Optimization design of the in-place-machining tool beam for FRPs bonded repair

Nan Zhang¹, Modi Liu¹, Song Mu¹ and Youliang Su¹,*

¹ School of Mechanical Engineering, Ningxia University, Yinchuan, 750021, China

*Corresponding author: suyl@mail.dlut.edu.cn

Abstract. Inward-bonded Patch technology is a common method for repairing defects and damage of (Fiber Reinforce Plastics) FRP parts. In the project, there is an urgent need for an in-situ machining machine with a concave step structure in the method. Such thin-walled, weakly rigid parts are easily deformed under pressure. Therefore, the machine beam is lightly designed to reduce the influence of compression deformation on the machining quality. In this paper, the annular (basalt fiber polymer composite) BFPC beam of a certain type of in-situ machining machine prototype is taken as the research object. Firstly, based on the analysis of the prototype working conditions, the comprehensive performance index of the beam is clarified. Using the topology optimization technology, the beam topology of the optimal topology is obtained. Finally, the establishment is established. The multi-objective optimization function with regular structural parameters as variables and minimum beam quality and deformation as the target has obtained the optimal topology and optimal performance of the beam structure.

Keywords. Inward-bonded patch; In-place machining; Machine tools; Multiobjective optimization; Topology; Structural design

1. Introduction

The high-performance fiber reinforced composite material has the advantages of high strength and stiffness, performance design, and overall manufacturing, and has become the material of choice for the manufacture of high-end equipment for aerospace [1]. The use of this type of advanced composite materials to manufacture aircraft bearing components can greatly improve the efficiency of equipment structure and improve equipment quality [2]. In the service, such composite parts often suffer from various types of damage such as low-speed impact damage, discrete source damage and environmental intrusion damage. Once such defects or breaks exceed manufacturing damage tolerances, repairs must be quickly performed to restore the serviceability of the composite parts. In particular, the main bearing parts use high quality and efficient repair technology to restore the integrity and reliability of the parts to meet the high quality and efficient manufacturing and remanufacturing requirements of such composite parts, and to ensure the high reliability of aerospace equipment. And it is important to reduce the huge maintenance costs [3,4].

At this stage, the repair of fiber reinforced composite parts is mainly cemented. As a common repair method, the internal patch bonding technology is widely used in aircraft manufacturing and remanufacturing. The process is: cutting off the matrix material around the defect or the damaged part to form a stepped or beveled concave structure, and the back layer fills the inner patch which is flush...
with the mother material, and can be cured by hot pressing to reach the same strength of original component. Among them, the low-loss and rapid resection of the surrounding materials is extremely critical, and the processing quality and efficiency directly determine the repair cost of the components and the bearing capacity after repair [5].

At present, domestic and foreign aviation companies still mainly use manual grinding and sanding by grinder and sandpaper to complete the cutting of surrounding materials. However, due to the lamination characteristics, heterogeneity, and low interlayer strength of the fiber reinforced composite material, the prior technique has poor processing adaptability to such composite material parts, resulting in poor processing quality and low efficiency. In order to meet the demanding repairing technical requirements, it is only possible to reduce the possibility of mechanical damage and defect expansion with extremely conservative micro-grinding; at the same time, due to the difference in worker proficiency and random errors, the size of different parts or parts of a single piece is caused. And the consistency of damage control is difficult to guarantee, the scrap rate is high, and the processing efficiency is low [6]. In addition, the prior technique can only use the CNC machine tool for cutting after disassembling the composite parts. Such thin-walled weak rigid composite parts are easily deformed during disassembly, clamping and secondary assembly, and the processing difficulty Large, time consuming and labor intensive. In summary, there is no high-quality and high-efficiency processing device for realizing the complementary structure of such fiber-reinforced composite parts in engineering practice, which cannot meet the increasingly urgent requirements for low-damage and high-efficiency processing of fiber-reinforced advanced composite components.

However, such FRP parts are mostly thin-walled and weakly rigid features, the in-situ processing device will cause deformation when it is adsorbed on the surface, and excessive deformation will affect the machining accuracy. Therefore, the lightweight design of such machine beam is particularly important to reduce the influence of compression deformation of the composite parts on the machining accuracy.

The lightweight topology design is widely applied by the method of structural topology optimization. The main topology optimization methods are base structure method, homogenization method, relative density method and progressive structure optimization method. Scholars mainly rely on the classical optimization theory of topology optimization to establish a target model to optimize the topology of the target [7]. Saverio Giulio Barbieri proposed a motorcycle piston design method based on topology optimization technology. The method takes the minimum mass of the part as the objective function and the target stiffness of the important parts of the piston as the design constraint. The results show that the proposed method has universal applicability for obtaining the geometric layout and thickness distribution of the structure [8]. Shen Jiaxing et al. optimized the frame components of a certain gantry machining center through the combination of topology optimization design, orthogonal experiment and parameter optimization design, and obtained the optimal design scheme [9]. Guan et al., based on SIMP variable density topological optimization theory, with minimum flexibility and maximum frequency as multi-objective function, structural volume fraction as constraint, and better structural scheme through optimization [10].

2. Prototype machine introduction

Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented. For the high-quality and high-efficiency machining requirements of the internal compensation structure in the repair process of fiber reinforced composite parts, this type of in-situ processing machine tool should have the function of suction type, multi-axis linkage, cover type cutting and follow-up dust removal. Prototype design. The machine tool includes covered cutting device, adjustable type of adsorption foot, dust removal device, etc., as shown in figure 1. The annular bed of the mineral material of the cover type cutting device adopts a square ring design to cover the area to be processed; the gantry type hollow beam is mounted on the annular bed, and the servo motor and the linear guide pair form a cover type cutting device X. The shaft type is connected with the gantry type hollow beam, and the servo motor and the
linear guide pair form a Y-axis of the cover type cutting device; the double oscillating head is mounted on the barrel type column, and is covered by the servo motor and the linear guide pair. And the X/Y/Z three-axis linkage realizes the cover cutting of the area to be processed.

According to the adsorption type in-situ processing method, the deformation of the thin-walled weak rigid auxiliary material has a great influence on the cutting amount, thereby affecting the processing precision and the processing quality. The internal complement structure varies according to different defects and types of damage, and the shape is different [5]. The stepped internal compensation structure of the above various shapes may be a milling method such as spiral milling or end milling.

![Figure 1. Working principle diagram.](image)

### 3. Finite element model establishment

From the prototype structure and processing analysis, it can be known that when the electric spindle of the machine tool is located in the middle position of the guide rail, the beam bears the maximum bending moment and deformation. In this paper, the typical working conditions at this time are studied. The workpiece material is fiber reinforced composite material. In this paper, the experimental data in [11] is used. At this time, the axial cutting force generated by milling is $F_Z = 463.13 \text{N}$. In order to discuss the limit case, the X, Y and Z directions are added respectively. The cutting force margin is 600N, and the gravity $G$ of the headstock or the like is considered to be 400N. At the same time, the beam is affected by the moment, and the moments of the cutting force along the three directions of the beam are obtained. $M_{YOZ}$, $M_{XOZ}$, $M_{XOY}$ are shown in Table 1.

| Font Size | $M_{YOZ}$ | $M_{XOZ}$ | $M_{XOY}$ |
|-----------|-----------|-----------|-----------|
| 200       | 180       | 300       |

Table 1. Torque received by the beam.

Make the model imported into the Ansys Workbench for analysis. The density of BFPC is 2450 kg/m$^3$, the modulus of elasticity is 46 GPa, the Poisson's ratio is 0.25, and the damping ratio is 0.0515. A fixed support is applied to both sides of the beam, and a moment and a force load are applied to the surface of the rail. Applying gravitational acceleration to the overall model. The finite element model is shown in figure 2.
4. Structural design

4.1. Topology optimization scheme
In order to make the beam lighter, the optimization of the design is based on the minimum quality of the BFPC model. In order to make the stiffness and strength of the BFPC model not lower, the static deformation and static stress of the BFPC model are not greater than the prototype structure. The strain, topology optimization results are shown in figure 3.

4.2. Model reconstruction and parameter optimization design
According to figure 3, there are many irregular edges in the topology-optimized model, which makes it difficult to process. Combining the existing manufacturing process and the processing characteristics of BFPC materials, the topology reconstruction results are structurally reconstructed, which makes it easy to process and manufacture.

Because the topology optimization results can only determine the structural layout and cannot determine the optimal size of the structure, the size of each structure should also be studied when reconstructing the model. The paper initially selected six structural dimensions as research factors as shown in figure 4. Each factor takes three levels, and the levels of each design factor are shown in table 2.
By establishing a beam parametric model and using the Workbench optimization module, the multi-objective parameter optimization design of each design variable is carried out. In the optimization, P1, P2, P3, P4, P5, and P6 are used as design variables; the static deformation and static stress of the beam model are not greater than the performance of the prototype structure, and the maximum stress and maximum strain of the model are not greater than the material. Yield stress and strain at yield are constraints.

Use Screening to optimize and set the sample points to 100. After solving, the results of appropriate rounding of each design variable are shown in table 3.

According to the size of each parameter in table 3, the beam model was established, and the software calculated mass of 9.73 kg was reduced by 27.9% compared with the prototype 13.5 kg. The optimized beam model was introduced into the software, the same loads and constraints were applied, and the static stress and deformation of the previous beam were compared, as shown in figures 5 and 6.
As shown in Table 4, it shows that the structure after topology optimization has smaller static stress and static deformation, which fully demonstrates that the structure after topology optimization has better comprehensive performance under the premise of quality reduction.

Table 4. Performance comparison before and after topology optimization.

|                      | Maximum stress / MPa | Maximum displacement / \( \mu \text{m} \) |
|----------------------|----------------------|------------------------------------------|
| Before topology optimization | 4.91                | 1.72                                      |
| After topology optimization | 4.04                | 0.91                                      |

5. Conclusion
Taking the annular BFPC beam of a certain type of in-situ machining machine prototype as the research object, firstly based on the analysis of the prototype working conditions, the comprehensive performance index of the beam is clarified, and the combination of topology optimization design and orthogonal experimental research and parameter optimization design is adopted. The structure and parameters of the BFPC beam were optimized and analyzed. The performance of the beam was analyzed. The static stress and static deformation of the beam were 4.04 MPa and 0.91 \( \mu \text{m} \), respectively, which were 17.7
% and 47.1% lower than the prototype structure. It proves that it has a better static strength and static stiffness while reducing the mass by 27.9%.

References

[1] Shaojie C 2008 Composite Technology and Large Aircraft Acta Aeronautica Et Astronautica Sinica 3 015
[2] Zhe H B Y Z Y 2000 Present Situation and Development Trend of Study on Machining Processing of Composite Materials AEROSPACE MATERIALS & TECHNOLOGY
[3] Xiaosu Y, Shanyi D, Litong Z 2009 Manual of Composite Materials. Beijing: Chemical Industry Press
[4] Katnam K B, Da Silva L F M, Young T M 2013 Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities. Progress in Aerospace Sciences 61: 26-42
[5] Holtmannspötter J, Czarnecki J V, Feucht F 2015 On the fabrication and automation of reliable bonded composite repairs. The Journal of Adhesion 91(1-2): 39-70
[6] Deyuan Z, Jing L 2012 Study on Ultrasonic Machining Technology of Aircraft Fastener Holes. China Mechanical Engineering, (04): 421-424
[7] Kun Z, Liang H, Xiangjian B 2019 Multi-working Condition Topology Optimization of Forklift Door Frame Based on Conditional Risk Assessment. China Mechanical Engineering, 30 (05): 568-577
[8] Barbieri S G, Giacopini M, Mangeruga V 2017 A Design Strategy Based on Topology Optimization Techniques for an Additive Manufactured High Performance Engine Piston. Procedia Manufacturing, 641-649
[9] Jiaying S, Ping X, Yu Yinghua 2018 Topological Optimization Design and Performance Analysis of BFPC Oblique bed CNC Lathe. Journal of Mechanical Engineering
[10] Yingjun G, Chengge J, Wei L 2018 Multi-Objective Topology Optimization for the Pillar Structure of XHGS256 Gantry Machining Center. Mechanical Design and Manufacture, (06): 28-31
[11] Liu G, Zhang H and Wang Y 2014 Study on cutting force and machining quality of orbital drilling for CFRP, J Acta Mater. Comp. Sin.(05) 1292 1299