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RESEARCH ARTICLE

Spatial Wind Flow Load and Shape Optimization for Folding Grid Shell Buildings

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ABSTRACT Wind-related disasters have emerged as a significant natural threat to humanity. This heightened concern necessitates careful consideration of the aerodynamic intricacies inherent in the surface characteristics of foldable reticulated shell houses, with particular attention paid to the substantial influence of wind loads. The objective of this study is to examine the spatial properties of foldable lattice shell houses through the establishment of a numerical wind tunnel model and subsequent simulations. The paper begins with an introduction to the CFD method, outlining its operational procedure. It further deduces the physical conservation principles governing mass and momentum, thereby establishing the relevant control equations. Additionally, the analysis encompasses the application of non-equilibrium wall conditions for the accurate calculation of building surface and ground wall motion and force characteristics. Finally, numerical simulations are performed on the foldable lattice shell house space, offering an effective tool and methodology for investigating wind pressure distribution and its implications. Through comparative analysis, it was determined that the optimized plan 18 with a rise-to-span ratio of 1/3, an end door inclination of 45°, and an end door height of 1/4 had better wind resistance performance. This plan reduced the gap between positive and negative pressure zones, improved the uniformity of surface wind pressure distribution, and weakened the wind loads' impact on the house. The research results indicated that reducing the rise-to-span ratio, end door inclination angle, and end door height can effectively improve the wind resistance performance of foldable lattice shell houses. The research on wind-induced response, numerical wind tunnel simulation, and shape optimization of foldable reticulated shell structures has certain innovation, and has important theoretical significance and engineering application value for the development of new camping foldable reticulated shells and wind resistance design of similar light houses.

INDEX TERMS Computational fluid dynamics, wind tunnel, folding type lattice shell houses, shape optimization, spatial wind body.

I. INTRODUCTION

With global climate change and frequent natural disasters, wind disasters have become a serious threat to humanity. Light houses are widely used for their convenience, mobility, and other characteristics [1], [2]. However, these houses are greatly affected by wind loads and are prone to severe damage in wind disasters. Among such lightweight movable houses, foldable reticulated shell houses are widely used camping houses. Due to their lightweight structure and complex surface aerodynamic characteristics, they are very sensitive to wind-induced responses, and wind load has become the main control load for their design and analysis [3], [4]. The Airfoil Research Center conducted wind tunnel tests on camping foldable reticulated shell houses with specific body shapes. The numerical wind tunnel method (NWT) elucidated the wind-induced response of specific lightweight foldable reticulated shell houses and the influence of parameters on wind load coefficients [5], [6]. Nevertheless, there remains a lack of comprehensive research regarding the optimization of the aesthetic aspects associated with foldable reticulated shell houses. Specifically, a detailed and systematic investigation

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into the impacts of variables such as rise span ratio (RSR), alterations in end door parameters, and wind direction has yet to be extensively explored or reported. This discrepancy indicates a lag in theoretical advancements compared to their practical implementation in engineering applications [7], [8]. To improve the wind resistance characteristics of complex foldable reticulated shell buildings, NWT was established to optimize the building shape of multi-body and multi-working conditions foldable reticulated shell buildings, and to obtain a reasonable shape with good wind resistance performance.

The development of computer software and hardware equipment has promoted the widespread application of numerical simulation technology in scientific research. Numerical wind tunnel methods use computers for wind tunnel tests, based on the principles of computational fluid dynamics (CFD), select reasonable turbulence models, and combine accurate numerical algorithms and graphic display technology to obtain intuitive and accurate calculation results. Compared to traditional on-site measurement and wind tunnel testing methods, numerical simulation has the advantages of short time cycle, low cost, and being able to simulate prototypes in real wind environments, without being affected by experimental interference effects. Especially by establishing numerical wind tunnels, it is possible to optimize the shape of building shapes under multiple coefficients and operating conditions, which has significant advantages for developing new engineering products. With the increasingly widespread application of numerical simulation of the average wind pressure on the surface of buildings and the surrounding wind flow field, more and more domestic and foreign studies are using numerical wind tunnel methods to accurately calculate various building structures. Numerical simulation methods are widely used in wind engineering research due to their high efficiency and low cost characteristics. Numerous studies have shown that a reasonable numerical wind tunnel can economically and effectively optimize the study of building shapes under various operating conditions. In order to obtain more accurate and reasonable calculation results, this article compares and verifies the numerical wind tunnel calculation results with the wind tunnel test results. This article will establish a reasonable numerical wind tunnel for lightweight foldable reticulated shell buildings, and use the numerical wind tunnel to analyze and study various building shape schemes under different wind directions, in order to carry out shape optimization design.

A detailed and systematic study was conducted on the wind-induced response of foldable reticulated shell houses, with wind load as the main control load for analysis and design. A numerical wind tunnel simulation was established based on wind tunnel tests, and the accuracy and reliability of the research were improved through comparison and verification with actual test data. In terms of shape optimization, by exploring and analyzing the effects of rise-to-span ratio, changes in end door parameters, and wind direction on folding lattice shell houses, 28 different building shapes were designed, and 140 numerical simulations were conducted to obtain a reasonable shape with good wind resistance performance. The optimization objective is to minimize the standard deviation between wind pressure distribution uniformity and body shape coefficient, and to conduct a body shape optimization analysis based on wind resistance design for lightweight foldable lattice shell houses, providing design theory and methods. In summary, the research on wind-induced response, numerical wind tunnel simulation, and shape optimization of foldable reticulated shell houses has certain innovation and has important theoretical significance and engineering application value for the development of new camping foldable reticulated shell houses and wind resistance design of similar light houses.

Nowadays, relevant research mainly focuses on the study of permanent houses in coastal areas, and the buildings studied are mainly double slope and four slope buildings, with a relatively simple body shape. There is a lack of research on wind resistance optimization design for complex shaped buildings such as lightweight foldable reticulated shell houses. There has been no systematic study on the reasonable appearance of lightweight foldable reticulated shell houses; The research on the optimization of the appearance of foldable lattice shell houses under multi coefficient and multi working conditions has not yet been carried out. Based on these understandings, research attempts to fill these gaps, with specific contributions as follows. Establish a numerical wind tunnel model through wind tunnel experiments, and based on this, conduct research on the reasonable shape of folding lattice shell houses; Optimize the design of the architectural form of multi body and multi working condition folding reticulated shell houses; Exploring a reasonable shape with good wind resistance performance, providing theoretical basis and engineering application value for the development of new camping folding lattice shell houses. In terms of computational methods and techniques, there may be some innovation in the research method of wind resistance optimization design based on numerical wind tunnel models; Through research, it has been found that a reasonable shape can enable lightweight foldable lattice shell houses to have good wind resistance characteristics under multiple coefficients and working conditions; Providing design theories and methods for optimizing the wind resistant appearance of similar lightweight buildings has reference and promotion value for the entire industry. This study fills the current research gap in the field of shape optimization of foldable lattice shell houses. Although previous studies have elucidated the wind-induced response and the influence of parameters on the wind load coefficient of specific lightweight foldable reticulated shell houses, research on the optimization of the shape of foldable reticulated shell houses has not yet been conducted in depth. At the same time, there is still a lack of detailed and systematic research on the effects of aspect ratio, changes in end gate parameters, and wind direction angle. Folding mesh shell houses are widely used in light houses, especially in camping situations. Due to its lightweight structure and complex surface aerodynamic characteristics, its wind resistance is easily affected. Therefore, studying the wind resistance characteristics of foldable reticulated shell houses has important theoretical significance and engineering application value. This study helps to improve the wind resistance characteristics of complex folded lattice shell houses, enabling them to have a reasonable appearance under wind loads. This kind of research not only provides design theories and methods but also plays a guiding role in the development of new camping folding mesh shell houses. Therefore, this study has good theoretical significance and engineering application value for the development of new camping folding mesh shell houses.

This study has four parts. The first part summarizes the relevant research on spatial wind flow and shape optimization both domestically and internationally. The second part elaborates on the basic theory of numerical calculation for the optimization of the shape of foldable reticulated shell houses. By comparing with wind tunnel test data, a reasonable numerical wind tunnel is established to determine the reasonable parameters and key technologies for numerical simulation of lightweight foldable reticulated shell houses under multiple body shapes and working conditions. The third part uses Computational Fluid Dynamics (CFD) method to numerically simulate the wind pressure distribution on the surface of lightweight foldable reticulated shell houses under multi-body and multi-working conditions, exploring different parameters' influence on the surface characteristics, and providing a data basis for wind resistance optimization design. The fourth part summarizes and reflects on the research experimental results.

The academic significance and contributions of this study are mainly reflected in the following four aspects. Firstly, improving the wind resistance performance of foldable grid shell houses: By systematically studying the spatial properties of foldable grid shell houses, theoretical basis is provided for their design and application in harsh wind environments. Through comparative analysis, an optimization plan has been proposed to effectively improve the wind resistance of grid shell houses, which has certain guiding significance for promoting the technological progress of folding grid shell houses. Secondly, enriching the application of computational fluid dynamics (CFD) methods in the analysis of aerodynamic performance in building spaces: This study used a numerical wind tunnel model, combined with physical conservation laws and control equations, to comprehensively analyze the wind pressure distribution and influencing factors in building spaces. This method has innovative significance in the wind environment response and shape optimization of foldable grid shell houses, providing new ideas for the analysis of structures similar to lightweight houses. Once again, theoretical support is provided for the wind resistance design and development of similar lightweight buildings: foldable grid shell houses, as a lightweight and detachable building structure, have broad application prospects in camping, disaster area emergency rescue and other scenarios. The results of this study not only contribute to improving the wind resistance performance of existing folding grid shell houses, but also provide methods and empirical references for the development and design of other similar structures. Finally, to gain a deeper understanding of the aerodynamic performance laws of foldable grid shell houses: This study takes wind pressure distribution and wind load influencing factors as the starting point, and through detailed numerical simulation and comparison, deeply explores the inherent laws of the aerodynamic performance of foldable grid shell houses. Providing richer theoretical basis and empirical data for subsequent related research is conducive to promoting further understanding of the capacity status in the field of wind engineering. In summary, this study has certain innovation in wind induced response, numerical wind tunnel simulation, and shape optimization of folded grid shell structures. It has important theoretical guidance significance and practical application value for the research and development of new folded grid shell houses and wind resistance design.

II. RELATED WORK

Relevant research on the flow and shape optimization of spatial wind bodies has been conducted. Bakhtiary et al. used model output statistical methods and machine learning models to evaluate the impact of climate change on wind characteristics in the North Atlantic region and reduced and predicted relevant data. By comparing the results of the total circulation model and the coupled model, a supervised machine learning method was developed for the first time to establish statistical relationships. The results indicate that wind speed is decreasing under future climate change, resulting in a 13% to 19% reduction in wind energy. These research findings are of great significance for the design, operation, and maintenance of coastal and offshore infrastructure [9]. Han et al. proposed an aerodynamic design optimization method based on the multistage Kriging method, which can combine simulation data of different fidelity levels. This method constructed the initial Machine Learning HK (MHK) model and constraint function through experimental design technology and output data with different fidelity, and then repeatedly updated the alternative model until the global optimal solution was found. The method's efficacy was confirmed through testing and application to optimize the aerodynamic shape. The outcomes indicated that this technique can considerably enhance optimization efficiency and outperforms current single or two-level fidelity methods [10]. Paramo et al. proposed a novel metaheuristic annealing algorithm. This algorithm demonstrated higher reliability, stability, and efficiency in testing six benchmark truss problems, and was more optimized than similar meta heuristic optimization methods [11]. Secco et al. introduced an effective mesh generation and deformation method for gradient-based aerodynamic shape optimization (ASO). A semi-automatic mesh generation method and a flexible mesh deformation method were developed to address the issues of poor quality and inefficient deformation methods in the mesh, and automatic differentiation was used to calculate the mesh deformation derivatives. The performance of this method was evaluated for speed, scalability, and robustness, and applied to large-scale ASO problems. In addition, the proposed method was implemented in open-source software packages and was a useful tool for dealing with aircraft, turbomachinery, and other issues [12]. Sun et al. used the improved two-point filling rule to establish the cross-verified Kriging model. Results indicated that the optimal shape can significantly improve aerodynamic performance, with higher lift and smaller drag compared to the training prototype. Sensitivity analysis indicated a strong nonlinear relationship between design variables and aerodynamic performance. The research provided key reference values for optimizing the aerodynamic performance [13]. Coar et al. studied how to use ice to create temporary rigid spatial structures in extremely cold climates and tested the structural performance of similar solid material shells. Tools and methods were developed in three building-scale ice shell projects using a curved active framework as a form acquisition system, emphasizing the information and method conversion between digital and physical tools. Finally, a research project was proposed to produce a coherent and effective designing and constructing workflow through curved active grid shells [14].

Schling et al. proposed a diagonal layout grid shell topology (D-Net) that can balance distributed forces and achieve orthotropic behavior, suitable for grid shell designs that were only under compression (or tension). The formula was derived for the D-Net direction and used Isogeometric analysis (IGA) for the calculation workflow. The structural performance of the D-Net design was compared with the other two types of grid shells through a prototype design shape and finite element analysis. Finally, the practical challenges of D-Net design and its potential in terms of architecture were discussed. This study opened the door to a new topology for grid shell design and comprehensively evaluated its theoretical, design, and structural performance [15]. Sehlström et al. proposed a representation method that extended the discontinuity in the Airy stress function to curved membrane structures for in-plane stress analysis, visualizing internal and cross-sectional stresses at boundaries, and enhancing understanding of the interaction between shape and force. This method supported design decisions related to shape discovery and force efficiency and explored its impact on the bending moment of edge beams through the prestressing of three existing cable networks [16]. Chen et al. utilized parameterization tools to study the effect of the shell structure of hexagonal sea urchin biomimetic cells on their mechanical properties. The results showed that when the porosity was 10% - 70%, the shell height and porosity remained unchanged, and the strain energy was the lowest; When the density was 1-4 units/m2 and the density and porosity of the shell element remained constant, the strain energy was the lowest; When the height of the shell element was 0-0.500m, the strain energy was the lowest, while the strain energy was the lowest when other parameters remained stable. Finally, three shell parameters with the lowest strain energy were found by using an evolutionary algorithm [17]. Zhao et al. proposed a geometric incompatibility function for structural elements to elucidate the self-locking mechanism of FGS. The results indicated that priority should be given to adjusting the h value for the self-locking ability controlling in the whole structure and it provided a reference for the structural design of self-locking FGS [18]. Talatahari et al. developed a search algorithm for drift tribe-charged systems, which improved the development and exploration rate of standard element heuristic methods. The numerical examples included a 10-story steel structure comprising 1026 structural components and a 60-story structure consisting of 8272 components to compare this method with other metaheuristic methods. This method can achieve better results. This method can be used for the optimal design of building structures [19].

In summary, these studies cover aerodynamic design optimization, aerodynamic shape optimization, spatial structure optimization, grid shell design, etc., providing theoretical and practical guidance for spatial optimization design and engineering applications. At present, there is relatively little research on wind resistance optimization design for complex shaped buildings such as lightweight foldable latticed shells. Existing research mainly focuses on permanent buildings in coastal areas, such as double slope and four slope buildings, which are relatively simple in size. Therefore, there is still a gap in research on the reasonable appearance of lightweight foldable lattice shell structures and the optimization of appearance under multi coefficient and multi working conditions. To reduce the damage caused by wind-induced response of light houses and the losses caused to humans by wind loads, the study will design a foldable lattice shell house, set different parameters, explore the spatial wind flow load of foldable lattice shell houses under different wind directions and parameter settings, and ultimately obtain the optimal plan for optimizing the spatial shape of foldable lattice shell houses. The optimization plan for the spatial shape of foldable reticulated shell houses studied and designed has certain theoretical significance and engineering application value for the development of new camping foldable reticulated shell houses.

III. NUMERICAL WIND TUNNEL BASED WIND FLOW LOAD AND SPACE SHAPE OPTIMIZATION OF FOLDED RETICULATED SHELL BUILDINGS

The research will elaborate on the basic theory of numerical calculation for the optimization of the shape of foldable reticulated shell houses. By comparing with wind tunnel test data, a reasonable numerical wind tunnel will be established to determine the reasonable parameters and key techniques for numerical simulation of lightweight foldable reticulated shell houses under multiple body shapes and working conditions.

A. NUMERICAL WIND TUNNEL MODEL CONSTRUCTION FOR FOLDING GRID SHELL HOUSING SPACE

The research process of this paper is as follows. The research is first based on the basic principles of computational fluid dynamics (CFD) and atmospheric boundary layer, and numerical wind tunnel simulations are conducted using the fluid dynamics calculation software FLUENT. Then, by comparing the wind tunnel test data of specific shape folded lattice shell models, explore and verify the reasonable numerical wind tunnel for lightweight folded lattice shell houses, and select the basic parameters and techniques for numerical simulation. Next, by collecting information on camping housing equipment, referring to the architectural design dataset and spatial grid structure technical specifications, combined with functional requirements, reasonable building model parameters are selected to design 28 types of building optimization models. Next, numerical simulations of a total of 140 operating conditions were conducted on 28 building optimization models using the aspect ratio, end door inclination angle, and end door height as dimensional parameters, and wind direction angles of 0 °, 30 °, 45 °, 60 °, and 90 ° as analysis parameters. Then, numerical simulation was conducted on the optimization model of foldable grid shell buildings under multiple parameters and working conditions to obtain the distribution patterns of surface wind pressure coefficient and wind load shape coefficient for different optimization models, and a comparative analysis was conducted on the surface wind pressure distribution patterns of each optimization model. Finally, analyze and explore the changes in body shape coefficient, standard deviation of positive and negative pressure, and wind pressure difference in various areas of the surface of lightweight foldable lattice shell houses with different body shapes. The optimization objective is to achieve a uniform distribution of wind pressure on the surface of the house and minimize the standard deviation of the body shape coefficient. Based on these results, a reasonable shape with good wind resistance performance is obtained.

CFD has been developed with the development of computer technology and numerical calculation technology. It is equivalent to conducting experiments in a virtual computer to simulate and simulate actual fluid flow situations. The basic principle is to numerically solve the differential equations that control fluid flow, obtain the discrete distribution of the fluid flow field in a continuous region, and approximate the simulation of fluid flow. The CFD method is used for numerical simulation of wind load on the building surface and around, including establishing a mathematical model, establishing a discretization method, calculating flow field, displaying calculation results, etc. The specific workflow is shown in Figure 1.

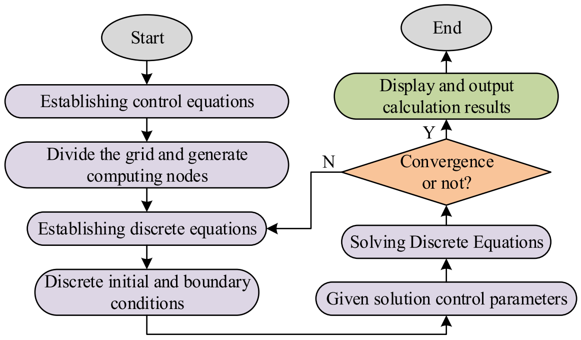


FIGURE 1. CFD workflow.

Fluids in motion must comply with the conservation laws of physics, including mass, momentum, and energy conservation. This paper is to explore wind pressure distribution on building's surface, therefore it does not consider fluid systems containing heat. For the fluid system with heat, it needs to comply with the conservation law of physics, that is, the control equation corresponding to the conservation law. To conform to the conservation law of physics, the motion law of fluid needs to conform to the conservation law to a certain extent, that is, the control equation corresponding to the conservation law [20], [21]. The conservation of mass equation, also known as the continuity equation, means that mass cannot increase or disappear out of thin air. The added mass in a fluid is equal to the mass flowing into the fluid at the same time. The mass conservation equation is shown in equation (1).

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho \omega}{\partial z}=0 \quad (1)$$

In equation (1), ρ represents density and t represents time. The vector symbol $div\alpha = \frac{\partial a_x}{\partial x} + \frac{\partial a_y}{\partial y} + \frac{\partial a_z}{\partial z}$ issubstituted into to obtain equation (2).

$$\frac{\partial \rho}{\partial t}+div\,(\rho\alpha)=0 \quad (2)$$

In equation (2), α represents the velocity vector.

The law of conservation of momentum states that when an external force acts on a fluid system, the change in momentum over time in the fluid system is equal to the sum of the external forces. Essentially, this law is an application of Newton's second law. When solving fluid system problems, it is necessary to consider the law of conservation of momentum. In the x, y, and z directions, the formula for momentum can be expressed as equations (3), (4), and (5).

$$\frac{\partial \rho u}{\partial t}+div\,(pu\mu)=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+F_x \quad (3)$$

$$\frac{\partial \rho v}{\partial t}+div\,(pv\mu)=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+F_y \quad (4)$$

$$\frac{\partial \rho \omega}{\partial t}+div\,(p\omega\mu)=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+F_z \quad (5)$$

In equations (3), (4), and (5), ρ represents the pressure on the fluid element, F_x, F_y, and F_z represent the volume forces in each direction of the element, and τ_{xx}, τ_{yx}, and τ_{zx} represent the components of the viscous stress τ.

To solve the convection field, it is required to determine reasonable flow field boundary conditions. In CFD, the basic

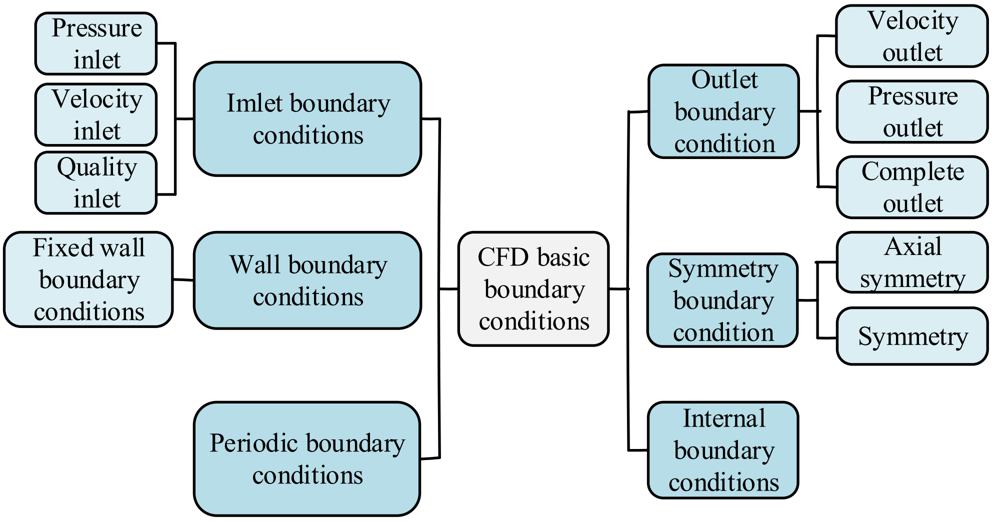


FIGURE 2. **Basic boundary conditions.**

boundary conditions mainly include inlet, outlet, wall, symmetric, periodic, and internal boundary conditions, as shown in Figure 2.

Based on extensive calculations and comparisons in the early stage, the velocity inflow boundary condition was selected as the wind field inlet boundary for the study. In response to this boundary condition, the flow field based on atmospheric boundary layer theory and wind tunnel experimental simulation was studied, and corresponding programs were written using user-defined functions. The exponential wind profile was used as a function of the atmospheric boundary layer wind profile in the program, as shown in equation (6).

$$U_z = U_0 \left(\frac{Z}{Z_0} \right)^{\chi} \tag{6}$$

In equation (6), Z_0 is the reference point height, U_0 is the average wind speed of the reference point, Z is the certain point height in the basin, U_z is the average wind speed at a certain height, and χ is the ground roughness index. According to China's load regulations, the reference point height Z_0 is 10m, the ground roughness χ is 0.12, and U_0 is taken as 10m/s. Referring to the relevant regulations on turbulence intensity, the turbulence intensity is shown in equation (7).

$$I = \begin{cases} I_0, & Z \leq Z_b \\ 0.1 \times \left(\dfrac{Z}{Z_g} \right)^{-\gamma}, & Z_b < Z \leq Z_g \end{cases} \tag{7}$$

In equation (7), according to the values specified in relevant regulations, for A and B wind farms, I_0 is taken as 0.18 and 0.23, γ is taken as 0.17 and 0.2, Z_b is taken as 5m, and Z_g is taken as 250m and 350m, respectively. The turbulence energy k is calculated as shown in equation (8).

$$k = 1.5 \left(\overline{uI} \right)^2 \tag{8}$$

The dissipation rate ε is calculated as shown in equation (9).

$$\varepsilon = 0.09^{0.75} k^{1.5} / l / \left(0.09^{0.25} l \right) \tag{9}$$

In equation (9), l is the turbulence scale, and the inlet boundary conditions are programmed using UDF, and normal operations are achieved using FLUENT. In the case where the flow velocity and pressure are unknown, the outlet boundary conditions can be used in two ways: pressure outlet boundary and outlet boundary. When the flow satisfies the fully developed flow assumption, the full development outflow boundaries condition is hired. Based on the motion and force characteristics of the building surface and flow field ground wall, non-equilibrium wall conditions without slip are used for calculation [22]. When calculating the top and both sides of the watershed, the symmetric boundary conditions of free sliding are used and empirical algorithms are applied. According to the standard wind tunnel test methods for construction engineering in China, the blockage ratio of the test model should be less than 5% and should not exceed 8%. The blockage is calculated as shown in equation (10).

$$\eta = \frac{A_m}{A_c} \tag{10}$$

In equation (10), A_m is the cross-sectional area of the wind tunnel test section, and A_c is the maximum projected area on the cross-section. The minimum distance between the test model and the wind tunnel should not be less than 15% width of the test area; The minimum distance from the test model to the top of the wind tunnel cannot be less than 15% of the height of the test area. The geometric scale should preferably be similar to the turbulence integration scale.

In numerical simulation, to meet the requirements of both computational accuracy and efficiency, setting a reasonable calculation domain size is needed. The study referred to the wind tunnel test specifications and relevant literature in

China, established a numerical wind tunnel for folding lattice shell houses, and selected an appropriate calculation domain size of 15 $L \times 12$ $B \times 10$ H (15 $L \times 8$ $L \times 5$ L). Among them, L is the length in the downwind direction, B is the width in the crosswind direction, and H is the height. 225m $\times$ 120m $\times$ 75m is taken as in the numerical wind tunnel. The blocking rate of the computational domain is 0.41%, which meets a blocking rate of less than 5%. It has been verified that it can effectively eliminate wind tunnel boundary effects. At the same time, we place the computational model on the axis of the computational domain and maintain a distance of 1/3 (5 L) of the length of the computational basin from the entrance of the computational domain, which is 70m from the inflow port of the computational domain, so that the fluid in the computational domain can freely and fully flow.

When conducting CFD calculations, it is necessary to divide the computational space into grids, and the rationality and quality of the grids are crucial for the accuracy of the calculations. According to the adjacency relationship between grid nodes, grids can be divided into three categories: structured grids, unstructured grids, and hybrid grids. The structural grid has ordered and regular adjacency relationships, and its internal grid points have the same number of adjacent grids. The adjacency relationship of unstructured grids is disordered and irregular. The hybrid grid is a hybrid arrangement of structural and unstructured grids according to usage requirements. The design concept of hybrid grids is to use structural grids in flow fields with high requirements for grid orthogonality, and unstructured grids in flow fields with low requirements for grid orthogonality but complex flow [23], [24], [25]. Therefore, it is particularly necessary to conduct reasonable grid division. The grid division diagram is shown in Figure 3.

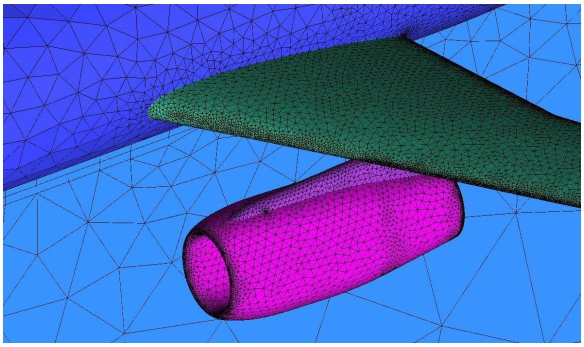


FIGURE 3. Grid division diagram.

In order to study the physical properties of turbulence, more precise numerical calculations are required. However, there is currently no single method that can accurately simulate all turbulence phenomena. Turbulence models can usually be divided into three categories, among which the eddy viscosity model is a commonly used model. The core idea of the eddy viscosity model is to describe the turbulent phenomena generated in the fluid by expressing Reynolds shear stress as the product of the time-averaged velocity gradient and the eddy viscosity coefficient, as shown in equation (11).

$$-\rho x u'v' = \mu_t \frac{\partial u}{\partial y} \tag{11}$$

In equation (11), μ_t is the eddy viscosity coefficient, and most commonly used turbulence models belong to the eddy viscosity model.

B. SPATIAL WIND FLOW LOAD AND SHAPE OPTIMIZATION FOR FOLDING GRID SHELL BUILDINGS

According to the equipment data and geometric dimensions of the camping house, with reference to the Technical Specification for Spatial Grid Structure, the dimensionless method is used to design the architectural model, while ensuring that the building has functional requirements such as drainage and lighting [26], [27], [28]. Referring to the research on the wind effect on the building surface in the domestic and foreign literature, the research selects RSR, the end door inclination, and the end door height as the optimization parameters, in which the end door inclination a is 40°, 45°, 55°, 90°, the end door height h is 0, 1/4 H (H is the building height), and RSR H/B is 1/2, 1/3, 1/4, and 2/3. There are 28 kinds of light-folded reticulated shell architectural models in total. The dimensions of the foldable grid shell house are shown in Figure 4.

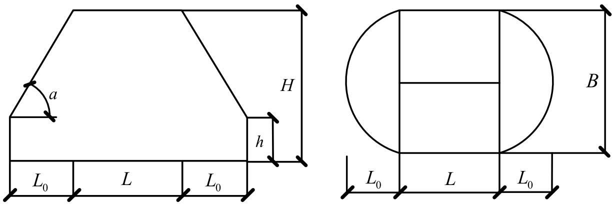


FIGURE 4. Building dimensions of foldable lattice shell houses.

The study used numerical simulation methods to simulate the wind pressure distribution of the model under 140 operating conditions, including wind fields at different wind directions (0 °, 30 °, 45 °, 60 °, and 90 °) at a wind speed of 10 m/s. By processing and analyzing wind pressure distribution data, the impact of optimization parameters on building surface wind load and deformation can be evaluated, and the optimal model can be selected and corresponding suggestions can be proposed. Folding grid shell houses are composed of a grid shell in the middle and end doors on both sides, so it is necessary to partition the building surface according to its surface shape and functional characteristics. During this process, it is necessary to pay attention to complying with relevant standards and safety requirements to ensure the structural safety of the accommodation [29], [30], [31]. Figure 5 shows the wind pressure zoning diagram of the surface of a foldable lattice shell roof.

According to the relevant provisions of China's building structural load code, the static wind pressure calculation

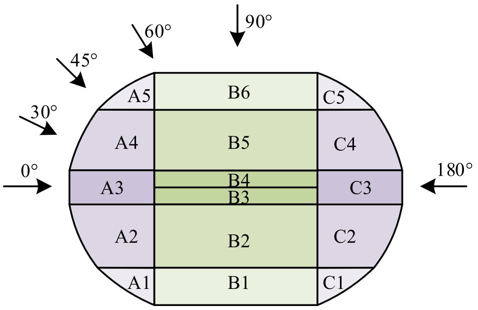


FIGURE 5. Surface wind pressure zoning diagram of folding grid shell roof.

formula is shown in equation (12).

$$\omega_k = \beta_z \mu_z \mu_s \omega_0 \tag{12}$$

In equation (12), β_z represents the wind vibration coefficient at height z; μ_z and μ_s represent the coefficient of wind pressure height variation and the shape coefficient of wind load, respectively; ω_0 represents the basic wind pressure. Generally, the dimensionless pressure coefficient C_p is used to characterize the wind pressure distribution on the building surface in this experiment, as shown in equation (13).

$$C_p = \frac{p - p_0}{\frac{1}{2}\rho U^2} \tag{13}$$

In equation (13), p is the surface pressure; p_0 and ρ are the pressure and mass density of the airflow; U is the average wind speed at the reference height of 10m. Due to the large amount of data and inconvenience in using the wind pressure distribution coefficient to describe the average wind pressure change, the surface of the building is separated into multiple areas by the distribution law of the wind pressure coefficient (WPC) in engineering calculations and analysis, so that the C_{pi} value in each area is as close as possible. The local shape coefficient C_{pi} of the i-th measuring point on the building surface is weighted and averaged by the product of the surface area A_i to which the measuring point belongs. The wind load body shape coefficients for each region is obtained as shown in equation (14).

$$\mu_s = \frac{\sum C_{pi} A_i}{\sum A_i} \tag{14}$$

Therefore, the impact of changes in the shape of folded lattice shell houses on the distribution of wind load on the building surface can be represented by the wind load shape coefficient μ_s.

The study investigates the influence of aspect ratio H/B on the distribution characteristics. The specific designs of Scheme 25, Scheme 4, Scheme 18, and Scheme 16 with RSR H/B of 2/3, 1/2, 1/3, and 1/4 at a 90° wind direction angle are shown below.

TABLE 1. Specific design of schemes under different aspect ratios.

Plan	Wind direction angle	H/B	α	h
Plan 25	90°	2/3	45°	1/4 H
Plan 4	90°	1/2	45°	1/4 H
Plan 18	90°	1/3	45°	1/4 H
Plan 16	90°	1/4	45°	1/4 H

At a 90 ° wind direction angle, the windward side of a folded lattice shell house is subjected to wind pressure, and its wind pressure coefficient shows a banded distribution. The leeward and lateral surfaces are subjected to wind suction, with a negative wind pressure coefficient. As the aspect ratio decreases, the maximum positive wind pressure coefficient on the windward side also decreases, with a minimum value of 0.5. The wind pressure coefficient on the leeward side shows a circular distribution, with a maximum negative wind pressure coefficient of -1.1. When the aspect ratio is 1/4, the distribution of wind pressure coefficients on the windward and leeward sides is relatively uniform, and there is no significant wind pressure protrusion. Under certain aspect ratios, the leeward side may also exhibit a positive wind pressure distribution similar to the windward side. However, there is still negative pressure at the ridge and separation area, so corresponding wind resistance design is needed. In summary, as the rise to span ratio decreases, the average wind pressure coefficient will also decrease more uniformly. Therefore, it is possible to consider choosing a house with a rise to span ratio of 1/4. However, the final choice still needs to be evaluated and judged based on the actual situation.

This study examines how the inclination angle α of the end gate affects the distribution characteristics of wind pressure on the surface of a house. The specific designs of Scheme 2, Scheme 4, Scheme 6, and Scheme 7 with end gate inclinations of 40°, 45°, 55°, and 90° under a 90° wind direction angle α are shown below.

TABLE 2. Specific design of schemes under different inclination angles of end doors.

Plan	Wind direction angle	H/B	α	h
Plan 2	90°	1/2	40°	1/4 H
Plan 4	90°	1/2	45°	1/4 H
Plan 6	90°	1/2	55°	1/4 H
Plan 7	90°	1/2	90°	0

At a 90 ° wind direction angle, the maximum wind pressure coefficient on the windward side of foldable lattice shell houses is 0.8, mainly concentrated in the B6 area. The leeward and lateral surfaces bear negative wind pressure, presenting a circular distribution. When the inclination angle of the end gate is 40 ° and 45 °, a high negative pressure zone is easily formed at the junction of the windward and leeward surfaces, and the negative wind pressure coefficient can reach a maximum value of 0.9. When the inclination angle of the end gate is 55 °, the high negative pressure area is mainly concentrated at the ridge of the roof, but the area is small. Choosing an appropriate inclination angle of the end gate can alleviate the impact of high and negative wind pressure zones, but it is important to note that stress concentration may occur at the ridge of the roof. When conducting wind resistance design, it is necessary to comprehensively consider the actual situation and choose a suitable building structure to cope with the impact of wind pressure distribution patterns in different directions.

The influence of the height h is then studied. The specific designs for Scheme 11 and Scheme 10 with gate heights h of 0 and 1/4 H at a 90° wind direction angle are shown below.

TABLE 3. Specific design of different end gate heights.

Plan	Wind direction angle	H/B	α	h
Plan 11	90°	1/3	45°	1/4 H
Plan 10	90°	1/3	45°	0

At a 90 ° wind direction angle, the windward side of a folded lattice shell house bears the maximum wind pressure, with a maximum wind pressure coefficient of 0.7. For the distribution of wind pressure on the leeward side, the height of the end gate has a certain impact. When the height of the end gate is 0, the wind pressure distribution on the leeward side is more uniform, and the maximum positive wind pressure coefficient decreases to 0.2. However, there is still a high negative pressure zone, and stress concentration may occur at the ridge of the roof. Therefore, in wind resistance design, it is necessary to choose the appropriate height of the end door based on the wind pressure pattern. Choosing a house with an end door height of 0 can improve its wind resistance performance, but it needs to be evaluated based on the actual situation and ensure the safety of the structure.

The overall process of researching and establishing a model is as follows:

1) Based on the fundamental principles of computational fluid dynamics (CFD), a wind tunnel numerical simulation model is established using FLUENT software.
2) Compare wind tunnel test data of foldable lattice shell models with specific shapes, explore and validate reasonable numerical wind tunnels for lightweight foldable lattice shell buildings, and select basic parameters and techniques for numerical simulation.
3) Collect information on camping residential equipment, query architectural design datasets and spatial grid structure technical specifications, combine functional requirements, select reasonable building model parameters, and design 28 building optimization models.
4) A total of 140 operating conditions were numerically simulated for 28 building optimization models using aspect ratio, end gate inclination angle, and end gate height as scale parameters, and wind direction angles of 0 °, 30 °, 45 °, 60 °, and 90 ° as analysis parameters.

TABLE 4. Grid dependency testing.

Test No	Grid size (number of nodes)	Wind speed (m/s)	Wind pressure (Pa)	Wind load (N)
1	10000	10	100	1000
2	20000	10	200	2000
3	30000	10	300	3000
4	40000	10	400	4000
5	50000	10	500	5000
6	60000	10	600	6000

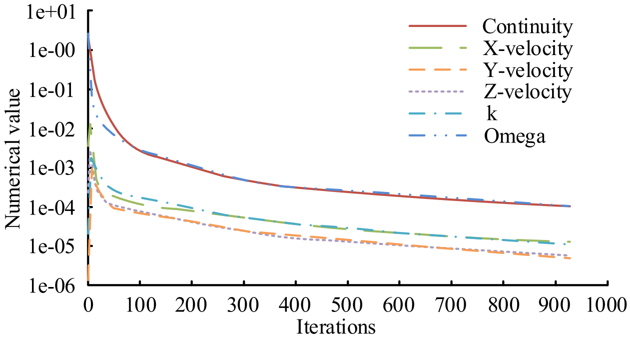
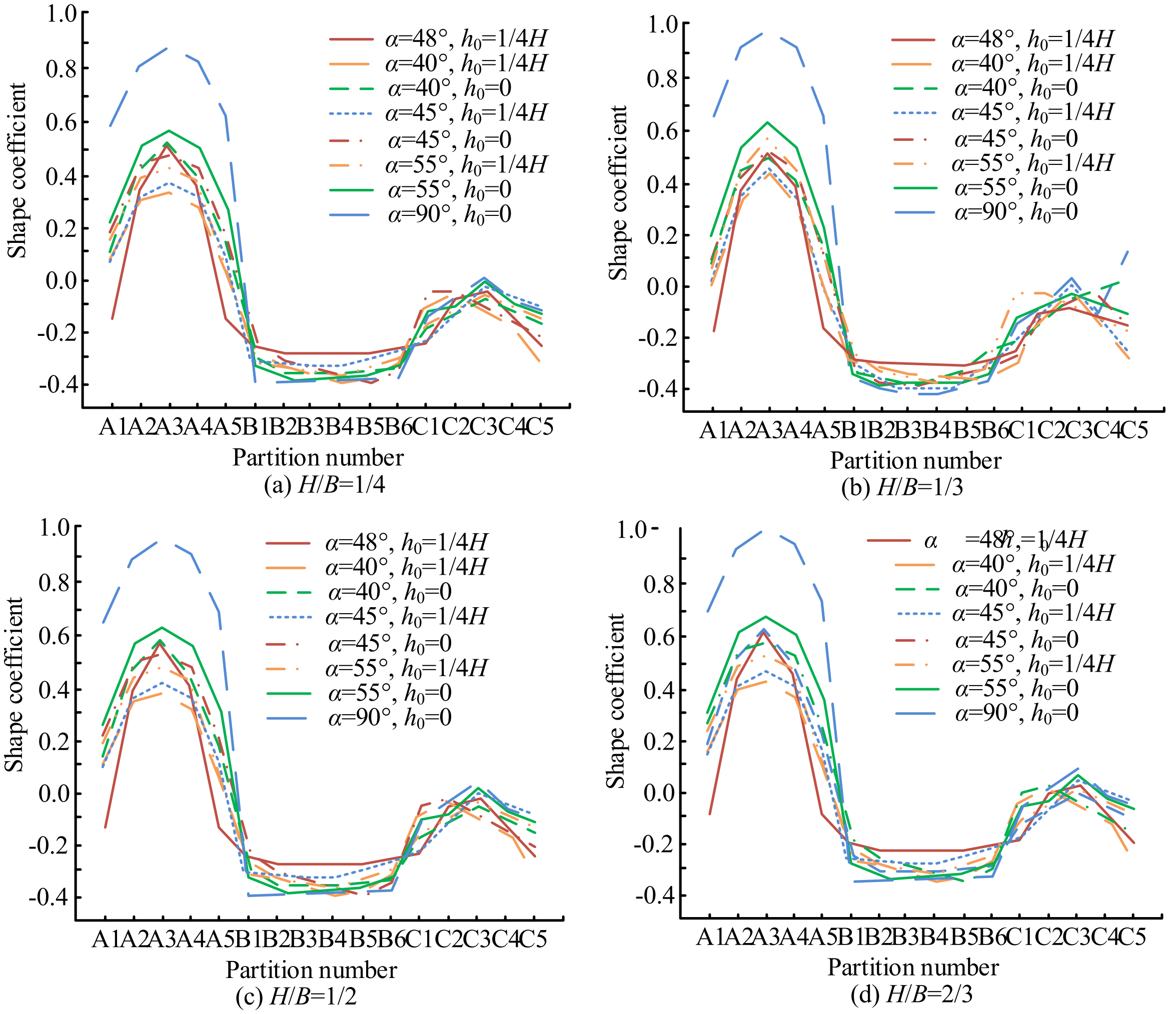


FIGURE 6. The variation curve of the residuals between each variable and the continuity equation.

5) Numerical simulation was conducted on the optimization model of foldable lattice shell buildings under multiple parameters and operating conditions to obtain the distribution patterns of surface wind pressure coefficient and wind load shape coefficient for different optimization models. The surface wind pressure distribution patterns of each optimization model were compared and analyzed.
6) Analyzed and explored the changes in body shape coefficient, standard deviation of positive and negative pressure, and wind pressure difference in different regions of lightweight foldable lattice shell houses with different shapes. The optimization goal is to achieve a uniform distribution of wind pressure on the surface of the house and minimize the standard deviation of the shape coefficient. Based on the above results, a reasonable shape with good wind resistance performance is obtained.

IV. WIND FLOW LOAD AND OPTIMIZATION PLAN FOR SPATIAL SHAPE OF FOLDING RETICULATED SHELL BUILDINGS

The study uses the CFD method to numerically simulate the surface wind pressure distribution of lightweight foldable lattice shell houses under multiple body shapes and working conditions, and explores the different parameters' effect on



(a) $H/B=1/4$ (b) $H/B=1/3$ (c) $H/B=1/2$ (d) $H/B=2/3$

FIGURE 7. Shape coefficient of building surfaces in different zones with different end door parameters under a 0° wind direction angle.

the surface wind pressure characteristics, providing a data basis for wind resistance optimization design.

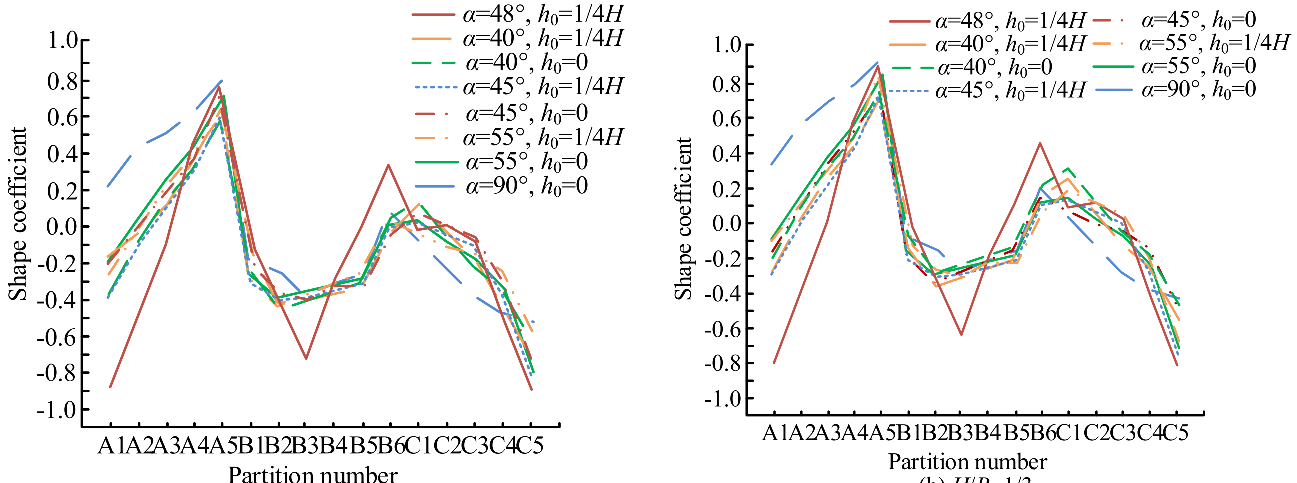
A. END DOOR PARAMETERS INFLUENCE ANALYSIS ON THE SURFACE WIND EFFECT OF FOLDABLE LATTICE SHELL HOUSES

In this study, a computational fluid dynamics (CFD) method was employed to simulate the aerodynamic characteristics of foldable lattice shell houses. The Eulerian modeling approach was used, and the simulations were conducted using the commercial CFD software FLUENT. To calculate the motion and force characteristics of building surfaces and ground walls, the FLUENT software was utilized to implement the non-equilibrium wall conditions. Grid dependency testing is shown in Table 4.

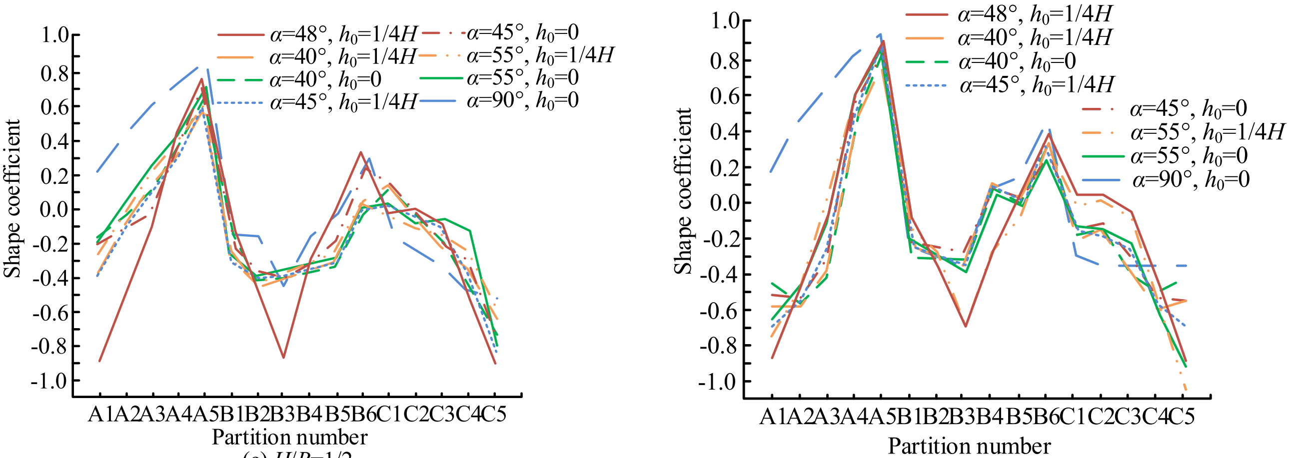
As the grid size (number of nodes) increases, the calculation results of wind pressure and wind load also increase. This indicates that the model has a certain sensitivity to grid size. However, if the grid size continues to increase, the change in the calculation results may become small, indicating that grid convergence has been achieved. Firstly, houses usually need to design surface openings based on practical usage needs. This means that the wind pressure effects inside and outside the house need to be explored and analyzed. This is because of the need for ventilation and dehumidification, as well as for light entering the room to improve comfort and air quality.

In addition, in actual use, houses are also affected by various factors such as wind, rain, snow, dust, and hail, and this study only analyzes ideal conditions.

For the wind tunnel model of foldable lattice shell houses constructed using the CFD method, FLUENT software is used to iteratively solve the numerical wind tunnel, and the residual between adjacent steps is used as the convergence standard reference value. In general, when the residual values of the control equation, turbulent kinetic energy, and dissipation rate all decrease by 4 orders of magnitude, and the monitoring curve tends to stabilize, it can be determined that the numerical solution of the flow field has converged. As shown in Figure 6, the monitoring of the residual variation curves of various variables and continuity equations during the numerical simulation calculation of foldable lattice shell



(a) *H*/*B*=1/4 (b) *H*/*B*=1/3



(c) *H*/*B*=1/2 (d) *H*/*B*=2/3

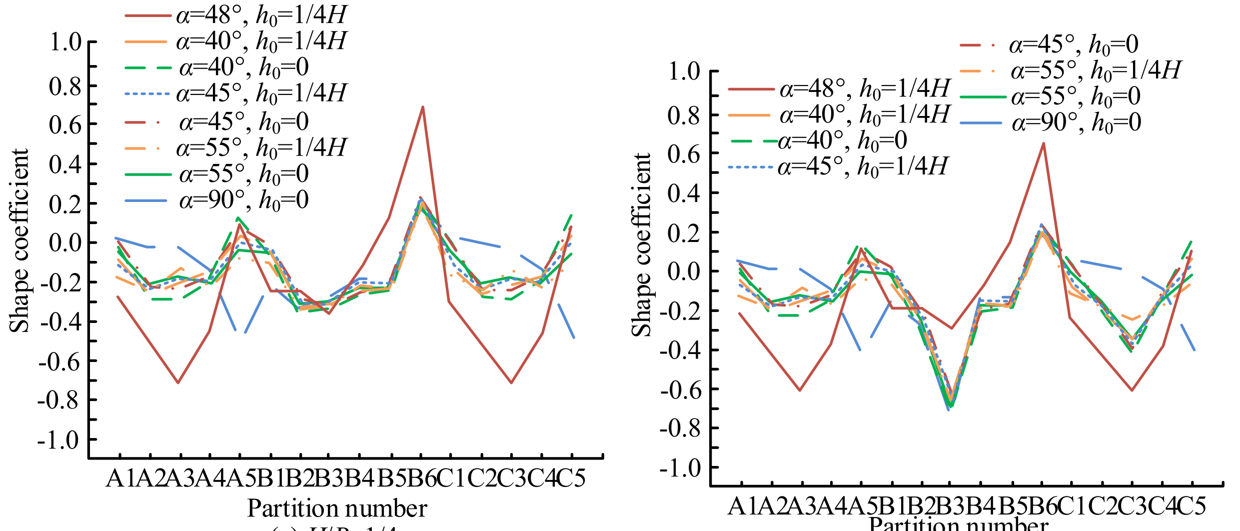
FIGURE 8. Shape coefficient of building surfaces in different zones with different end door parameters under a 45° wind direction angle.

houses at a wind speed of 10m/s and a wind direction angle of 0 ° is performed.

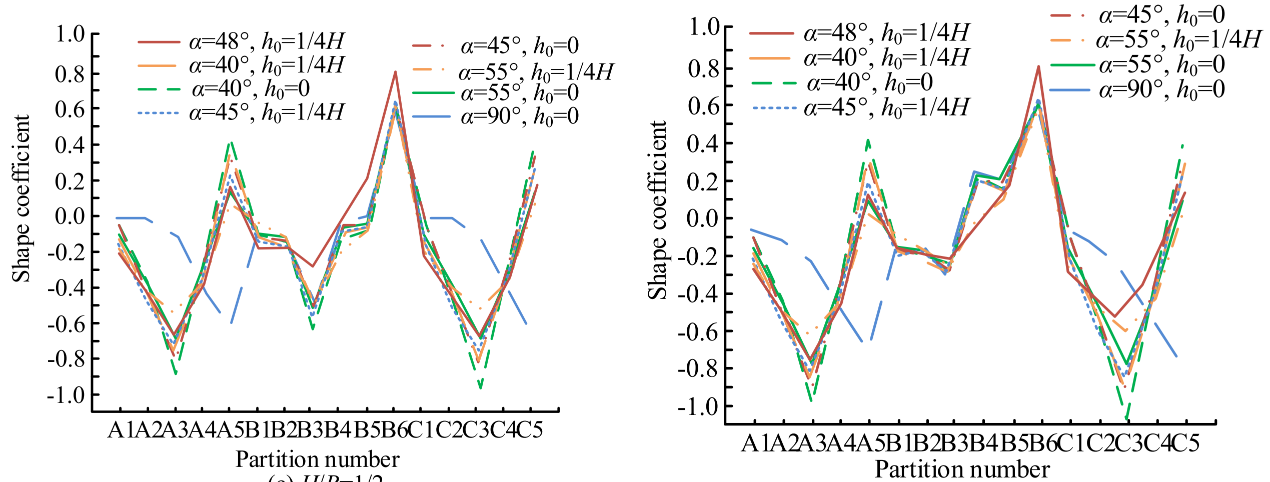
The folding mesh shell proposed in the study is composed of three parts: the end doors on both sides and the middle mesh shell. The end door part is mainly determined by two end door parameters: the end door inclination angle α and the end door height h. Experimental analysis was conducted for end door parameters' impact on the surface wind effect of folding houses under different wind direction conditions. Figure 7 compared the effects of end door parameters on the surface wind effect of folding houses at a 0° wind direction angle.

According to Figure 7, under a 0° wind direction angle, different RSR and end door parameters had different effects on the surface shape coefficient of the house. When RSR was 1/4, a decrease in the inclination angle and height of the end gate can significantly reduce the body shape coefficient, while schemes 18 and 16 had little impact on wind load. When the aspect ratio was 1/3, a decrease in the inclination angle of the portal and the presence of the portal height can both reduce the body shape coefficient. When RSR was 1/2, the trend of body shape coefficients was similar for all schemes, but Scheme 7 generated a relatively large positive pressure in Zone A on the windward side and was not suitable for selection. When the aspect ratio was 2/3, the maximum value of the body shape coefficient appeared in the A3 region of the model of Scheme 26 with an end gate inclination of 55° and an end gate height of 0. However, the change in the body shape coefficient on the leeward side of Scheme 25 was relatively small. Based on the trend of changes in body shape coefficients of various models, the inclination angle of the end gate in Scheme 3 was 45° and the height of the end gate was 0, which had a small impact on wind load response and can be used as a reference. The end door parameters influence comparison of folding houses at a 45° wind direction angle is shown in Figure 8.

From Figure 8, different aspect ratios and end door parameters had an impact on the surface shape coefficient of a



(a) *H*/*B*=1/4 (b) *H*/*B*=1/3

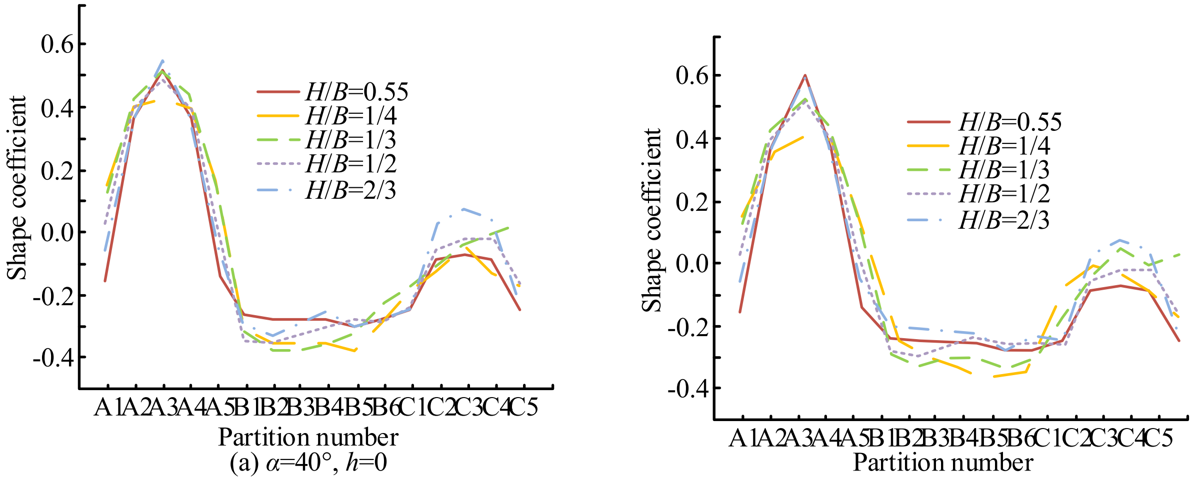


(c) *H*/*B*=1/2 (d) *H*/*B*=2/3

FIGURE 9. **Shape coefficient of building surfaces in different zones with different end door parameters under a 90° wind direction angle.**

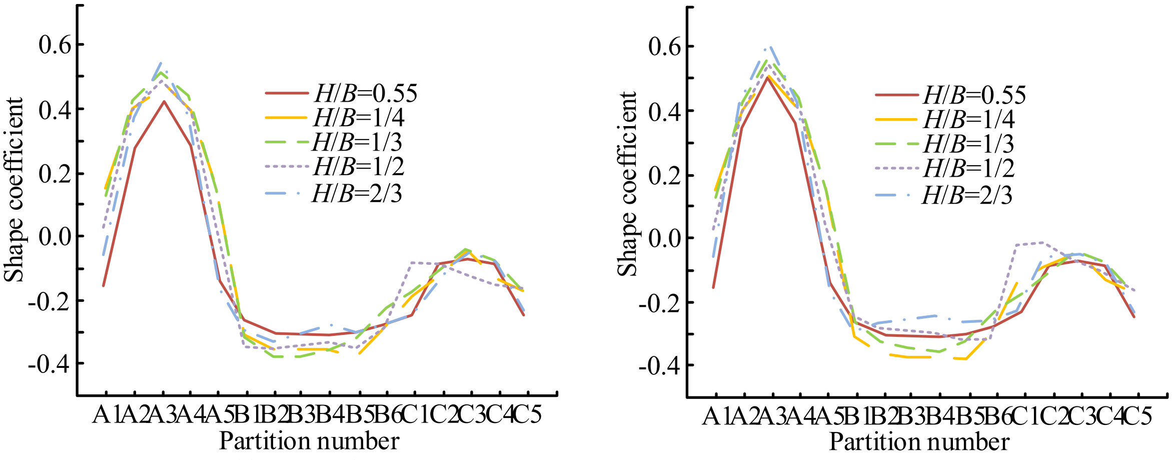
house at a 45° wind direction angle. When the aspect ratio was 1/4, the shape of a house with a 90° angle of the end gate increased the wind load on the surface of the house. However, Scheme 15 with a 40° angle of the end gate and a 0° height of the end gate, and Scheme 18 with a 45° angle of the end gate and a 1/4 *H* height of the end gate had a smaller shape coefficient, which can alleviate the wind load on the building surface. When the aspect ratio was 1/3, an increase in the inclination angle and height of the end gate can effectively reduce negative wind pressure, but it increased wind pressure. However, Scheme 8 with an inclination angle of 40° and a height of 0 for the end door, and Scheme 11 with an inclination angle of 45° and a height of 1/4 *H* for the end door, can improve the wind resistance performance of the house. When RSR was 1/2 and 2/3, Scheme 07 with a 90° angle of the end door had a high body shape coefficient in Zone A and Zone C, and it was not recommended to use it. However, Scheme 1 with a 40° angle of the door and a 0° height of the end door had a small negative WPC in Zone C and a uniform distribution of body shape coefficients in each zone, which was beneficial for improving the wind resistance performance of the house. When the aspect ratio was 2/3, Scheme 27 had a larger amplitude of body shape coefficient in Zone B3. The end door parameters influence comparison of folding houses at a 90° wind direction angle is shown in Figure 9.

From Figure 9, when the aspect ratio was 1/4 under a 90° wind direction angle, the original model scheme 00 exhibited significant negative wind pressure amplitudes and stress concentration in some areas. Scheme 21 with a 90° inclination angle of the end gate was prone to wind-induced damage. Scheme 18, with an inclination angle of 45° and a height of 1/4 *H* of the end door, can improve the wind resistance of foldable lattice shell houses. When the aspect ratio was 1/3 at a 90° wind direction angle, scheme 13 with an end gate inclination of 55° and an end gate height of 1/4 *H*



(a) α=40°, h=0

(b) α=40°, h=1/4H



(c) α=55°, h=0

(d) α=55°, h=1/4H

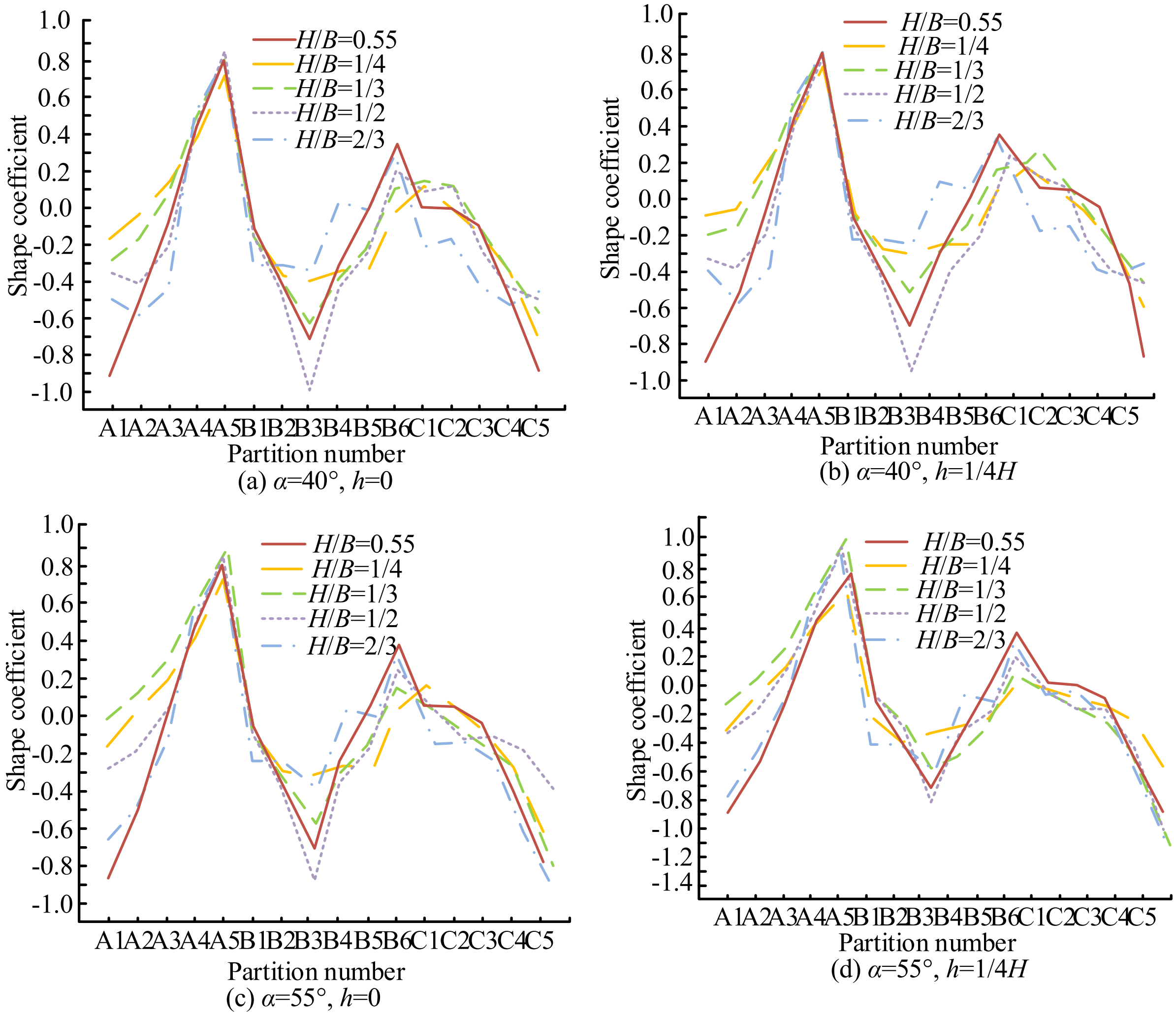
FIGURE 10. Shape coefficient of building surfaces in different zones with different RSR under 0° wind direction angle.

resulted in a maximum reduction of 54% in the body shape coefficient of the original model in some areas. Option 6, with an inclination angle of 55° and a height of 1/4 H at the end gate, had a small and uniform variation in surface shape coefficient at RSR of 1/2, which can effectively resolve the wind pressure in the A1 zone. When RSR was 2/3 at a 90° wind direction angle, Scheme 28 with a 90° end gate inclination was not recommended, while Scheme 27 with a 55° end gate inclination and a 1/4 H end gate height had stronger wind resistance performance.

B. ASPECT RATIO INFLUENCE ANALYSIS ON THE SURFACE WIND EFFECT OF FOLDABLE LATTICE SHELL BUILDINGS

The main grid shell in the middle of the folding grid shell house studied is mainly determined by RSR. As the main structure of the house, the grid shell is the main part of wind load impact on the house and greatly influences the wind-induced response of the house surface. An experimental analysis was conducted on the influence of the aspect ratio on the surface wind effect of foldable houses under different wind direction conditions. Figure 10 shows the influence comparison on the surface wind effect of foldable houses at a 0° wind direction angle.

According to Figure 10, the overall trend of the shape coefficient of building surfaces with different RSR was basically consistent under a 0° wind direction angle. When the inclination angle of the end gate was 40° and the height of the end gate was 0, Scheme 15 can effectively reduce the body shape coefficient in Zone A, but Scheme 5 had a higher body shape coefficient in Zone B and Zone C compared to other body shapes. Scheme 1 had a more uniform distribution and smaller body shape coefficient in Zone B and Zone C, which can effectively reduce the negative WPC in the high negative pressure zone. When the inclination angle of the end door was 40° and the height of the end door was 1/4 H, there was a positive correlation between RSR and the change in body shape coefficient, but a negative correlation between the B and C areas. When RSR was 2/3, it can improve the wind resistance performance of the B and C areas of the house. When the inclination angle of the end door was 55° and the height of the end door was 0, other solutions had not effectively improved the wind resistance performance of the



(a) α=40°, h=0

(b) α=40°, h=1/4H

(c) α=55°, h=0

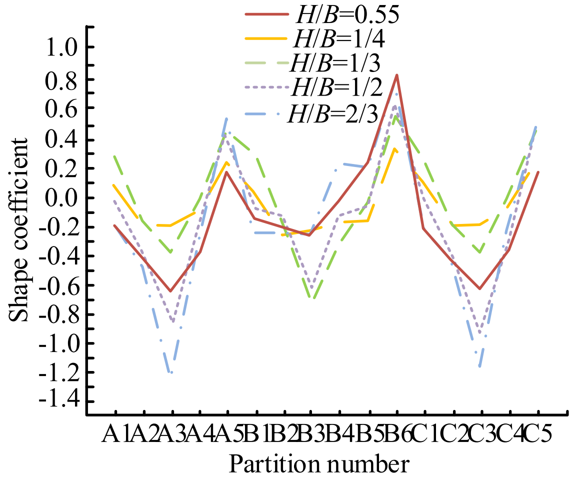
(d) α=55°, h=1/4H

FIGURE 11. Shape coefficient of building surfaces in different zones with different RSR under 45° wind direction angle.

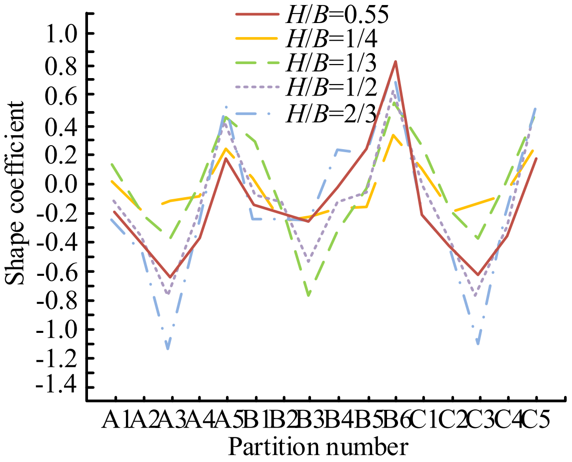
house. Figure 11 shows the comparison of the influence of RSR on the surface wind effect of foldable houses at a 45° wind direction angle.

According to Figure 11, the overall trend of the shape coefficients of each partition on the building surface was similar under different RSR under a 45° wind direction angle. When the inclination angle of the end gate was 40° and the height of the end gate was 0 or 1/4 H, the reduction of RSR can effectively reduce the body shape coefficient in Zone A. Scheme 15 and Scheme 14 with RSR of 1/4 had good wind resistance performance in Zone B. Scheme 14 had a more uniform and reasonable distribution of body shape coefficients in Zone B, which can effectively avoid stress concentration at the separation point of the airflow. When the inclination angle of the end gate was 55° and the height of the end gate was 0, the overall trend of the body shape coefficient was positively correlated with RSR, and when RSR was 1/4, the body shape coefficient was more uniform. When the inclination angle of the end door was 55° and the height of the end door was 1/4 H, a positive correlation is found between RSR and the body shape coefficient, but the correlation between the negative pressure area under pressure was not significant. When RSR was 1/4, the body shape coefficient of the house surface in the positive and negative pressure area was small and the change amplitude is small, which can make the house uniformly subjected to wind force. Figure 12 shows the comparison of the influence of RSR on the surface wind effect of foldable houses at a 90° wind direction angle.

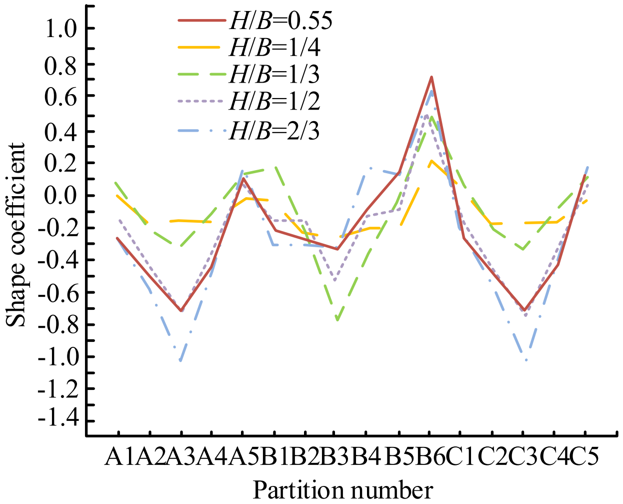
According to Figure 12, the shape coefficients of each partition on the surface of buildings with different RSR were symmetrically distributed under a 90° wind direction angle, and the trend of change was basically consistent. When the inclination angle of the end gate was 40°, there was a significant positive correlation between the distribution of the body shape coefficient in the A and C regions of the crosswind surface and the variation of RSR. Scheme 16 with RSR of 1/4 had a maximum reduction in the body shape coefficient of 79.1% in areas with high wind pressure, and the



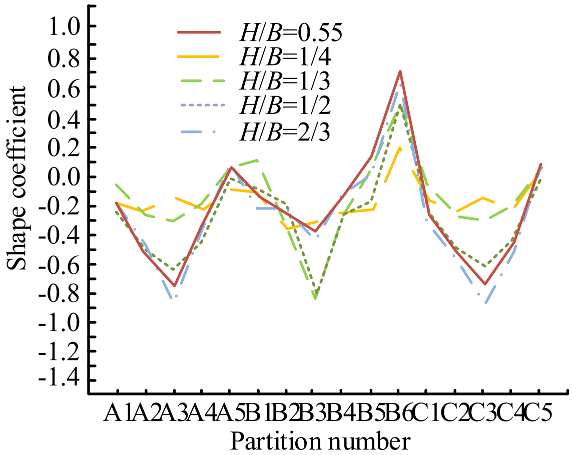
(a) α=40°, h=0



(b) α=40°, h=1/4H



(c) α=55°, h=0

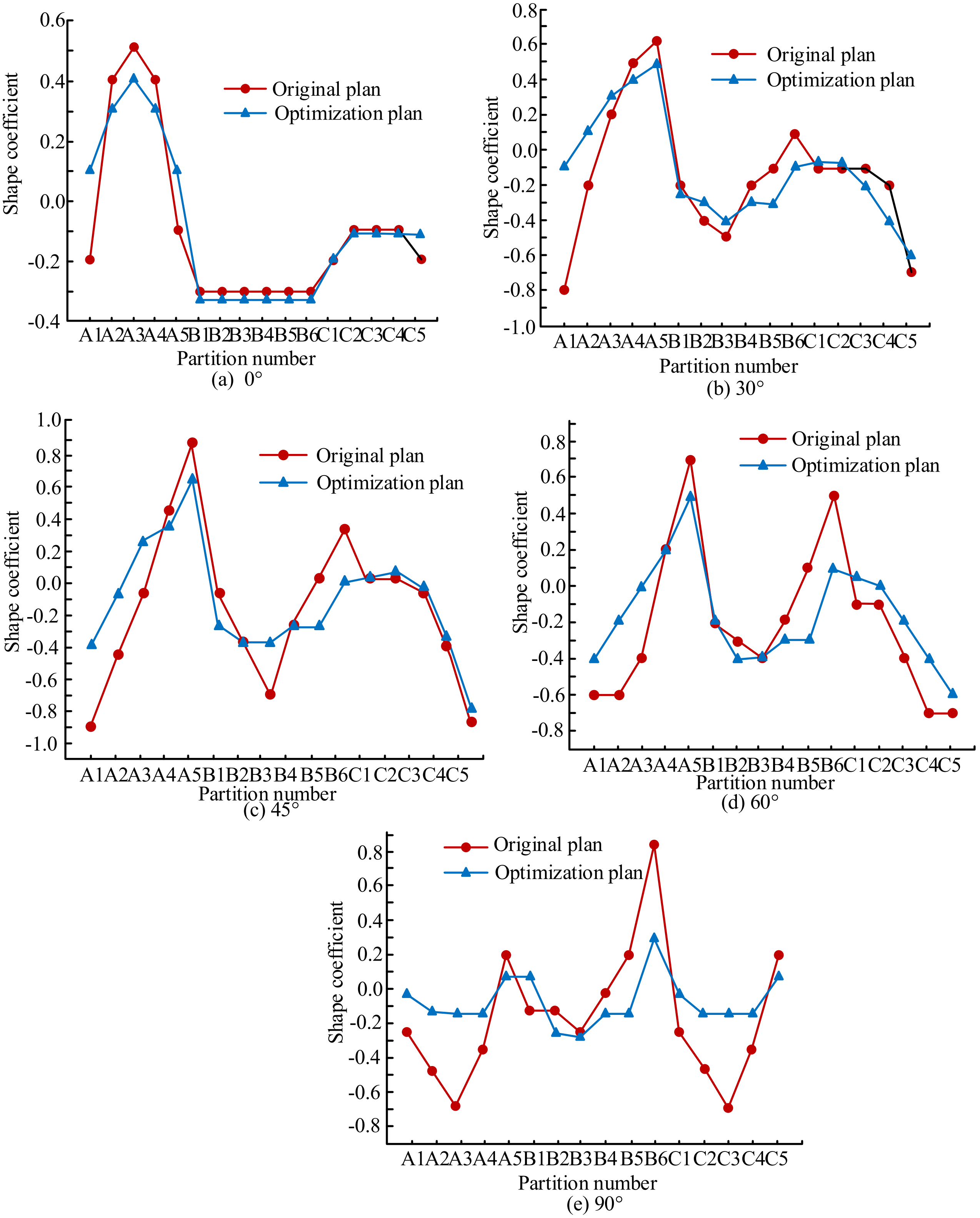


(d) α=55°, h=1/4H

FIGURE 12. **Shape coefficient of building surfaces in different zones with different RSR under 90° wind direction angle.**

distribution was more uniform, which can effectively improve the wind resistance performance of the surface of the folded lattice shell house. When the inclination angle of the end gate was 55°, there was a positive correlation between the shape coefficient and RSR in the crosswind areas A and C, and when RSRwas 1/4, the shape coefficient of each zone was significantly reduced compared to other RSR, which can alleviate the distribution of the most unfavorable wind load on the surface of the house and make the house uniformly stressed. The optimization objective was to minimize the standard deviation between the body shape coefficient and the body shape coefficient. Through comparative analysis of 28 optimization schemes for the shape of folding lattice shell houses under multiple coefficients and working conditions, Scheme 18, which had better wind resistance performance, was selected as the optimal shape scheme for complex folding lattice shell houses. The comparison of body shape coefficients between the optimized scheme and the original scheme under different wind directions is shown in Figure 13.

According to Figure 13, after comparative analysis, the wind resistance performance of foldable lattice shell houses can be effectively improved by reducing RSR, end door inclination angle, and end door height. Under different wind directions, the optimized plan 18 significantly improved the surface shape coefficient compared to the original plan, reduced the difference between positive and negative pressure zones, improved the uniformity of surface wind pressure distribution, and weakened the impact of wind loads on the house. The decrease in the aspect ratio caused the airflow to crawl slowly, reducing the extreme value of wind pressure and the number of negative pressure zones. A decrease in the inclination angle of the end gate to 45° can slow down the climbing speed of the incoming flow and improve the overall wind resistance. However, a height of 1/4 H of the end gate hindered the wind near the ground, further reducing



(a) 0°

(b) 30°

(c) 45°

(d) 60°

(e) 90°

FIGURE 13. Comparison of body shape coefficients between the optimized scheme and the original scheme under different wind directions.

the wind pressure. Through comprehensive comparative analysis, it can be concluded that the optimized plan 18 can significantly reduce the wind effect of the folded lattice shell house and improve the wind resistance performance of the house. By optimizing the shape of foldable lattice shell houses, especially adopting optimization plan 18 with a rise-to-span ratio of 1/4, an end door inclination of 45°, and an end door height of 1/4 H, the surface wind pressure distribution of the house can be more uniform, reducing the impact of wind load on the house, and improving the overall wind resistance performance of the house. The optimized body shape scheme also reduces the airflow vortices generated by the negative high-pressure zone and surface wind suction, significantly reducing the extreme value of surface wind pressure and its occupied area. Comprehensive analysis shows that the optimized folded grid shell housing scheme 18 has a smaller standard deviation of body shape coefficient and a more reasonable wind pressure distribution, which can meet the usage requirements and improve wind resistance performance. In addition, establishing a reasonable numerical wind tunnel model can effectively optimize the shape of buildings under various parameters and operating conditions, providing a reliable reference for practical engineering applications.

This study used computational fluid dynamics to simulate the surface wind pressure distribution of lightweight foldable grid shell houses under various body shapes and operating conditions. Firstly, different end door parameters, including the tilt angle and height of the end door, have a significant impact on the wind pressure effect of foldable grid shell houses. According to the simulation results, reducing the tilt angle and height of the end door can significantly reduce the body shape coefficient, thereby reducing the impact of wind load. However, this also depends on the aspect ratio (RSR) of the house. For example, when the RSR is 1/2, the trend of body shape coefficient changes is similar for all schemes, but Scheme 7 generates relatively large positive pressure on the windward side, so it is not suitable for selection. These findings have important reference value for the optimization design of building wind loads. Secondly, Scheme 18 has the best effect in improving wind load performance. When the wind direction angles are 0 °, 45 °, and 90 °, the shape coefficient and wind pressure distribution of Scheme 18 are relatively reasonable, demonstrating good wind resistance performance. Among them, Scheme 18, which reduces the rise to span ratio (RSR) to 1/4, the inclination angle of the end door to 45 °, and the height of the end door to 1/4, can make the wind pressure distribution on the surface of the house more uniform, reduce the impact of wind load on the house, and improve the overall wind resistance performance of the house. This also indicates that this optimization scheme can effectively improve wind load performance by adjusting building shape and size parameters.

The research results indicate that factors such as end door parameters and aspect ratio have a significant impact on the wind pressure characteristics of building surfaces. Firstly, the study found that the end door parameters (including tilt angle and height) have a significant impact on the surface wind effect of foldable grid shell houses. The reduction of tilt angle and height can significantly reduce the surface shape coefficient of a house, thereby helping to reduce wind loads. In addition, an increase in height can effectively reduce negative wind pressure, but it will increase positive wind pressure. Secondly, the aspect ratio (RSR) has a significant impact on the wind effect on the surface of houses. According to experimental analysis, reducing RSR can effectively reduce the shape coefficient of the house surface under various wind conditions, especially in certain areas with high wind pressure, which may achieve a maximum reduction of 79.1%. This uniform wind pressure distribution helps to improve the wind resistance performance of the house. By changing parameters, including reducing RSR, lowering the tilt angle and height of the end door, the wind resistance performance of foldable grid shell houses can be improved. The optimized plan can significantly improve the surface shape coefficient of the house, reduce the gap between positive and negative pressure zones, improve the uniformity of surface wind pressure distribution, and reduce the impact of wind load on the house. Finally, through the research in this article, it can be concluded that with the decrease of RSR, the tilt angle of the end door, and the height of the end door, the wind resistance performance of foldable grid shell houses can be significantly improved. Therefore, in practical engineering applications, this optimization scheme should be selected as much as possible to better withstand the impact of wind and ensure the stability of the house. The above results and discussions provide an effective data foundation for wind pressure optimization design, and provide reliable references for practical engineering applications.

V. CONCLUSION

With the intensification of global climate change, the wind resistance performance of lightweight movable houses has become a serious challenge facing humanity. Folding lattice shell houses have the characteristics of light weight and easy portability, but their surface aerodynamic characteristics are complex, and the influence of wind load needs to be considered. Based on CFD, a numerical wind tunnel model was established to study the spatial shape optimization schemes with RSR H/B of 1/2, 1/3, 1/4, and 2/3, end door inclination α of 40°, 45°, 55°, and 90°, and end door height h of 0 and 1/4 H. The influence of different parameters on the surface wind pressure distribution characteristics of foldable lattice shell houses was explored. Scheme 18, with an RSR of 1/3 at a 90° wind direction angle, a 45° end door inclination angle, and a 1/4 H end door height, can improve the wind resistance of foldable lattice shell houses. Through comparative analysis, it was determined that the optimized scheme 18 with an RSR H/B of 1/3, an end gate inclination angle α of 45°, and an end gate height h of 1/4 H had better wind resistance performance, and the shape coefficient of scheme 18 at a 0° wind direction angle is only -0.33. In terms of numerical wind tunnel modeling, appropriate technical parameters were selected, including calculation domain size, upwind format, calculation method, turbulence model, and mesh generation scheme. The wind tunnel model constructed using the CFD method was iteratively solved using FLUENT software, and the residual between adjacent steps was used as the convergence standard reference value. The results showed that the residual, turbulent kinetic energy, and dissipation rate of the control equation were reduced by 4 orders of magnitude, and the monitoring curve tended to stabilize, indicating that the numerical solution of the flow field had converged. After analysis, it has been proven that the numerical wind tunnel constructed through research can obtain numerical calculation results with high accuracy, good stability, and rationality.

The research results of this article have enhanced our understanding of the optimization of the shape of folding lattice shell houses. By establishing a numerical wind tunnel and selecting appropriate calculation parameters and methods, the research results are more accurate and stable. However, this is still only a theoretical model, and subtle differences in the real environment may have an impact on the results, requiring further practical verification. The decrease in the inclination angle of the end door and the increase in the height of the end door can effectively reduce the shape coefficient of each partition on the surface of the house, indicating that in design, low angles and high doors can make the house better resistant to wind pressure. This means that when facing severe wind pressure environments, designers need to consider the entrance design of the house. The article mentions that the shape coefficient of each partition on the surface of the house decreases with the decrease of the rise to span ratio, and it is concluded that when the rise to span ratio is reduced to 1/4, the surface of the house is less affected by wind load and the force is relatively uniform. This seems to indicate that for design requirements that minimize the impact of wind loads as much as possible, priority should be given to using a smaller rise span ratio. Compared to other directions, wind directions of 0 and 90 degrees can cause smaller wind loads, indicating that the positioning direction of the house is crucial for considering wind pressure. This is an important factor affecting wind load and requires appropriate adjustments in practical engineering. Finally, an optimization scheme is proposed in the article that can significantly improve the wind resistance performance of foldable lattice shell houses, which provides important reference for practical engineering design, especially in areas with harsh wind pressure environments. However, these findings are not static theories, and although they have guiding significance for design, they still need to be adjusted based on actual environments and specific needs. In summary, research on the optimization and implementation of the shape of foldable reticulated shell houses has shown that reasonable external design and numerical wind tunnel simulation can significantly improve the uniformity of wind pressure distribution on the surface of the house, improve wind resistance and stability, and provide useful references for practical engineering design and application.

There are still certain limitations in current research. Firstly, the study only considered the impact of average wind on the wind-induced response of buildings, and did not take into account the effect of turbulent fluctuations. In reality, turbulent pulsation has a significant impact on the wind-induced response of buildings. Secondly, the numerical simulation building model established in this article adopts a rigid model, without considering the deformation effect and fluid structure coupling effect caused by turbulence on the surface of the folded lattice shell house. This simplification may lead to errors in the research results in practical applications. Thirdly, the practicality of housing design. When conducting shape optimization research, the building model was set as a closed building without doors and windows, and the shape optimization of the house in the state of opening was not studied. However, in practical applications, the design of the house needs to consider surface opening, which lacks practicality. Fourthly, this article only studies the optimization of the appearance of houses under wind load, without considering the combined effects of multiple factors such as wind, rain, snow, sand, and hail that may affect the actual use of the house.

To address the above limitations, future research may require the following work. Firstly, further research will be conducted on the effect of pulsating wind on the surface wind pressure of folded lattice shell buildings, taking into account the comprehensive response of average wind and pulsating wind on the wind pressure effect of buildings. Secondly, considering the effects of deformation and fluid structure coupling on wind pressure distribution of buildings, it may be necessary to update or modify the model to consider these more realistic factors in numerical simulations. Thirdly, conduct a study on the shape optimization of foldable lattice shell houses with openings, and explore the internal and external wind pressure effects of houses with openings, making the research results more practical. Fourthly, it is necessary to further consider the coupling effects of multiple factors, such as wind, rain, snow, sand, and hail, to further optimize the reasonable shape to cope with more complex environmental conditions.

REFERENCES

[1] V. Bani, H. Sadeghi, and A. Toosi, "Determination of wind pressure coefficients on cylindrical roofs (Barrel roofs)," *J. Struct. Const. Eng.*, vol. 9, no. 8, pp. 180–197, 2022.

[2] Y. Li, P. P. Sun, A. Li, and Y. Deng, "Wind effect analysis of a high-rise ancient wooden tower with a particular architectural profile via wind tunnel test," *Int. J. Architectural Heritage*, vol. 17, no. 3, pp. 518–537, Mar. 2023.

[3] R. Paul and S. Dalui, "Shape optimization to reduce wind pressure on the surfaces of a rectangular building with horizontal limbs," *Periodica Polytechnica Civil Eng.*, vol. 65, no. 1, pp. 134–149, 2021.

[4] P. Sanyal and S. K. Dalui, "Effect of corner modifications on 'Y' plan shaped tall building under wind load," *Wind Struct.*, vol. 30, no. 3, pp. 245–260, 2020.

[5] C. Wang, B. Nan, T. Wang, Y. Bai, and Y. Li, "Wind pressure acting on greenhouses: A review," *Int. J. Agricult. Biol. Eng.*, vol. 14, no. 2, pp. 1–8, 2021.

[6] S. K. Nagar, R. Raj, and N. Dev, "Experimental study of wind-induced pressures on tall buildings of different shapes," *Wind Struct.*, vol. 31, no. 5, pp. 441–453, 2020.

[7] N. Gaur, R. Raj, and P. K. Goyal, "Interference effect on corner-configured structures with variable geometry and blockage configurations under wind loads using CFD," *Asian J. Civil Eng.*, vol. 22, no. 8, pp. 1607–1623, Dec. 2021.

[8] A. Kumar and R. Raj, "Study of pressure distribution on an irregular octagonal plan oval-shape building using CFD," *Civil Eng. J.*, vol. 7, no. 10, pp. 1787–1805, Oct. 2021.

[9] A. Yeganeh-Bakhtiary, H. EyvazOghli, N. Shabakhty, B. Kamranzad, and S. Abolfathi, "Machine learning as a downscaling approach for prediction of wind characteristics under future climate change scenarios," *Complexity*, vol. 2022, Aug. 2022, Art. no. 8451812.

[10] Z. Han, C. Xu, L. Zhang, Y. Zhang, K. Zhang, and W. Song, "Efficient aerodynamic shape optimization using variable-fidelity surrogate models and multilevel computational grids," *Chin. J. Aeronaut.*, vol. 33, no. 1, pp. 31–47, Jan. 2020.

[11] C. Millan-Paramo and J. E. A. Filho, "Size and shape optimization of truss structures with natural frequency constraints using modified simulated annealing algorithm," *Arabian J. Sci. Eng.*, vol. 45, no. 5, pp. 3511–3525, May 2020.

[12] N. R. Secco, G. K. W. Kenway, P. He, C. Mader, and J. R. R. A. Martins, "Efficient mesh generation and deformation for aerodynamic shape optimization," *AIAA J.*, vol. 59, no. 4, pp. 1151–1168, Apr. 2021.

[13] Z. X. Sun, M. Y. Wang, L. Y. Wei, F. B. Kong, and G. W. Yang, "Aerodynamic shape optimization of an urban Maglev train," *Acta Mechanica Sinica*, vol. 37, no. 6, pp. 954–969, Jun. 2021.

[14] L. Coar, J. Hare, L. De Laet, Y.-J. Cha, G. Suh, J. Piper, and V. Jiang, "A study of digital and physical workflows used for the creation of fabric-formed ice shells with bending active frames," *Int. J. Space Struct.*, vol. 36, no. 1, pp. 13–25, Mar. 2021.

[15] J. H. Lee, Y. C. Kim, D. J. Cheon, and S. W. Yoon, "Wind pressure characteristics of elliptical retractable dome roofs," *J. Asian Archit. Building Eng.*, vol. 21, no. 4, pp. 1561–1577, Jul. 2022.

[16] A. Sehlström, K.-G. Olsson, and C. J. Williams, "Design of tension structures and shells using the airy stress function," *Int. J. Space Struct.*, vol. 37, no. 2, pp. 94–106, Jun. 2022.

[17] K. Lin, S. Xiao, A. Zhou, and H. Liu, "Experimental study on long-term performance of monopile-supported wind turbines (MWTs) in sand by using wind tunnel," *Renew. Energy*, vol. 159, pp. 1199–1214, Oct. 2020.

[18] Z. Zhao, L. Yu, and W. Hu, "Self-locking mechanism of foldable grid structures and capability evaluation of their structural units," *Structures*, vol. 27, pp. 583–594, Oct. 2020.

[19] S. Talatahari, H. Veladi, M. Azizi, A. Moutabi-Alavi, and S. Rahnema, "Optimum structural design of full-scale steel buildings using drift-tribe-charged system search," *Earthq. Eng. Eng. Vibrat.*, vol. 21, no. 3, pp. 825–842, Jul. 2022.

[20] J. Wang, H. Liu, Z. Chen, and K. Ma, "Wind tunnel test of wind-induced snowdrift on stepped flat roofs during snowfall," *Natural Hazards*, vol. 104, no. 1, pp. 731–752, Oct. 2020.

[21] A. Sarkar, A. Biswas, and M. Kundu, "Development of q-rung orthopair trapezoidal fuzzy Einstein aggregation operators and their application in MCGDM problems," *J. Comput. Cogn. Eng.*, vol. 1, no. 3, pp. 109–121, Apr. 2022.

[22] J. C. R. Alcantud, "Convex soft geometries," *J. Comput. Cogn. Eng.*, vol. 1, no. 1, pp. 2–12, 2022.

[23] S. Li, Z. You, H. Gao, Q. Wang, G. Wu, and G. Ma, "Force measurement and support integrated device in hypersonic wind tunnel," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–9, 2022.

[24] S. F. Dai, H. J. Liu, J. H. Yang, and H. Y. Peng, "Wind loads on roof-mounted isolated solar panels of tall buildings through wind tunnel testing," *Sol. Energy*, vol. 231, pp. 607–622, Jan. 2022.

[25] K. T. Tse, G. Hu, J. Song, H. S. Park, and B. Kim, "Effects of corner modifications on wind loads and local pressures on walls of tall buildings," *Building Simul.*, vol. 14, no. 4, pp. 1109–1126, Aug. 2021.

[26] F. Ding and A. Kareem, "Tall buildings with dynamic facade under winds," *Engineering*, vol. 6, no. 12, pp. 1443–1453, Dec. 2020.

[27] S. Loehle, F. Zander, M. Eberhart, T. Hermann, A. Meindl, B. Massuti-Ballester, D. Leiser, F. Hufgard, A. S. Pagan, G. Herdrich, and S. Fasoulas, "Assessment of high enthalpy flow conditions for re-entry aerothermodynamics in the plasma wind tunnel facilities at IRS," *CEAS Space J.*, vol. 14, no. 2, pp. 395–406, Apr. 2022.

[28] A. K. Bairagi and S. K. Dalui, "Estimation of wind load on stepped tall building using CFD simulation," *Iranian J. Sci. Technol., Trans. Civil Eng.*, vol. 45, no. 2, pp. 707–727, Jun. 2021.

[29] A. K. Bairagi and S. K. Dalui, "Distribution of wind pressure around different shape tall building," in *Advances in Structures, Systems and Materials: Select Proceedings of ERCAM*. Singapore: Springer, 2020, pp. 31–38.

[30] M. Jafari and A. Alipour, "Aerodynamic shape optimization of rectangular and elliptical double-skin façades to mitigate wind-induced effects on tall buildings," *J. Wind Eng. Ind. Aerodynamics*, vol. 213, Jun. 2021, Art. no. 104586.

[31] H. I. Burgan, "Numerical modeling of structural irregularities on unsymmetrical buildings," *Tehnički vjesnik*, vol. 28, no. 3, pp. 856–861, 2021.

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