Wind Resistance Capacity analysis of Emergency Inflatable High Altitude Lamp

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Abstract. In working conditions such as night construction sites, the supplement of high-altitude light sources is an important guarantee for the smooth progress of the project. In the actual use of high-altitude lamp, it is necessary to check according to load conditions and wind load forms to prevent the slender high-altitude lamps from being harmed due to instability. By applying wind load and gravity load on the lighting platform, this paper used finite element analysis software to simulate the operating conditions of the inflatable high-altitude lamp; selected the airbag configuration model to analyze the force form of the inflatable high-altitude lamp, gave the reasonable range of inflatable lamps used under various load forms, and predicted the failure modes under various loads.

1. Introduction

The use of high-altitude lights has spread to all aspects of people's lives, bringing great convenience to night travel and work [1]. In more developed cities, there are less cases of no light source or insufficient light source at night [2]. Due to its portability, light weight, and good mobility, emergency inflatable high-altitude lights can be assembled and stored at any time by charging and deflating to meet the needs of supplementing night light sources under specific working conditions. It is used in mobile construction and other specific engineering rescue sites more applications [3].

When the high-altitude light is too high, the sensitivity of the structure to wind load increases, and wind load and wind vibration are the main reasons for structural instability [4]. Qiao Fengbin [5] et al. conducted a modal analysis of a slender structure under wind load. Zhao Zhiqiang [6] et al. analyzed the natural wind equivalent load form and action mode; Liu Min [7] et al. based on different wind speeds and windward areas The Bonvli equation is used to obtain the wind pressure calculation formula.

From the existing research results, wind load is an important indicator that affects the practicability of the slender structure [8], and it is necessary to further analyze the wind resistance and bearing capacity of the high-altitude light restraint form.

2. Establishment of Finite Element Model

An inflatable lamp cylinder used in this design is made of high strength fiber cloth double-sided composite polyether polyurethane film. The shape is cylindrical thin wall straight cylinder. In order to slow down the concentrated stress, the R angle transition is used at both ends of the cylinder.
Polyurethane film material parameters: surface density 550g/m², tensile strength 1200N/cm², gas leak rate 0.1L/m²·atm/24h. An inflatable lamp is a stainless steel base, which can be completely fixed to the bottom end of the structure during simulation and replaced by a rigid plane on the ground where the inflatable lamp is placed; the lamp part of the inflatable lamp is made of carbon fiber / aluminum alloy and the mass is 10 kg, is fixed at the top of the column. The simulation can simplify it to the top gravity load; the material parameters used for modeling are shown in Table 1:

| Tensile strength | Density | Diameter * Length | Pressure bearing capacity | Quality of lamps | Thin film thickness | Elastic modulus | Transition angle |
|------------------|---------|-------------------|---------------------------|------------------|---------------------|----------------|-----------------|
| 40*10⁶ Pa        | 1833 kg/m³ | 1 m * 10 m       | 50*10³ Pa                 | 10 kg            | 0.0003 m           | 50*10⁶ Pa      | 0.005 m         |

The finite element model adopts a shell model for modeling. The enveloping volume of the air column is 32.85 m³, and the mass of the polyurethane film used in the air column is 18.06 kg; the windward side of the air column is a rectangular cross-section through the cylinder axis, with an area of $S_1 = d \times L = 10$ m²; the upper and lower sections of the air column are circular pressure-bearing surfaces with an area of $S_2 = \pi/4 \times d^2 = 0.785$ m². The finite element model of the inflatable high-altitude light is shown in Figure 1a), and the physical model is shown in Figure 1b):
As the main structure of the inflatable lamp post, in addition to the original size modeling and the corresponding material parameter assignment, the inflatable column also bears the following constraints and stress conditions: 1. The upper end of the air column comes from the gravity of the lamp mass, which is simplified as a surface Force; 2. The gravity of the air column; 3. The air pressure on the inner wall of the air column; 4. The wind force applied to the windward side. The force decomposition is shown in Figure 2. The total force of the air column is the superposition of different force conditions.

3. Analysis of bearing capacity under static load
The static load condition refers to the force of the gas column when it is not subjected to the wind load. At this time, the gas column is only subjected to its own gravity, the gravity of the lamp, and the internal pressure of the gas column. The diagram is shown in Figure 3.

The truncated part of the gas column is projected along the axial direction, and the balance formula of the force is obtained:

\[ \sum F = 0 \]

\[ p_a \cdot S_2 - G_{\text{Light}} - G_a - p_{\text{tense}} \cdot d \cdot t = 0 \]  

(1)

In the formula:
- \( p_a \) is the internal pressure of gas column (Pa);
- \( d \) is the diameter of gas column (m);
- \( S_2 \) is confined surface area (m²);
- \( G_{\text{Light}} \) is Gravity for lamps (N);
- \( G_a \) is truncated air column weight (N).
- \( G_a \) is related to the distance \( x \) between the cross section and the bearing surface \( G \) of which related to the distance between the section and the bearing surface, the formula is:

\[ G_a = (S_2 + \pi \cdot d \cdot x) \cdot \gamma_1 \cdot \gamma \quad (0 < x < L) \]  

(2)

In the formula:
- \( x \) is the distance between the cross section and the pressure bearing surface (m);
- \( L \) is the length of the gas column;
- \( \gamma_1 \) is the surface density of the film (kg / m²).
Because the membrane material can only bear tensile stress, but cannot bear compressive stress, in order to prevent air column failure, the membrane tension $p_{\text{tense}} \geq 0$ is required under static load; by substituting the film tension constraint equation and equation (2) into equation (1), the minimum gas column pressure $p_{\text{min}}$ is obtained.

$$p_{\text{min}} = \frac{[10+9.8 + (1^2 \cdot \pi / 4 + \pi \cdot 10) \cdot 0.55 \cdot 9.8]}{(1^2 \cdot \pi / 4)} = 345.6 \text{ Pa}$$

In order to verify the correctness of theoretical calculations and finite element analysis, finite element simulation analysis applied 345±25Pa air pressure to the air column under static load to check the bearing capacity and failure conditions of the air column, and according to the safety factor $n=2$ 700Pa is applied to the air column to check the safe air pressure during static load, and the settlement result is shown in Figure 4.

According to figure 4a) It can be concluded that when the air pressure of the air column is less than $p_{\text{min}}$, the air column cannot carry effectively, and the structure will lose stability under heavy load; according to Fig. 4b), when the air pressure of the air column is greater than $p_{\text{min}}$, the structure will not lose stability and carry effectively, but the air column will be compressed axially under heavy load; according to Fig. 4c), when the air pressure of the air column is greater than $n \cdot p_{\text{min}}$, the structure will lose stability It can effectively carry out the load, and the axial compression is small, which meets the use requirements. The result of finite element simulation is very close to that of theoretical calculation, which shows that this method is reliable for checking the wind resistance ability of street lamp air column.

4. Analysis of bearing capacity under static load
The wind pressure is the pressure on the unit area of the windward side. According to Bonvli equation, the ideal wind pressure is [9]:

$$p_b = 0.5 \gamma_2 \cdot v^2$$

In the formula: $p_b$ is wind pressure (kN/m²); $\gamma_2$ is air density (kg/m³); $v$ is wind speed (m/s).

Since the relationship between air density $\gamma_2$ and heavy weight $r$ satisfies $r = \gamma_2 \cdot g$, there is $\gamma_2 = r / g$. The formula (4) is transformed into:

$$p_b = 0.5 \cdot r \cdot v^2 / g$$

Figure 4. Air-column loadings.
This formula is the standard wind pressure formula. Under the standard condition, the air density \( \gamma = 0.01225 \text{ kN/m}^3 \), \( g = 9.8 \text{ m/s}^2 \), the results are as follows:

\[
P_b = \frac{v^2}{1600}
\]  

(6)

When the structure is high, the windward side is non-planar, and the wind load is in the form of vibration, formula (6) needs to be modified according to the actual working conditions. When the inflatable high altitude lamp is subjected to wind load, the corrected actual wind pressure is [9]:

\[
p_c = \beta \cdot \mu_c \cdot \mu_p \cdot (A \cdot p_b)
\]

(7)

In the formula: \( \beta \) is the wind vibration coefficient; \( p_c \) is the actual wind pressure.

Different height levels of the air column have different values of wind vibration coefficient \( \beta \). Wind vibration coefficients at different levels:

\[
\beta = 1 + \frac{L_k \cdot \varepsilon \cdot \gamma}{L \cdot \mu_c}
\]

(8)

In the formula: \( L_k \)—the Central Height of the gas column,
\( \varepsilon \)—the pulsation increasing coefficient. The pulsation coefficient of an object less than 30 m in height is generally 1.28;
\( \mu_c \)—The Coefficient of wind pressure height. The Wind Pressure Height Coefficient of the gas column is 1.14;
\( \gamma \)—Fluctuation Influence Coefficient. The shape coefficient of the gas column is 0.53;
\( \mu_p \)—the shape factor of the air column. Generally speaking, for any wind direction, the wind surface of this air column can be regarded as a circular arc surface, and the \( \mu_p \) value is 0.8;
\( A \)—Geographical terrain coefficient. Considering that the surrounding environment and buildings of the place where the air column is installed and used may be complicated, \( A \) is 1.1.

The wind vibration coefficient and actual wind pressure of street lamp air column are calculated as follows: its height center \( L_k = 5 \text{ m} \);

Wind vibration coefficient: \( \beta = 1 + \frac{5}{10} \times \frac{1.28 \times 0.53}{1.14} = 1.2975 \)

Actual wind pressure that the air column may experience:

\[
p_c = 1.2975 \times 1.14 \times 0.8 \times 1.1 \times \frac{v^2}{1600} = \frac{v^2}{1239} \text{ kN/m}^2
\]

(9)

In this paper, the finite element simulation wind pressure is loaded according to the corresponding value of \( p_c \).

5. Finite element analysis of wind resistance of air column

According to the simulation in the previous section, when the air pressure inside the air column is greater than 700 Pa under static load, the influence of the self-weight of the structure and the gravity load of the lamp can be offset. In this section, the wind pressure of \( p_c \) is applied on the basis of the original bearing capacity of the air column, and the bearing capacity and failure mode of the air column under the wind load are analyzed, so as to provide the basis for the later practical use.

According to formula (7), the relationship between wind speed and wind pressure and wind grade can be calculated, as shown in Table 2:
Table 2. Comparison of wind speed and wind pressure [10-11].

| Wind stage | Name of name  | Wind speed (m/s) | Wind pressure(N/m²) |
|------------|---------------|------------------|---------------------|
| 0          | No wind       | <0.20            | <0.0033             |
| 1          | Soft Wind     | 0.30~1.50        | 0.073~1.812         |
| 2          | Light wind    | 1.60~3.30        | 2.07~8.79           |
| 3          | The breeze    | 3.40~5.40        | 9.22~23.54          |
| 4          | Wind          | 5.50~7.90        | 24.59~50.37         |
| 5          | Wind          | 8.00~10.70       | 50.16~90.41         |
| 6          | Strong winds  | 10.80~13.80      | 94.14~153.70        |
| 7          | Wind          | 13.90~17.10      | 155.94~236.00       |
| 8          | Strong winds  | 17.20~20.70      | 238.77~345.84       |

In order to improve the wind resistance of the air column, the anchor cable is used to fix the bottom part, so two groups of models are used to analyze the air load, as shown in Figure 5: (1) fixed air column of base; (2) fixed air column of rope. At the bottom end, the fixed air column of the base is completely fixed by the connecting base, and the rigid ground is used in the finite element model. The rope fixed air column is to apply four UHMWPE cables at the L/5 of the base on the basis of the rigid base. Improve wind resistance by increasing constraints.

![a) Base fixed](imageA)

![b) ropes fixed](imageB)

Figure 5. Schematic diagram of gas column fixation.

The corresponding pressure is applied to the two groups of models, and the bearing capacity and failure form are analyzed. The model of fixed form of base is analyzed first, and the air pressure of 1 kPa~10 kPa is applied, and the wind speed of 0~10 m/s is analyzed. According to the simulation results, several typical bearing conditions are selected, as shown in Table 3:

| Wind stage | Name of name  | Wind speed (m/s) | Wind pressure(N/m²) |
|------------|---------------|------------------|---------------------|
| 0          | No wind       | <0.20            | <0.0033             |
| 1          | Soft Wind     | 0.30~1.50        | 0.073~1.812         |
| 2          | Light wind    | 1.60~3.30        | 2.07~8.79           |
| 3          | The breeze    | 3.40~5.40        | 9.22~23.54          |
| 4          | Wind          | 5.50~7.90        | 24.59~50.37         |
| 5          | Wind          | 8.00~10.70       | 50.16~90.41         |
| 6          | Strong winds  | 10.80~13.80      | 94.14~153.70        |
| 7          | Wind          | 13.90~17.10      | 155.94~236.00       |
| 8          | Strong winds  | 17.20~20.70      | 238.77~345.84       |
Figure 6. Schematic illustration of the deformation of a fixed gas column at the base.

Table 3. Bearing conditions of fixed air column with base.

| Working condition number | Air pressure (kPa) | Wind speed (m/s) | Maximum stress (MPa) | Maximum deflection (m) |
|--------------------------|-------------------|-----------------|----------------------|------------------------|
| Conditions 1             | 3                 | 3               | 17.99                | 0.98                   |
| Conditions 2             | 5                 | 3               | 27.79                | 0.54                   |
| Conditions 3             | 10                | 3               | 27.23                | 0.58                   |
| Conditions 4             | 5                 | 3.5             | 30.58                | 1.22                   |

According to the comparison and analysis of working conditions 1, 2 and 3, it can be concluded that:
1. The maximum stress of the three working conditions relative to the tensile strength of 40 MPa is not invalid; 2. When the air pressure is increased by 100%, the maximum stress change range is 2%, and the maximum deflection change range is 7.4%; 3. When the air pressure is decreased by 40%, the maximum stress change range is 35%, and the maximum deflection change range is 81%; 4. When the air pressure is more than 5 kPa, the maximum deflection change range is 7.4%; 5. When the pressure is less than 5 kPa, the overall pressure of the air column structure is insufficient and the stiffness decreases greatly, so the pressure should not be less than 5 kPa. Therefore, 5 kPa can be used as the appropriate inflation pressure.

According to the comparison and analysis of working conditions 2 and 4, it can be concluded that:
1. When the wind speed increases from 3 m/s by 16.7% to 3.5 m/s, the maximum stress increases by 10%, and the maximum deflection increases by 126%, and the air column is not invalid; 2. When the wind speed is greater than 4 m/s, the maximum stress increases by 10%; 3. According to the comparison of the variation range of air pressure and wind speed, it can be found that the influence of wind speed on the deformation of air column is much greater than that of air pressure, and the wind resistance of air column structure is poor. In conclusion, when the base is fixed, the air pressure of 5 kPa can be used as the appropriate air pressure, and the maximum bearing wind speed of the structure is 3.5 m/s.

In order to verify the improvement of wind resistance ability of fixed rope to air column structure, the model of fixed rope form is selected, the air pressure is 5 kPa, and the appropriate wind speed is selected for analysis, as shown in Figure 7; several typical load-bearing conditions are selected according to the simulation results, as shown in Table 4:
Figure 7. Diagram of deformation of fixed gas column with rope.

Table 4. Load bearing conditions of fixed air column with rope.

| Working condition number | Air pressure (kPa) | Wind speed (m/s) | Maximum stress (MPa) | Maximum deflection (m) |
|-------------------------|--------------------|------------------|----------------------|------------------------|
| Conditions 5            | 5                  | 5.5              | 21.25                | 0.38                   |
| Conditions 6            | 5                  | 6                | 21.01                | 0.98                   |
| Conditions 7            | 5                  | 6.5              | 21.36                | 1.97                   |
| Conditions 8            | 5                  | 20               | 81.09                | Instability of instability |

According to Table 4 and Figure 7, when the air pressure is constant 5 kPa, the maximum deflection increases with the increase of wind load; when the wind speed reaches 6 m/s, the air column slightly turns over at the fixed end of the rope; if the wind speed continues to increase, the air column turns over at the fixed end of the rope, and the maximum wind speed borne by the fixed way is 6 m/s; when the wind speed reaches 20 m/s, when the maximum wind speed is 6 m/s, the gas column is completely unstable, the maximum stress is greater than the tensile strength, and the gas column breaks.

6. Conclusions
According to the results of finite element simulation and theoretical derivation, the following conclusions are obtained

1. The overall bearing part of the inflatable high altitude lamp is polyurethane air column. When it does not bear the wind force, it can carry 10 kg and bear its own gravity when it is charged at 345 Pa, but the compression deformation is obvious, so it needs to use a safety factor when it is under static load, that is, it can bear the load safely when it is charged at 700 Pa;

2. When only the bottom end of the inflatable high altitude lamp is fixed, the safe bearing wind speed is 3 m/s, and if the wind speed is too high, the air column will lose its stability and failure; when the air pressure reaches 5 kPa, the increase of the air pressure again has no obvious effect on the rigidity of the air column, but leads to the increase of the average stress of the air column film and the risk of fracture failure; when the air pressure is lower than 5 kPa, the stiffness of the air column decreases obviously and the bearing capacity decreases rapidly, so 5 kPa is the appropriate pressure;

3. Because the inflatable high altitude lamp needs to carry, the cross-sectional area of the inflatable high altitude lamp is 8-10 times of that of the rigid street lamp under the same length, resulting in the increase of the windward area; under the same wind speed, the inflatable high altitude lamp bears greater wind load, so the wind resistance performance is not high;
4. The maximum bearing wind speed of the high altitude emergency lamp can be increased from 3.5 m/s to 6 m/s when the air column is 2 m away from the ground; to improve the wind resistance of the inflatable high altitude lamp, the restraint mode or air column structure should be further optimized.

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