) Niumai's old house; (c) Wangqiu's house; (d) Niumai's new house.

It can be seen from the curve changes of Figs. 6(a) and (b) that the temperature change trend of each floor of the two old houses is consistent, the temperature of the first to third floors is close, and the indoor temperature uniformity is good. In Figs. 6(c) and (d), the temperature fluctuation of bedrooms, living rooms, and other rooms in the new residential houses is small, and the temperature fluctuation is less than 1°C, indicating that the thermal stability of bedrooms and living rooms is good.

3.1.2 Relative humidity analysis

Figure 7 shows the humidity change curve of each measuring point during the test. The humidity changes with the change in temperature, and the changing trend is inversely related. During the day, the highest humidity occurs between 8:00–9:00 in the morning, and the lowest humidity occurs between 14:00–15:00 in the afternoon. Among the rooms, the relative humidity of the living room and the bedroom changes the least, followed by the living room and the hallway, and the kitchen humidity changes the most. At the same time, it can be seen from the test results that the indoor relative humidity of the two old houses varies from 23.4% to 75.8%, and the average relative humidity is 58.72%. The indoor relative humidity of new residential buildings varies from 18.8% to 68%, and the average relative humidity is 47.14%. The relative humidity of the new folk houses is about 10% lower than that of the old folk houses. The main reason is that the doors and windows of the old folk houses are small, the indoor sunshine is less, the indoor temperature is low, and the indoors is humid. Second, there is no height difference between the indoors and outdoors of the first floor of the old residential building, and water easily seeps through the soil, which makes the indoors more humid. Another factor is that the ventilation of the old residential buildings was worse than that of the new residential buildings, and the indoor humidity was higher, which was found in the survey.

3.2 Analysis of simulation results

3.2.1 Analysis of thermal comfort

For the simulation analysis of the thermal environment, Fig. 8 reflects the thermal comfort simulation results of the research object. The simulation results are presented by the evaluation index PMV of the human thermal response.[53] Second, according to the PMV value obtained by the software simulation, we conducted a statistical analysis of the PMV score for the whole year.

In 8,760 hours a year, the predicted thermal evaluation of

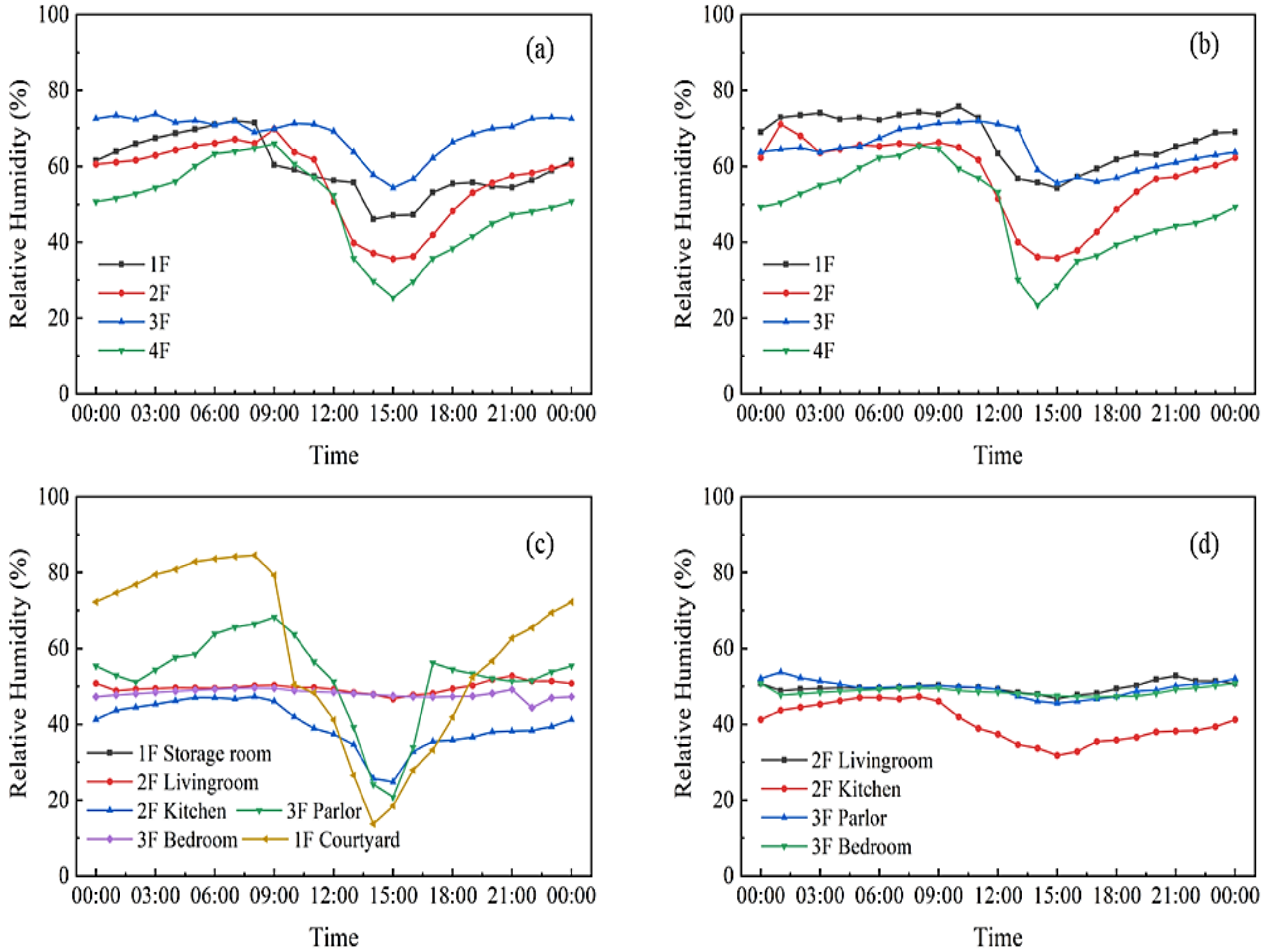


Fig. 7 Humidity change of measuring points: (a) Luozhu's old house; (b) Niumai's old house; (c) Wangqiu's house; (d) Niumai's new house.

Luozhu's old house and Niumai's old house, Luozhu's old house has a moderate thermal environment 22.7% of the time, and Niumai's old house has a moderate thermal environment 73.9% of the time. Moreover, 77.3% and 26.1% of the year, the houses are rated as slightly cold or slightly hot. There was no evaluation of overcooling or overheating during the year. In the predicted thermal evaluation of the two new residential buildings, Wangqiu's house has a suitable thermal environment for 69.1% of the year, and Niumai's new house has a suitable thermal environment for 27.7% of the year. The houses are slightly cold or hot for 30.9% and 27.7% of the time, respectively, with neither being too cold nor too hot during the year.

3.2.2 Energy consumption analysis

In order to evaluate the energy consumption characteristics of Muya folk houses, the cumulative heat load was used as the analytical index, and TRNSYS software was used to establish a building simulation model. Owing to the local special geographical and climatic characteristics, the weather is cool in summer and cold in winter, and there is no need for cooling in summer. Therefore, we focus on the analysis of heat load during the heating season (October to April of the following year).

It can be seen from Fig. 9 that with the change of time, the building heat load gradually increases as it approaches the autumn and winter seasons, and reaches the maximum in January, followed by December and February. The minimum is in April. Fig. 9 shows a comparative analysis of the total cumulative heating load of each building during the simulation period. The maximum heating load of each building is as follows: Luozhu's old house, 17.5 kW; Niumai's old house, 24.3 kW; Niumai's new house, 20.5 kW; and Wangqiu's house, 25.2 kW. Fig. 10 displays a comparison of the heating load of the residential buildings adopting the modern construction method and traditional construction method in the Muya area in winter. From the calculation results, the cumulative heat load of the old Muya folk houses is higher than that of the new Muya folk houses but lower than that of the buildings constructed with modern common construction methods, and the energy consumption can be reduced by about 44.5–66%. Therefore, the traditional construction method of Muya folk

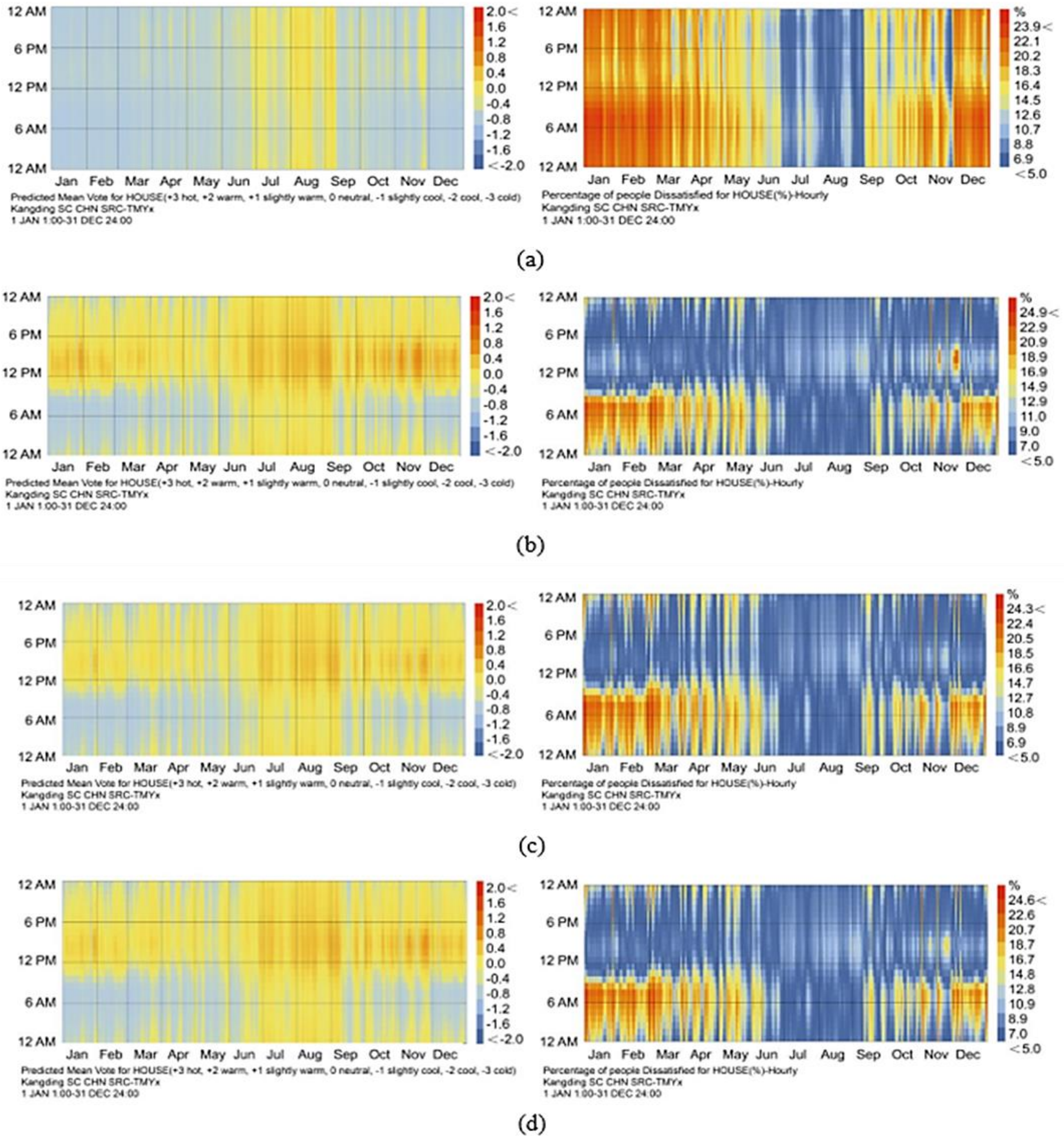


Fig. 8 Analysis chart of annual thermal comfort evaluation: (a) Luozhu's old house; (b) Niumai's old house; (c) Wangqiu's new house; (d) Niumai's new house.

houses is more conducive to energy saving than the building construction method of a modern reinforced concrete frame structure. Among them, the energy efficiency of the new Muya folk houses is better.

3.2.3 Ventilation analysis

For the wind environment, Phoenics software was used to simulate the indoor wind environment. The simulation results of the indoor air environment of Muya residential buildings are shown in Fig. 11. The indoor airflow on each floor of Luozhu's old house and Niumai's old house is poor, and the airflow velocity in most areas of the room is less than 0.3 m/s. The ventilation effect of the two new houses is better than that of the old houses. Outdoor air flows into the living rooms,

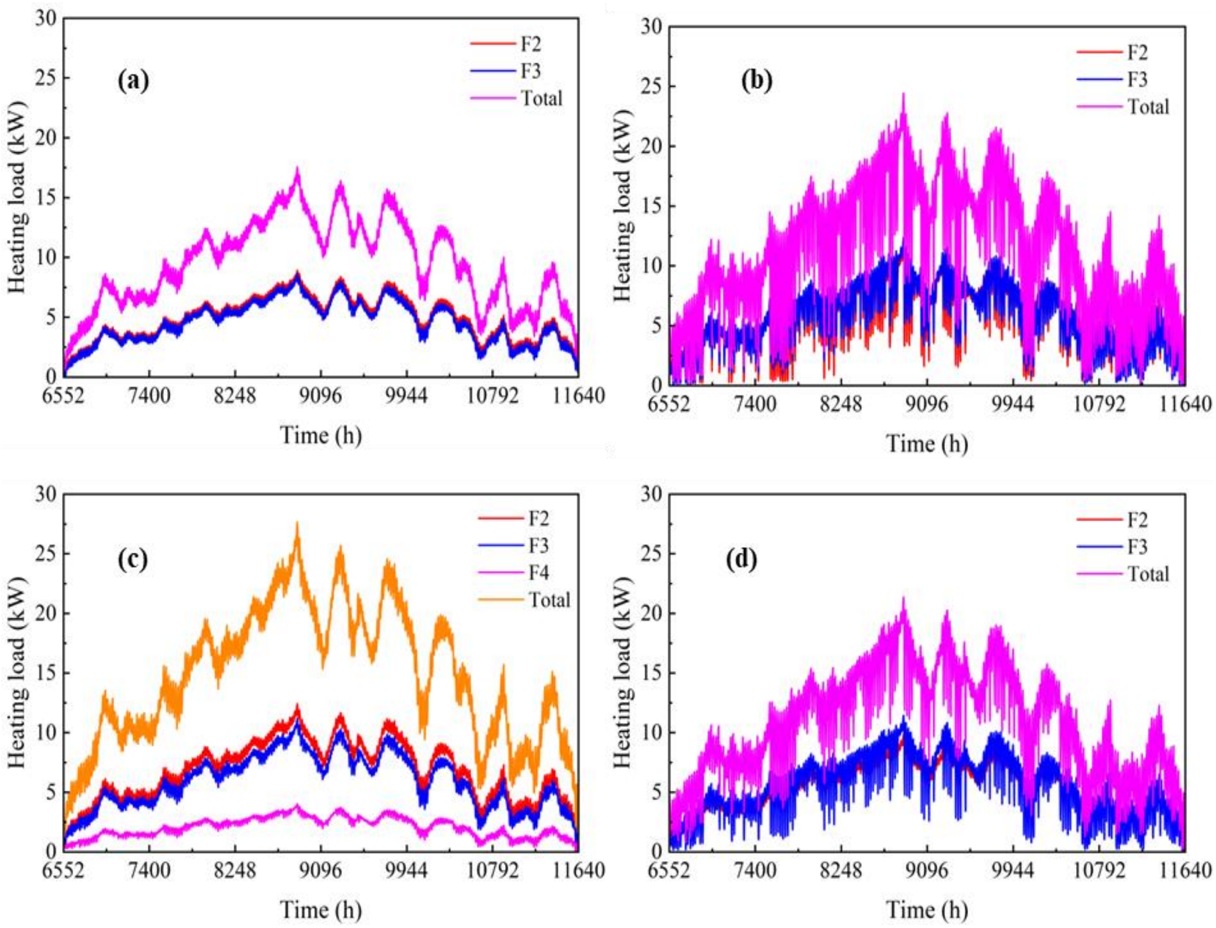


Fig. 9 Thermal load analysis: (a) Luozhu's old house; (b) Niumai's old house; (c) Wangqiu's house; (d) Niumai's new house.

kitchens, and bedrooms on the second and third floors, and the indoor air velocity reaches 0.2–0.7 m/s. The ventilation of old houses is worse than that of new houses, but the indoor ventilation of both needs to be improved to help create a suitable living environment.

3.3 Discussion on the utilization of climate adaptive technology in Muya folk houses

3.3.1 Application of featured materials

For the utilization of the characteristic materials of Muya folk houses, our research group conducted experimental tests on the rock-grown lonicera rupicola laid on the floor and roof. The test found that the heat transfer coefficient of rock-grown lonicera rupicola with a density of 216 kg/m³ was 0.041 W/(m·K).[54] The thermal conductivity is similar to that of commonly used thermal insulation materials. Through the

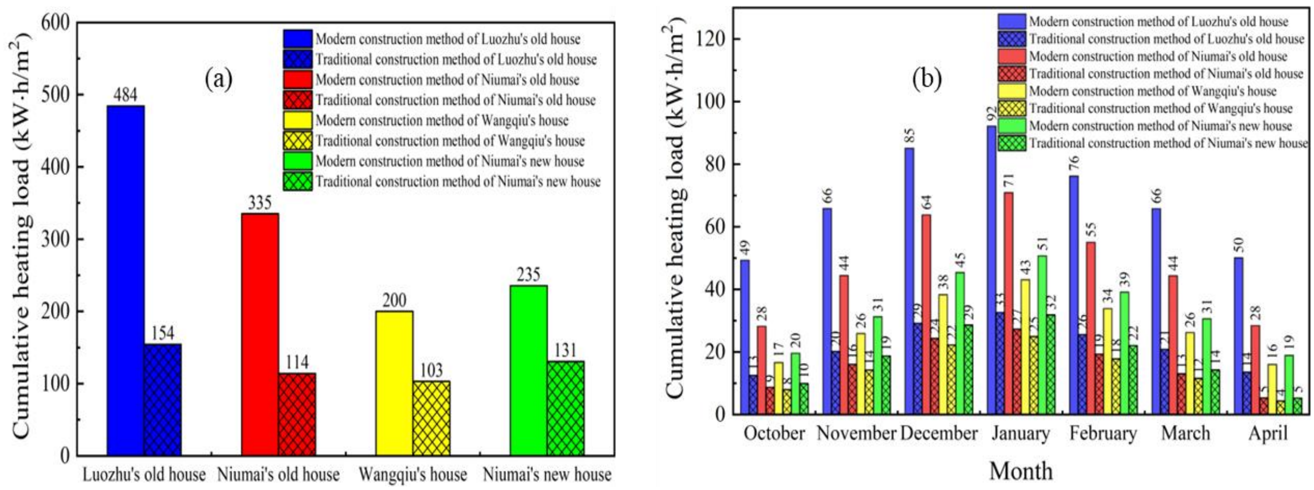


Fig. 10 Comparison of the thermal load of residential buildings: (a) Comparison of energy consumption of different construction methods; (b) Comparison of monthly energy consumption of different construction methods.

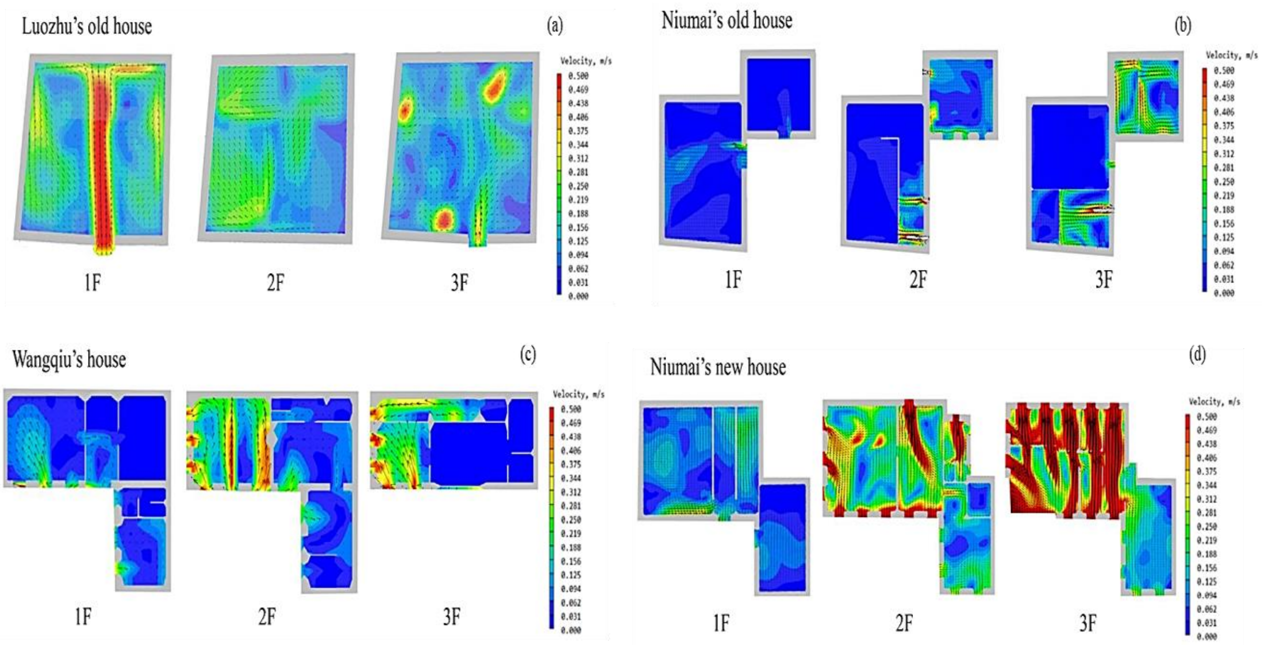


Fig. 11 Analysis of indoor ventilation: (a) Luozhu's old house; (b) Niumai's old house; (c) Wangqiu's house; (d) Niumai's new house.

comparative analysis of the accumulated heating load under the different thicknesses of lonicera rupicola (Seen in Fig. 12), it can be found that the material commonly used in the Muya area has a better energy-saving effect. In addition, other characteristic materials such as architectural coatings commonly used in the area are also derived from local natural minerals and plant materials. The use of this series of featured materials is both environmentally friendly and cost-effective.

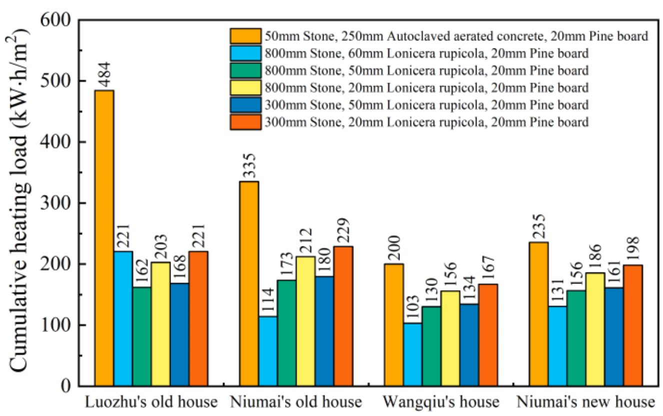


Fig. 12 Comparative analysis of the accumulated heating load under the different thicknesses of lonicera rupicola.

3.3.2 Solar energy utilization

The number of window openings in the old Muya folk houses is small in number and area. Owing to the thick walls and deep penetration, the buildings have poor ventilation. However, through the simulation and comparison of the ventilation of the Muya folk houses, we found that the indoor temperature of the old folk houses was lower than that of the new folk houses. Except for the differences in construction practices, the number and area of windows in the new folk houses were larger than that of the old folk houses. The locality was a high-altitude area with sufficient sunlight and high solar radiation intensity, and proper window opening was conducive to daylight and increasing indoor temperature. Therefore, the use of solar energy in passive buildings plays an important role in improving the indoor thermal environment in winter and is an effective strategy for residential construction and sustainable energy utilization in high-altitude areas.

3.3.3 Natural ventilation

It could be seen from the measured data that during the day, especially from 12:00–18:00 pm, the outdoor temperature was basically higher than the indoor temperature of each room. Natural ventilation is formed by the combined action of heat pressure and wind pressure. Owing to the temperature difference between indoor and outdoor air, hot-pressure ventilation is formed. At the same time, wind pressure enhances the effect of indoor natural ventilation. Properly increasing the number of window openings and the area of window sashes is not only conducive to the utilization of solar energy but also to the improvement of indoor ventilation and the thermal environment.

4. Conclusions

Muya folk houses are typical traditional wood and stone buildings and are located in a special area and climate. They use distinctive craftsmanship and materials, and carry thousands of years of minority culture, making them extremely valuable for research. Taking four new and old

Muya folk houses as the research objects, our study used the method of combining field measurements and a numerical simulation to quantitatively analyze the architectural environment. Firstly, 70% of the year was thermally comfortable, and the thermal comfort of new folk houses was higher than that of old dwellings. Secondly, the one-year heat load of the new Muya folk houses was lower than that of the old folk houses, but the overall energy consumption of the two Muya folk houses was lower than that of the modern construction techniques and materials. The heat load consumed is conducive to promoting low-carbon construction and energy conservation and emission reduction. In addition, although the thermal environment met the relevant standards, the indoor light environment and wind environment problems still need to be solved. Finally, the idea of strengthening passive solar energy utilization and enhancing natural ventilation is proposed as a strategy to improve the architectural environment of traditional Muya folk houses. Traditional buildings on the Qinghai-Tibet Plateau have taken the initiative to cope with regional characteristics such as extreme climate, fragile environment, and limited technology in their construction activities, and have developed profound green construction wisdom. In future studies, the value and enlightenment of traditional architecture will be found more, and the inheritance and renewal of traditional green design principles will be explored in the design practice of new buildings, which will contribute to the further development of green architecture and the integration and innovation of regional characteristics and green technology.

Acknowledgments

This research work was financially supported by the Sichuan Provincial Youth Scientific and Technological Innovation Research Team on Ecological Adaptability of Plateau Architecture (grant No. 2022JDTD0008) and the National Natural Science Foundation of China (grant No. 52008358).

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

[1] Enerdata, Total Energy Consumption, 2021, Available: https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html.

[2] G. Majewski, Ł. Orman, M. Telejko, N. Radek, J. Pietraszek, A. Dudek, Assessment of thermal comfort in the intelligent buildings in view of providing high quality indoor environment, *Energies*, 2020, **13**, 1973, doi: 10.3390/en13081973.

[3] M. Hamdy, A. Hasan, K. Siren, Applying a multi-objective optimization approach for design of low-emission cost-effective dwellings, *Building and Environment*, 2011, **46**, 109-123, doi: 10.1016/j.buildenv.2010.07.006.

[4] M. Fahmy, M. M. Mahdy, H. Rizk, M. F. Abdelaleem, Estimating the future energy efficiency and CO_2 emissions of passive country housing applying domestic biogas reactor: A case study in Egypt, *Ain Shams Engineering Journal*, 2018, **9**, 2599-2607, doi: 10.1016/j.asej.2017.08.004.

[5] S. Bodach, W. Lang, J. Hamhaber, Climate responsive building design strategies of vernacular architecture in Nepal, *Energy and Buildings*, 2014, **81**, 227-242, doi: 10.1016/j.enbuild.2014.06.022.

[6] L. Zhijian, Evaluating potentials of passive solar heating renovation for the energy poverty alleviation of plateau areas in developing countries: a case study in rural Qinghai-Tibet Plateau, China, *Solar Energy*, 2019, **187**, 95-107, doi: 10.1016/j.solener.2019.05.049.

[7] G. G. Abdel-Azim, K. A.-A. Osman, The importance of cultural dimensions in the design process of the vernacular societies, *Ain Shams Engineering Journal*, 2018, **9**, 2755-2765, doi: 10.1016/j.asej.2017.09.005.

[8] Xi, Zhao, Evaluation of thermal environments for cliff-side cave dwellings in cold region of China, *Renewable Energy*, 2020, **158**, 154-166, doi: 10.1016/j.renene.2020.05.128.

[9] X. Wang, H. Ren, W. Cai, Y. Wu, M. Chen, The change trend and influent factors of time series of energy consumption in China, *Heating Ventilating & Air Conditioning*, 2017, **47**, 21-26.

[10] Central People's Government of the People's Republic of China, Opinions of the CPC Central Committee and the State Council on the complete, accurate and comprehensive implementation of the new development concept and the completion of carbon peak and carbon neutralization, 2021, http://www.gov.cn/xinwen/2021-10/24/content_5644613.htm.

[11] H. B. Rijal, K. Yoshida, M. A. Humphreys, J. F. Nicol, Development of an adaptive thermal comfort model for energy-saving building design in Japan, *Architectural Science Review*, 2021, **64**, 109-122, doi: 10.1080/00038628.2020.1747045.

[12] S. S. Chandel, V. Sharma, B. M. Marwah, Review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions, *Renewable and Sustainable Energy Reviews*, 2016, **65**, 459-477, doi: 10.1016/j.rser.2016.07.038.

[13] A.-T. Nguyen, Q.-B. Tran, D.-Q. Tran, S. Reiter, An investigation on climate responsive design strategies of vernacular housing in Vietnam, *Building and Environment*, 2011, **46**, 2088-2106, doi: 10.1016/j.buildenv.2011.04.019.

[14] J. T, Kim, Natural ventilation with traditional Korean opening in contemporary house, *Building and Environment*, 2010, **45**, 51-57, doi: 10.1016/j.buildenv.2009.05.016.

[15] G. Evola, L. Marletta, V. Costanzo, G. Caruso, Different strategies for improving summer thermal comfort in heavyweight traditional buildings, *Energy Procedia*, 2015, **78**, 3228-3233. doi: 10.1016/j.egypro.2015.11.785.

[16] A. Oikonomou, F. Bougiatioti, Architectural structure and environmental performance of the traditional buildings in Florina, NW Greece, *Building and Environment*, 2011, **46**, 669-689. doi: 10.1016/j.buildenv.2010.09.012.
[17] A. Dili, M. Naseer, T. Varghese, Thermal comfort study of Kerala traditional residential buildings based on questionnaire survey among occupants of traditional and modern buildings, *Energy and Buildings*, 2010, **42**, 2139-2150, doi: 10.1016/J.ENBUILD.2010.07.004.
[18] A. Dili, M. Naseer, T. Varghese, Passive environment control system of Kerala vernacular residential architecture for a comfortable indoor environment: a qualitative and quantitative analyses, *Energy and Buildings*, 2010, **42**, 917-927, doi: 10.1016/J.ENBUILD.2010.01.002.
[19] L. Tang, M. Nikolopoulou, N. Zhang, Bioclimatic design of historic villages in central-western regions of China, *Energy and Buildings*, 2014, **70**, 271-278, doi: 10.1016/j.enbuild.2013.11.067.
[20] Z. Huang, M. Yu, L. Zheng, C. Gong, Z. Wu, One-year field study on indoor environment of Huizhou traditional vernacular dwellings in China, Procedia Engineering, 2017, **205**, 1316-1322. doi: 10.1016/j.proeng.2017.10.092.
[21] A. Ghaffarian Hoseini, U. Berardi, N. D. Dahlan, A. Ghaffarian Hoseini, What can we learn from Malay vernacular houses?, *Sustainable Cities and Society*, 2014, **13**, 157-170. doi: 10.1016/j.scs.2014.04.008.
[22] M. Indraganti, Thermal comfort in naturally ventilated apartments in summer: Findings from a field study in Hyderabad, India, *Applied Energy*, 2010, **87**, 866-883. doi: 10.1016/j.apenergy.2009.08.042.
[23] M. Indraganti, Using the adaptive model of thermal comfort for obtaining indoor neutral temperature: Findings from a field study in Hyderabad, India, *Building and Environment*, 2010, **45**, 519-536. doi: 10.1016/j.buildenv.2009.07.006.
[24] R. Shanthi Priya, M. C. Sundarraja, S. Radhakrishnan, L. Vijayalakshmi, Solar passive techniques in the vernacular buildings of coastal regions in Nagapattinam, TamilNadu-India - a qualitative and quantitative analysis, *Energy and Buildings*, 2012, **49**, 50-61, doi: 10.1016/j.enbuild.2011.09.033.
[25] M. Kumar, Singh, Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India, *Building and Environment*, 2010, **45**, 320-329, doi: 10.1016/j.buildenv.2009.06.009.
[26] S. Dhaka, J. Mathur, G. Brager, A. Honnekeri, Assessment of thermal environmental conditions and quantification of thermal adaptation in naturally ventilated buildings in composite climate of India, *Building and Environment*, 2015, **86**, 17-28. doi: 10.1016/j.buildenv.2014.11.024.
[27] A. F. Mohamed, Comparative study of traditional and modern building techniques in Siwa Oasis, Egypt: Case study: affordable residential building using appropriate building technique, *Case Studies in Construction Materials*, 2020, **12**, e00311. doi: 10.1016/j.cscm.2019.e00311.
[28] H. Sun, M. Leng, Analysis on building energy performance of Tibetan traditional dwelling in cold rural area of Gannan, *Energy and Buildings*, 2015, **96**, 251-260. doi: 10.1016/j.enbuild.2015.03.035.
[29] W. Yu, B. Li, R. Yao, D. Wang, K. Li, A study of thermal comfort in residential buildings on the Tibetan Plateau, China, *Building and Environment*, 2017, **119**, 71-86. doi: 10.1016/j.buildenv.2017.04.009.
[30] Y. Liu, J. Liu, L. Yang, J. Li, Measureing study of passive solar house for traditional dewlling building in lhasa area, *Acta Energiae Solaris Sinica*, 2008, **29**, 391-394. doi: 10.3321/j.issn:0254-0096.2008.04.002.
[31] D. Wang, Y. Liu, Y. Wang, J. Liu, Measurement and evaluation of indoor thermal environment of residential buildings in Lhasa in winter, *Building Science*, 2011, **27**, 20-24.
[32] L. Huang, Y. Leng, Field study of winter indoor thermal environment of traditional dwelling in Nyingchi, Tibet, *South Architecture*, 2012, **1**, 92-96. doi: 10.3969/j.issn.1000-0232.2012.01.092.
[33] L. Li, Analysis and Test of Indoor Thermal Environment of Tibetan Traditional Timber-house in Shangri-la, *Huazhong Architecture*, 2009, **27**, 156-159. doi: 10.3969/j.issn.1003-739X.2009.11.048.
[34] Z. X. Dawa, L. J. Huang, Climatic-responsive design strategies and cultural expression of Tibetan traditional folk building, *Huazhong Architecture*, 2012, **30**, 171-174. doi: 10.13942/j.cnki.hzjz.2012.04.049.
[35] A. Deguchi, Thermal comfort of Tibetan people in indoor space, Proceedings of the 2010 International Conference on Science and Technology of the Built Environment, May 07, 2010, Nanjing, China, 2010, 114-123.
[36] Y. Chen, C. C. Liu, Structure, structure and technology of Tibetan dwellings in two areas of Ganzi Prefecture, Proceedings of the 2004 Asian Ethnic Architecture Conservation and Development Symposium, China National Architecture Research Association, 2004, 84-89.
[37] X. Huang, Analysis of the existing Muya Tibetan-style dwellings in the Kangba area, *Chinese Science and Technology*, 2016, **215**, doi: 10.3969/j.issn.1671-2064.2016.09.181.
[38] X. X. Gu, The research on the contemporary design of kangding traditional tibetan culture, Master Thesis, Southwest Jiaotong University, Chengdu, 2016.
[39] W. Y. Cai, Y. Cao, Analysis of the differences and evolution of religious space in tibetan dwelling houses in kangding, *Chinese & Overseas Architecture*, 2018, 65-69.
[40] D. Zeren, Inheritance and development of kangba muya characteristic village culture, *Northern Literature*, 2018, 169-171, doi: 10.3969/j.issn.0476-031X.2018.11.124.
[41] Ministry of Housing and Urban-Rural Development of the People's Republic of China, Standard for test methods of building thermal environment, July 31, 2014.
[42] P. Wilde, Building Performance Analysis. Hoboken, NJ, USA, Wiley, 2018, doi: 10.1002/9781119341901.
[43] Ministry of Housing and Urban-Rural Development of the People's Republic of China, Standard for green performance calculation of civil buildings, December 01, 2018.
[44] Ministry of Housing and Urban-Rural Development of the People's Republic of China, Standard for Green Performance

Calculation of Civil Buildings, Beijing, China, China Architecture & Building Press, 2018.
[45] Ministry of Housing and Urban-Rural Development of the People's Republic of China, Standard for weather data of building energy efficiency, November 05, 2014.
[46] E. Fernandes, Energy Performance of Buildings, Switcherland, Springer International Publishing, 2016.
[47] A. Dutta, A. Samanta, Reducing cooling load of buildings in the tropical climate through window glazing: a model to model comparison, *Journal of Building Engineering*, 2018, **15**, 318-327, doi: 10.1016/j.jobe.2017.12.005.
[48] D. B. Crawley, L. K. Lawrie, F. C. Winkelmann, W. F. Buhl, Y. J. Huang, C. O. Pedersen, R. K. Strand, R. J. Liesen, D. E. Fisher, M. J. Witte, J. Glazer, EnergyPlus: creating a new-generation building energy simulation program, *Energy and Buildings*, 2001, **33**, 319-331, doi: 10.1016/s0378-7788(00)00114-6.
[49] F. Chlela, A. Husaunndee, C. Inard, P. Riederer, A new methodology for the design of low energy buildings, *Energy and Buildings*, 2009, **41**, 982-990, doi: 10.1016/j.enbuild.2009.05.001.
[50] H. S. Rallapalli, A comparison of EnergyPlus and eQUEST whole building energy simulation results for a medium sized office building, Master's thesis, Arizona State University, Arizona, 2010.
[51] Domenico, Mazzeo, PhD, EnergyPlus, IDA ICE and TRNSYS predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a PCM module, *Energy and Buildings*, 2020, **212**, 109812, doi: 10.1016/j.enbuild.2020.109812.
[52] ASHRAE, ASHRAE Handbook of Fundamentals, Atlanta, ASHRAE, 2009.
[53] Ministry of Housing and Urban-Rural Development of the People's Republic of China, Evaluation standard for indoor thermal enviroment in civil buildings, May 28, 2012.
[54] L.-X. Lu, X.-L. Wang, S.-L. Li, Y. Tang, X.-M. Mai, Thermal performance of lonicera rupicola grass as a building insulation composite material, *Advanced Composites and Hybrid Materials*, 2023, **6**, 8, doi: 10.1007/s42114-022-00578-0.

Author Information

Luxi Lu, *School of Architecture, Southwest Minzu University, School of Architecture and Urban Planning, Shenzhen University.*

Tianke Zhang *is M.D. at Administrative Committee of Eastern New District of Baise.*

Xiaoliang Wang *is Associate professor, School of Architecture, China-Portugal Joint Laboratory of Cultural Heritage Conservation Science supported by the Belt and Road Initiative, Southwest Minzu University.*

Yu Han is *Master Degree Candidate at School of Architecture, China-Portugal Joint Laboratory of Cultural Heritage Conservation Science supported by the Belt and Road Initiative, Southwest Minzu University.*

Xianmin Mai *is Professor, Dean, School of Architecture, Southwest Minzu University.*