Application of Carbon fiber-reinforced plastic composite material in automotive bumper

Yiheng Liu*
Nanwai King ‘s College School Wuxi, Jiangsu, China

*Corresponding author: yihengliu@nkcswx.cn

Abstract. The emission problem of these traditional gasoline vehicles has become more and more serious. To reduce emission, an important method is to reduce the weight of the car. In this study, a standard model of a vehicle bumper is used to conduct the experiment on lightweight bumper design. The material simulated in the model of the bumper is CFRP material. The angle of each laminate of CFRP material and the layout of the laminate structure contains six layers are modeled in Hypermesh software. Then CFRP material is used to replace the traditional aluminum and reduce the weight of the front bumper component.

Keywords: lightweight, CFRP material, Hypermesh.

1. Introduction
Composite material has been playing a more and more important role in all areas like Engineering, Manufacturing, etc, as in-depth research revealed that composite material shows many outstanding properties compared to other material. Recently, composite materials, especially CFRP material widely used in ship building and auto manufacturing industry as a lightweight choice of material. We have seen previous researches on carbon fiber being used on building structure, industrial machines. Carbon fiber has also been largely used in transportation industry, where lightweight contribute significantly to design eco-friendly and efficient products [1]. The material has been largely used in plane constructed by companies like Boeing and Airbus. This article sees the prospect of the material and will be analysing the possibility to apply CFPR material to the bumper of cars, with respect the collision standard to increase the physical property and weight performance of it. Specifically, we will be focused on discussing how laminate structured carbon fibre material is applied to vehicle bumpers and how the internal structure affects the performance of the structure.

The whole process of the article will first go through the analysis of CFRP Material properties, which help to understand the failure criteria of the material structure, which then using CAD and CAE software to model the front bumper of a vehicle for finite element analysis. According to design of experiment, 30 groups of results are obtained and used for machine learning to obtain a mathematical model between the angle input and the outcome. The result is finally optimized using NSGA-II algorithm to obtain a best solution for the problem.
2. Mechanical Model for CFRP Anisotropic Materials

For elastomer of anisotropic materials which is continuous and even, while obey Hooke’s Law when being in the state of balance or motion, the concentration of internal forces caused by external forces is called stress. In three mutually orthogonal planes, the normal of each orthogonal plane is parallel to the corresponding axes. In this coordinate system, the stress component of a point at any position in the object is:

\[ [\sigma] = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \]  

(1)

Where \( \sigma_x, \sigma_y, \sigma_z \) is the normal stress and \( \tau_{xy} = \tau_{yx}, \tau_{xz} = \tau_{zx}, \tau_{yz} = \tau_{zy} \) is the shear stress.

When an elastic body is deformed by external forces, the stress-strain component at any point in the body is:

\[ [\varepsilon] = \begin{bmatrix} \varepsilon_x & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_y & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_z \end{bmatrix} \]  

(2)

Where \( \sigma_x, \sigma_y, \sigma_z \) is the linear strain and \( \tau_{xy} = \tau_{yx}, \tau_{xz} = \tau_{zx}, \tau_{yz} = \tau_{zy} \) is tensor shear strain.

Then the constitutive relationship of anisotropic elastomers can be evolved by combining the displacement equation, geometric equation and conformation equation of the body, as shown in equation (3):

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{xy} \\
\tau_{xz} \\
\tau_{yz}
\end{bmatrix} =
\begin{bmatrix}
D_{11} & D_{12} & D_{13} & D_{14} & D_{15} & D_{16} \\
D_{21} & D_{22} & D_{23} & D_{24} & D_{25} & D_{26} \\
D_{31} & D_{32} & D_{33} & D_{34} & D_{35} & D_{36} \\
D_{41} & D_{42} & D_{43} & D_{44} & D_{45} & D_{46} \\
D_{51} & D_{52} & D_{53} & D_{54} & D_{55} & D_{56} \\
D_{61} & D_{62} & D_{63} & D_{64} & D_{65} & D_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\lambda_{xy} \\
\lambda_{xz} \\
\lambda_{yz}
\end{bmatrix}
\]  

(3)

Among them, \([D]\) is the stiffness symmetric matrix, \(D_{11}, D_{12}, \ldots, D_{66}\) is the engineering stiffness constant coefficient, \(\lambda_{xy}^0, \lambda_{xz}^0, \lambda_{yz}^0\) is the engineering shear strain value, and has \(\varepsilon_{xy} = \frac{\lambda_{xy}^0}{2}, \varepsilon_{xz} = \frac{\lambda_{xz}^0}{2}, \varepsilon_{yz} = \frac{\lambda_{yz}^0}{2}\).

In a three-dimensional orthogonal coordinate system, an anisotropic material is orthotropic if the points at any position on the elastomer are full enough to have a symmetric plane perpendicular to each other in the x, y and Z directions. In the stiffness symmetric matrix \([D]\), \(D_{16} = D_{26} = D_{36} = D_{35} = D_{45} = 0\). Therefore, the stiffness symmetric matrix \([D]\) becomes a simpler form, with nine independent stiffness constant coefficients retained, that is:

\[
[D] =
\begin{bmatrix}
D_{11} & D_{12} & D_{13} & 0 & 0 & 0 \\
D_{21} & D_{22} & D_{23} & 0 & 0 & 0 \\
D_{31} & D_{32} & D_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & D_{35} & 0 & 0 \\
0 & 0 & 0 & 0 & D_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & D_{66}
\end{bmatrix}
\]  

(4)
3. Strength and Failure Criteria of Composite Materials

Material strength refers to the ability to resist damage when the material is subjected to external forces. With the increase of external forces, the stress inside the material itself gradually increases. When a certain stress limit is reached, the material will be damaged, resulting in material failure such as deformation, fracture etc., leading to the loss of structural integrity of the material [2]. Therefore, the stress limit is often referred as the strength of the material. Most of the factors affecting the strength are due to: Inherited properties of the materials themselves, such as physical and chemical properties; Load states, such as static, dynamic, one-dimensional, multidimensional loads; and Environmental factors, such as temperature environment, media conditions, etc.

Isotropic materials have no directionality, that is, each point of action has the same resistance to pressure in all directions. However, unlike isotropic materials, anisotropic materials, such as composite materials, have distinct directionality, which have different mechanical properties in different directions, and shows large differences in strength from different directions. For a single-layer composite material structure, there are five characteristic indexes to measure its strength, which are longitudinal tensile strength ($X_t$), longitudinal compressive strength ($X_c$), in-plane shear strength ($S_c$), transverse tensile strength ($Y_t$) and transverse compressive strength ($Y_c$). The strength in each direction of the structure is shown in Fig.1

![Figure 1. Characteristic strength of composite materials in all directions](image)

In recent years, the theory of anisotropic materials has been continuously applied and developed, and a large number of researchers have been attracted in this field. For the damage research of anisotropic materials, relevant scholars can summarize different failure criteria based on different failure assumptions, and have been widely recognized and favored. The commonly used strength failure criteria, including maximum stress-strain failure criterion, Tsai-Hill failure criterion, Chang-Chang failure criterion, Tsai-Wu tensor strength criterion, etc. All these theories contribute to help deciding how CFRP material can be used to substitute traditional engineering materials.

3.1. Failure criterion of maximum stress and maximum strain

Failure criterion of maximum stress and maximum strain is a failure criterion proposed and widely used by earlier designers. It also has the characteristics of simple prediction and good prediction effect. As long as the observed strength or stress-strain values exceed the corresponding fixed threshold values, the material studied (which generally exhibits brittleness) will undergo structural failure and failure [3].

The conditions based on the maximum stress failure criterion for unidirectional composite materials are:

$$
\begin{align*}
|\sigma_x| &< X_t (X_c) \\
|\sigma_y| &< Y_t (Y_c) \\
|\sigma_s| &< S_c 
\end{align*}
$$

(5)
The conditions based on the maximum strain failure criterion for unidirectional composite materials are:

\[
\begin{align*}
\varepsilon_x &< \varepsilon_{xt} \\
\varepsilon_y &< \varepsilon_{yt} \\
\varepsilon_S &< \varepsilon_{Sc}
\end{align*}
\] (6)

Among them, the maximum longitudinal tension strain, the maximum longitudinal compression strain, the maximum transverse tension strain, the maximum transverse compression strain, and the maximum planar shear strain.

3.2. Tsai-Hill failure criterion

This criterion is based on the basis of the simple form of maximum stress and maximum strain failure criterion and the fact that it cannot be used on heterogeneous materials under certain circumstances. Compared with the former, the curve of the object under this criterion is continuous and smooth, the damage intensity is displayed more reasonably, and the combination of theory and experiment is more accurate. The failure criteria are represented by

\[
\frac{\sigma_x^2}{E_x} + \frac{\sigma_y^2}{E_y} + \frac{\sigma_x \sigma_y}{E} + \frac{\sigma_{xy}}{S} = 1
\] (7)

4. Finite Element Analysis of CFRP bumper

4.1. Methodology

Finite element analysis is the method that dissect continuous area into small sections with different shape and size, then uses specific algorithm to connect each dissect area for computer analysis. The force applied on each area is calculated independently and the effect on other elements is analysed.

In engineering, the usual method to use carbon fibre to substitute other materials is equivalence design. This is the method that the property of the structure using the original material is kept the same as the carbon fibre structure, where allows us to calculate the size and shape of the carbon fibre structure.

In this experiment, carbon fibre material is used to substitute aluminium alloy that is commonly used on bumpers [4]. During collisions, the front bumper is usually bended as it contacts with rigid wall and is affect by the external force. In such case, the bending rigidity should be considered equivalent to the alloy structure. Therefore, equal rigidity equivalence design is applied to the experiment.

The formula of stress has been

\[
\sigma = \frac{M^2}{8EI}
\] (8)

Which in the formula \( M \) has been the bending moment, \( I \) been the inertia and \( E \) been the Young’s Modulus of the material. Besides, the formula for inertia is

\[
I = \frac{bh^3}{12}
\] (9)

Where \( b \) and \( h \) been the wideness and thickness of the material. Using the equal rigidity equation:

\[
E_a I_a = E_l I_t
\] (10)

We have the equation that
\[ h_{l} = h_{a} \sqrt[3]{\frac{E_{a}}{E_{l}}} \]  

(11)

As we assumed that the thickness of the original alloy material case been 1.80mm, according to the data given in table 1, the thickness of CFRP material is calculated to be 1.92mm.

| Table 1. The Properties of the Material Being Chosen |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                | Elastic Modulus (GPa) | Shear Modulus (GPa) | Poisson's ratio | Density (Kg/m^3) | Yield Strength (MPa) | Tensile Strength (MPa) |
| Aluminum Alloy                 | 68.2              | 26              | 0.33            | 2700            | 80              | 173             |
| Composite Material             | 56.5              | 12.5            | 0.3             | 1455            | /               | 823.1           |

In Hyper mesh [5], the main algorithm in the software is using Lagrange or Lagrange function to describe incremental method. It is defined at the initial time \( t_{0} \). The particle coordinate is \( x_{0} = (X_{1}, X_{2}, X_{3}) = X_{j}(j = 1, 2, 3) \), the coordinate of the particle at any time \( t \) is \( x_{t} = (X_{1}, X_{2}, X_{3}) = X_{i}(i = 1, 2, 3) \). The trajectory equation of this particle is as follows:

\[ x_{i} = x_{i}(X_{j}, t) \quad i, j = 1, 2, 3 \]  

(12)

When \( t = 0 \), the initial condition is

\[ x_{i}(X_{j}, 0) = X_{i}, \dot{x}_{i}(X_{j}, 0) = V_{i}(X_{j}, 0) \]  

(13)

In equation (13), \( \dot{x}_{i} \) is the velocity equation of a particle at any time \( t \); \( V_{i} \) is the initial velocity.

The basic equations of dynamics are as follows:

Momentum Equilibrium Condition:

In range V:

\[ \beta_{ij,j} + \rho l_{i} = \rho \ddot{x}_{i} \]  

(14)

Boundary Condition:

On S1 Boundary:

\[ \beta_{ij} n_{j} = \bar{t}_{i}(t) \]  

(15)

On S2 Boundary:

\[ x_{i}(X_{j}, t) = D_{i}(t) \]  

(16)

On S0 Boundary:

\[ (\beta_{ij}^{+} - \beta_{ij}^{-})n_{j} = 0 \]  

(17)

In the above formula, \( \beta_{ij} \) is beta stress, \( \rho \) is mass density, \( l_{i} \) is the volume force per unit mass, \( \ddot{x}_{i} \) is the acceleration of the particle, \( n_{j}(i = 1, 2, 3) \) is the outer normal vector of the boundary, \( \bar{t}_{i}(t)(i = 1, 2, 3) \) is the surface load; \( D_{i}(t)(i = 1, 2, 3) \) is a given displacement function.

4.2. FEM Model

Hypermesh software was used to build the model.Fig.2 shows the CFRP bumper model and Fig.3 shows the Laminate Structure.
5. Conclusion
In this study, CFRP material is analyzed in detail, and it’s used to take place of traditional aluminum material, which reduce the weight of front bumper. And the structure of the CFRP bumper has been modelled and then being meshed for the finite element analysis using Hyper Mesh software.

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