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A quantitative study of the climate-responsive design strategies of ancient timber-frame halls in northern China based on field measurements

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ABSTRACT

The risks of global warming and the depletion of fossil fuels call for a re-examination of traditional buildings, which have shown satisfactory climate adaptability. Although vernacular dwellings have received considerable attention, few studies investigate other building types. In this paper, the thermal environments of ancient timber-frame halls in northern China were investigated based on field measurements to obtain more evidence of traditional ecological ideology and related strategies. As one of the main types of public buildings in ancient China, six typical halls with different orientations, openings, and ceilings but similar spatial scales and materials were selected; their air temperature, relative humidity (RH), air speed, surface temperature, and globe temperature on typical summer and winter days were measured. The results show that the indoor air temperature of the ancient halls under free-running conditions fluctuated between 22.52 and 29.46 °C in summer and between −8.91 and −2.64 °C in winter, meaning that the indoor environments are comfortable in summer but too cold in winter according to GB/T 50785-2012, which is the Chinese standard for evaluating indoor thermal environments. Further analysis shows that the key strategy for comfort in summer is to have high heat capacity to provide shelter from hot air and solar gains; natural ventilation is considered to be merely an auxiliary approach. Climate-responsive design strategies for winter consist of a south-facing orientation with a maximum window-to-wall ratio and significant thermal insulation to utilize solar gains and to provide shelter from cold air. In addition, the results reveal that ancient halls are limited in their ability to use climatic resources due to technical restrictions.

1. Introduction

Recently, the risks of global warming and the depletion of fossil fuels have required reductions in energy consumption in many countries. The building sector is one of the largest economic sectors worldwide; it generally accounts for one-third of the global energy consumption and leads to a significant amount of greenhouse gas emissions [1]; therefore, climate-responsive building design has become a necessity rather than an option for energy conservation and carbon emission reduction [2]. Revisiting traditional buildings with satisfactory climate adaptation is considered necessary for inspiring climate-responsive building designs.

Traditional buildings are constructed using locally available resources to address local needs. Their construction techniques and specifications are based on knowledge achieved through trial and error. Because the climate, socio-cultural factors, economy, materials and technology vary among locations, the traditional buildings that compose the built environment are also region-specific. As examples of harmony between people, architecture and nature, traditional buildings are a valuable resource for modern buildings because of their effective and flexible solutions that promote sustainability.

Efforts have been made by researchers worldwide to study the climate-responsive design strategies of traditional buildings. Investigations of this nature have been reported in China, France, Greece, India, Japan, Korea, Turkey, Vietnam and many other countries [3–18]. Researchers address the climate-responsive design strategies of traditional buildings in two different ways: qualitatively and quantitatively. The qualitative approach involves the assessment of the environmental performance of different building elements in relation to local climatic conditions [3–7]. The quantitative approach is based on either field measurements of different

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climatic parameters or computer simulations; this approach leads to conclusions concerning the effectiveness of climate-responsive design strategies of traditional buildings [8–18]. However, because almost all the traditional buildings involved in the above studies are vernacular dwellings, little attention has been paid to other building types, such as traditional buildings for the purposes of administration, sacrifice, religion, and education. This research gap can be attributed to the fact that residential buildings form the majority of civil buildings from ancient to modern times. Since vernacular dwellings have more similar functions and design principles with contemporary residential buildings than public buildings, their climate-responsive design strategies have been applied mostly to contemporary residential buildings accordingly [19].

In China, large public buildings constitute less than 4% of all civil buildings but account for more than 20% of the total energy consumption. The electricity consumption per unit area of a large public building is 10–20 times that of a residential building [20] due to the energy-intensive solutions employed in large public buildings to create comfortable conditions, including mechanical cooling, forced ventilation and artificial lighting. The northern region of China experiences cold, dry winters and hot, humid summers. This relatively harsh climate makes it more difficult to reduce the energy consumption of large public buildings. Because buildings must rely on mechanical systems to maintain thermal comfort under extreme conditions, the wisdom of designing according to the climate is often ignored in the design of large public buildings. Therefore, designing sustainable large public buildings is an important issue, especially in northern China. However, residential and public buildings are significantly different. Hence it is necessary to revisit public buildings that were designed and constructed in ancient times.

Ancient timber-frame halls are one of the main public building types in ancient China. They were used by emperors and secretaries and were constructed to hold sacrifice, religion and many other public activities. Moreover, they were built by the authorities who possessed sufficient funds and used high-level construction techniques to provide comfortable indoor environments and express their owners' authority. In other words, ancient timber-frame halls represent the architectural and artistic styles of that era as well as the highest level of construction ability during a certain period of time. The primary difference between the halls and vernacular dwellings is size. In addition, they differ in their exterior forms, interior decorations, materials and details according to their official status and function. These differences could lead to differences in their climate-responsive strategies, which could be more applicable to contemporary public buildings. These halls are no longer being built. For the purposes of protection, most of them are not fitted with mechanical systems and still provide traditional indoor environments, which is beneficial for learning the wisdom of the ancients. Since a number of climate-responsive design strategies used in vernacular dwellings have been summarized in previous studies and supported the climate-responsive designs of contemporary residential buildings around the world, revisiting ancient timber-frame halls in northern China will also inspire climate-responsive designs of large public buildings at present time to decrease energy consumption and promote sustainability.

This study aims to (1) investigate the indoor environments of ancient timber-frame halls and (2) discover the climate-responsive strategies used in them. In this study, the thermal environments of six ancient halls in northern China were measured in summer and winter. Based on the measurement results, the thermal comfort of each building was evaluated using the adaptive model proposed by GB/T 50785-2012, the Chinese standard for evaluating indoor thermal environments [21]. Then, the results were analysed comparatively, and some building design elements were found to have important influences on the indoor thermal environment. Finally, conclusions were drawn to outline the climate-responsive design strategies.

2. Ancient timber-frame halls in northern China

2.1. General data on the geography and climate of northern China

China can be divided into four geographical regions in terms of location, natural conditions and cultural background: the northern region, the southern region, the northwest region and the Qinghai Tibet region (Fig. 1a) [22]. Located between 34°N and 53°N latitude and between 100°E and 135°E longitude, the northern region lies to the west of the Greater Khingan Range and Qinghai Tibet Plateau, north of the Inner Mongolian Plateau, south of the Huai River and Qin Mountains and to the east of Bohai and the Yellow Sea. The majority of the ancient timber-frame halls are located in the southern part of this region (Fig. 1b).

Fig. 1c shows the five climatic zones in China [23]: the Severe Cold Zone, the Cold Zone, the Hot Summer and Cold Winter Zone, the Hot Summer and Warm Winter Zone, and the Mild Zone. Most of the ancient timber-frame halls in northern China are located in the Cold Zone (Fig. 1d). The Cold Zone typically experiences cold, dry winters and hot, humid summers. In January, the mean minimum temperature varies between −10.4 and −4.0 °C, and the mean maximum temperature ranges from 0.7 to 4.2 °C. In July, the mean minimum temperature falls within the range of 18.8–23.4 °C, and the mean maximum temperature falls within the range of 29.5–31.1 °C. The mean relative humidity (RH) varies between 42.7% and 66.1% in January and between 70.4% and 79.1% in July. In addition, there are abundant solar resources in this region, with a solar radiation of 603.8–811.9 MJ/m^2 in winter and 1457.0–1666.0 MJ/m^2 in summer. The prevailing wind in this region comes from the south during the hot season, with a mean wind speed of 0.9–2.7 m/s, and from the north during the cold season, with a mean speed of 1.5–2.8 m/s. The annual precipitation in the region falls within the range of 300–1000 mm, with less rainfall in spring but heavier showers in summer and autumn. The annual number of days on which rain falls ranges between 60 and 100 d, with less than 15 days [24] of snowfall.

2.2. Description of the ancient timber-frame halls

Throughout history, the Chinese have always employed an indigenous system of construction. As shown in Fig. 2, in this system, an ancient timber hall consisted of a platform, a structure with a timber post-and-lintel skeleton and a curved roof. The raised platform served as the base of the structure, and the structure supported the curved roof with overhanging eaves. This construction permits complete freedom for walling and fenestration and, by simply adjusting the proportion between the walls and openings, renders a building practical and comfortable in many climatic conditions while also meeting the other occupant needs.

3. Outline of the field measurements

3.1. Building descriptions

The six timber-frame halls selected for this study were Xiang Hall of the Imperial Ancestral Temple (Building TM), Guanyin Pavilion of the Dule Temple (Building DLS), Long'en Hall of the Putuo Yu Ding Dongling (Building CX), Long'en Hall of the Puxiang Yu Ding Dongling (Building CA), Daxiongbao Hall of the Huayan Temple (Building HYS) and Daxiongbao Hall of the Shanhua Temple (Building SHS). These halls were all built in different dynasties and