Chapter 13
Design Research on Climate-Responsive Building Skins from Prototype and Case Study Perspectives

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Abstract As low-carbon and sustainable development has become a global trend, climate-responsive building envelopes still gain traction in the architecture world. However, relevant design and research remain too disconnected to drive further breakthroughs. Thus, this chapter explores an integrated design-research approach for climate-responsive building skins, especially for the continental climates in China. The study begins with a practical case in China's Cold Zone to demonstrate how architects consider climate responsiveness when designing building skins and reveal the challenges the static structures might face in responding to external dynamic climates. A research prototype of climate-responsive skin was extracted from the Cold Zone case and materialized in a full-scale test platform. A series of comparative experiments are performed to identify the optimal solution for each of the four key design features and their optimal combinations for summer and winter, respectively. The thermal performance impact of each design feature and the energy-saving behaviors of the seasonal optimal configurations are also evaluated quantitatively. In order to integrate the highly differential summer and winter configurations for maximized climate responsiveness, a novel dynamic skin prototype with rotatable triangular blades is further presented. Overall, the study aims to bridge the gap between the research and design of climate-responsive building skins, thereby providing a reference for their application in similar climates.

Keywords Climate responsiveness · Building skin · China · Continental climates

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13.1 Climate-Responsive Building Skins

As one of the core topics in architecture, climate responsiveness remains relevant in the context of the global endeavor to cope with climate change and pursue sustainable development (Papadikis et al., 2019). Discussions about the climate responsiveness of buildings involve the impact of climatic elements on indoor environments and comfort levels, requirements for structural safety and material durability, and the possibilities of adjusting user behaviors responding to the environment (Hao, 2016). Among all building components, envelopes play an essential part in allowing buildings to respond to the changing climate. It is because they are the main interface separating the indoor and outdoor environment, a shield or buffer against light, heat, humidity, wind, rain, snow and other climatic factors, and an important carrier for human factors engineering (HFE). In this context, such concepts as "climate responsive skins", "bioclimatic skins", "smart skins" and "adaptive building envelopes" emerge. Currently, research on the climate responsiveness of transparent envelopes represented by double-skin facades has been evolving due to the springing up of high-rise office buildings, while opaque envelopes are relatively less studied (Ibanez-Puy et al., 2017). For most building types, however, the latter tends to cover a better part of the surface area, and their role in climate regulation cannot be ignored. Therefore, this paper selects opaque envelopes as the main object of design and research.

In terms of design practice, architects in different parts of the world have been exploring ways to make building skins more climate-responsive. Considering the tropical climate of Africa, Jean Prouvé equipped his prototype Maisons Tropicale with continuous, adjustable louvered aluminum sunscreens to reflect the intense sunlight, as well as the double roof structure and central roof vent to remove heat quickly. Built in the Chesapeake Bay in the United States, KieranTimberlake's Loblolly House is covered with overlapping cedar boards, which serve as a "filter for rain, wind and solar radiation (Kieran & Timberlake, 2008)". In response to China's hot summer and cold winter, Shanlong Tan used semi-transparent polycarbonate materials to wrap the building at Xiuning primary school, balancing ventilation and insulation through some air vents. Facing the Spanish Mediterranean climate, H Arquitectes and DATAAE adopted polycarbonate shutters as the bioclimatic skins of the ICTA-ICP research center. Controlled by environmental sensors, the shutters automatically shut down during cold and wet weather, and open to increase ventilation when the weather is hot and dry.

In terms of academic studies on the climate responsiveness of opaque building envelopes, researchers focus more on opaque ventilated facades (OVF) and have come a long way. It is observed that most studies about OVF focused on the hot temperate climates in southern Europe and the Mediterranean region (e.g., Italy and Spain), which can be further categorized as a temperate oceanic climate (Cfb type) (Fantucci et al., 2020; Labat et al., 2012) and the hot-summer Mediterranean climate (Csa type) (Aparicio-Fernández et al., 2014; Peci Lopez et al., 2012) according to the Köppen–Geiger classification (Kottek et al., 2006). With the rapid development and global spread of OVF, the research field has gradually expanded to other climate zones like tropical and subtropical areas (Zhang & Yu, 2017; Fernandes Maciel & Carvalho, 2019; Gregorio-Atem et al., 2020) and some particular application scenarios like extremely windy climate (Mammadova et al., 2021). However, studies for continental climates (D type) with hot, humid summers and cold, dry winters, such as in the cold zones in China, are still rare.

Secondly, As a result, most current studies devoted themselves to investigating the thermal behavior of OVF in the dominant hot seasons (Marinosci et al., 2014; Stazi et al., 2014), and it is widely agreed that the shading effect of the external skin and the natural convection of the ventilated air duct can help to remove part of the heat load cross the facade, thus reducing the indoor heat gain in the summer period. Although papers about the winter behavior of OVF are relatively more minor, they have drawn more attention in recent years (De Masi et al., 2021; Peci Lopez & de Adana Santiago, 2015). Some authors proved that installing an OVF brought positive winter energy savings by preventing the outdoor cold winter or recovering the heated air in the cavity for indoor warming. However, winter investigations still acted like supplements for the summer studies due to their less significant energy-saving rates. The winter configurations of OVF often inevitably give way to their summer versions, resulting in nonoptimal performances in the cold seasons. Consequently, the annual benefits of OVF cannot be fully discovered, leading to restrictions on further popularization, especially in regions with significant seasonal variability.

Thirdly, these OVF studies are centered on such typical commercial systems as rainscreen ventilated facades (Marinosci et al., 2014) and open-joint ventilated facades (Sánchez et al., 2017). Less exploration of more skin structures has led to the failure to meet the increasingly diverse needs for design. Furthermore, the gap between practice and research is widened by the fact that architects and researchers, which are by nature two different professions, do not necessarily have shared values, expertise and work methods.

In order to bridge this gap, and with the advantage of being both architects and researchers, the authors aim to explore an integrated design-research approach to climate-responsive building skins, aiming to expand their application border to continental climates with hot, humid summer and cold, dry winter. This paper begins by introducing a practical case in the Cold Zone of China, and elaborating on how the building skin was designed to respond to the dynamic climate, thus revealing the gains and limitations of architects' efforts. On this basis, the authors extracted the opaque ventilated facade with louver cladding as the prototype, materialized it in a Cold Zone-specific test platform, and then conducted comparative experiments on its key design features to obtain the optimal configurations suited to summer and winter conditions respectively. Finally, to integrate the highly differentiated skin structures for summer and winter, the authors propose a new triangular blade prototype with a variable structure, which is expected to outperform traditional static skins and achieve maximum climate responsiveness.

13.2 A Case Study in Continental Climate

13.2.1 Project Description and Climatic Features

Located in Shunyi District, Beijing, CSC Zero-carbon Pavilion (CSC Pavilion), serves as a small community center. It is also a Nearly Zero Energy Building with BREEAM Outstanding and LEED Platinum certifications. The building is composed of three b-shaped building units around the sunken courtyard in the center, which function as the meeting room, exhibition hall and gym respectively, with a total construction area of about 157 square meters (Fig. 13.1).

The CSC Pavilion was developed to respond to the continental climates in China, characterized by hot, humid summers and cold, dry winters. In determining the main building structure, the design team used the prefabricated laminated timber structure and the light-timber framed insulated envelopes, aiming to reduce the embodied carbon in material uses and to restrict the environmental impacts of on-site construction or the potential demolishing in the future. Moreover, to improve the energy efficiency during the operation stage, the CSC pavilion was further designated as an integrated platform for various passive architectural design strategies and active energy-saving building technologies. As one of the promising passive solutions, the concept of climate-responsive building skin was introduced from the very early design stage and successfully implemented in the construction phase, especially for the opaque parts.

Fig. 13.1 The meeting and exhibition units of CSC Pavilion

Beijing is a typical city located in China’s Cold Zone, which has a humid continental climate, or Dwa type (Fig. 13.2). In this zone, temperatures vary greatly in different seasons; it is hot and rainy in summer, and cold and dry in winter. The average outdoor temperatures in the two seasons are 27 and −2.9 °C respectively, and the prevailing winds are S and N respectively. This shows that responding to the Cold Zone’s climate is more complex and challenging than other climates that were only dominated by hot or cold seasons (Fig. 13.3).

Moreover, Beijing is located in the Normal Zone regarding solar radiation resources in China, with cumulative solar radiation averaging around 1550 and

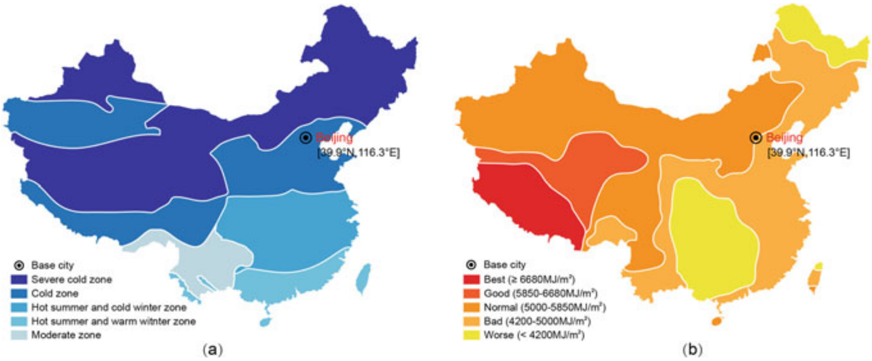


Fig. 13.2 **a** Climate zones for building thermal design and **b** Solar resource zoning of China

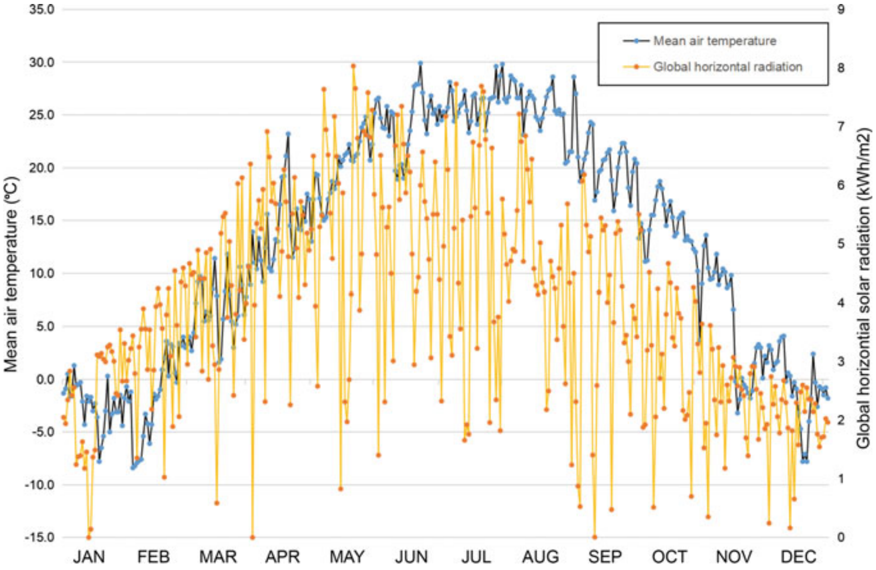


Fig. 13.3 Climatic features of a typical city in the Cold Zone (Beijing)

710 MJ in summer and winter, respectively. However, this relatively intense solar radiation will differently impact the building performance according to the season. During the summer, it usually causes the penetration of undesired solar heat into buildings, bringing indoor overheating risks; during the winter, it turns to serve as a positive heat source for reducing heating demands. As the interface directly contacting with the external climatic factors, the building skin's dynamic regulation capacity for solar radiation becomes a challenging issue.

13.2.2 Design of the Climate-Responsive Skin

The design team defined the south facade of CSC Pavilion as the primary interface for indoor lighting, ventilation, and visual access, meaning that the full- or semi-transparent envelopes were mainly adopted, such as the highly insulated single glazed facades in the gym and meeting units, and the double-glazed ventilated facade integrated with thin-film photovoltaic modules in the exhibition unit. Nevertheless, it should be noted that, as the climatic responsiveness of these transparent-type facades had been explored in the previous studies (Lin, 2018), this paper mainly focuses on the opaque ventilated facade, which was applied to the east, west and north facades of each unit, and a small number of such modules were used on the south side of the gym unit.

In more detail, this OVF system consists of three layers. The external skin is formed by carbonized timber battens and anchored to the internal base wall through a supporting steel frame. The internal light-wood framed wall provides basic thermal insulation, water- and air-tightness. These two layers are separated by a 150 mm-width air cavity, serving as a buffer zone or a ventilation duct.

Considering the inherent difficulties of static skin structures in responding to the changing external climate, the ventilation state of the OVF cavity was changed by adjusting the timber batten's openness for different facade orientations to enable a response to both summer and winter climates in the Cold Zone. For the east, west and south facing facades exposed to direct solar radiation, the utilization of a closed cavity will cause overheating inside and provide cavity temperature even higher than the ambient one, thus bringing extra cooling loads in summer. In this regard, the team learned from the working principle of ventilated facades, opening multiple groups of wooden battens at the bottom and top of the external skin to form air inlets and outlets. By introducing the solar chimney effect, the vertical airflow driven by the thermal buoyancy was successfully established and exhausted the undesired hot air in the cavity. The timber louvers at the vents were opened by rotating at particular angles (40–80°), guaranteeing sufficient areas for air exchange between the cavity and the outdoor environment. As shown in Fig. 13.4, the varieties in angle, number, and position of the rotated timber batten provided more aesthetic possibilities for the whole facade system. It even created icon shapes representing different building functions, like the beating-heart icon beside the entrance of the gym unit (Fig. 13.5).

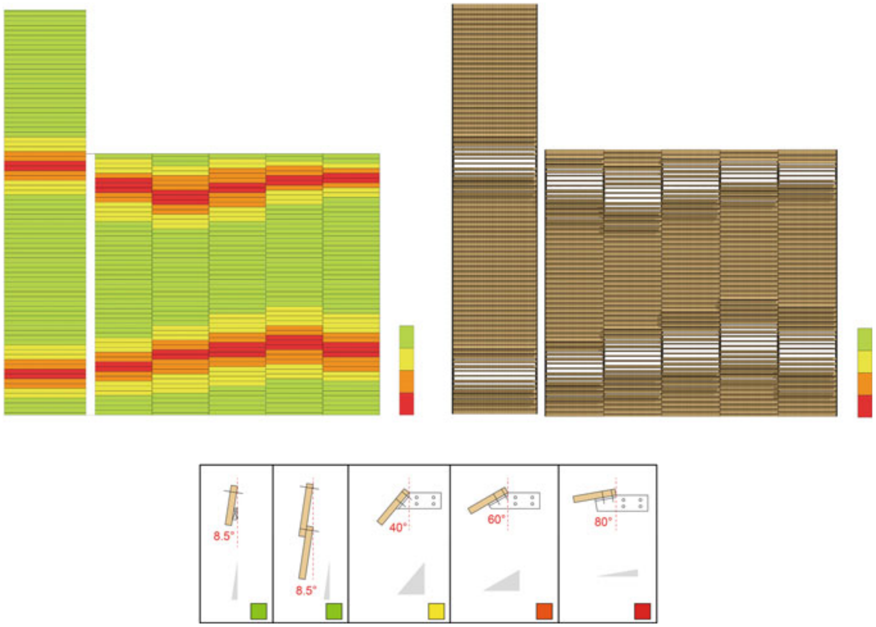


Fig. 13.4 Patterns for CSC Pavilion's timber louvers

However, it should be noted that, further evaluations for the thermal and energy impact of the ventilated facades in the cold winter are also essential.

For the north facing facade, free from direct solar radiation and acts as the primary windward side in winter, a thermal buffer formed by the closed cavity helps prevent heat loss through the internal walls. Thus, in this orientation, the timber louvers are no longer opened but are closely connected to create a continuous interface.

In terms of the physical implementation, the external skin of CSC Pavilion, with a total area of 369 square meters, was divided into 64 prefabricated modules (Fig. 13.6). These modules were supported by a steel frame while the carbonized timber battens were attached to the frame through wood angle adjusters.

For time-saving, the team initially planned to prefabricate the whole skin module in the factory. However, the 1:1 mock-up showed that the regular shape of the modules would be broken when integrated with the timber battens, especially the rotated ones. This not only occupied more transportation resources but was also more prone to damage during the transportation and installation process due to its more complex and fragile structure. Therefore, the architects separated the timber battens, which were carbonized and trimmed only in the factory, from the steel frame, which was prefabricated and integrated along with the angle adjusters. After the prefabricated steel frame was hoisted and fixed on-site, skilled workers would nail the timber battens onto the adjusters in a very short time (Fig. 13.7). This "moderate prefabrication" strategy worked as it capitalized on the complementary advantages of factory


(a) (b)

Fig. 13.5 The western facades of the **a** exhibition and **b** gym units of CSC Pavilion

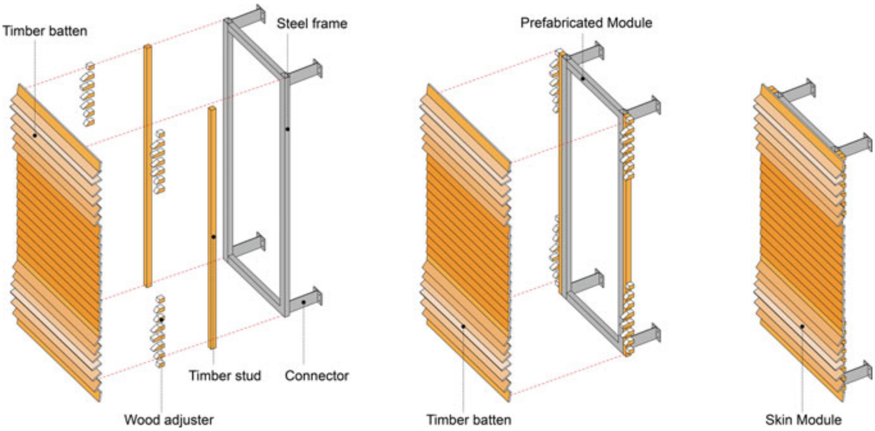


Fig. 13.6 Structure of CSC Pavilion's skin module

prefabrication and on-site assembly. It was a cost-efficient solution that it took only five workers one week to complete the whole installation.

Fig. 13.7 Prefabrication and assembly of the skin modules **a** mock-up module; **b** steel frame; **c** wood adjuster; **d**–**e** installation of steel frame with adjusters; **f** installation of timber battens

13.2.3 Limitations and Challenges

The practice of the CSC Pavilion shows how Chinese architects make building skins more responsive to the continental climate. Their specific design strategies, construction methods, and performance presentations will provide references for future practice in similar climates. However, exploring climate-responsive skins simply based on practical cases has its limitations.

Firstly, the fast construction pace in China leaves construction teams little time for systematic prototype studies. Their understanding of skin-specific climate responsiveness comes primarily from their knowledge base of thermal engineering and limited meteorological insight.

Secondly, such practical factors as aesthetics, cost, construction time, and the owner's preference often come into play in the design process. The preference for static structures in most projects, for example, results in a skin system that can only respond to the ever-changing external climate in a limited or moderate manner. Even if the testing process is carried out after construction, it will be, more often than not, reduced to the verification of the original design plan due to temporal and spatial constraints: it is difficult to conduct long-term comparative experiments with multiple variables to discover how the building skin responds to the external climate or to reach specific strategies for structure optimization.

Based on this, the authors recognize the necessity of shifting the exploration of climate-responsive skins from sole reliance on case design toward integration with prototype research. Fortunately, the authors' team, which comprises both researcher and architect members, is well-positioned to explore an integrated design-research approach to climate-responsive building skins.

13.3 Prototype Research

13.3.1 Prototype Extraction

Based on the previous practice in China and the analysis of other existing cases, the prototype of opaque climate-responsive skin is not complex and mainly consists of three parts: the internal wall, air cavity and external skin. The innermost wall is responsible for fundamental functions such as thermal and sound insulation, fire prevention, waterproofing and air-tightness, serving as the ultimate barrier between the indoor and outdoor environments. The intermediate cavity acts as a buffer or coupling zone for different environmental factors (heat, moisture, wind, solar radiation, etc.) between the internal wall and the external skin, usually with structural components connecting the two. And the external skin, which may be composed of multiple materials, is directly exposed to the ambient climate, severing for light and solar radiation filtration, wind and rain prevention, thermal and sound insulation, and determines the overall visual image of the building. However, when it comes to the specific configuration for each layer, a multitude of variables could emerge: (1) the material, color, smoothness, opening ratio, inclination, the opening position of the external skin; (2) the geometry of the air cavity, the connection with the indoor and outdoor environments, the internal division, and the application of mechanical ventilation devices; (3) thermal resistance and inertia of the internal wall, as well as its surface material, color and roughness settings. The variation and combination of different parameters offer a wealth of possibilities for the forms and climate responsiveness of the opaque building envelope with a double-layer structure.

On this basis, the authors extracted a simplified skin prototype from CSC Pavilion's timber-batten facade for the following experimental investigation. Its reasons can be attributed to three: First, as one of the general facade techniques, the batten skin shares a worldwide application, making this study more practical and typical; Second, the practice of CSC Pavilion can provide direct guidance and reference on implementing prototype skin physically; Finally, few performance investigations of batten skin are conducted under the typical continental climates, which determines the necessity of prototype exploration.

To simplify the research boundary conditions, the external battens of the prototype skin are no longer rotated but uniformly set parallel to the internal wall. For this prototype, four key design features are further extracted by a comprehensive analysis of previous studies and relevant practices: (1) the color and (2) the joint opening ratio of the external skin; (3) the air vents openness and (4) the cavity depth. From the performance perspective, the first two features are more related to solar radiation control, while the latter two are associated with cavity ventilation regulation. From the design perspective, these four features have the most significant impact on the overall form of the skin, and are thus the focus of architects' attention.

13.3.2 Prototype Experiments

Based on the extracted skin prototype and its key design features, the research team planned to conduct a systematic study of the climate responsiveness of the prototype skin under real climate, so as to reach its optimal design and operation strategies. Supported by Tsinghua University and Tsinghua Redbud Innovation Institute, the team built a full-scale test platform in Tianjin (Fig. 13.8), a city only 90 km away from Beijing with a very similar climate. Consisted of two identical (3000 × 3000 × 3200 mm) and non-interfering (distance >7 m) test rigs, the platform enables comparative experiments and analysis of control variables under the same external climatic conditions. On this basis, the research team materialized the extracted skin prototype as follows:

The eastern and western walls of the test rigs are constructed of a wooden frame with a depth of 140 mm and filled with foam polyurethane insulation. They are covered with oriented strand boards with a thickness of 9 mm, as well as white breathing membranes. With a comprehensive heat transfer coefficient of about 0.22 W/m^2·K, these walls provide the basic thermal insulation.

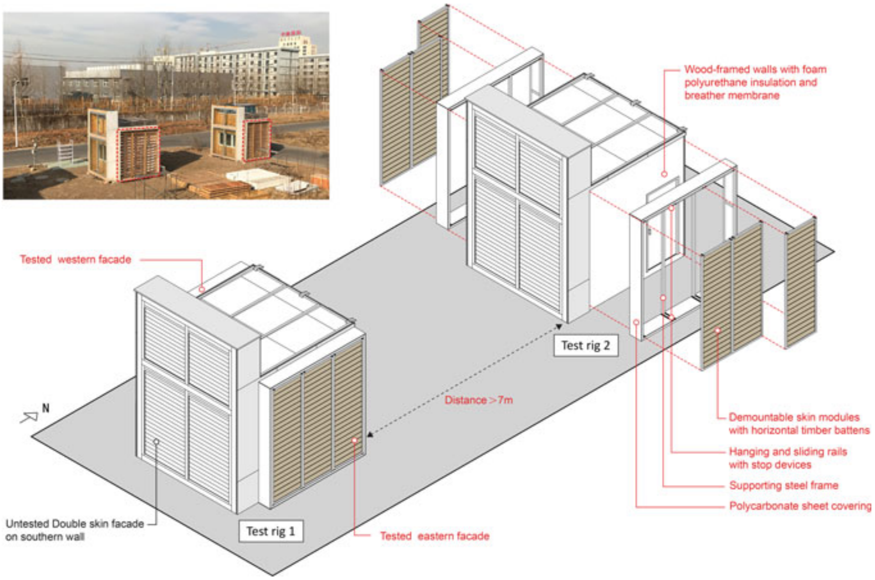


Fig. 13.8 Comparative test platform & structure of the timber batten skin

The external skin consists of three demountable skin modules of the same size (3000 × 920 × 50 mm), which, after being mounted to the rectangular steel frame on the outer side of the internal wall, can be slid and stopped freely perpendicular to the internal wall by means of hanging rails with stop devices, thus creating cavities of different depths ranging from 50 to 350 mm. It is worth noting that the other faces of the steel frame are covered with polycarbonate sheets to avoid unorganized connectivity of the cavity with the ambient air.

Each skin module consists of uniform horizontal wooden battens (820 × 125 × 10 mm) combined with a timber frame. Three design features can be adjusted by changing the patterns and assembly methods of timber battens: The joint opening ratio of the skin can be controlled (0/6.25/12.5/25/50%) by adjusting the distance between adjacent battens; The air vents openness can be changed by retaining or removing battens at the top and bottom; The external cladding color (white or wood) can also be altered by wearing a different coat.

Based the test platform and its variable facades, the research team conducted a series of comparative experiments on the skin prototype under summer and winter conditions (Fig. 13.9).

Firstly, in-field experiments were performed to measure the outer and inner surface temperatures of the internal wall. With the measurement of the internal walls' thermal conductance (C_{wall}), their penetrating heat flux were successfully calculated and transformed into the daily cumulative thermal gain (E_{gain}) and thermal loss (E_{loss}) values for each tested configuration. Through comparing these thermal performance metrics, the optimal solution for respective design features were determined.

Secondly, the impact of different design features on the envelope's thermal performance was compared. As shown in Fig. 13.10, a normalized analysis involving all

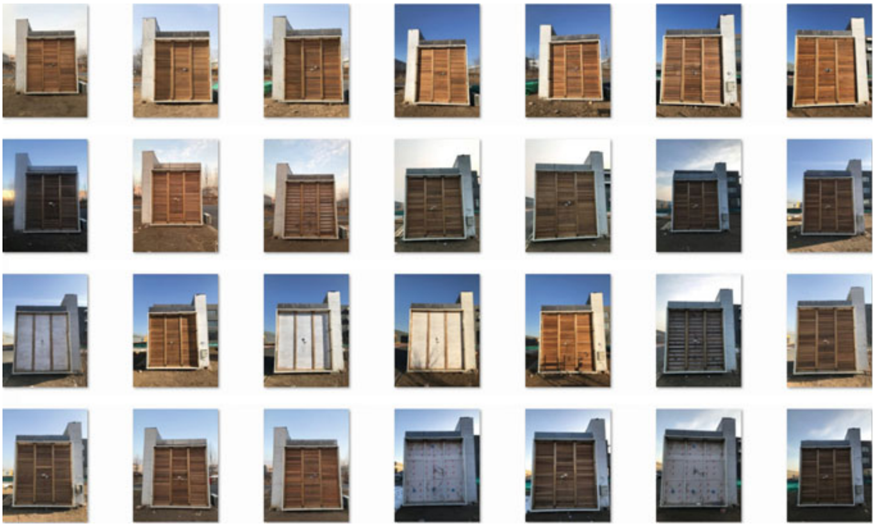


Fig. 13.9 Various skin configurations under experiments

skin configurations was conducted using the E_{gain} value of Facade B and the E_{loss} value of Facade A* as the summer and winter thermal benchmarks. In the summer tests, the thermal influence of four design features on resisting heat gain were ranked as follows: joint opening ratio (30.6%) > external cladding color (17%) > air vents openness (7.8%) > cavity depth (4.8%). It is evident that the former two design features are directly linked to the design of external skins, with the joint opening ratio of 6.25% and bright color being the optimal solutions. In other words, it is suggested to maximize the shading effect of the external skin and reduce its solar radiation absorption. The latter two features are tied to the cavity ventilation state, with a cavity depth of 200 mm and additional top and bottom vents promoting vertical airflow as the optimal solutions. Therefore, for the skin to respond to summer climates, the design team should prioritize the resistance to direct solar radiation and optimize the structure to facilitate thermal exchange between the cavity and the external environment. In the winter tests, the thermal influence of four design features on resisting heat loss was ranked as follows: joint opening ratio (19.8%) > cavity depth (12.5%) > cladding color (2.2%). Among them, 0% is the optimal solution for joint opening ratio, aiming to minimize the contact between the external cold air and the internal wall, no additional air inlets and outlets on the skin are needed. In addition, a medium depth for the sealed cavity is best for thermal insulation. Moreover, in winter, the adoption of external skins with dark color and a high absorption rate in solar-rich areas will slightly improve thermal performance. Therefore, under winter conditions, the closed cavity should be used on a priority basis to create an insulation buffer.

Thirdly, the best solutions for four key design features were systematically integrated to obtain optimal configurations responding to summer and winter climates. These optimal configurations with double-layer structures were further compared with the conventional single-layer facade to verify their performance advantage and connect to the actual application scenario. It should be noted that these tests were conducted with the air conditioners activated, and their daily energy consumption data were collected by power meter plugs. Based on the energy use comparison, it is found that the optimal skin configurations, when applied only to the east and west facades of the test rigs, can bring a considerable saving of cooling energy (11.4%) in summer and heating energy (6.7%) in winter.

13.3.3 Prototype Integration

The two optimal combinations discussed above have proven effective in addressing the hot summer and cold winter in China's Cold Zone, improving climate responsiveness from the energy perspective. However, its construction is markedly different in summer and winter. If the skin system is restricted to static structures, it can only be designed to respond to the region's prevailing climate. For example, although the energy-saving ratio of the winter-specific skin prototype is relatively low, its absolute energy saving is 2.3 times higher than that of the summer solution. The optimal combination for winter use should thus be prioritized in optimizing the skin,

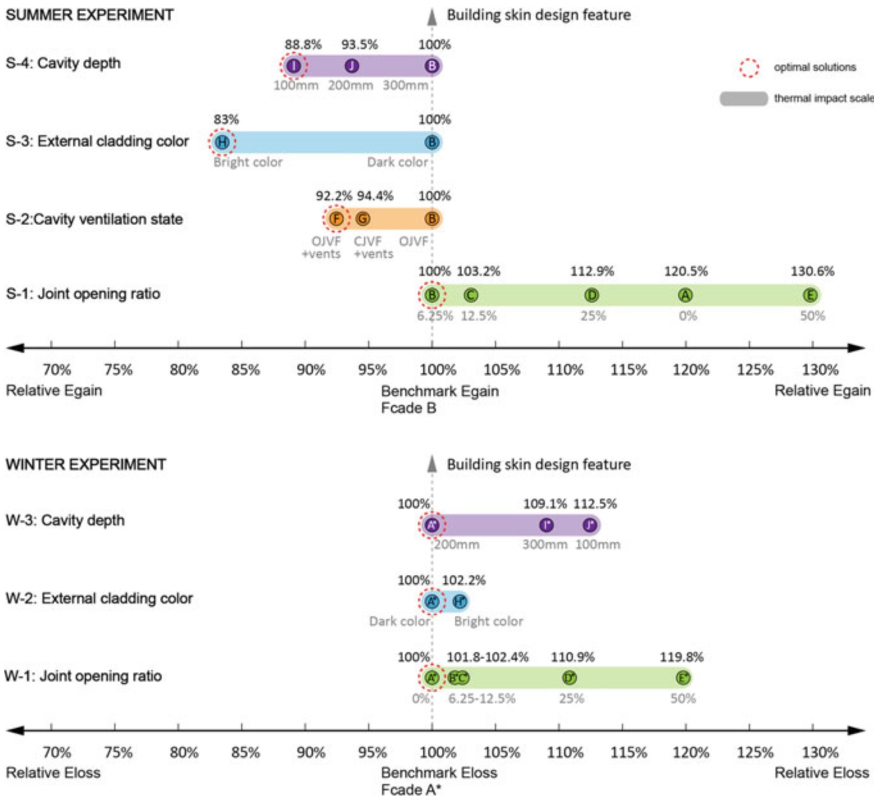


Fig. 13.10 Impact of key design features on thermal performance and respective optimal solutions

which, however, will also lead to weakened responsiveness to the summer climate. Therefore, introducing variable or dynamic structures might be an effective alternative. Nevertheless, new technical difficulties could arise, including the need to (1) integrate all design features on the same skin system; (2) make each feature independently controllable; (3) build a variable structure that is stable and easy to operate; and (4) meet basic performance requirements such as waterproofing, rain proofing, airtightness, and structural durability.

The conventional slatted wooden skins cannot meet the above objectives due to their differentiated structural requirements for summer and winter applications. Inspired by the Roman architect Vitruvius's Periaktoi, a kind of wooden prism device designed to rapidly change theatre scenes in ancient Greek and Rome (Fig. 13.11), the authors propose a variable triangular blade skin system for use in different climate scenes. Unlike Vitruvius's design, these triangular blades are installed horizontally and arranged from top to bottom to form a complete climatic interface. Their inner sides and the internal wall create the cavity space as a climatic buffer. At the same time, each side of the blade can be made of different materials, and the axial rotation

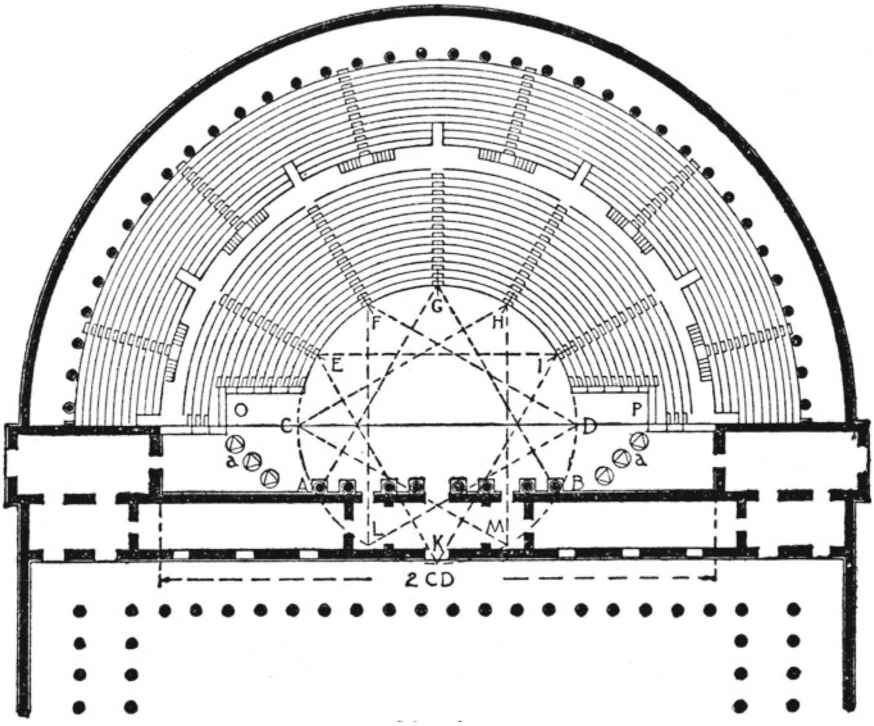


Fig. 13.11 Plan of a roman theater using Periaktoi (Harrison et al., 2013)

of the blade allows the climatic interface to be freely switched, thus making the skin much more climate-responsive and diverse in its appearance. Furthermore, due to the unique cross-section of the triangular blades, when all of them rotate together, changes in their distance will bring different joint opening ratios.

Based on this triangular blade prototype, the research team integrated the summer and winter optimal skin configurations obtained in Sect. 13.3.2. As shown in Fig. 13.12, the three sides (Sa, Sb, Sc) of a triangular blade can be made of dark-colored wood, bright-colored wood and heat reflective materials (e.g., aluminum foil) respectively. Different blades are connected to each other by a hinged drive rod, and synchronously rotated from 0 to 90° around the axis by an electric push rod. And their position is controlled by a baffle fixed at the junction of the Sa and Sc side.

In winter, the Sc faces of the blades are tightly connected to form an interface parallel to the internal wall. In addition to a sealed cavity, the heat-reflective materials on the Sc faces will also enhance the insulation performance of the skin. At the same time, the dark-color material on the Sa side is also rotated to a position that directly faces the sunlight, thus absorbing heat from solar radiation to further warm up the air cavity. In summer, the blades can be rotated 90° inward along the axis. In this case, their light-colored sides turn to face the sunlight and help reduce heat gain by directly reflecting the intense sunlight. The mutual shading effect of the

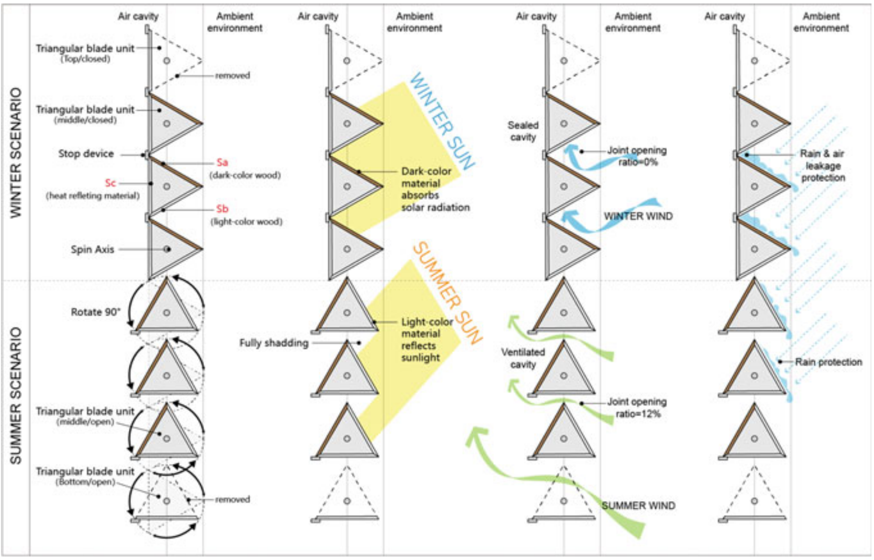


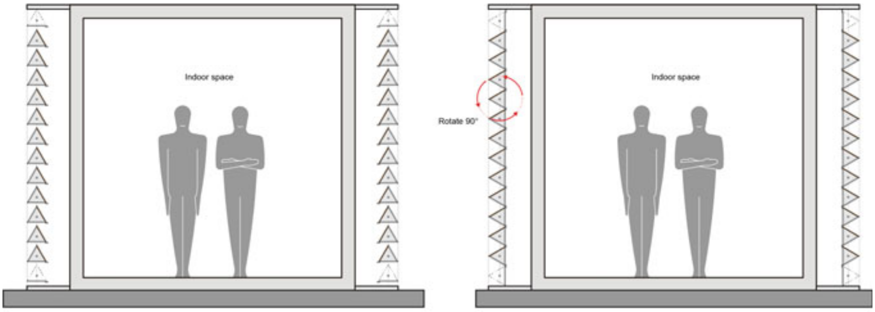
Fig. 13.12 Structure and climate responsiveness of triangular blades

adjacent blades can also prevent solar radiation from entering the cavity. The gaps between the rotated blades also connect the cavity and the ambient air, creating an open-joint ventilated facade (with a joint opening ratio of about 12%). Additionally, to strengthen buoyancy-driven ventilation within the cavity, it is also possible to remove the Sa and Sb sides of the top and bottom blades, leaving the remaining Sc sides to ensure the closure of the cavity in winter and work as vents in summer. Overall, the above triangular blades enable changes in the joint opening ratio, external cladding color and cavity ventilation state under different climatic conditions. Moreover, in winter, the limit plate between the blades equips the skin with an airtight and watertight structure; in summer, its equilateral triangular section forms a rainproof structure, thus ensuring the weather resistance of the prototype. As to the cavity size, it has been proved that the same 200 mm-deep cavity simultaneously brings the best thermal performance in summer and winter, which this triangular blade skin system can directly adopt.

Therefore, the final summer and winter modes for this triangular blade skin were obtained and presented in Fig. 13.13.

13.4 Conclusion

As China pledges to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 (Jia & Lin, 2021), its building sector has contributed to the national decarbonization efforts through active reduction of energy consumption in the operational



(a) (b)

Fig. 13.13 The **a** summer and **b** winter modes of the triangular blade skin

phase. In this process, passive design and technology solutions, including climate-responsive skins, have an essential role to play. However, while both architects and scientists have worked to explore the climate responsiveness of building skins, the differences in their approaches have led to a gap in design and research, making it difficult to realize the full potential of the skins. To narrow this gap and focus on the typical continental climates in China, the authors have tried to explore an integrated design-research approach to climate-responsive building skin through case studies and prototype research.

The case in Cold Zone of China shows how architects have consciously taken climate responsiveness into account in the whole process of constructing the skin system, from planning and design to construction and operation. However, these seasonal climatic differences have become too much for static skin structures to response simultaneously. Architects have no other choice but to resort to such compromise strategies as layered and origination-based controls to make the skin responsive to the prevailing climate, which will inevitably cost the overall optimal performance.

In this context, the authors extracted the prototype of louver skins from the Cold Zone case and materialized it in a full-scale test platform, where comparative experiments were performed to identify the optimal solutions for four key design features (joint opening ratio, cladding color, cavity depth and air vents openness) and their optimal combinations for summer and winter. The team also evaluated the impact of each feature on the thermal performance of the skin quantitatively. The experimental results show that climate-responsive skins help save much more energy than conventional single-layer skins, with energy-saving rates increasing by 11.4 and 6.7% in summer and winter, respectively. In addition, the highly variable structure of the skin, which was designed to respond to climates in different seasons, has confirmed the limitations of traditional static structures and provided guidance on the design of dynamic skins. Driven by the prototype research, architects should try to do more, using their expertise and experience to construct a reliable, operable and affordable skin system that responds dynamically and intelligently to the ever-changing climates. In this regard, the authors proposed a novel skin prototype with triangular blades, and integrated the optimal solutions for summer and winter use by means of the blades' diverse materials and rotatable structure.

Based on a Chinese case, this research attempts to demonstrate the feasibility and necessity of a design-research approach that collects the wisdom of architects and scientists to create more climate-responsive skin solutions and even drive the sustainable development of buildings, with a view to providing some reference for similar work in the future. In the authors' view, the research serves as a point of departure for future exploration of more topics, such as the multi-climatic factor coupling mechanism of the skin system, methods of improving the responsiveness accuracy, the determination of the threshold for dynamic skin operations, and the application of new intelligent materials to dynamic skins.

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