Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Research on the impact of cross cable nets on air-inflated membrane structures and methods for optimized arrangement

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Abstract

The wind-resistant capacity of air-inflated membrane structures without reinforced cable nets is relatively poor. In practical engineering applications for large-span air-inflated membranes, it is common to incorporate a certain number of cables into the design to create a structural system where both membrane structure and reinforced cable nets work together to withstand external forces. By optimizing the distribution of internal forces in membrane structure and cables, it is possible to effectively enhance the structural stiffness, reduce membrane structure stress, control membrane deformation, and prevent extensive damage to the membrane structure in strong winds. This approach is conducive to expanding the span of an air-inflated membrane structure. In this paper, numerical simulations are carried out for various cable net arrangements, where the cable net directions are distributed as transverse, diagonal tangent and diagonal geodesics, and the axial force in cable net segments, membrane structure stress and deformation under different arrangements are compared. The results indicate that arranging cross cable nets along the diagonal geodesic line direction on the membrane surface minimizes the risk of sliding while achieving the most even distribution of forces between cable nets and membrane structure, which results in the most optimal load-bearing performance. A uniform arrangement of reinforced cable nets can contribute to a more even distribution of internal forces in air-inflated membrane structures. In practical engineering design, it is necessary to adjust the arrangement of cross cable nets to make it more uniform, so that to optimize the overall mechanical performance of air-inflated membrane structure. This paper proposes a method for optimizing the arrangement of cross cable nets in air-inflated membrane structures using a parameter-driven strategy, which can enhance the safety, reduce the cost of air-inflated membrane structures, and provide valuable insights into the design of air-inflated membrane structures.

Keywords: air-inflated membrane structures, cross cable nets, optimized arrangements method

1. Introduction

Air-inflated membrane structures utilize the pressure difference between indoor and outdoor environments to establish a structural system with certain rigidity and stability. Due to the poor wind resistance performance, reinforcement cable nets are typically arranged to constrain the membrane surface, thereby reducing membrane stress and deformation and enhancing the wind resistance performance of air-inflated membrane structures. However, since the cable lengths calculated by most current methods are not the shortest curves on membrane surface, it results in poor adhesion between the cables and the membrane surface, causing relative slippage of cables and membrane surface under wind loads and weakening the restraining effect of cable net on membrane surface. Numerous scholars have investigated the issue of cable slippage on membranes. Li Xunrui et al.[1] simulated the contact relationship between cables and membranes using ANSYS, considering the influence of the friction coefficient between cables and membrane surfaces on the membrane structure. He Yanli et al.[2] introduced a dynamic method to solve the frictional slippage problem, providing a more precise representation of the stress distribution on the membrane surface considering cable slippage under wind or snow loads. These studies illustrate the adverse effects of cable swinging and slipping on the structural integrity of air-inflated membrane structures but do not offer specific solutions.

This paper proposes a novel cable segment generation method based on thermal stress finite element analysis. The method utilizes the finite element method for thermal stress analysis to flatten the curved surface, generate geodesic lines on the flattened membrane surface, and then reproject them onto the curved surface to obtain geodesic lines on the membrane curved surface. Based on this, a method for optimizing the cross cable nets arrangement of air-inflated membrane structures using a parameter-driven strategy is proposed. Through practical validation, the proposed method achieves the dual optimization goals of reducing the steel usage in the cable nets and improving its load-bearing capacity. Moreover, the proposed method demonstrates good stability and high efficiency.

2. Cable net arrangement and optimization

2.1. The method of cable segment generation

To mitigate the impact of cable-membrane slippage on membrane structures while also achieving higher efficiency and convenience in cable net arrangement on membrane surface, this paper proposes a novel method for generating cable segments based on thermal stress finite element analysis. This method utilizes thermal stress finite element analysis to flatten the curved surface, transforming the spatial problem into a planar one. Geodesic lines are then generated on the flattened membrane surface and reprojected onto the curved surface to obtain geodesic lines on the membrane surface. Generating cable segments along these geodesic lines can reduce the swinging amplitude of cables, diminish the effects of cable-membrane friction, simplify the numerical computation process, and enhance the efficiency of cable net generation.

2.2. The objectives of optimizing cable net arrangement

For air-inflated membrane structures with different spans, especially large-span structures, arranging diagonal cable nets can meet the requirements for rigidity and strength, ensuring that the steel usage of cable nets and the maximum cable axial force can be controlled within reasonable ranges. Therefore, in this paper,a diagonal cable net arrangement is employed for membrane surfaces. While satisfying the specifications, the optimization objectives for the cable net arrangement are focused on the following two points:

(1) Minimizing the total length of cable segments and the maximum cable axial force under the same cable net arrangement to reduce the steel usage of the cable net.

(2) Ensuring uniform stress distribution in the cable net as much as possible under conditions of similar cable usage to reduce deformation of the membrane structure.

2.3. The optimization methods for cable net arrangement

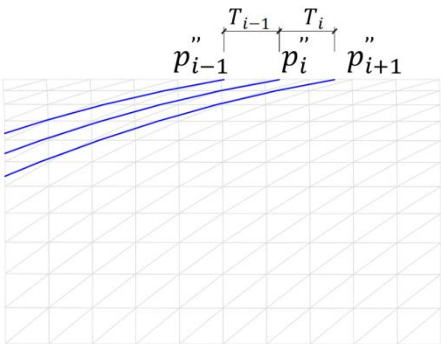
The density and uniform distribution of the cable net will affect the key engineering indicators such as membrane surface stress, maximum cable tension, and steel usage. However, the cable net formed according to the above cable net arrangement method may also have problems such as unreasonable local spacing and uneven overall stress distribution. Based on the above, this paper proposes a method for optimizing the cross cable net arrangement for air-inflated membrane structures using a parameter-driven strategy, which is divided into the following three parts:

(1) To address the issue of unreasonable local spacing in cable net, a method for locally optimizing the cable net arrangement is proposed. By defining optimization and non-optimization areas, where the endpoint spacing of cable segments [T_i]in the non-optimization area remains unchanged, while in the

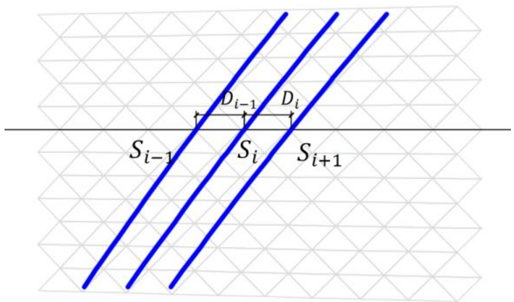
optimization area, the endpoint spacing of cable segments [T_i] is iteratively adjusted to change the density of the cable net in the area.

(2) To solve the problem of uneven overall distribution of cable net, a method for uniformizing cable net arrangement is proposed. Using the ridge line of the membrane as a reference, iteratively adjust the spacing between the intersection points of cable segments and the membrane ridge line [D_i] to achieve a uniform arrangement of cable net.

(3) Adjusting the orientation angle of the baseline and the reference line according to the actual form of the membrane surface, and both the above optimization methods of (1) and (2) can be combined for use on the same structure.



(a) enlargement diagram of the edge area



(b) Zoomed-in diagram of the central area

Figure 1: Schematic diagram of cable net

Based on the above optimization method, the relevant parameters for optimizing the arrangement of the cross cable net are refined, including: baseline angle, optimization area range, interval of space between endpoints of segments in optimization area, space between endpoints of segments in non-optimization area, and interval of space between the intersection points of cable segments and the membrane ridge lines.

3. Research content

3.1. Model establishment

To verify the superiority of the proposed method for arranging cross cable net, STCAD software was used to model the air-inflated membrane structures, employing both the method proposed in this paper and the traditional method. The initial conditions for both models were identical: the air-inflated membrane structure had a length of 300 meters, a span of 120 meters, and a height of approximately 50 meters. The dead load on membrane surface [D] was set to $0.03\mathrm{kN/m^2}$, with basic snow pressure [S]was set to $0.3\mathrm{kN/m^2}$, basic wind pressure [w_0] was set to $0.4\mathrm{kN/m^2}$, and a wind vibration coefficient of 1.0 was set, designated $W1$ as the wind load condition.

For the air-inflated membrane structure with proposed cross cable net arrangement, the parameters for net arrangement were as follows: a baseline angle of 45°, an optimization area range of 15m near the baseline starting point, an interval of [0.6m, 3m] for the spacing between endpoints of segments in optimization area, a space of 3m between endpoints of segments in non-optimization area, and no interval was set for space between the intersection points of cable segments and the membrane ridge line. This arrangement is referred to as Plan A, as shown in Figure 2.

For the air-inflated membrane structure with traditional cross cable net arrangement, the parameters for net arrangement were as follows: a baseline angle of 45°, no optimization area set, a space of 3m between endpoints of segments across the entire area, and no interval was set for space between the intersection points of cable segments and the membrane ridge line, as shown in Figure 3.

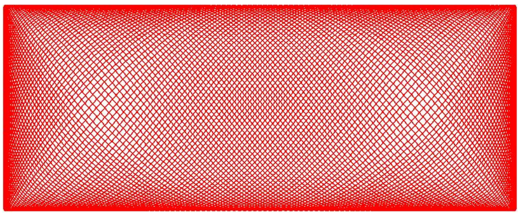


Figure 2: Cable net arrangement of Plan A

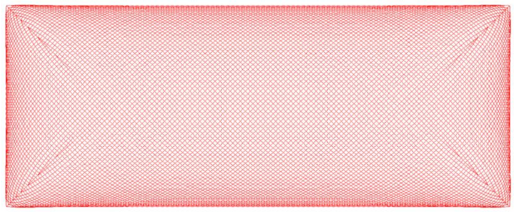
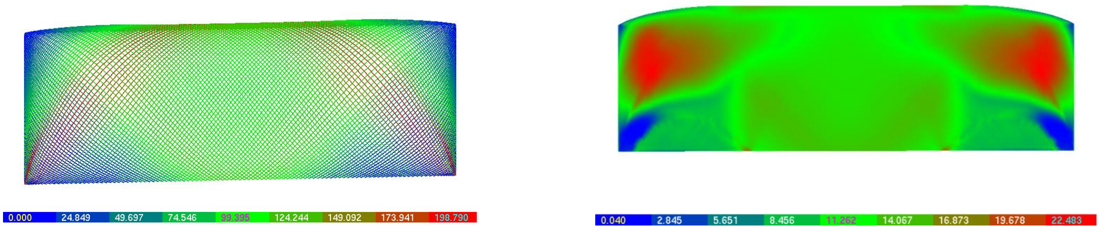


Figure 3: Arrangement of traditional cable net

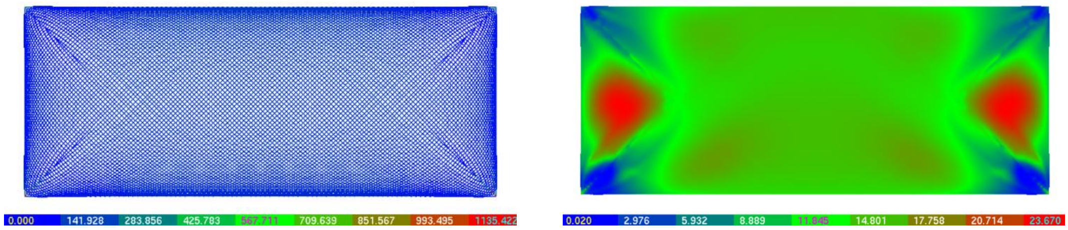
3.2. Comparative analysis of two models

Using STCAD software, the membrane structures with both types of cable net arrangement were subjected to load analysis. The load combination condition for deformation calculation was set to $1.0\,D + 1.0\,W1$, while for internal forces calculation, the load combination condition was set to $1.0\,D + 1.5\,W1$. The axial force distribution and membrane stress distribution for both arrangement methods were obtained, as shown in Figure 4 and Figure 5.



(a) Cloud diagram of axial force of cable net (kN)　　(b) Cloud diagram of membrane surface stress (kN/m)

Figure 4: Cloud diagram of axial force and membrane surface stress of Cable net arrangement Plan A



(a) Cloud diagram of axial force of cable net (kN)　　(b) Cloud diagram of membrane surface stress (kN/m)

Figure 5: Cloud diagram of axial force and membrane surface stress of traditional cable net

As shown in Figure 4 and Figure 5, the membrane stress distribution is similar for both arrangement methods, with the maximum stress on the membrane surface differing by no more than 5%. However, for the traditional diagonal cable net, the maximum axial force is 1135.42 kN, significantly higher than the maximum axial force of 198.79kN in Plan A. In both cases, the maximum axial forces are concentrated at the diagonal points of cable net, where the segmental axial forces are excessively high, necessitating section thickening, which would significantly increase the steel usage in the cable net. Compared to the traditional diagonal cable net, the segment generation method proposed in this paper significantly reduces the maximum axial forces of the segments, demonstrating the superiority of the segment generation method.

3.3. Cable net arrangement optimization

Although Plan A exhibits significant advantages in terms of cable tension compared to the traditional cable net, as shown in Figure 4, it is evident that the cable net near the edges in Plan A is sparser than in other areas, which indicates that the cable segments at the edges bear a larger load, resulting in a greater number of segments with excessive tension. Therefore, Plan A will be further optimized using both local optimization and uniform arrangement approaches.

The parameters for Plan B (employing local optimization for Plan A) are as follows: a baseline angle of 45°, an optimization area range of 15m near the baseline starting point, an interval of [1.7m, 2.7m] for space between endpoints of segments in optimization area, a space of 3m between endpoints of segments in non-optimization area, and no interval was set for the spacing between the intersection points of cable segments and the membrane ridge line, as shown in Figure 6.

The parameters for Plan C (employing a uniform arrangement for Plan A) are as follows: using the membrane ridge line as a reference line, a baseline angle of 45°, an optimization area range of 15m near the baseline starting point, and an interval of [1.25m, 1.5m] for space between the intersection points of cable segments and the membrane ridge line in optimization area, as shown in Figure 7.

Conducting load analysis for Plan B and Plan C, the cable tension and membrane stress cloud diagrams are obtained, as shown in Figure 8 and Figure 9.

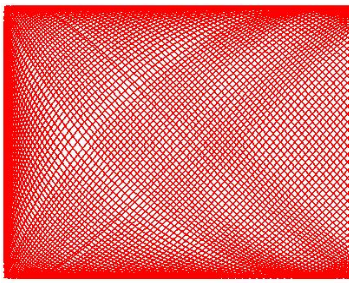


Figure 6: Cable net arrangement of Plan B (Left half)

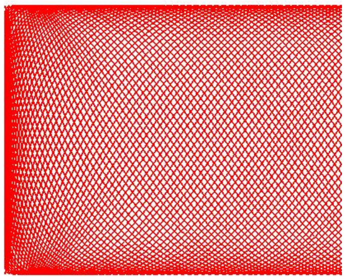
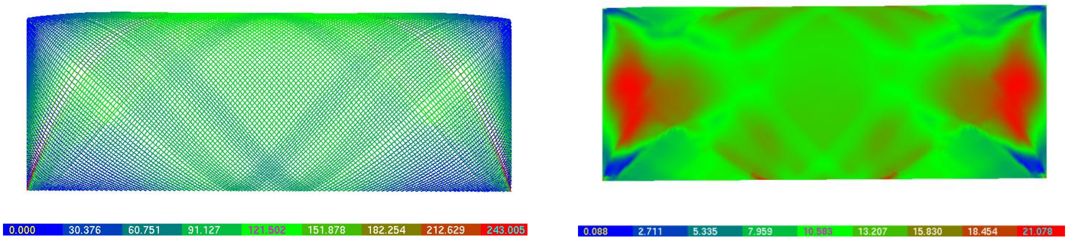
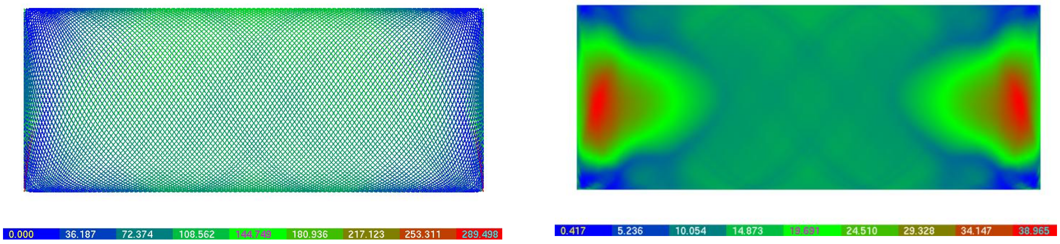


Figure 7: Cable net arrangement of Plan C (Left half)



(a) Cloud diagram of axial force of cable net (kN) (b) Cloud diagram of membrane surface stress (kN/m)

Figure 8: Cloud diagram of axial force and membrane surface stress of Cable net arrangement Plan B



(a) Cloud diagram of axial force of cable net (kN) (b) Cloud diagram of membrane surface stress (kN/m)

Figure 9: Cloud diagram of axial force and membrane surface stress of Cable net arrangement Plan C

Comparing Figure 4 with Figure 8, it is observed that compared to Plan A, densification of the cable net in Plan B leads to an increase of 15% in the total cable length. And there is a stress concentration near the diagonal point, and the maximum axial force of the segments increases by 22%. However, the load shared by the cable segments in other areas decreased, and the length of cable segments with axial forces exceeding 180kN decreased by approximately 88%. The maximum membrane stress difference between Plan A and Plan B did not exceed 10%, which indicates that local optimization arrangement can effectively alleviate the issue of excessive local stresses in the cable net, but the impact on membrane stress and deformation is not significant.

Comparing Figure 8 with Figure 9, it is evident that compared to Plan B, Plan C achieves a more uniform stress distribution in the cable net after uniform arrangement optimization. The total cable length decreased by 13%, but the length of segments with axial forces exceeding 180kN increased by approximately 80%. The maximum axial force of the cable segments also increased by about 19%, concentrated in the corner regions of the membrane structure. Comparing Figure 4 with Figure 9, it is observed that the difference in total cable length between Plan A and Plan C does not exceed 0.18%. In Plan C, the length of cable segments with axial forces exceeding 180kN decreased by 78%, while the maximum axial force of the cable segments increased by 46%, primarily concentrated in the corner regions of the membrane structure. This indicates that uniform arrangement optimization can improve the overall stress distribution in the cable net but may lead to increased local stress on cable segments and membrane deformation.

To achieve the optimization goals of reducing steel usage in the cable net while ensuring uniform cable tension, a combined optimization arrangement scheme is adopted, featuring a sparse central cable net and dense edge cable net. This is referred to as Plan D, with parameters: a baseline angle of 45°, an optimization area range of 15m near the baseline starting point, an interval of [1.9m, 3.2m] for the spacing between endpoints of segments in the optimization area, a spacing of 3.6m between endpoints of segments in the non-optimization area, and an interval of [1.25m, 1.5m] for the spacing between the intersection points of cable segments and the membrane ridge line, as shown in Figure 10. The cable tension and membrane stress for Plan D are shown in Figure 11.

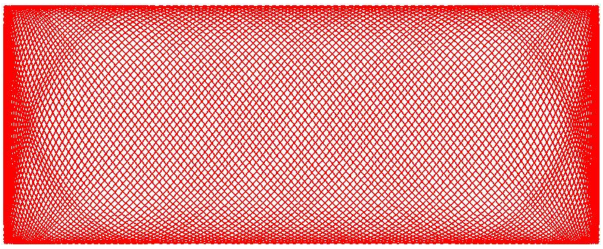
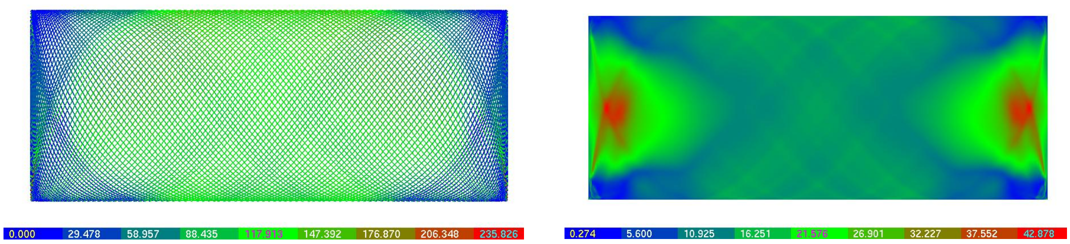


Figure 10: Cable net arrangement of Plan D



(a) Cloud diagram of axial force of cable net (kN) (b) Cloud diagram of membrane surface stress (kN/m)

Figure 11: Cloud diagram of axial force and membrane surface stress of Cable net arrangement plan D

The total length of cables, maximum cable axial force, length of cables with axial force exceeding 180kN, maximum membrane stress, and membrane displacement under the same load conditions for each scheme were respectively calculated in Table 1.

Table 1: Statistical Data Table for Four Arrangement Plans

NO.	Total cable length (m)	Difference (%)	Maximum axial force (kN)	Cable length with axial force exceeding 180kN (m)	Maximum membrane stress (kN/m)	Maximum horizontal displace-ment (mm)	Maximum vertical displace-ment (mm)	Final air pressure (pa)
Plan A	46845	±0.00	198.79	974.31	22.48	3508	3116	686
Plan B	53758	14.76	243.00	117.46	21.08	3507	3191	708
Plan C	46931	0.18	289.50	210.31	38.96	3588	3051	691
Plan D	44783	-4.41	235.83	52.81	42.88	3632	3141	661

Based on the stress cloud diagram in Figure 11 and the data in Table 1, it can be observed that compared to the previous three plans, Plan D has the least total cable length and length of cables with axial force exceeding 180kN. The maximum axial force of cable segments is only 19% higher than Plan A , which is lower than Plan B and C. Additionally, the maximum membrane stress increases by 10% compared to Plan C, but remains below 120 kN/m , well within the expected range. The maximum horizontal displacement and vertical displacement differ by no more than 4% compared to the three plans. From the analysis results, it is evident that this optimization scheme achieves the objectives of reducing the steel usage in the cable net and improving the stress distribution.

In summary, the optimization method for the arrangement of cross cable nets driven by parameters such as baseline angle, optimization area range, interval of space between endpoints of segments in optimization area, space between endpoints of segments in non-optimization area, and interval of space between the intersection points of cable segments and the membrane ridge line, can achieve the optimization goals of reducing the steel usage in cable nets, ensuring uniform distribution of forces in the cable nets, and reducing deformation of the membrane structure.

4. Conclusion

The paper proposes a method for segment generation based on thermal stress finite element analysis, and presents an optimization approach for the arrangement of cross cable nets in air-inflated membrane structures using a parameter-driven strategy. Through case analysis, the following conclusions are drawn:

(1) Compared with traditional stiffening cable nets, the segment generation method based on thermal stress finite element analysis proposed in this paper significantly reduced the lateral displacement and maximum axial force of the cables. This method addresses the issue of reduced load-bearing capacity in membrane structures due to the inability of cable nets to tightly adhere to the membrane surface, demonstrating its feasibility and applicability.

(2) By establishing a parameter-driven optimization method for the arrangement of cross cable nets based on parameters such as baseline angle, optimization area range, interval of space between endpoints of segments in optimization area, space between endpoints of segments in non-optimization area, and interval of space between the intersection points of cable segments and the membrane ridge

line, optimized arrangement of cable nets can be rapidly generated according to different parameters. This approach also enhances the safety and cost-effectiveness of air-inflated membrane structures.

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