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Research on Structural Performance Analysis of Agricultural Greenhouses Based on ANSYS

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Abstract: To investigate the effects of different cross- section shapes on the mechanical properties ofagricultural greenhouse frame structures, static analysis of a single-span agricultural greenhouse frame under wind and snow loads was carried out. Firstly, wind and snow loads were calculated. Secondly, with identical material parameters, boundary conditions and load cases, four combinations of arch tube and longitudinal beam cross-section shapes were designed, and three-dimensional models were established for finite element analysis. Finally, the deformation, stress and stability of structures under snow and wind loads were comparatively studied.the results show that under snow load, the maximum displacement and maximum equivalent stress of the frame with elliptical arch tubes and elliptical longitudinal beams are reduced by 11.876 mm and 103.18 MPa respectively compared with the frame of circular arch tubes and circular longitudinal beams; the maximum displacement decreases by 39 % and the maximum equivalent stress decreases by 25.8 %. Under wind load, its maximum displacement is reduced by 14.688 mm, with an overall reduction of 30.2 %. The greenhouse skeleton adopting the combined cross-section of elliptical arch tubes and elliptical longitudinal beams can effectively improve the performance and safety of agricultural greenhouses.

Keywords: Agricultural greenhouse; Frame structure; Cross-section shape; Finite element analysis; Wind and snow loads.

1. Introduction

Agricultural greenhouses are the core infrastructure of China's facility agriculture. The greenhouse industry has now developed into a large-scale operation, and the structural safety of greenhouse frames directly determines the stability of crop growth environments, ensuring sustained and stable production and income in facility agriculture. Unlike conventional industrial or civil buildings, greenhouse frames are typically assembled from thin-walled, lightweight members, resulting in characteristics such as low self-weight, relatively low overall stiffness, and weak lateral load resistance[1]. Under extreme meteorological loads such as heavy snow and strong winds, greenhouse frames are prone to significant deformation, localized stress concentration, and even global instability and collapse, leading to damage of plastic films and extensive crop losses, which cause serious economic consequences[2]. Therefore, studying the mechanical performance of greenhouse frames under wind and snow loads holds significant engineering value for enhancing disaster prevention and mitigation capabilities in facility agriculture.

Scholars both domestically and internationally have conducted extensive research on the load-bearing characteristics of greenhouse structures, primarily focusing on structural layout, support systems, material parameters, and load responses. Xie Lijuan et al. [3] effectively improved the overall stiffness and ultimate bearing capacity of greenhouses by optimizing longitudinal bracing arrangements, member layouts, and node connection methods. Xiang Bintao et al. [4] demonstrated that cross-sectional shapes can alter section moment of inertia, bending rigidity, compressive stability, and load transfer paths. Wang Cong et al. [5] performed wind-induced vibration analysis on plastic greenhouses, identifying the influence patterns of ridge height and shoulder height on nodal displacement and wind-induced vibration coefficients, and proposed practical recommendations for wind-induced vibration coefficient values. Qiao Haiyang et al. [6] used finite element simulation to model axial tension and compression processes of members and validated the accuracy of their models through experiments. Ren Jie [7] established a three-dimensional finite element model of greenhouse frames using ANSYS, confirming that wind load is the controlling load and revealing structural failure modes under different loading conditions. Zhang Tianhu et al. [8] conducted static analysis and structural optimization of greenhouse frames under wind and snow loads; Dong et al. [9] employed finite element methods to investigate deformation, stress, and stability characteristics of large-span greenhouses, analyzing the impact of ridge height on ultimate bearing capacity. Additionally, Wang Yun et al. [10] summarized key design considerations for steel-frame greenhouses based on photovoltaic greenhouse projects; Wang Chujie et al. [11] analyzed internal force and stress distributions in portal-frame greenhouse members; Li Yan et al. [12] studied displacement patterns of connected greenhouse arches under dead and combined wind-snow loads; Gong Wei et al. [13] determined design wind pressures for greenhouses based on typhoon intensity; Zhang Huamin [14] explored connection and reinforcement schemes for light steel greenhouse nodes; Wei Gang et al. [15] conducted safety analyses and optimized cross-sections for single-tube arch frames; Jiang Yingchun et al. [16] and Xu Jing et al. [17] independently investigated dynamic wind-induced vibration responses of greenhouses; WANG C et al. [18] obtained equivalent static wind loads for arched greenhouses using Fluent; and Shi Yini et al. [19] verified the reliability of truss-arch frame finite element models through model tests and ABAQUS simulations.

Most existing studies focus separately on either cross-sectional forms or structural responses under single load conditions, lacking systematic research on the deformation and stress characteristics of structures with differentiated cross-sectional combinations of arch members and longitudinal beams under combined wind and snow loads. In actual engineering applications, arch members and

longitudinal beams work together to resist wind and snow loads, and the combination of their cross-sections directly influences the overall structural behavior—a topic that remains insufficiently discussed.

To address this research gap, this study takes a single-span agricultural greenhouse frame as the subject, constructs a 3D geometric model using SolidWorks, and performs finite element mechanical analysis using ANSYS. Based on consistent material properties, boundary conditions, and wind-snow load scenarios, four sets of cross-sectional combination schemes for arch members and longitudinal beams are designed. The study compares displacement and stress distribution patterns under different cross-sectional combinations, clarifying the mechanisms by which cross-sectional pairing affects the mechanical performance of greenhouse frames. The findings provide theoretical guidance for optimizing greenhouse frame structures and improving their disaster-resistance capabilities.

2. Skeleton Structure of Greenhouse

2.1. Structure and Parameters of Greenhouse

This study focuses on a typical single-span agricultural greenhouse with a width of 6.0 m, length of 10.5 m, ridge height of 2.5 m, eave height of 1.6 m, and arch spacing of 0.8 m. The greenhouse frame mainly consists of arches, side posts, longitudinal beams, connectors joining the beams and arches, and clamping slots. For ease of comparison, all analytical models adopt identical overall dimensions, layout configurations, and connection details. The overall structure of the greenhouse is shown in Figure 1.

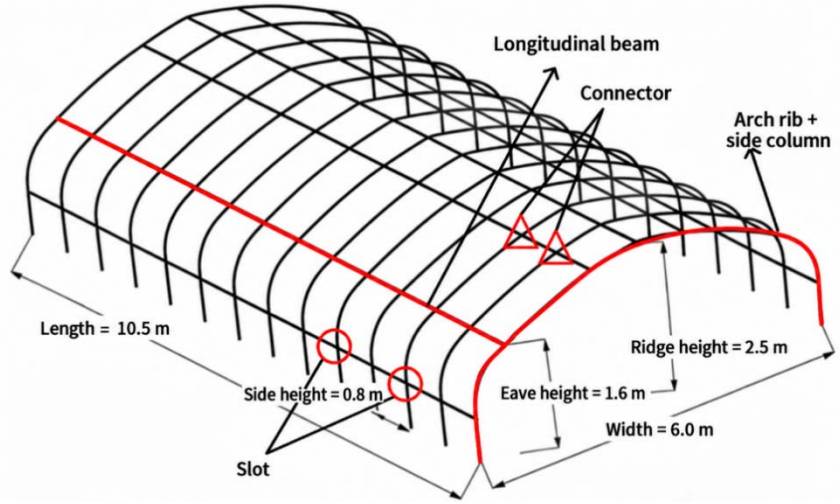


Figure 1. Schematic diagram of greenhouse frame structure

The greenhouse frame is made of 201 stainless steel, with material parameters shown in Table 1.

Table 1. Material Parameters of Greenhouse Frame

Materials	Density/ ($kg \cdot m^{-3}$)	Elastic Modulus/ Gpa	Yield Strength/ Mpa	Poisson's Ratio
201 Stainless Steel	7860	206	292	0.27

3. Finite Element Model of Greenhouse Frame

3.1. Model and Boundary Constraints

A three-dimensional geometric model of the greenhouse frame was established using SolidWorks, and finite element modeling and calculation were carried out in ANSYS. A full greenhouse consists of numerous components with complex connections. If all components were modeled as solid structures, the computational cost would be excessively high, which is not suitable for parametric comparison. Therefore, reasonable simplifications were implemented on the original model while maintaining the main stress characteristics and overall stiffness properties.

Model simplification follows the principles below [20]:

Load-bearing components that dominate the overall stress and deformation, including arch tubes, columns, longitudinal beams and main connectors, are retained;

The covering film is not modeled separately. Its self-weight and transmitted external loads are applied to the frame in the form of equivalent loads;

Local details that have minor influences on global mechanical performance, such as small connectors, holes and chamfers, are neglected to reduce the degrees of freedom of the model;

4.Since the structure is basically uniform along its longitudinal direction, three representative adjacent frames are intercepted for analysis to improve computational efficiency, so as to reflect the mechanical behavior of the whole structure.

In practical engineering, the column bases of greenhouses are generally rigidly connected to the ground via concrete foundations. For positions where coordinated deformation of components needs to be represented, the degrees of freedom of relevant nodes are processed by coupling constraints to ensure consistent deformation of connected components in corresponding directions. The boundary conditions of the model are set in accordance with current relevant specifications. The simplified model is shown in Figure 2.

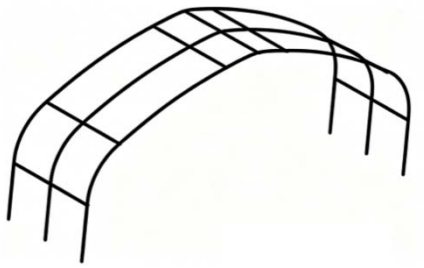


Figure 2. Simplified Model of Greenhouse

3.2. Mesh Generation

To accurately reflect the three-dimensional mechanical characteristics of members with different cross-sections, three-dimensional solid elements were adopted in the model. Mesh refinement was performed at key positions such as connecting pipes, columns and longitudinal beams. The meshing zones are illustrated in Figure 3. After mesh independence verification, the maximum element size of the model was determined to be 216.504 mm and the minimum element size 10.825 mm. The model contains 804102 elements and 1608207 nodes. This meshing scheme can balance computational accuracy and efficiency, meeting the requirements for subsequent finite element analysis.

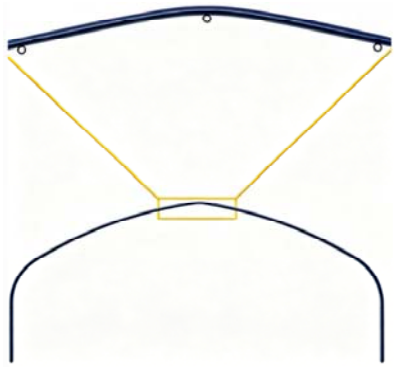


Figure 3. Meshing Zones of Greenhouse Facility

4. Calculation of Wind and Snow Loads

4.1. Permanent Load

Permanent loads mainly include the self-weight of the steel frame, the weight of covering materials and other fixed auxiliary devices. The frame is made of 201 stainless steel. The wall thickness of frame members is 2 mm, with a cross-sectional area of approximately 578 mm² and a mass per unit length of about 1.13 kg/m. The greenhouse surface is covered with 0.05 mm thick polyethylene film, whose self-weight is applied as an equivalent surface load. The auxiliary fittings are considered as a uniformly distributed vertical load of 0.07 kN/m².

4.2. Crop Load

Crop load consists of the weight of suspended crops, cultivation containers and substrates, which is applied as a uniformly distributed load on the roof. According to relevant specifications, the characteristic value of crop load for vegetable greenhouses is taken as 150.0 N/m². The characteristic values of common crop loads are shown in Table 2.

Table 2. Characteristic Values of Crop Load

Number	Crop Type	Area load (kN/m^2)
1	Solanaceous fruits	0.15
2	Small potted plants	0.30
3	Large potted plants	1.00

4.3. Wind Load

The wind load is calculated in accordance with relevant specifications:

$$w = \mu_s \mu_z w_0 \tag{1}$$

Where, wis the characteristic value of wind load, in kN/m2; μ_s is the shape coefficient of wind load; μ_z is the height variation coefficient of wind pressure; w_0 is the basic wind pressure, in kN/m^2.

The shape coefficient of wind load is determined by the shape and dimensions of the greenhouse. The greenhouse investigated in this paper adopts a single-span arched roof, and its wind load shape coefficient μ_s is 0.8. Agricultural greenhouses are mostly located in rural areas. The height variation coefficient of wind pressure reflects the variation law of wind pressure with site, landform and height. The calculation height of the greenhouse can be taken as the average height, namely the sum of the eave height and half of the roof height. For this greenhouse, z=(2.5 m/2)+(1.6 m/2)=2.05 m, Combined with the site conditions and structural height, the height variation coefficient of wind pressure μ_z is specified as 0.7 according to the code. For agricultural greenhouses with a design working life of 20 years, the basic wind pressure w_0 is taken as370.0 N/m^2.

4.4. Snow Load

According to the Load Code for Agricultural Greenhouse Structures, the uniform snow load acting on the greenhouse can be calculated by the following formula:

$$s_k = \mu_r s_o \tag{2}$$

where: s_k is the characteristic value of snow load (kN/m^2); μ_r is the roof snow distribution coefficient; s_o is the basic snow pressure(kN/m^2). The inclination angle of this greenhouse is less than 25°, so μ_r = 1 .

The greenhouse frame does not belong to a long-span structure; therefore, the snow pressure is adopted based on a 10-year return period. To reflect the influence of extreme snowfall in the study area, the maximum basic snow pressure recorded in the recent 10 years, s_o =300.0 N/m^2, is selected for calculation. The maximum snow load calculated by Equation (2) is 0.3×10-3Mpa。This load is used to analyze the deformation, stress and stability of models with different cross-sections under vertical load.

4.5. Load Combination

For lightweight agricultural greenhouse structures, variable loads usually dominate in structural design. According to the

current code, the design value of the basic combination effect of loads can be expressed as:

$$S_d = \gamma_g S_{gk} + \gamma_{q1} S_{q1k} + \sum_{i=2}^{n} \gamma_{qi} \psi_{ci} S_{qik} \quad (3)$$

where, γ_g = partial safety factor for permanent load; γ_{qi} = partial safety factor for variable load; γ_{q1} = partial safety factor for the leading variable load; S_{gk} = characteristic value of permanent load; S_{qik} = characteristic value of variable load; S_{q1k} = characteristic value of the leading variable load; ψ_{ci} = combination factor for non-leading variable load;n= number of variable loads.In this study, wind load and snow load are defined as leading variable loads. In addition, the following two load cases are considered in the mechanical analysis:

Case 1: Permanent load + uniform snow load + crop load

Case 2: Permanent load + wind load + crop load

In accordance with China's Load Code for the Design of Building Structures[21], the partial factors γ for these two load cases and the partial factors / combination factors ψ of various loads are listed in Table 3.

Table 3. Values of partial factor γ and combination factor ψ for two load cases

Load Cases	Partial factors for various loads γ /Combination factors ψ			
	Permanent load	Wind load	Snow load	Crop load
1	1.0	1.0	-	1.2/0.7
2	1.0	-	1.2 (Uniform)	1.2/0.7

5. Simulation Analysis of Stress and Deformation

To investigate the influence of cross-sectional shape on the mechanical performance of the greenhouse frame, four cross-section combination schemes were compared in this study. The schemes differ only in the cross-sectional shapes of arch tubes and longitudinal beams, while material parameters, overall dimensions, boundary conditions and load cases remain unchanged. All models have equal cross-sectional areas so that the stress states of different frames can be compared under identical loads. The parameters for different combinations of arch cross-sections and longitudinal beam cross-sections are listed in Table 4.

Table 4. Structural parameters of greenhouse frame

Section combination	Cross-section shape of arch bar	Cross-section shape of longitudinal beam	Frame dimensions
1	Elliptical	Elliptical	10.5×6.0×2.5
2	Elliptical	Circular	10.5×6.0×2.5
3	Circular	Elliptical	10.5×6.0×2.5
4	Circular	Circular	10.5×6.0×2.5

5.1. Analysis of Structural Response under Snow Load

5.1.1. Deformation Analysis

The deformation results of the four cross-section combinations under snow load are shown in Figure 6. The comparison of models with different cross-sections indicates that cross-sectional shape has a significant effect on the wind-resistant response of the structure. Among them, the maximum displacement of Combination 3 is 48.722 mm, and that of Combination 1 is 34.033 mm. The maximum displacement of Combination 1 is 14.689 mm lower than that of Combination 4. Meanwhile, Combination 1 exhibits more uniform overall deformation, demonstrating superior wind-resistant stiffness and deformation coordination capacity.

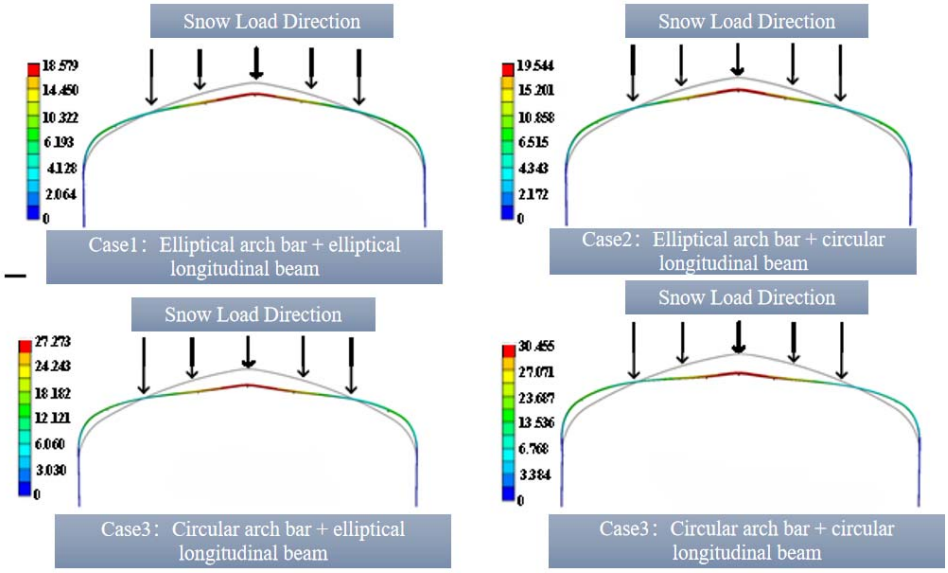


Figure 4. Displacement of various frames under the same snow load case

5.1.2. Stress Analysis under Snow Load

Figure 5 presents the equivalent stress distribution of the four cross-section combinations under snow load. It can be observed that high-stress regions are mainly concentrated at the joints between arch tubes and columns, near the eaves and at the constrained column bases. This indicates that these

locations are the most critical stress zones and weak positions requiring special attention in subsequent design. Combination 4 exhibits more severe stress concentration at connecting joints and supporting parts, with a maximum stress of 399.21 MPa. In contrast, Combination 1 has relatively uniform stress distribution and a lower peak stress, whose maximum value is only 294.89 MPa. The maximum stress of Combination 1 is 104.32 MPa lower than that of Combination 4. This is because the elliptical cross-section has a larger moment of inertia along the main force-bearing direction, which helps improve the flexural performance of members and reduce local stress peaks. Overall, the greenhouse frame is dominated by bending effects under snow load, and large equivalent stresses are mainly concentrated near joint connections and constraint regions. The cross-sectional shape has a significant influence on the flexural stiffness of members and nodal stress distribution.

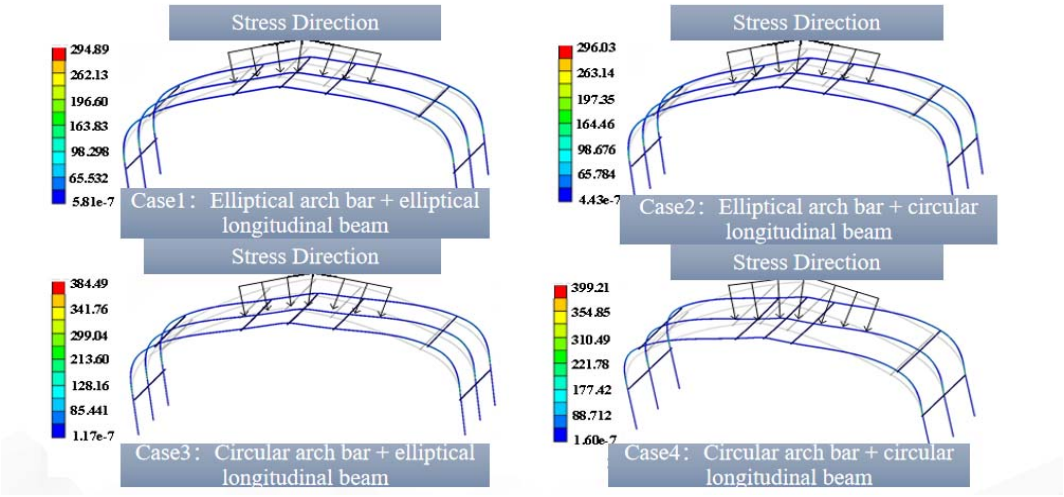


Figure 5. Stress diagrams of each frame under the same snow load case

5.2. Analysis of Structural Response under Wind Load

5.2.1. Setting of Wind Load Cases and Response Characteristics

The deformation results of the four cross-section combinations under snow load are shown in Figure 6. Comparisons among models with different cross-sections reveal that cross-sectional shape exerts a remarkable influence on the wind-resistant response of the structure. The maximum displacement of Combination 3 is 48.722 mm, while that of Combination 1 is 34.033 mm. The maximum displacement of Combination 1 is 14.689 mm lower than that of Combination 4. Meanwhile, Combination 1 presents more uniform overall deformation and possesses better wind-resistant stiffness and deformation coordination capacity.

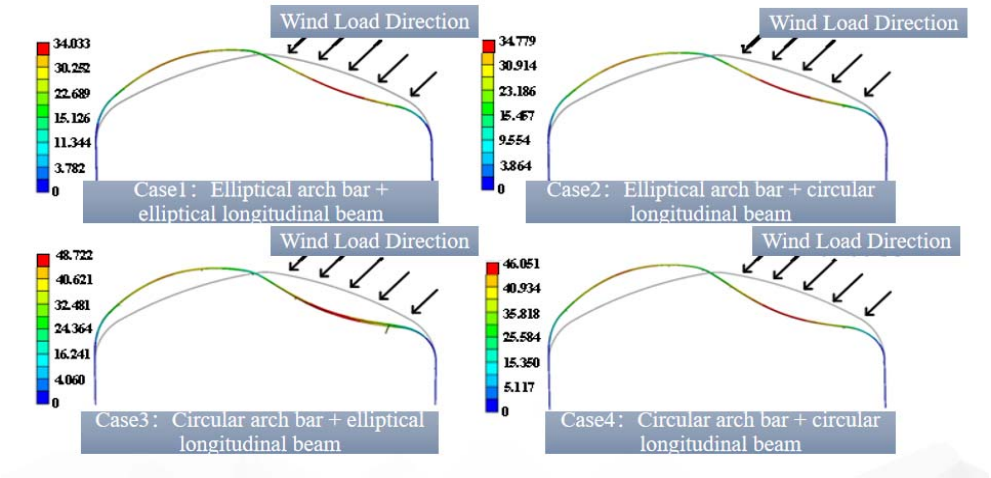


Figure 6. Displacement of each frame under the same wind load case

5.2.2. Stress Analysis under Load

Under wind load, the arch frames with different cross-section forms show significant differences in mechanical responses. By comparing the stress responses of the four cases, it can be found that the arch tube with elliptical cross-section presents obvious advantages in reducing the stress peak. Its maximum stress level is approximately 15%–25% lower than that of arch tubes with circular cross-section, as shown in Figure 7. This is because the elliptical cross-section has a higher bending moment of inertia and can better resist the bending deformation induced by wind load.The effect of the longitudinal beam cross-section is coupled with that of the arch tube cross-section. When the arch tube adopts the elliptical cross-section, the overall stress level reaches the

minimum value (222.29 MPa) and the stress distribution is the most uniform when matched with elliptical longitudinal beams. In contrast, when the arch tube is of circular cross-section, matching it with elliptical longitudinal beams will instead lead to a remarkable rise in stress peak (292.79 MPa), accompanied by obvious stress concentration. This phenomenon indicates that excessive difference in sectional stiffness will aggravate local stress.Overall, Combination 1 has the optimal mechanical performance under wind load, which can effectively reduce the overall structural stress level and improve the wind resistance of the greenhouse. In comparison, Combination 3 has the poorest mechanical performance. Such cross-section matching schemes should be avoided in engineering design. Meanwhile, the connecting joints between arch tubes and longitudinal beams shall be strengthened to mitigate local stress concentration.

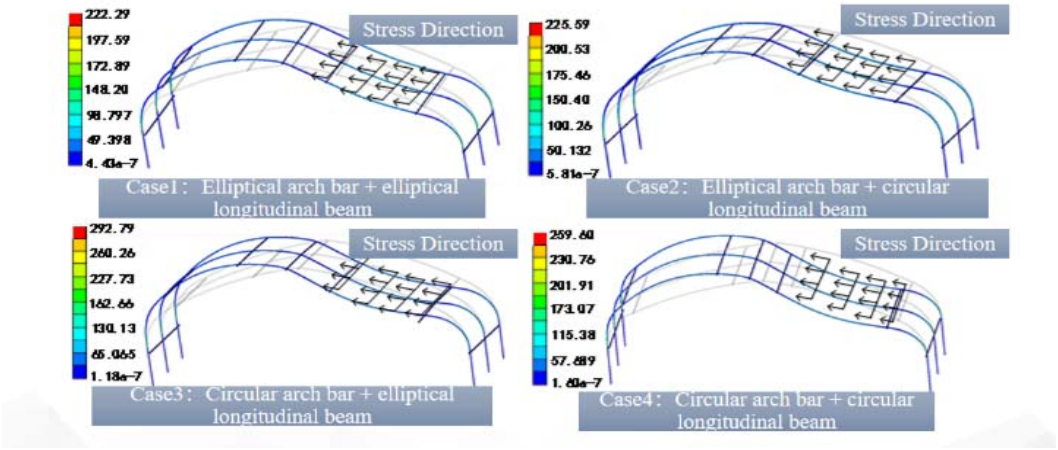


Figure 7. Stress diagrams of each frame under the same wind load case

6. Conclusion

Based on the finite element analysis method, this paper conducts a comparative study on the mechanical performance of agricultural greenhouse frames with four different cross-section combinations under snow load and wind load. The results show that under the same material consumption, boundary conditions and load cases, frames with different cross-section forms generally share the same basic stress mode, but obvious differences exist in displacement magnitude, stress value and stability performance. Under snow load, the maximum displacement of Combination 4 (circular arch tube– circular longitudinal beam) is 30.455 mm, while that of Combination 1 (elliptical arch tube–elliptical longitudinal beam) is 18.579 mm, representing a reduction of 39%. The maximum equivalent stress decreases from 399.21 MPa to 296.03 MPa, with a reduction of 25.8%, demonstrating superior snow-resistant performance. Under wind load, the maximum displacement of Combination 4 (circular arch tube–circular longitudinal beam) is 48.721 mm, and the maximum displacement of Combination 1 (elliptical arch tube–elliptical longitudinal beam) is 34.033 mm, which is 30.2% lower than the former. It indicates that the elliptical cross-section possesses better wind-resistant stiffness and global stability. Comprehensive comparison reveals that Combination 1 (elliptical arch tube–elliptical longitudinal beam) achieves the best overall performance, whereas Combination 4 (circular arch tube–circular longitudinal beam) has the poorest performance. With the cross-sectional area kept unchanged, the greenhouse frame adopting the cross-section combination of Combination 1 (elliptical arch tube–elliptical longitudinal beam) can effectively improve the performance and safety of agricultural greenhouses.

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