Optimum Design of Ply-up of T800 Carbon Fiber Composite Laminates with Holes

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Abstract. Based on the HyperWorks software, this paper takes the layup sequence of carbon fiber composite laminates as the design variables, the main strain of the laminates and the continuous angle layup not exceeding four layers as constraints, and the maximum bearing capacity as the design goal. The optimized design of the laminate and the corresponding experimental verification were carried out. The experimental results are in good agreement with the simulation analysis results, indicating that the optimization design method proposed in this paper is reasonable.

1. Introduction

The carbon fiber composite materials have been widely used in the aerospace field. However, in the application of carbon fiber composite materials, it is inevitable to open holes that used bolts for connection, so it is necessary to analyze and design the mechanical properties of composite laminates with holes in the connection situation.[123] After the carbon fiber structure is perforated, it will have a greater impact on the structural bearing capacity[4567]. The corresponding results have shown that nearly 70% of aircraft accidents are directly related to the self-assembled connection parts, and nearly 80% of fatigue cracks are generated at the connection holes.[8910] Therefore, it is very necessary to optimize the design and evaluate the mechanical properties of carbon fiber laminates with circular holes.

2. Finite Element Analysis of Carbon Fiber Laminates Containing Round Holes

Based on the HyperWorks software, a geometric model as shown in Figure 1 was established. The size of the geometric model of the laminate was 150mm × 36mm × 2mm, and the circular hole was located at the center of the plate with a diameter of 6mm. The composite material laminate is made on the basis of the filament wound composite material shell, and the same winding angle as the filament wound composite material shell is used: 90°, 0°, 45°, -45° for layup, and the thickness of the single-layer board is 0.15mm, a total of 16 layers.

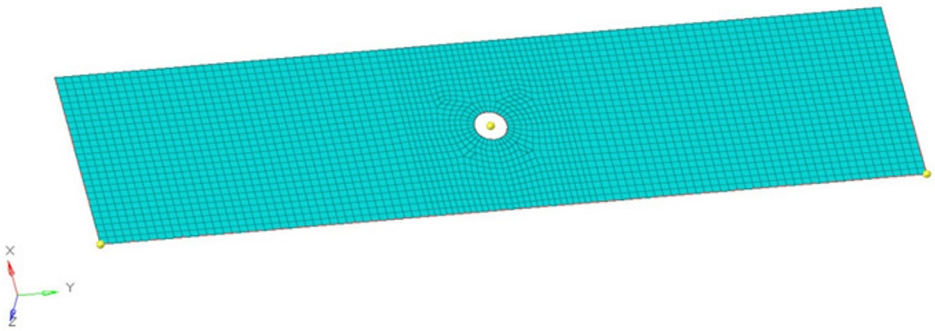

Figure 1. Mesh diagram of porous carbon fiber laminate

After the mesh is divided, one end of the carbon fiber laminate with holes is loaded with a tensile force of 2000N, and the other end is fixed, and the failure criterion is the HILL criterion. The calculated stress nephogram is shown in Figure 2. It can be seen from the figure that the maximum stress reaches 47.75MPa, and the maximum stress appears around the circular holes of the porous carbon fiber laminate.

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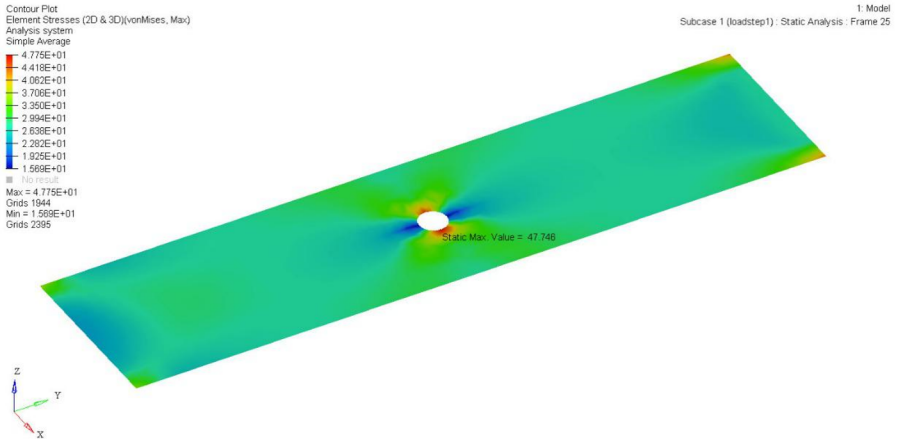

Figure 2. Stress cloud map

According to the Hill criterion, the material failure factor number is 0.0039. As shown in Figure 3, the most likely failure location is around the circular hole of the circular hole-containing carbon fiber laminate, and its value is less than 1, indicating that failure failure will not occur.

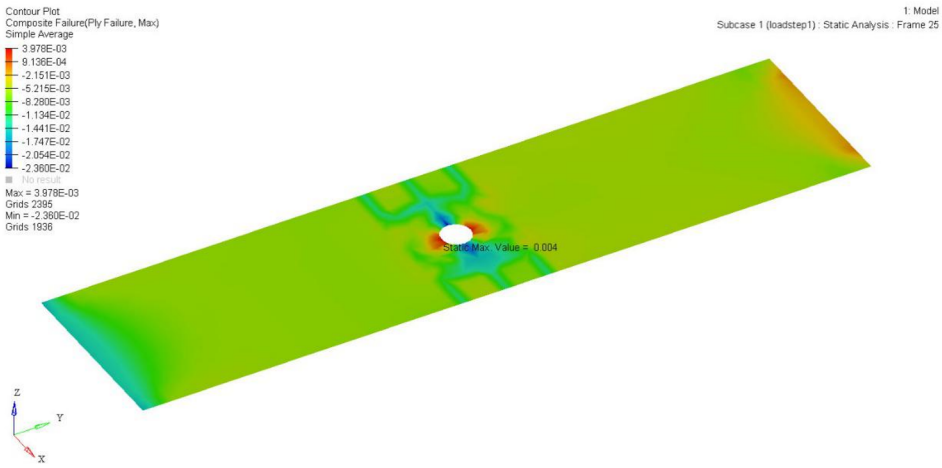

Figure 3. HILL criterion failure cloud map

3. Lamination optimization of carbon fiber laminates with circular holes

Based on HyperWorks software. Optimize the design of composite structures. First, the design boundary of the laminate is cut. The design variable is the thickness of each unit layer, and the volume fraction is less than 0.3 as the optimization constraint. The thickness of the single-layer laminate is 0.15mm; the minimum manufacturable thickness of the single-layer is 0.125mm.; After optimization of the laminate, the maximum thickness is 2.4mm, and the minimum thickness is 2mm. The optimization goal is to minimize the flexibility, and the laminate is optimized.

The iterative change curve of the objective function is shown in Figure 4. It can be seen from the figure that after 22 steps of iteration, the objective function converges, the flexibility decreases significantly, and the iteration is stable, indicating that the optimization of free size has obvious effects.

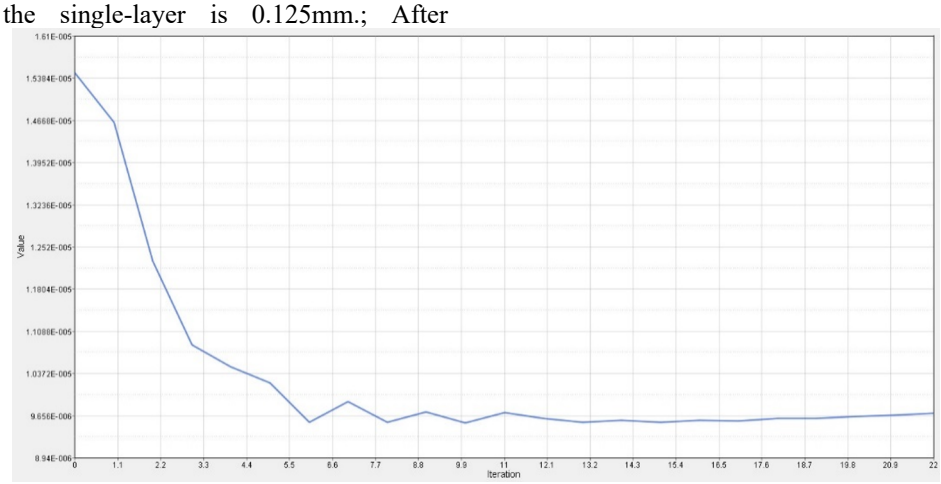

Figure 4. The iterative change curve of the objective function

In the second stage of preliminary design, size optimization is adopted, the model after the first stage optimization is imported, the design variable is the thickness of each single-layer board, the constraint panel is checked, and new constraints are manufactured. The maximum principal strain of the single-layer board of the laminate is less than 5500, the minimum principal strain is greater than -4000; the minimum manufacturable thickness of the laminate is specified to be 2mm; the structural performance response is established as the strain and mass of the composite laminate, and the minimum mass of the laminate is the optimization goal. The iterative change curve of the objective function is shown in Figure 5. It can be found that after three steps of iteration, the objective function converges, the weight decreases significantly, and the iteration is stable, indicating that the optimization of size has obvious effect.

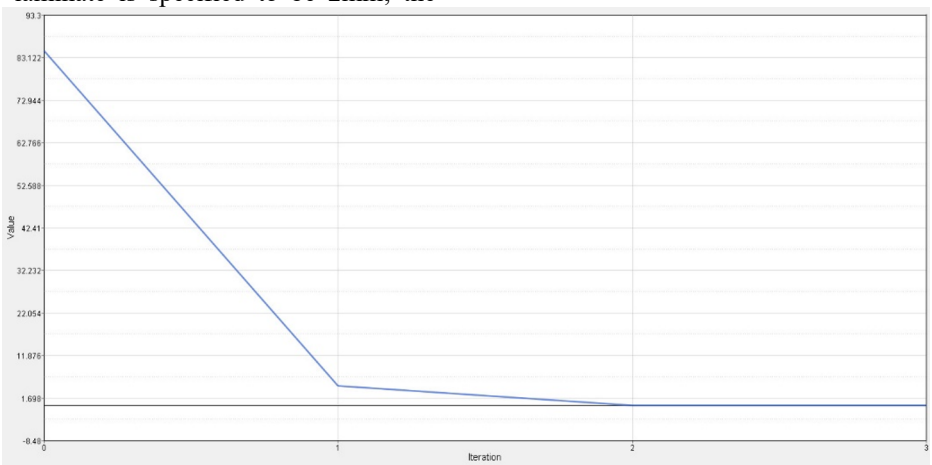

Figure 5. Iterative change curve of size optimization objective function

In the third stage of detailed design, the optimal layup sequence of the carbon fiber composite laminate is determined, and the final file generated by the second stage of size optimization is imported. The optimized strength is checked, and the strain cloud diagram is shown in Figure 6. The optimized principal strain result is 685.9, which meets the requirements of the allowable value.

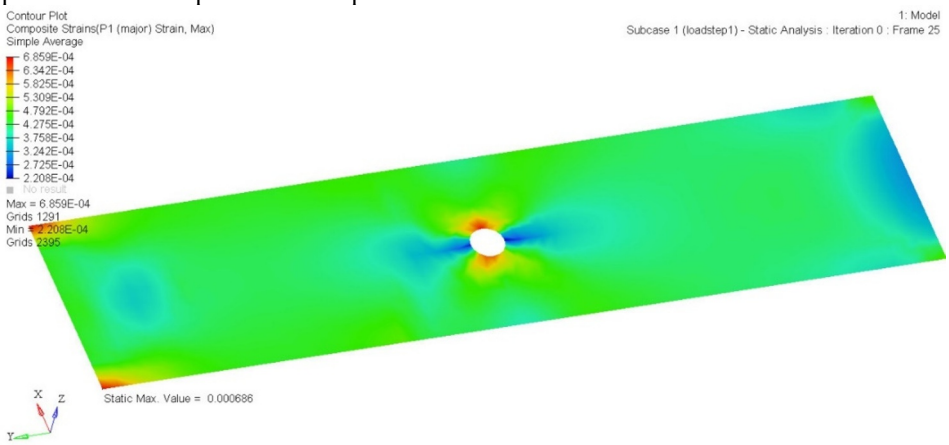

Figure 6. Strain value of P1 after optimization

The failure of the material is judged using the hill failure criterion. The failure factor distribution is shown in Figure 7. The maximum failure factor is 0.0053, which is less than 1, so it is considered that the failure strength meets the requirements.

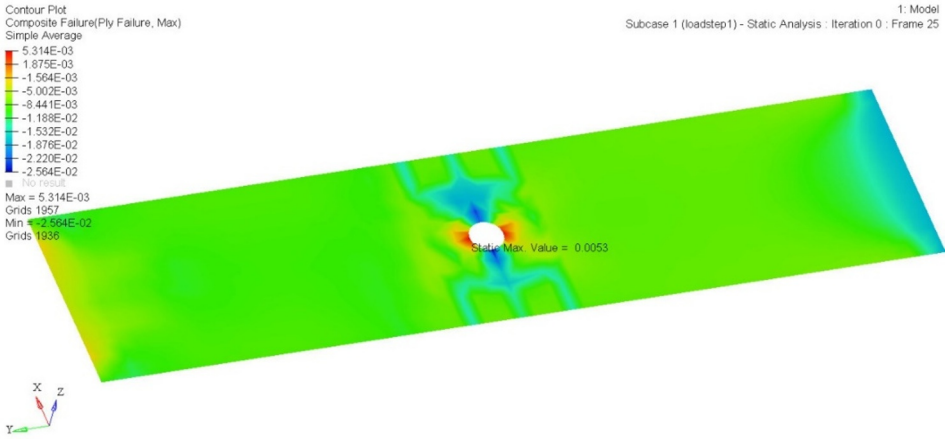

Figure 7. The theoretical failure value of HILL after optimization

Optimizing the layup sequence of carbon fiber composite laminates can reduce the weight and enhance the specific strength of the laminates. The results show that the load-carrying capacity still meets the requirements after the layup sequence of the carbon fiber composite laminate is optimized, and the optimization method is reasonable and reliable. The optimization of the layup sequence of carbon fiber composite laminates has gone through 16 iterations, and the final optimization sequence is as follows:

[90°,0°,45°, -45°,0°,0°, -45°,45°,90°, -45°,90°,90°,0°]

Experimental verification:

The test material selects the carbon fiber composite laminate specimens before and after optimization to verify the optimized design results. The test standard refers to ASTM D5961/D5961M-2017, the tensile loading rate of the electronic tensile testing machine is 2 mm/min, and 5 test pieces of carbon fiber composite laminates before and after optimization are selected. The test piece is shown in Figure 8.

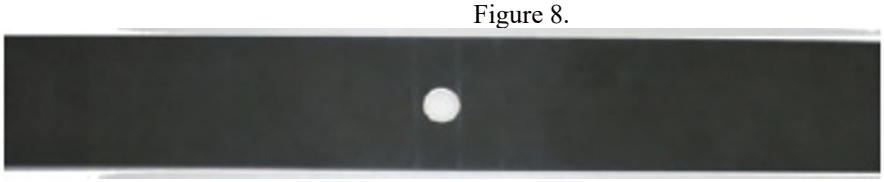

Figure 8. The morphology of test specimen

First, the verification of the size optimization results is carried out. The size of the specimen is 150mm×36mm×2.4mm, the thickness of the single-layer board is 0.15mm, and 5 composite material laminates are selected. The size of the carbon fiber composite material after the optimization of the size of the test piece reaches 150mm × 36mm × 2mm, the thickness is 0.125mm, and 5 composite material laminates are selected. The tensile test of mechanical properties of the carbon fiber composite laminates before and after optimization is carried out. 38.3276kN.

After the size optimization, the maximum stress of the five groups of mechanical tensile tests are: 33.6578kN, 36.4574kN, 34.46225kN, 36.6054kN, 36.5219kN, and the average maximum stress of the five groups of tensile tests is 35.5409kN.

Compared with the test results, it can be seen that due to the influence of the thickness of the board, the 2mm thick laminate is less than the 2.4mm thick laminate bearing capacity, taking the composite material reliability margin as 10%, the quality optimized composite material laminate can withstand a load of 31.90kN. When the axial load is applied, the design and use requirements are met, the quality of the laminate is reduced, and the cost is reduced.

After that, 5 sets of mechanical tensile tests were performed on the laminates with a thickness of 2 mm after the layering sequence was optimized. The maximum stress values are: 36.9101kN, 36.9066kN, 37.0371kN, 37.2496kN, and 37.0716kN, respectively. The average maximum stress of five sets of tensile tests is 37.0351kN, which is the ultimate bearing capacity of the laminate after the optimization of the layup sequence.

Comparing the test results, it can be seen that, combined with the optimization results, after optimizing the layup sequence, the composite board material has a greater bearing capacity, which has increased from an average of 35.5409kN to an average of 37.0351kN. The test results are in good agreement with the reliability of the optimized laminate, which proves that the optimization method is feasible.

4. Results and Discussion

In this paper, the optimal design of the T800 carbon fiber composite laminate structure with round holes is carried out, and the conclusions are as follows:

1) It can be seen from the simulation analysis that when the laminate is subjected to axial load, the parts prone to failure are mainly concentrated in the circular hole of the laminate.

2) After quality optimization, the single-layer thickness of the laminate is reduced to 0.125mm, and the overall mass is reduced by 16.7%. The optimized strength results meet the design requirements.

3) The simulation results are in good agreement with the test results. The composite laminate can achieve the purpose of reducing the amount of fiber, reducing the cost and reducing the quality within the range of meeting the safety margin of material strength.

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