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Optimization of Laminating Angles for Skirt Panels of EMUs Front Using Composite Materials Based on the Cheetah Optimizer

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Abstract: With the development of composite materials, their lightweight and high-strength characteristics have caused more widespread use from aerospace applications to automotive and rail transportation sectors, significantly reducing the energy consumption during the operation of EMUs (Electric Multiple Units). This study aims to explore the application of composite materials in the lightweight design of EMU front skirts and proposes a design method based on three-dimensional Hashin failure criteria and the Cheetah Optimizer (CO) to achieve maximum lightweight efficiency. The UMAT subroutine was developed based on the three-dimensional Hashin failure criteria to calculate failure parameters, which were used as design parameters in the CO. The model calculations and result extraction were implemented in MATLAB, and the Cheetah Optimizer iteratively determined the optimal laminating angle design that minimized the overall failure factor. After 100 iterations, ensuring structural integrity, the optimized design reduced the weight of the skirt panel by 60% compared to the original aluminum alloy structure, achieving significant lightweight benefits. This study provides foundational data for the lightweight design of EMUs.

Keywords: Composite; Cheetah Optimizer; EMU; FEA

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1. Introduction

Composite materials, as new materials, are characterized by their lightweight, high strength, high customizability, reliability in extreme environments, and closed-loop recyclability, making them increasingly popular in transportation applications. With advancements in composite material research, their applications have expanded from aerospace to automotive and rail transportation. For instance, the CRH EMU's energy consumption decreased by 17% after adopting composite materials [1].

In the design of composite material components, optimization methods can be categorized into structural optimization and parameter optimization. Structural optimization is mainly carried out by changing the geometric shape of the entire composite material component, etc., while parameter optimization is mainly carried out by changing the ply angle, etc., without changing the geometric shape. Huang *et al.* conducted a lightweight design for a space-borne optical remote sensor using composite materials through structural topology optimization and fiber orientation parameter optimization, achieving structural lightweighting while meeting stiffness and strength requirements [2]. Islam *et al.* experimentally tested and simulated the mechanical properties of JUCO fiber-reinforced composites under tensile and bending static strength conditions [3]. They found out that the experimental results are highly consistent with the data of the finite element simulation results and fiber orientation angles significantly affect the mechanical performance of fiber-reinforced composites. This indicates that optimizing the lamination angles in simulations, without changing the number of layers, can effectively improve the static strength mechanical properties of composite materials.

Sohouli *et al.* developed a design optimization framework for composite material lamination angles based on a novel Decoupled Discrete Material Optimization, using non-convex and convex sequential approximation optimization methods to optimize composite material thin plates with four discrete angles (0°, 45 °,-45°,90°) [4]. Zhang *et al.* improved the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm with intelligent algorithms, implementing multiscale simulations via Python code to achieve lightweighting and lamination angle optimization for carbon-fiber-reinforced composite drive shafts, enhancing comprehensive performance while meeting reliability requirements [5]. Tran *et al*. proposed a meta-heuristic optimization algorithm combining the Shrimp and Goby Association Search Algorithm (SGA), Balancing Composite Motion Optimization (BCMO), and Differential Evolution (DE), optimizing lamination angles for composite laminate plates under vibration and buckling conditions without four discrete angles [6].

Wu *et al.* used finite element methods to calculate the vibration frequency of composite structures and conducted a supporting vector regression dataset for optimizing lamination angles [7]. They will develop a multi-objective optimization loop based on machine learning. Wang *et al*. trained a Multi-DNN model and introduced transfer learning for fine-tuning to predict failure factors, combining genetic algorithms and models to optimize composite pressure vessels, obtaining the optimal lamination angles [8].

This paper focuses on the front skirt panels of EMUs, employing the Cheetah Optimizer in MATLAB with auxiliary iterations using ABAQUS and Python, optimizing lamination angles using the factor of three-dimensional Hashin failure criteria as design parameters. After 100 iterations, the optimal composite material lamination angles were obtained with the minimum overall failure factor.

2. Intelligent algorithms and failure criteria

The Cheetah Optimizer (CO) is inspired by the hunting behavior of cheetahs [9]. Cheetahs often hunt in groups, each group containing several cheetahs. Each cheetah represents a solution containing all parameters to be optimized. In this study, five lamination angles will be the parameters to be optimized. Since cheetahs are dispersed relative to their prey, the cheetah that is the closest one to the prey will become the leader, representing the current best solution. However, the leader may lose its leading position if it moves away from the prey or is surpassed by other cheetahs. The basic logic of the CO involves initializing cheetah groups, calculating fitness to identify the leader, and iterating to obtain the global optimal solution. The CO consists of four stages: searching for prey, waiting strategy, attack strategy, and abandoning the hunt.

During the prey search stage, a cheetah explores its territory to locate prey. For the cheetah it can choose two ways to locate prey, which are observing the prey in place and moving around actively to search for the prey. After spotting its prey, if the conditions aren't favorable for an immediate hunt, the cheetah will choose to hide and wait patiently for a better opportunity—either for the prey to come closer or for another to create a situation that aids in the hunt. The reason for this behavior is that although cheetahs have strong explosive power, they cannot maintain such a high-speed pursuit of prey for a long time. Therefore, cheetahs need to ensure the efficiency of catching prey. This is also the advantage of the CO, which will not waste computing power on possibly wrong solution routes. The waiting strategy inspired by this behavior involves hiding and waiting for a better opportunity to hunt.

The attack strategy includes two steps: sprinting and capturing the prey. Sprinting is the cheetah sprinting towards prey at its fastest speed. Capturing is when a cheetah catches the prey by its advantage of high-speed running and flexibility. Abandoning the hunt is also a strategy that avoids wasting computational resources on possibly incorrect solutions. There are two situations for this strategy. One of them is that the cheetah fails to hunt prey and return to its territory or original position, preparing for the next hunt. The other is when the hunting takes too much time, but still fails to hunt prey, then the cheetah will return to the latest position it found the prey to search for a new target.

The Hashin failure criterion used in this research, widely used for predicting composite material failures, divides failures into fiber failure and matrix failure, further subdivided into fiber tensile failure, fiber compressive failure, matrix tensile failure, and matrix compressive failure [10]. The failure criteria are calculated by Equations (1) to (4).

(1) Fiber tensile failure:

$$F_{ft} = \left(\frac{\sigma_1}{X_T}\right)^2 + \alpha\left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \alpha\left(\frac{\sigma_{13}}{S_{13}}\right)^2 \geqslant 1 \tag{1}$$

(2) Fiber compressive failure:

$$F_{fc} = \left(\frac{\sigma_1}{X_C}\right)^2 \geqslant 1 \tag{2}$$

(3) Matrix tensile failure:

$$F_{mt} = \left(\frac{\sigma_2 + \sigma_3}{Y_T}\right)^2 + \left(\frac{1}{S_{23}^2}\right)\left(\sigma_{23}^2 - \sigma_{22}\sigma_{33}\right) + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 \geqslant 1 \tag{3}$$

(4) Matrix compressive failure:

$$F_{mc} = \left(\frac{\sigma_2 + \sigma_3}{2S_{23}}\right)^2 + \left(\frac{\sigma_2 + \sigma_3}{Y_C}\right)\left[\left(\frac{Y_C}{2S_{23}}\right)^2 - 1\right] + \frac{1}{S_{23}^2}\left(\sigma_{23}^2 - \sigma_2\sigma_3\right) + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 \geqslant 1 \tag{4}$$

3. Model and conditions

This study focuses on the lightweight and optimization simulation design of the front skirt panel of a city rail vehicle. The front of the vehicle experiences direct wind pressure during operation. The geometric model of the front is shown in **Figure 1**. The skirt panel is the area with the highest stress concentration, hence the choice for simulation. The T800S-3900-2B quasi-isotropic composite material was selected for the lightweight design of the front skirt panel, with material parameters listed in **Table 1** [11]. The finite element mesh model was established using Hypermesh software, with solid elements C3D8R, thickness 0.2 mm, and mesh size 10 mm. The main loading condition considered is surface pressure due to wind pressure during train operation. The surface pressure load value was calculated using Bernoulli's equation, shown by Equation (5), considering a maximum speed of 143 km/h and a wind speed of 23.53 m/s, resulting in a total wind speed of 63.25 m/s and a wind pressure load of 2.5 KPa [12]. The finite element model with applied loads is shown in **Figure 2**.

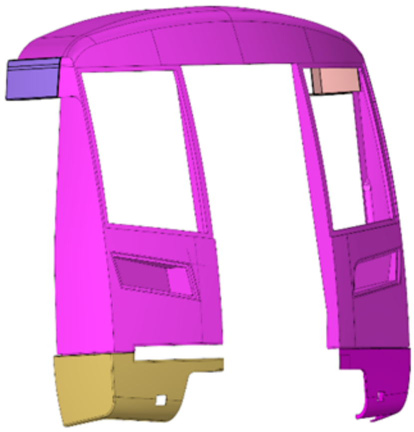

Figure 1. Geometric model of the vehicle front

Table 1. Material parameters of T800S-3900-2B

E_1(GPa)	E_2(GPa)	G_{12}(GPa)	v_{12}	v_{23}
132.6	8.0	4.03	0.34	0.45
X_T(MPa)	X_C(MPa)	Y_T(MPa)	Y_C(MPa)	S_L(MPa)
3100	1242	56.5	307	90.3

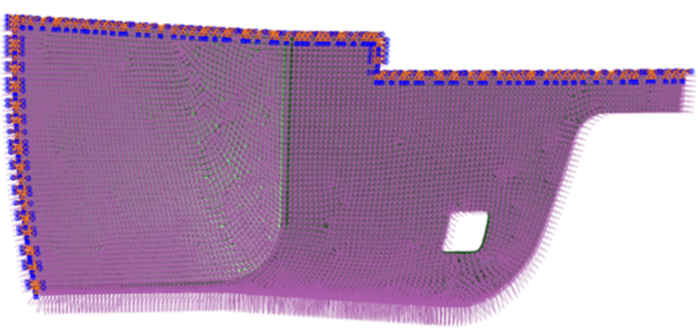

Figure 2. FE model of the skirt panel with conditions

$$wp = 0.5\rho v^2 \quad (5)$$

4. Lightweight optimization simulation

The Cheetah Optimizer was executed on the MATLAB platform, with six cheetah groups, each containing two cheetahs. Since the two failure factors of composite skirt panels at the current layer count were similar, the average of the two failure factors was used as the evaluation criterion, the overall failure factor. MATLAB commands were used to call ABAQUS for failure factors calculations. Since MATLAB cannot directly read ABAQUS OBD files, Python scripts were written for initializing the cheetah groups, performing the search phase, and abandoning the hunting phase, ultimately outputting failure factors to MATLAB variables. After 100 iterations, the optimal lamination angles were [-14, -18, -31, -3, 24]s with an overall failure factor of 0.72. The entire optimization result is shown in **Figure 3**. Some lamination angle designs had overall failure factors greater than 1, indicating that at least one failure mode will occur, confirming that the layer count design was not overly redundant, thus achieving effective lightweighting.

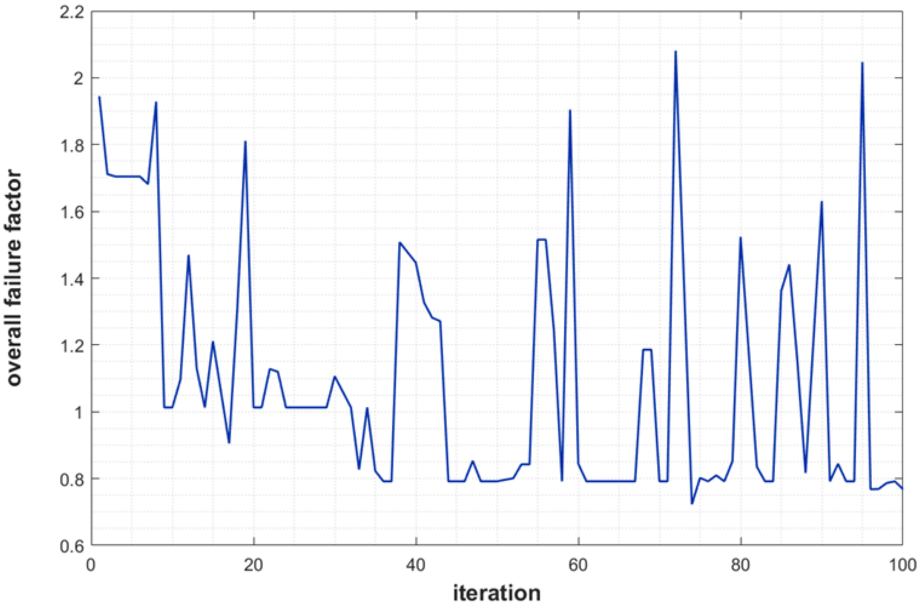

Figure 3. Optimization result

5. Conclusion

This study used T800S-3900-2B quasi-isotropic composite material to replace the original aluminum alloy material for the front skirt panel of a city rail vehicle. The surface pressure was calculated using Bernoulli's equation. Using MATLAB and Python in conjunction with ABAQUS, the Cheetah Optimizer was applied for 100 iterations, yielding the optimal lamination angles under common operating conditions. Compared to the original aluminum structure, the skirt panel's weight was reduced by 60%, providing reference data for applying composite materials to other force-bearing components of rail vehicles.

Disclosure Statement

The authors declare no conflict of interest.

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