Mechanical simulation analysis of lightweight blades using glass fiber phenolic resin composites

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Abstract. This paper uses simulation methods to verify the reliability of applying glass ferroaluminium alloy laminates to subway fan blades. Through the force analysis of its blades, it is found that the material has a wider application prospect in subway fan blades, and it can achieve better energy-saving effects than the existing aluminium alloy blades.

Keywords: fan, blade, composite material.

1. Introduction
With the gradual acceleration of urban development in recent years, subway transportation has become more and more important in people's lives as a means of travel with larger passenger capacity, fast speed, and more energy-saving.

During the operation of the subway, the subway fan needs to be used to discharge the generated heat and a small amount of exhaust gas, which makes the subway fan need to run for a long time, and the energy consumption is high. Therefore, the design of the fan occupies a more critical position in the energy-saving design scheme of the subway fan. In recent years of new material application scenarios, glass fiber-aluminum alloy laminates are composite materials composed of alternate layers of aluminum alloy and glass fiber reinforced resin composite materials. Due to their good fatigue resistance and impact resistance, It has been widely used in the aerospace industry.

After research, a lightweight, high-temperature resistant material such as fiberglass-aluminum alloy laminates can be applied to the blades of subway fans to achieve better energy-saving effects. This paper conducts mechanical analysis on the application of glass fiber-aluminum alloy laminates on subway fan blades, and provides feasibility evidence for the lightweight design of blades from the perspective of mechanics.

2. Experiment
2.1. Material mechanical properties
Use glass fiber phenolic resin composite material-aluminum alloy composite material to make subway fan blades. Compared with epoxy resin-based composite materials, glass fiber phenolic resin composite material-aluminum alloy composite material has stronger mechanical properties at high temperatures. According to the data, at 180°C, the tensile properties of the three-dimensional and five-directional woven epoxy resin composite material decreased by 15.37%, while the tensile strength of the laminated composite material decreased by 34.42% under the same conditions.
The reason was that the composite material was exposed to high temperatures. Due to the destruction of the resin, so that each layer of composite material delamination. The phenolic resin-based composite material has higher strength and is not easily damaged at high temperatures. Compared with the epoxy resin-based composite material, it can bear the working environment of subway fan blades. Compared with carbon fiber, glass fiber is electrically neutral, has no potential corrosion, has a large elongation and thermal expansion coefficient, and has a small curing residual stress. Therefore, glass fiber composite materials and aluminum alloy composites are ideal materials. The tensile properties of the glass fiber composite material-aluminum alloy meet the metal volume fraction theory, which can provide a theoretical basis for the performance calculation of the glass fiber composite material-aluminum alloy composite material.

2.2. Material resistance to temperature and humidity

In terms of resistance to temperature and humidity, due to the protection of the outer metal layer, the fiber metal layer can always absorb moisture generated by distilled water or salt spray, reducing its damage to the fiber layer of the metal layer. The glass fiber-aluminum alloy laminate has superior flame resistance. The single-sided flame burn-through results at 2500°C show that when the thickness of the aluminum layer of the laminate is 0.2-0.3mm, the burn-through time of the glass fiber-aluminum alloy laminate is 1mm thick. Dozens of times the aluminum alloy plate. The reason is that the outermost aluminum plate of the glass fiber-aluminum alloy laminate melts rapidly (melting temperature is 500°C), but the carbonization time of the inner fiber resin layer is relatively slow. This is because the glass fiber has a higher melting point, which can prevent flame penetration. Transparent glass fiber-aluminum alloy laminate. In addition, the coefficients of thermal expansion of each component of the glass fiber-aluminum alloy laminate (aluminum alloy sheet, glass fiber, resin) are different, which will cause the glass fiber-aluminum alloy laminate to be heated to layer and form an air layer that isolates heat.

2.3. Lightweight materials

In terms of weight reduction, the current main material used for subway fan blades is aluminum alloy, while composite fan blades have excellent performance. Composite materials are an effective way to reduce product weight. Compared with the performance requirements of civil aviation engine fan blades, subway fan blades are used the performance is far lower, and it is necessary to design and study composite fan blades that meet the requirements of subways. There are few cases and studies on composite fan blades for subways at home and abroad.

2.4. High temperature resistance of materials

Subway fan blades should have high temperature resistance, that is, when installed in the station ventilation and smoke exhaust system, the fan must be able to work continuously for 1h when the medium passes through 250℃ and 0.5h when the medium passes through 280℃. It is installed in the tunnel ventilation and smoke exhaust system. It can work continuously at 150℃ for 1h. Compared with pure resin materials, fiber metal plate has the characteristics of high temperature resistance, and has high specific strength, high specific rigidity and good corrosion resistance and fatigue resistance. At the same time, under tensile conditions, temperature plays a leading role; bending; Under load, the temperature has a significant influence on the plate deformation before reaching the softening point, and the strain rate becomes prominent after the temperature reaches the softening point.

Ma Hongyi’s article gives a detailed description of the selection of glass fiber composite materials-aluminum alloy materials. Compared with carbon fiber, glass fiber is electrically neutral, does not have potential corrosion, has a large elongation and thermal expansion coefficient, and has a small curing residual stress. Fiber composite materials and aluminum alloy composites are ideal materials. The tensile performance of glass fiber composite material-aluminum alloy meets the metal volume fraction theory, which can provide a theoretical basis for the performance calculation of glass fiber composite material-aluminum alloy composite material [1].
Li Jialu’s article studied the tensile properties of three-dimensional five-directional braided epoxy resin composites and resin-based laminate composites at room temperature, 80°C, 150°C and 180°C. The results show that the tensile strength of the three-dimensional five-directional composite material at 80°C and 150°C is similar to room temperature, the tensile strength at 180°C is reduced by 15.37%, and the tensile strength ratio of the laminated composite material at 80°C, 150°C and 180°C. The room temperature decreased by 3.45%, 13.3% and 34.42% respectively. The reason for the large decrease in the high-temperature tensile strength of the laminated composite is that at high temperature, the resin is destroyed, causing the laminated composite to delaminate [3].

Chen Yujie’s article studies the effect of temperature and strain rate on the deformation of thermoplastic glass fiber-aluminum alloy laminates under warm conditions. In the experiment, the temperature is 25℃, 80℃, 140℃, 165℃, 185℃, and the strain rate is 1.10, 100mm/min. Research results: under tensile conditions, temperature plays a dominant role; under bending load conditions, temperature has a significant effect on plate deformation before reaching the softening point, and the strain rate becomes prominent after the temperature reaches the softening point [4].

The literature review of Cui Xu’s article proposed that FML has high specific strength, high specific stiffness, good corrosion resistance and fatigue resistance; at the same time, fiber metal plate (FML) has high temperature resistance compared with other pure resin-based composite materials, and is often used in aerospace and other fields [5].

Yang Wenke’s article pointed out that in terms of resistance to temperature and humidity, the fiber metal layer can always absorb moisture generated by distilled water or salt spray due to the protection of the outer metal layer, reducing its damage to the metal and fiber layer. The glass fiber-aluminum alloy laminate has superior flame resistance. The single-sided flame burn-through results at 2500°C show that when the thickness of the aluminum layer of the laminate is 0.2-0.3mm, the burn-through time of the glass fiber-aluminum alloy laminate is 1mm thick. Several dozen times of aluminum alloy plate [6].

Han Qigang’s article explains the laminate burn-through test. The outermost aluminum plate of the glass fiber-aluminum alloy laminate melts quickly (melting temperature is 500 ℃), but the carbonization time of the inner fiber resin layer is relatively slow. This is because of the melting point of the glass fiber. Higher, it can prevent flames from penetrating glass fiber-aluminum alloy laminates. In addition, the thermal expansion coefficients of the components of the glass fiber-aluminum alloy laminate (aluminum alloy sheet, glass fiber, resin) are different, which will cause the glass fiber-aluminum alloy laminate to be heated and layered and form an air layer that isolates heat [7].

Zhu Guoliang’s literature has done research on the thermal decomposition and recovery technology of glass fiber-aluminum alloy laminates. The principle of the heat recovery method is that the decomposition of the resin in GLARE at high temperatures will completely separate the aluminum alloy sheet and the fiber layer. The selected new scrap is the cutting material for the aircraft A380 fuselage window. The glass fiber-aluminum alloy laminate is mainly composed of 2024 aluminum alloy sheet with oiled epoxy resin primer BR127 and S2 glass fiber impregnated with epoxy resin FM 94 Prepreg composition. Under non-isothermal thermal analysis, the research results show that the resin has been completely decomposed when heated to 500°C (heating rate of 5°C/min) in an air atmosphere. According to the results of non-isothermal thermal analysis, four isothermal temperature studies of 230℃, 310℃, 350℃ and 450℃ are selected (the isothermal research method is to keep the temperature at a given temperature for 3 hours, then turn off the power and cool to room temperature). The decomposition degree of resin in the air is 7.2%, 43.4%, 69.4% and 100% respectively [8].

The above documents indicate that the tensile properties of pure resin glass fiber epoxy composite laminates at 180 ℃ decreased by 34.42%, mainly due to the destruction of the resin at high temperatures, causing the laminate to delamination; glass fiber-aluminum alloy layer Compared with other laminates composed of fiber and aluminum alloy, glass fiber has a similar thermal expansion coefficient to aluminum alloy, has low residual stress, is electrically neutral, and does not undergo potential corrosion with aluminum alloy. It is an ideal material.
2.5. Material composite structure analysis

Carrying out simulation design the subway fan blade has a composite structure of glass fiber composite material and aluminum alloy. It is divided into three layers. The aluminum alloy and glass fiber composite material are alternately combined. The thickness of each layer of glass fiber composite material or aluminum alloy is 1mm. The material properties of glass fiber composite material and aluminum alloy are as follows:

Table 1. Aluminum alloy material properties Material.

| Material | E1/GPa | E2/GPa | G12/GPa | v12  | t/mm |
|----------|--------|--------|---------|------|------|
| 2024-T3  | 72     | -      | 27      | 0.33 | 0.5  |

Table 2. Performance of glass fiber/phenolic resin prepreg.

| Parameter                              | Value     |
|----------------------------------------|-----------|
| Longitudinal stiffness E11/GPa         | 48.75a    |
| Transverse stiffness E22/GPa           | 14.33a    |
| Out-of-plane stiffness E33/GPa         | 14.33a    |
| Poisson's ratio v12, v13               | 0.252a    |
| Poisson's ratio v23                    | 0.32a     |
| Shear modulus G12, G13/MPa            | 5100a     |
| Shear modulus G23/MPa                  | 5100a     |
| Longitudinal tensile strength Xf/MPa   | 1280b     |
| Longitudinal compressive strength Xc/MPa | 800b     |
| Transverse tensile strength Yf/MPa     | 40b       |
| Transverse compressive strength Yc/MPa | 145b      |
| Shear strength S12, S23, S13/MPa       | 73b       |
| Out-of-plane tensile strength Zf/MPa   | 40b       |

2.6. Load analysis of subway fan blades

The subway fan blades are mainly subjected to two forces during operation. One is the pressure of the airflow, which will cause the blade to bend and deform, and the other is the centrifugal force that the subway fan bears when it rotates, which is the blade stretching. Among them, centrifugal force is the main force for blade deformation.

Studies have shown that the stress caused by centrifugal force gradually increases along the tip of the blade to the root, and it is zero at the tip and maximum at the root. Assuming that the subway fan blades are straight graded blades, the centrifugal force pc generated for the blades can be obtained according to the empirical formula:

\[ p_c = m \times \omega^2 \times r_c \]

Where:
- \( m \) —— blade mass (kg);
- \( r \) —— the distance from the center of gravity to the axis of the blade (m);
- \( \omega \) —— The rotational angular velocity of the impeller (s\(^{-1}\));
- \( \omega = \pi n / 30; \)
- \( n \) —— Rotation speed of impeller.

The formula for calculating the tensile stress \( \sigma_c \) (Pa) at the root of the leaf is as follows:

\[ \sigma_c = \frac{p_c}{S} \]

Where:
- \( S \) —— The contact area between the blade and the hub (m\(^2\)).
In the calculation of the load force caused by the air flow pressure, assuming that the load force acts on the average radius of the blade, the load force \( p_h \) can be decomposed into \( p_u \) along the tangential direction and \( p_z \) in the axial direction.

The tangential force \( p_u \) is proportional to the shaft power and inversely proportional to the number of blades and the circumferential velocity at the average radius of the blades, then:

\[
p_u = \frac{1000 \times p_{sh}}{Z \times u_m}
\]

Where:
- \( p_{sh} \)——impeller shaft power (kW);
- \( Z \)——number of blades;
- \( u_m \)——Circumferential velocity (m/s) at the average radius of the blade.

The axial force \( p_z \) depends on the product of the static pressure difference of the impeller, the length of the blade and the pitch on the average radius of the blade. The calculation formula is as follows:

\[
p_z = \Delta p_{st} \times l \times t
\]

Where:
- \( \Delta p_{st} \)——The static pressure difference of the impeller (Pa);
- \( l \)——is the length of the blade (m);
- \( t \)——The pitch of the blades on the average radius (m).

The stress \( p_h \) is the vector sum of the tangential force \( p_u \) and the axial force \( p_z \), then:

\[
p_h = \sqrt{p_u^2 + p_z^2}
\]

![Figure 1. Air pressure on the blade.](image)

The blade bending moment \( M_h \) caused by the airflow pressure is given by:

\[
M_h = p_h \times \frac{1}{2} \times \cos(\theta_h + \theta_p)
\]

Where:
- \( l \)——The length of the blade;
- \( \theta_h \)——the angle between the normal line of the root section and the tangent to the circumference;
- \( \theta_p \)——The angle between the load force \( p_h \) and the circle tangent.

The maximum bending stress is blown at the root of the blade, then:

\[
\sigma_h = \frac{M_h}{W}
\]

Where:
- \( W \)——the bending section coefficient of the root section of the leaf (m3).

Therefore, the total stress at the root of the blade when the impeller rotates is:

\[
\sigma_y = \sigma_c + \sigma_h
\]

For a given safety factor \( n \), it should satisfy:
Where:

\[ n = \frac{\sigma_s}{\sigma_y} \]

\( \sigma_s \) —— yield limit;
\( \sigma_y \) —— total stress on the blade;
\( n \) —— Safety factor, generally \( n = 5 \).

The ratio of the hub to the blades of the subway fan is 0.5, the diameter of the subway fan is 1500mm, the density is made of aluminum alloy (2.7g/cm³), and the speed is 1450r/min. The value is substituted into the tensile stress formula, and the tensile stress of the subway fan is 13.3 MPa. Suppose the safety factor is 5, and the calculated load generated by the centrifugal force of the subway fan blade is 66.5MPa. The wind pressure load of the subway fan blades is 2000Pa.

3. Finite element simulation

The finite element analysis software is used to perform finite element analysis on the prototype of the subway fan blade. The prototype size of the subway fan blade is 30*100*3mm, and the calculated load generated by the centrifugal force of the subway fan blade is 66.5MPa. The wind pressure load of the subway fan blade is 2000Pa. The simulation results are as follows:

![Figure 2. Displacement total deformation](image)

![Figure 3. Displacement deformation perpendicular to the sample plane](image)

![Figure 4. Equivalent stress diagram of the aluminum alloy part of the fan blade](image)
The multi-dimensional Tasi-wu failure criterion is selected for composite material strength analysis, and its expression is:

$$F_{11} \sigma_{1}^{2} + F_{22} \sigma_{2}^{2} + 2F_{12} \sigma_{1} \sigma_{2} + F_{66} \tau_{12}^{2} + F_{1} \sigma_{1} + F_{2} \sigma_{2} = 1$$

$F_{11}$, $F_{22}$, $F_{66}$, $F_{1}$, $F_{2}$ are the strength parameters of the stress space. The strength ratio greater than 1 indicates that the material has failed, and the strength ratio less than 1 indicates that the material has not failed. The smaller the value, the greater the safety margin. The Tasi-wu failure criterion takes into account the effects of different stresses and interactions and the effects of different single-layer tensile and compressive strengths on the failure of materials. It is the most widely used in composite structural strength analysis and engineering.
According to the results of ABAQUS finite element simulation, the strength of composite material subway fan blades can meet the needs of use. When the safety factor $n$ is 5, the Caiwu failure factor of glass fiber composite material is 0.723<1 and can still meet the strength requirements. The equivalent stress is 115.6MPa.

4. Conclusion
Through the above data display and simulation experiment results, it can be known that the subway fan blades using glass fiber composite materials can better meet the current application requirements of existing subway fans. Compared with the existing subway fan, the fan using glass fiber composite material has the advantages of light weight, low noise, and good energy-saving benefits. With the further expansion of the application range of composite materials, the existing subway fan blades can be partially replaced, so as to obtain a subway fan with better performance and certain energy-saving benefits.

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