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# INTEGRATING TIMBER PANEL ELEMENTS INTO HISTORIC CHINESE TIMBER-FRAMED HOUSES TO ENHANCE MULTIPLE BUILDING PERFORMANCES

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**ABSTRACT:** The traditional timber-framed house has a several thousand-year-long history in China, and it is an important part of Chinese architectural culture. Despite their high historic value, these buildings have limitations in comparison with today's standards, especially in terms of indoor comfort. This study explores the potential of integrating modular timber panel elements (TPE) into historic Chinese timber-framed houses to enhance multiple building performance, i.e., thermal-acoustic insulation for a comfortable indoor environment and better noise reduction. Comprehensive analyses are carried out on the application of TPEs for the building envelope, including exterior walls, roofs, floors, doors, and windows, to demonstrate the feasibility of using these techniques and to quantify the improvement of building performance. This study innovatively contributes to healthy and energy-efficient living conditions by revitalizing historic Chinese timber-framed houses.

**KEYWORDS:** Timber panel element, Historic Chinese timber-framed house, Building performance enhancement, Prefabrication potential, Thermal-acoustic insulation

## 1. INTRODUCTION

Timber framing has been a traditional building method for constructing framed structures in many regions of the world for millennia [1]. China is one of the earliest countries to adopt wooden structures. Timber buildings are the protagonist of ancient Chinese architecture, representing an important part of Chinese traditional culture [2]. A fundamental achievement of Chinese timber architecture is the load-bearing timber frame, a network of interlocking wooden supports forming the skeleton of a building. This is considered China’s major contribution to architectural technology worldwide [3]. Although these historic timber-framed houses have such a high historic value, these buildings have largely failed to meet people’s modern living standards due to the increase in living requirements [4]. This is because some functions of the building envelope are inadequate, such as thermal and sound insulation and fire prevention. Therefore, these historic buildings need to be transformed for modern use. According to international experience in renovating traditional timber-framed buildings, many methods have been used to improve indoor comfort, structural stability, fire protection, and other building performance [5]. Among them, the use of timber panel elements (TPEs) can not only improve building performance but also help reduce costs. Therefore, TPEs have become increasingly popular in the European building industry in recent years [6]. It is worth mentioning that no scientific research results related to using TPEs in Chinese timber-famed houses have been found after a literature review. There is no concrete evidence to verify whether TPEs suit these specific building types. Therefore, this paper explores the integration of TPEs into Chinese historic timber buildings and simulates and analyses to what extent TPEs enhance building performance.

## 2. ANALYSIS AND METHODS

### 2.1 BACKGROUND ANALYSIS

Chinese timber buildings can be categorized into three types in terms of structural forms, namely, *Chuandou* (column and tie construction), *Tailiang* (post and lintel construction), and *Jinggan* (log cabin construction). Although the two former types are both timber-framed structures, *Chuandou* consumes less timber and is more structurally stable than *Tailiang*. Therefore, the vast majority of traditional ordinary residential buildings were built as *Chuandou*. Their exterior walls define the building enclosure but may not be load-bearing elements [3]. The enclosure system is relatively independent of the main structure.

According to the “shearing layers” concept, first conceived by architect Frank Duffy and later developed by Steward Brand in his book *How Buildings Learn: What Happens After They're Built* [7], there are 6 layers of a building: site, structure, skin, service, space plan, and stuff. Based on this 6S theory, TPEs can be applied to structure, skin, and service. However, a TPE has the most potential as a skin layer in relation to improving the performance of Chinese historic timber-framed buildings.

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As mentioned above, the enclosure system is often independent of the load-bearing structure system, so the skin can be renewed and replaced during the entire life cycle of a building. For the application of TPEs, the envelope elements in *Chuandou* houses, including exterior walls, roofs, foundations, floors, windows, and doors, need to be first analyzed (Figure 1).

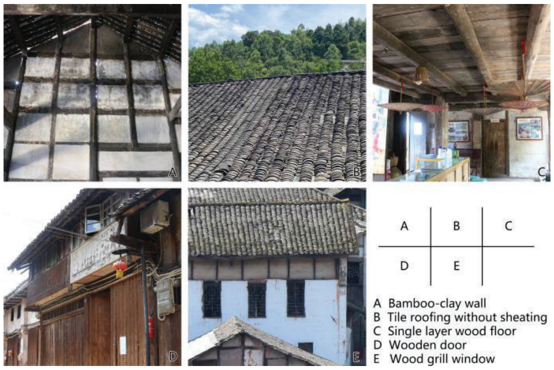


***Figure 1:*** *Envelope system of a historic Chuandou house*

### 2.1.1 Exterior walls

The exterior walls take up the largest proportion of the envelope system, and their thermal performance also directly affects the building's indoor comfort. Wall infill materials are mainly clay, stone, and brick, among which clay has the longest history and widest prevalence [8]. Compared with walls made of other materials, clay walls are more economical and durable and have better performance in terms of fire prevention, sound insulation, and heat preservation. Despite the advantages of clay walls, there are also many difficulties in evaluating wall performance. The wall thickness and composition vary greatly in different places according to the local climate and natural environment. The wall is usually made of a mixture of several local materials, such as clay, straw, and bamboo, and it is difficult to check the thermal or acoustic standard values, and it is necessary to measure the relevant indicators for every single case.

### 2.1.2 Roofs

The roofs in a building envelope should not only prevent the intrusion of rain and snow but also offer good insulation. For the vast majority of *Chuandou* buildings, the double-pitch roof is the most common form. Taking houses in southern China, for example, tile roofing without sheathing is very common because of its simple structure, convenient construction, and economical applicability [9]. However, the thermal and sound insulation performances of the roofing are abnormally poor and do not meet the thermal and sound insulation requirements of today's building codes.

### 2.1.3 Foundations and floors

The foundation not only bears all the loads transmitted from the superstructure but also prevents moisture from penetrating. There are many types of foundations for historic *Chuandou* buildings, such as raw soil, composite soil, slate, and mortar [10]. Among them, composite ground has a wider range of applications because of its better thermal properties and stability. For floors, wooden planks are often laid directly on top of beams. This is a simple and common method, but the sound insulation performance is seriously poor.

### 2.1.4 Door and windows

Regardless of the types of exterior walls, the typical doors of traditional houses are made of single-layer wooden boards. As far as the material is concerned, wooden doors have good thermal performance, but the boards are vulnerable to deformation, and gaps can appear between the boards. If not properly maintained, the airtightness will be extremely poor, especially between the door leaves, threshold, and walls, where large gaps are located. Similar problems occur in windows, as the materials used are the same as in doors. Since most windows are used solely for lighting and ventilation, there is no consideration for airtightness or sound insulation at all [10].

## 2.2 DATA MODELING

Integrating TPEs into a *Chuandou* building has the potential to improve building performance. To determine the thermal and sound insulation performance enhancement, this study proposed possible TPE applications and compared the performance of building envelope elements with the original state. The size and number of panel elements are directly related to the size and spacing of the columns and ties in the building.

In this study, typical *Chuandou* houses in the Sichuan Basin in south-western China are used as modelling prototypes. The experimental design was carried out based on the research results of Huang's study [11] and the personal survey of the authors in the ancient village of Fubao in Sichuan Province. The foundation of the building model is set as 5×8 m, and the height is 7.5 metres. The first floor is 3.5 metres high, and the attic floor is 2–4 metres (Figure 2) [11]. According to local construction methods, the double-pitch roof is covered by the most common tile roofs 25 mm thick. The exterior wall is set to 50 mm thick with bamboo-clay infills, and the foundation material is set as 150 mm thick and mixed with lime, sand, and clay. Because the historic wooden doors and windows are made of a single-layer wooden board, they are uniformly set as 20 mm thick pine boards in the model. Based on the research and calculation of local buildings and the references of papers in related fields [10] and the comparison with the building code *Design Standard for Energy Efficiency of Rural Residential Buildings (GB/T 50824-2013)* [12], the following data have been obtained (Table 1).

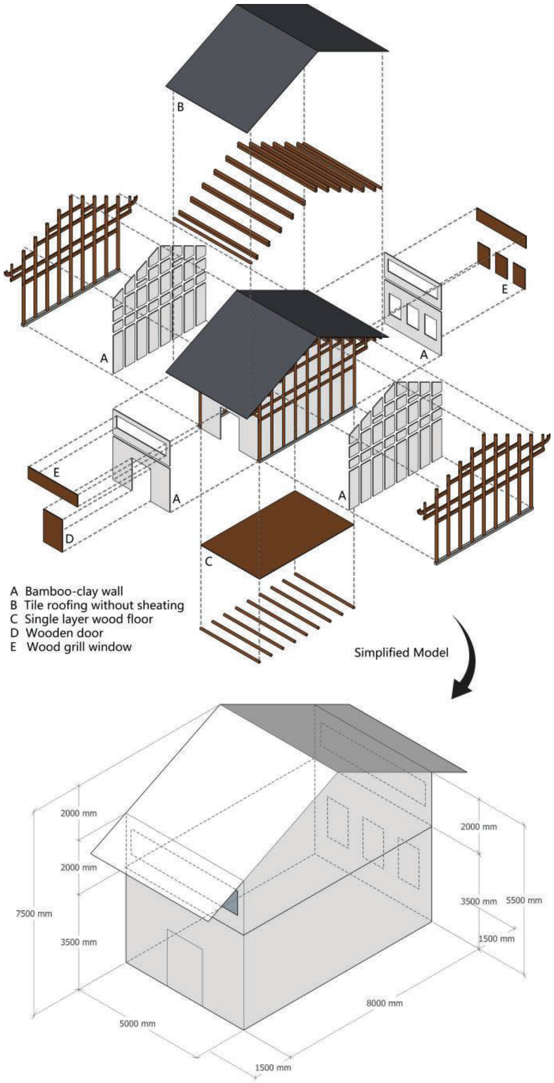


***Figure 2:*** *Simplified model from a historic Chuandou house*

***Table 1:*** *Thermal performance of the building envelope*

| Envelope elements | Thermal Resistance/R (m²·K/W) | Standard Requirement/R (m²·K/W) | Comment |
|---|---|---|---|
| Walls | 0.29 | 0.52 | ○ |
| Roof | 0.18 | 1.10 | ○ |
| Ground | 0.22 | - | - |
| Floors | 0.216 | - | - |
| Doors | 0.14 | 0.18 | ○ |
| Windows | 0.14 | 0.16 | ○ |

○Unqualified - Inapplicable

In addition, the computational model in this study is set to a location in Fubao in south-eastern Sichuan Province. Based on the thermal analysis of this building model by Ecotect Software, the following results can be drawn. It illustrates the energy gain/loss for a year from 1 January to 31 December (Table 2, Figure 3). The process of conduction through the building envelope loses the maximal heat by approximately 91.6%. Heat gains that disrupt comfort in summer months are approximately 26.2% because of conduction. Passive solar radiation gains that affect the architecture of the building are approximately 48.9% over a year. According to the data, the heat lost in the form of conduction through the building envelope accounts for the vast majority.

***Table 2:*** *Heat gains for the original model*

| Category | Losses |  | Gains |  |
|---|---|---|---|---|
|  | Heat (Wh) | Proportion (%) | Heat (Wh) | Proportion (%) |
| Fabric (Conduction) | 727,886 | 91.6 | 359,426 | 26.2 |
| Sol-Air | 0 | 0 | 670,837 | 48.9 |
| Solar | 0 | 0 | 45,271 | 3.3 |
| Ventilation | 58,008 | 7.3 | 42,528 | 3.1 |
| Internal | 0 | 0 | 237,331 | 17.3 |
| Inter-Zonal | 8,741 | 1.1 | 17,834 | 1.2 |
| Total | 794,635 | 100 | 1,373,227 | 100 |

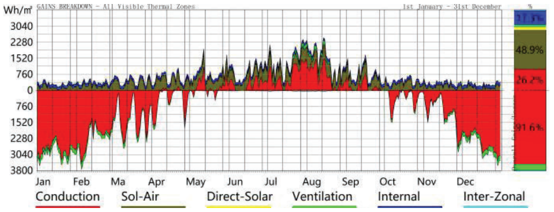


***Figure 3:*** *Thermal performance of the original model*

A temperature analysis of the hottest and coldest days in the year was conducted, from which the related analysis results can be observed in Figure 4. The green and orange lines indicate the hourly internal temperature change of the ground and attic floors of the original model, respectively. The blue line indicates the outdoor temperature change. The differences between indoor and outdoor temperatures are very small, which indicates that the thermal insulation performance of the building envelope is weak.

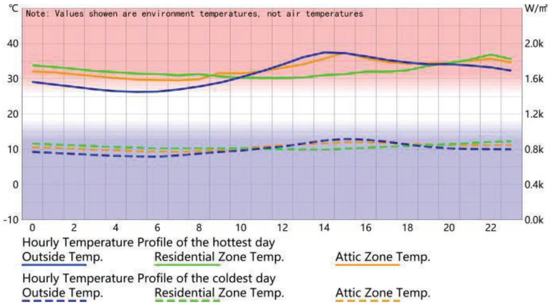
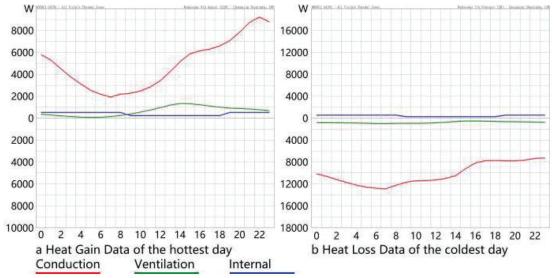


***Figure 4:*** *Hourly temperature change on the hottest and coldest day in a year*

Figure 5 indicates that much more heat is lost or gained through the building envelope than through ventilation. On the hottest day, the conducting heat gain of the building envelope can reach 9,000 W or more. The situation in winter is even worse, and the conducting heat loss can reach 12,000 W.



a Heat Gain Data of the hottest day

b Heat Loss Data of the coldest day

***Figure 5:*** *Heat gain and loss on the hottest and coldest days in a year*

According to the thermal analysis above, the building envelope is the key factor in improving the building's thermal performance.

In addition to the bad thermal performance, the sound insulation is also poor. This problem is closely related to the structure, materials, and constructional characteristics. The roof has no sound insulation measures because of the clay tiles directly on the rafters, so the falling sound of rainwater can be noisily heard inside, especially on the attic floor. The low density and poor airtightness of bamboo–clay walls and wooden board walls are the main causes of poor sound insulation performance. The plank floor laid directly on the wooden beams has poor resistance against walking noises concentrated at 20–200 Hz. When walking, there is also noise from the mutual squeezing of the wooden boards caused by slight deformation. Doors and windows are also problematic for sound insulation. According to field research and a literature analysis, the standardized sound pressure level differences of enclosure structural components such as walls and floors are all no more than 30 dB. According to the requirements in the relevant specifications (*Technical Standard for Infills or Partitions with Timber Framework GB/T 50361-2018*[13] and *Code for Design of Sound Insulation of Civil Buildings GB 50118-2010*[14]), the acoustic environment is not qualified.

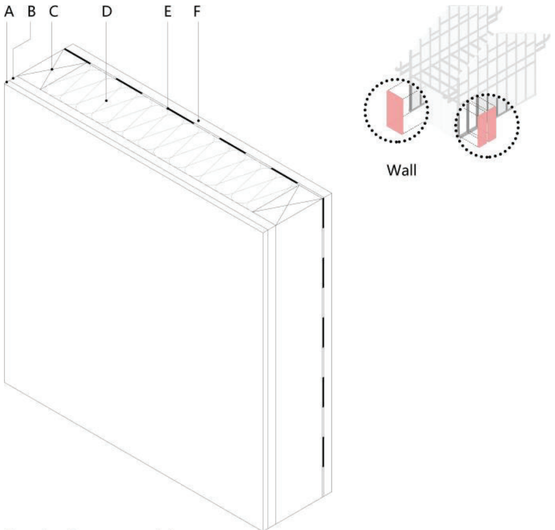
## 3. INTEGRATING A TPE INTO A BUILDING ENVELOPE

### 3.1 DESIGN OF TPE COMPONENTS

Prefabricated timber panels are elements that are produced in a factory and can be well-insulated, fireproof, waterproof, or soundproof. Their dimensions can vary according to the structural system and the material used. Various performances that provide energy conservation or efficiency can be realized in a prefabricated TPE that improves the living quality of the indoor environment by providing visual, thermal, and acoustic comfort [15]. The thermal and sound insulation performance are examined using Ecotect and INSUL after construction designs are implemented to integrate the TPE into the building envelope parts of the *Chuandou* house.

#### 3.1.1 Exterior walls

TPEs have the potential to be applied in infill compartments in the exterior walls of the *Chuandou* house (Figure 6). The TPE infill wall is composed of a 10 mm plaster board, 15 mm gypsum fibre board, 90×45 mm timber studs, mineral wool, vapour barrier, and 15 mm gypsum fibre board from outside to inside. This allows for calculating the heat transfer coefficient and thermal resistance of this wall scheme according to the thermal parameter table of building materials in *Thermal design code for civil buildings (GB/T 50176-2016)* [17]. The calculation indicates that the U value (thermal transmittance) of the wall is 0.42 W/(m²·K), and the R-value (thermal resistance) is 2.35 m²·K/W, meeting the related requirements in the same design standard [12]. The sound insulation performance of the wall was simulated in INSUL, and the following data were obtained (Figure 7). The air-weighted sound insulation $R_w$ of the wall is 53 dB, the traffic noise spectrum correction $C_{tr}$ is -6 dB, and the $R_w$+$C_{tr}$ value is 47 dB, which meet the relevant requirements in the *Code for Design of Sound Insulation of Civil Buildings (GB 50118-2010)* [14].



**Structural component layer**

A Plaster Board 10mm (λ=1)
B Gypsum Fibre Board 15mm (λ=0.32)
C Timber Studs 90mm×45mm (λ=0.12)
D Mineral Wool 90mm (λ=0.04)
E Vapor Barrier
F Gypsum Fibre Board 15mm (λ=0.32)

Thermal performance:
U = 0.42 W/(m2/·K)
R = 2.35 (m²·K)/W
Acoustic performance:
$R_w$ = 53 dB
C = -2 dB
$C_{tr}$ = -6 dB
$R_w$ + $C_{tr}$ = 47 dB
(100-3150Hz)

***Figure 6:*** *Construction of the TPE infill wall*

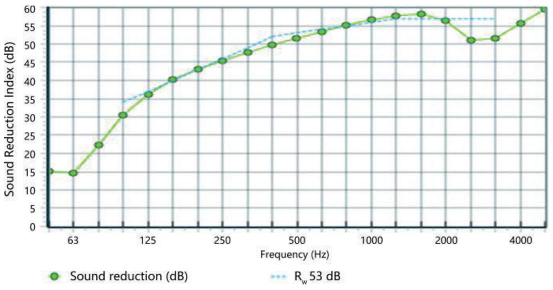


***Figure 7:*** *Sound insulation simulation of the TPE infill wall*

#### 3.1.2 Roof

There is the possibility of introducing a TPE into a traditional double-sloping roof as an intermediate layer between purlins and tiles. Figure 8 shows the construction design of the TPE roof layers, which consist of 80 mm thick wood battens, a waterproof membrane, 12 mm OSB, 90×45 mm timber studs, mineral wool, a vapour barrier, 15 mm OSB and 15 mm gypsum fibreboard from outside to inside. It is calculated that the U value of the roof is 0.41 W/(m²·K), and the R-value is 2.46 m²·K/W, meeting the relevant requirements in *GB/T 50824-2013*[12]. The sound insulation performance of the roof was also simulated in INSUL, and the following data were obtained (Figure 9). The $L_{iA}$ value (floor impact sound level) of the roof is 45 dB, which meets the relevant requirements in *GB 50118-2010* [14].

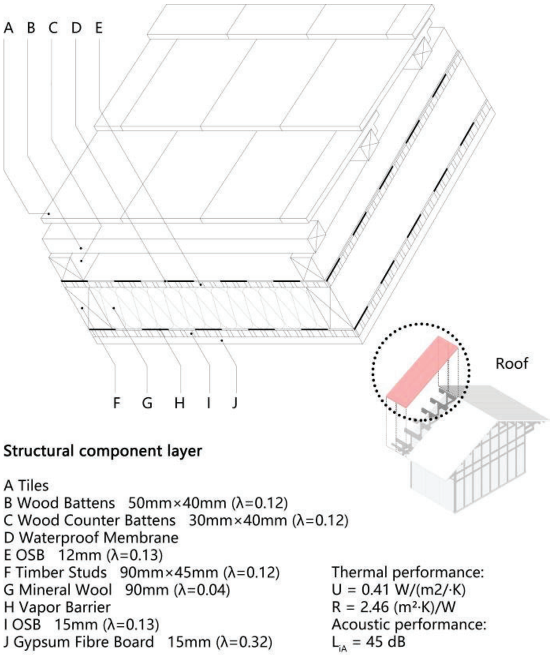


***Figure 8:*** *Construction of the TPE roof*

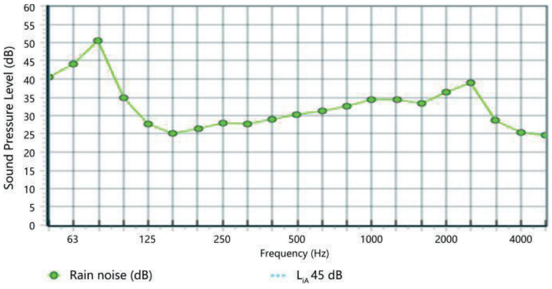


***Figure 9:*** *Sound insulation simulation of the TPE roof*

### 3.1.3 Floors

It is possible to apply the TPE on top of the floor beams. Figure 10 shows the construction design of the TPE floor layers, which is composed of 12 mm OSB, 90×45 mm timber studs, mineral wool, 15 mm OSB, and 12 mm gypsum fibreboard from upside to downside. It is calculated that the U value of the floor is 0.40 W/(m²·K), and the R-value is 2.50 m²·K/W. The sound insulation performance of the floor was simulated in INSUL, and the following data were obtained (Figure 11). The $L_{n,w}$ value (weighted normalized impact sound pressure level) of the roof is 68 dB, which meets the relevant requirements in *GB 50118-2010* [14].

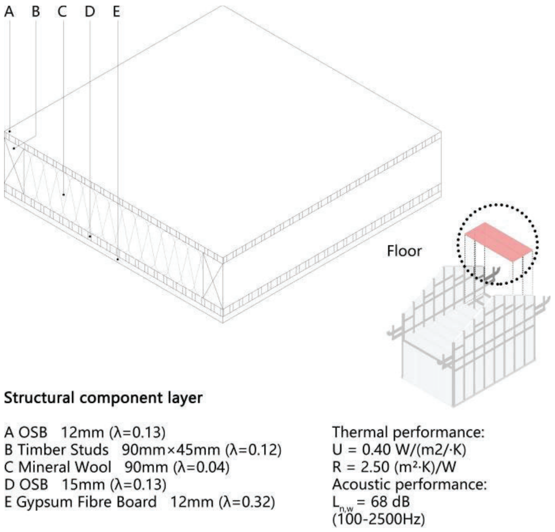


***Figure 10:*** *Construction of the TPE floor*

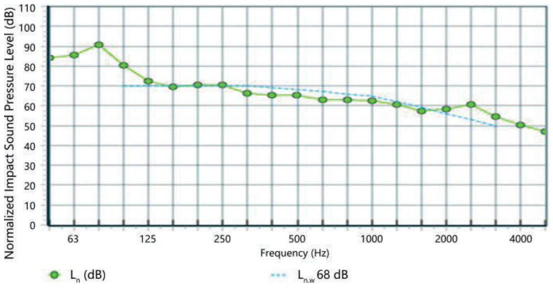


***Figure 11:*** *Sound insulation simulation of the TPE floor*

### 3.1.4 Door and windows

Traditional doors and windows can also be transformed into TPEs, optimizing the physical properties. The doors are constructed of double wooden panels sandwiching a 20 mm particle board, while the windows are constructed of double glazing sandwiching a 15 mm air layer (Figure 12). It is calculated that the U values of the doors and windows are 0.95 W/(m²·K) and 1.5 W/(m²·K), and the R values are 1.06 m²·K/W and 0.67 m²·K/W, respectively, meeting the relevant requirements in *GB/T 50824-2013*[12]. The sound insulation performance of the doors and windows are simulated in INSUL, and the following data were obtained (Figure 13). The $R_w$-value of the doors is 36 dB, the pink spectrum correction C is -2 dB, and the $R_w$+C value is 34 dB. The $R_w$-value of the windows is 36 dB, the traffic noise spectrum correction $C_{tr}$ is -5 dB, and the $R_w+C_{tr}$ value is 31 dB. Both meet the relevant requirements in *GB 50118-2010* [14].

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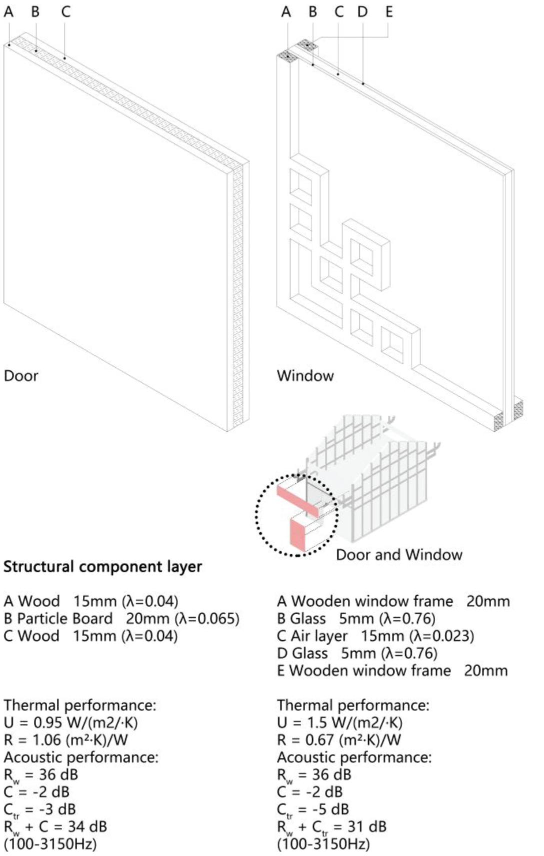


***Figure 12:** Construction of the TPE door and window*

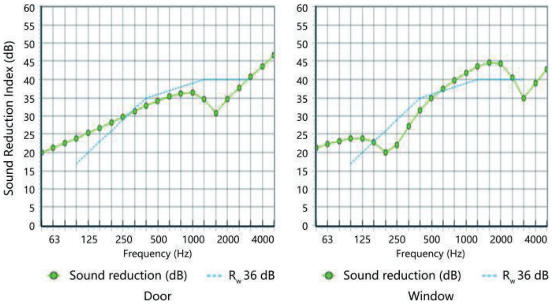


***Figure 13:** Sound insulation simulation of the TPE door and window*

## 3.2 BUILDING PERFORMANCE ENHANCEMENT

Table 3 and Table 4 show the thermal and sound insulation performances of each envelope component. It can be seen from the data that the thermal and sound insulation performance of the building enclosure layer has been significantly improved after using TPEs, all of which have filled the relevant national specifications and standards (*GB/T 50824-2013* [12], *GB/T 50361-2018* [13], *GB 50118-2010* [1]).

***Table 3:** Thermal performance of TPEs*

| Envelope structure parts | Original Thermal Resistance/ R (m²·K/W) | TPE Thermal Resistance/ R (m²·K/W) | Increased ratio | Comment |
|---|---|---|---|---|
| Walls | 0.29 | 2.35 | 810.34% | ● |
| Roof | 0.37 | 2.46 | 664.86% | ● |
| Floor | 0.216 | 2.50 | 1157.41% | - |
| Door | 0.14 | 1.06 | 757.14% | ● |
| Windows | 0.14 | 0.67 | 478.57% | ● |

● Requirement filled - Inapplicable

***Table 4:** Acoustic performance of TPEs*

| Envelope structure parts | Original Sound Insulation | TPE Sound Insulation (dB) | Standard Requirement (dB) | Comment |
|---|---|---|---|---|
| Walls | <30 dB | $R_w+C_{tr}=47$ | $R_w+C_{tr}\geq45$ | ● |
| Roof | | $L_{iA}=45$ | $L_{iA}\geq40$ | ● |
| Floor | | $L_{n,w}=68$ | $L_{n,w}<70$ | ● |
| Door | | $R_w+C=34$ | $R_w+C\geq30$ | ● |
| Windows | | $R_w+C_{tr}=31$ | $R_w+C_{tr}\geq30$ | ● |

● Requirement filled

On the basis of the original architectural model, the wall was designed as a 130 mm thick TPE wall, the roof part was replaced with a 212 mm TPE roof, a 129 mm TPE floor was added, and a 50 mm thick soundproof door and 65 mm thick windows were added. In this study, the above structures were brought into the original model, thermal analysis was carried out in Ecotect to obtain new simulation data, a comparison between the original data and the optimized data was carried out, and finally, a conclusion was drawn.

By applying all the designed TPE envelope components in the presented building model, it can be seen that the amount and ratio of heat loss or gain through the building envelope in the whole year are significantly reduced after using TPEs. Especially in summer, heat conduction through the building envelope is nearly ten times lower than before, with original values of 359,426 Wh to 37,593 Wh (Table 2, Table 5, Figure 14). The fabric heat loss is reduced to 93,597 Wh from 727,886 Wh. Passive solar radiation gains that affect the architecture of the building are also reduced to 52,092 Wh from 670,837 Wh. This is a reduction of almost 13 times. In addition, the total heat loss and gain of the building throughout the year have been significantly reduced, and the proportion of the building envelope in heat transfer has also been decreased. This shows that the thermal insulation performance of the TPE is very superior.

***Table 5:** Heat loss and gains after installing TPEs*

| Category | Losses | | Gains | |
|---|---|---|---|---|
| | Heat (Wh) | Proportion (%) | Heat (Wh) | Proportion (%) |
| Fabric (Conduction) | 93,597 | 56.1 | 37,593 | 10.2 |
| Sol-Air | 0 | 0 | 52,092 | 14 |
| Solar | 0 | 0 | 32,433 | 8.8 |
| Ventilation | 59,729 | 35.8 | 36,119 | 9.8 |
| Internal | 0 | 0 | 198,653 | 53.9 |
| Inter-Zonal | 13,347 | 8.1 | 12,162 | 3.3 |
| Total | 166,673 | 100 | 369,052 | 100 |

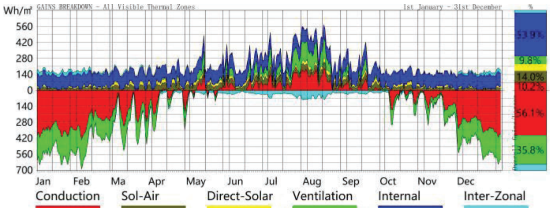


***Figure 14:*** *Thermal performance for the model using TPE*

Figure 15 shows that the temperature difference between the outside and the inside of the building has widened by using TPEs. Especially on the coldest day of the year, the indoors are always warmer than the outside the whole day long, and the temperature difference is more than 5 ℃. However, the indoor temperature on the hottest day of the year is kept at approximately 35 ℃, which is 2 to 3 ℃ warmer than before. This may have something to do with the abated natural ventilation in the building due to the improved airtightness.

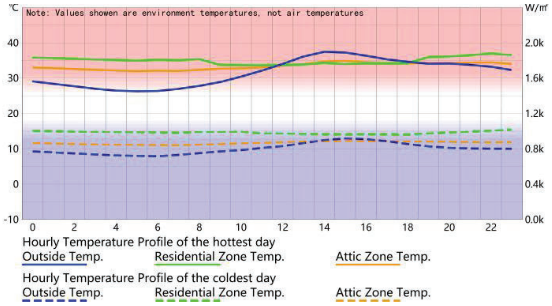
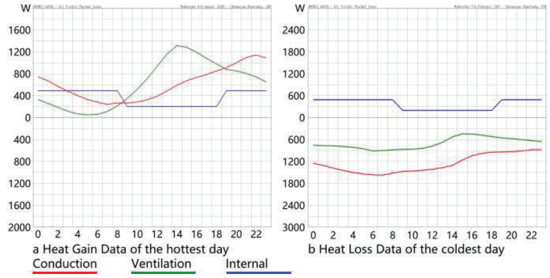


***Figure 15:*** *Hourly temperature change of the hottest and coldest day in the year after using TPEs*

Figure 5 and Figure 16 show that the maximum heat gain on the hottest day is reduced from 9,000 W to 1,200 W, and the maximum heat loss on the coldest day is also reduced from 13,000 W to 1,600 W after using TPEs. The heat lost or gained by the building through heat conduction is approximately 7-8 times less than the original value.



a Heat Gain Data of the hottest day

b Heat Loss Data of the coldest day

***Figure 16:*** *Heat loss and gain on the hottest and coldest days in the year after using TPEs*

Figure 17 shows the yearly total hours by temperature in the simulation. The time for indoor temperature within the comfort band between 18 ℃ and 26 ℃ lasts 3,968 hours and takes up 45.3% of a year without using TPEs. After using TPEs, the comfort time increased to 4,573 hours and accounted for 52.2% of the total hours for the year, with a 6.9% increase. From this comparison, it can be concluded that the thermal comfort of the historic *Chuandou* house has been improved in general through the application of TPEs.

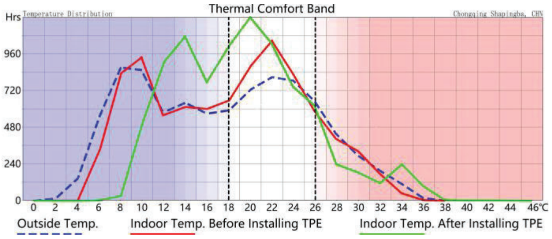


***Figure 17:*** *Comparison of total hours by temperature*

## 4. DISCUSSION

Through this study, it can be seen that the use of TPEs plays a significant role in improving the performance of historic Chinese timber-framed buildings. TPEs, which integrate the functions of enclosure, heat preservation, and sound insulation, can effectively improve living comfort. The proposed solutions consist of cladding the building envelope with a new skin based on prefabricated timber panels, improving the thermal and acoustic performance and architectural quality. The use of preassembled timber-based components and external installation reduces construction costs and time and embodied energy, which is a sustainable approach from social, economic, and environmental viewpoints.

However, this approach of this study also shows limitations. Only two performance, thermal and acoustic insulation, have been simulated and compared. Other performance, such as fire resistance and moisture-proofing, are ignored in the analysis.

In the simulation, the thermal insulation of the building in winter has been significantly improved, but the indoor temperature in summer is surprisingly higher than without TPEs. The factor leading to this result may be that the airtightness of the building has improved, so the natural ventilation for heat dissipation is also reduced. In fact, for houses in southwestern China, which are very warm in summer, the natural ventilation of the building should also be considered.

This study only designed the details of the TPE components themselves, but the details for the interface and connection between TPEs and the main building structure are not considered. Therefore, cold bridges may occur in practice and differ greatly from the experimental results. In addition, the weight of the TPE components was not taken into account, which in fact has something to do with structural safety.

## 5. CONCLUSION

China’s historic timber construction technology used to be extensively spread and advanced, but new developments in modern timber construction in Europe and North America has progressed forwards in many aspects. With the promulgation and implementation of China's national standard *Technical Standards for Prefabricated Wooden Structures* and the new version of *Standard for Design of Timber Structures (GB 50005-2017)* [17] and the

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promotion of national policies to encourage the development of prefabricated buildings, China's timber construction industry is experiencing steady growth.

This paper has gone through the design of building envelope components, integrating TPE prefabricated components into historic Chinese buildings, and obtained experimental results by software simulations. The results show the potential effectiveness of TPEs in improving building performance and demonstrate their application feasibility. However, these simulations still need practical verification, which will be a further research direction in the future. Moreover, this paper can provide a reference for the research and development of the modern adaptability of historic Chinese timber architecture.

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