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The Design and Calculation of the Exoskeleton Backplate Based on the Composite Sandwich Structure

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Abstract. Aiming at the problem of heavy mechanical structure of the exoskeleton backplate, a lightweight backplate of T700 carbon fiber reinforced hollow glass microspheres/epoxy composite based on sandwich structure is proposed in this paper. By analyzing the influence of the thickness of face layer and core layer on the mechanical properties of composite sandwich structure, a composite backplate structure with face layer thickness of 4mm and core layer thickness of 8mm is designed. The simulation calculation and test of the sandwich backplate were carried out. The results show that the error between the simulation results and the experimental values is small, and the reliability of the results is high, which provides more lightweight design of the exoskeleton backplate.

1. Introduction

Assisting exoskeleton is a mechatronic wearable robot developed to mimic human. It is a kind of auxiliary operation equipment that provides assistance through human-machine co-control technology. It can not only be used in emergency rescue, individual combat, material handling and other fields, but also can help lower limb paralysis rehabilitation training, which has potential application demand [1-2]. At present, one of the bottlenecks in the development of exoskeleton is its bulky structure. Multi-material composite structure design is a key way for exoskeleton to achieve lightweight and improve carrying capacity [3-5]. In this paper, a lightweight T700 carbon fiber microsphere/epoxy composite is designed based on the sandwich structure. Through the simulation calculation and test of the mechanical properties of the sandwich structure, it is found that it has a strong bending stiffness.

2. Backplate design of exoskeleton

2.1. Backplate design based on composite sandwich structure

Figure 1 shows the exoskeleton backplate designed in this paper. Its main function is to provide the installation base for the upper limb and connect the lower limb. Because the upper limb of the exoskeleton bears a load of 50kg, it puts forward a severe test on the design performance of the backplate. And the weight of the backplate is also limited.

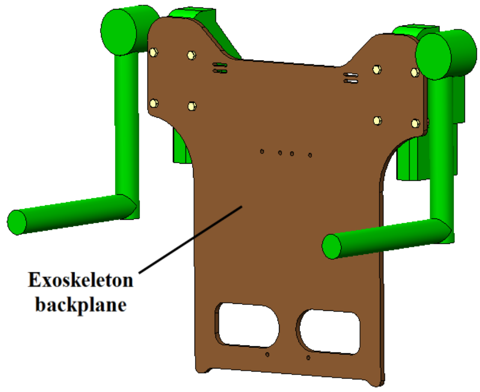

Figure 1. Design of exoskeleton backplate.

The new sandwich structure designed in this paper is mainly composed of T700 carbon fiber face layer, hollow glass microspheres core layer and epoxy adhesive, as shown in Figure 2. The mechanical characteristics of sandwich structure are similar to the principle of I-beam. The upper and lower layers are equivalent to the upper and lower edge strips of I-beam, providing bending stiffness and tensile strength of sandwich structure. The core layer is equivalent to the web of I-beam, providing the transverse shear stiffness, and stabilizing the upper and lower layers to prevent local buckling.

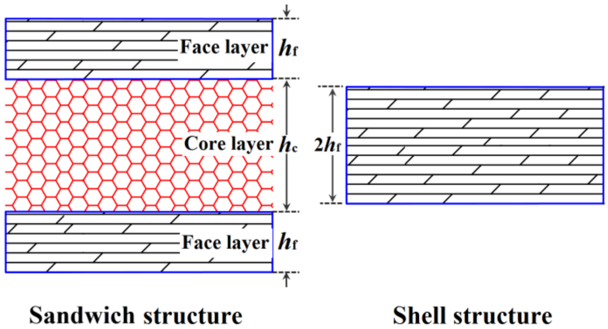

Figure 2. Cross-sectional diagram of sandwich structure and traditional shell structure.

2.2. The design of the mechanical properties of the sandwich structure

The thickness of the upper and lower layers of the sandwich structure is h_f, the core layer thickness is h_c, and the thickness of the traditional shell structure is $2h_f$ in Figure 2. It is assumed that the upper and lower layers are made of the same material, and the traditional shell structure is also the same. The elastic modulus and Poisson's ratio are E_f and V_f respectively, and have the same mass. The internal tensile strength of the two structures is the same, that is, $K=2E_f h_f/(1-v_f^2)$, but the bending stiffness of the two structures is completely different. The bending stiffness formula is as follows:

$$D_{shell}=\frac{E_f(2h_f)}{12(1-v_f^2)}=\frac{2E_f h_f^3}{3(1-v_f^2)} \quad (1) \qquad D_{sandwich}=\frac{2E_f h_f(h_c/2)}{1-v_f^2}=\frac{E_f h_f h_c^2}{2(1-v_f^2)} \quad (2)$$

Based on the above formula, the bending stiffness ratio of sandwich structure to shell structure is obtained as follows:

$$\frac{D_{sandwich}}{D_{shell}}=\frac{3}{4}(\frac{h_c}{h_f})^2 \quad (3)$$

When $h_c/h_f=2、4$, the bending stiffness of sandwich structure is 3 times and 12 times of that of shell structure respectively.

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For the same unit size of internal load N, the face stress of the two structures is the same, that is $\sigma_f = N/(2h_f)$. However, for the moment M of the same unit size, the face stress of the two structures is completely different. The stress formulas of the upper and lower faces of the two structures are as follows:

$$\sigma_{shell} = \pm\frac{6M}{(2h_f)^2} = \pm\frac{3M}{2h_f^2} \quad (4) \qquad \sigma_{sandwich} = \pm\frac{M}{h_f h_c} \quad (5)$$

Based on the above formula, the stress ratio of sandwich structure and shell structure can be obtained as follows:

$$\frac{\sigma_{sandwich}}{\sigma_{shell}} = \frac{2h_f}{3h_c} \quad (6)$$

When $h_c/h_f = 2、4$, The bending stress of sandwich structure is 0.33 times and 0.17 times of shell structure respectively. Therefore, the sandwich structure has higher bending stiffness and strength than the traditional shell structure.

2.2.1. Effect of face layer thickness on mechanical properties

Figures 3 and Figure 4 show the variation of mechanical constants and stiffness of sandwich structure with the thickness of face layer and core layer. When the thickness of the face layer is constant, with the increase of the core thickness, the elastic modulus and shear modulus of the sandwich structure decrease in X and Y directions, but the stiffness increases. The elastic modulus, shear modulus and stiffness values are the maximum when the face layer thickness is 4mm and the core layer is 8mm.

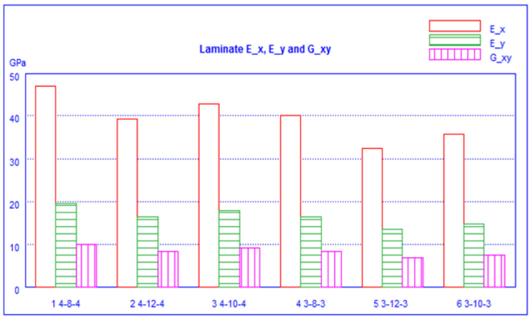

Figure 3. Variation of mechanical constants with thickness of face layer and core layer.

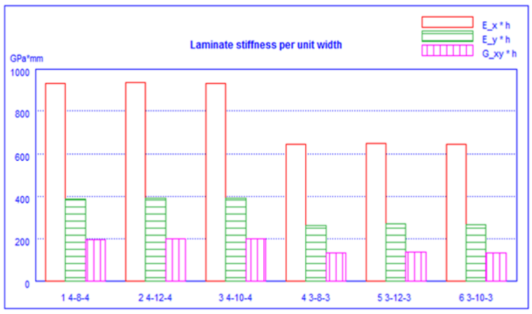

Figure 4. Variation of stiffness with thickness of face layer and core layer.

2.2.2. Effect of core thickness on initial failure stress

Figure 5 shows the variation of the initial failure stress with the thickness of core layer. With the increase of the core thickness, the initial failure stress of the sandwich structure decreases significantly. According to the analysis of mechanical constants, stiffness, initial failure stress and failure strain of composite sandwich structure, the exoskeleton backplate with face thickness of 4mm and core thickness of 8mm is preliminarily designed, as shown in Figure 6.

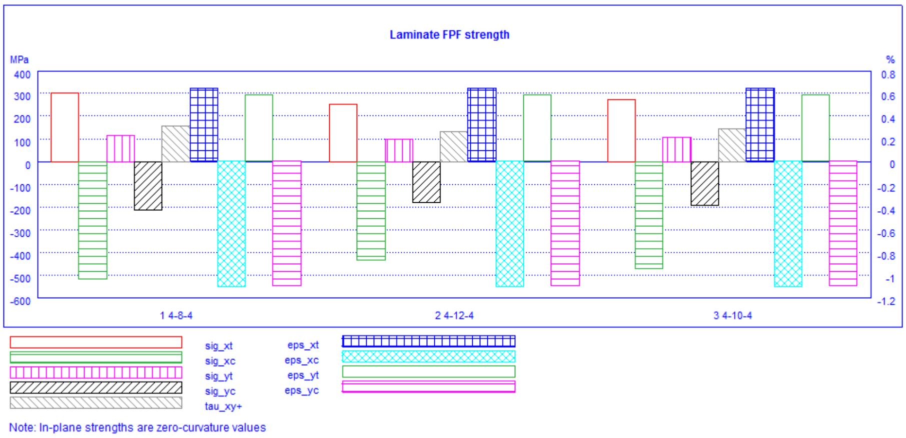

Figure 5. Variation of the initial failure stress with the thickness of core.

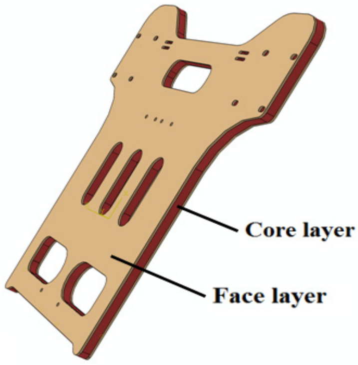

Figure 6. The composite sandwich structure.

3. Simulation calculation and test verification

3.1. Finite element calculation

3.1.1. Constraint condition

In this paper, ABAQUS is used to calculate the sandwich structure. And the constraint conditions are shown in Figure 7. The torque of 350Nm was applied to the double end position respectively. The position of the connecting hole between the lower of the backplate and the lower limb was fixed. T700 carbon fiber was selected as the face layer, and hollow glass microsphere/epoxy was used as the core layer.

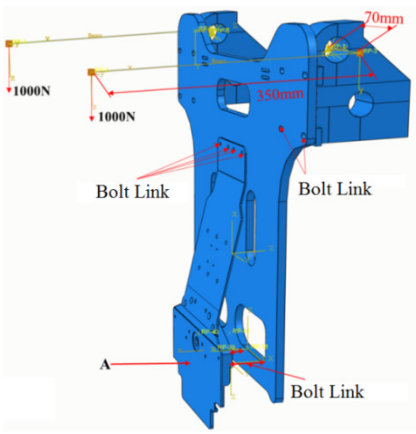

Figure 7. Diagram of loading on backplate.

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3.1.2. Stress strain analysis of backplate

Figure 8 and Figure 9 show the simulation results of sandwich structure. The maximum stress appeared at the bottom connecting hole of the backplate, and the value was 271.2MPa. The maximum strain also appears at this position, and its value is 6973$\mu\varepsilon$. The composite sandwich structure is a new type, and there is no corresponding allowable value of material performance and structural design [6]. In order to verify the reliability of simulation, it is necessary to carry out corresponding experimental verification.

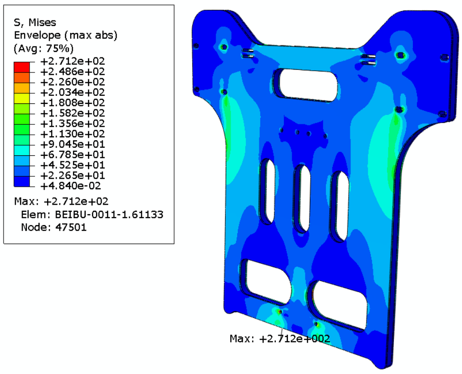

Figure 8. Stress distribution of backplate.

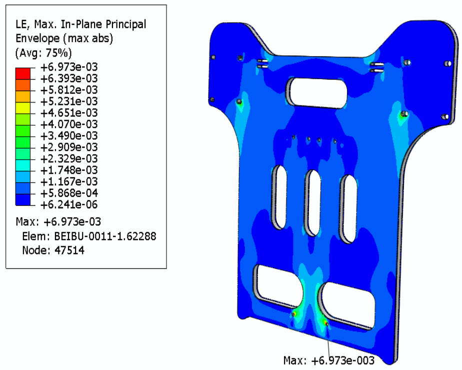

Figure 9. Strain distribution of backplate.

3.2. Test verification

In order to optimize better design results of sandwich structure, mechanical performance testing of exoskeleton backplate is carried out with the DH5921 dynamic strain instrument and bridge strain gauge. The test platform is shown in Figure 10. The applied load condition is 0-1500N at the end of upper limb.

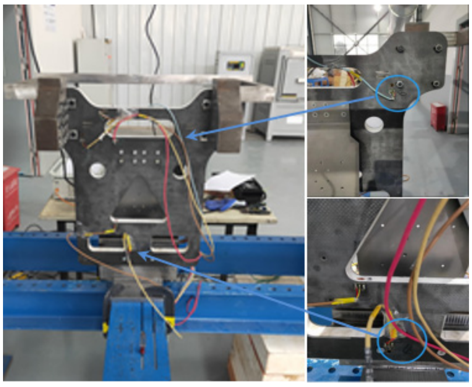

Figure 10. The test platform of backplate.

Figure 11 shows the relationship between loading force and strain during the testing of backplate. It can be seen that with the increase of the loading force, the stress measured by the strain gauge at each position increases. However, no cracking occurred during the whole loading test. When the loading force decreases slowly, the strain also decreases to zero, which indicates that only elastic deformation occurs in the whole loading process. When the strain value is positive, it indicates that the tensile strain occurs mainly at back of the backplate; when the strain value is negative, it indicates that the compression deformation occurs mainly in front of the backplate.

Figure 12 shows the comparison between the test strain value and the simulation value. The change trend of the test strain value and the simulation strain value is consistent, and the relative error is small, indicating that the simulation result is credible. This provides more ideas for the design of exoskeleton backplate.

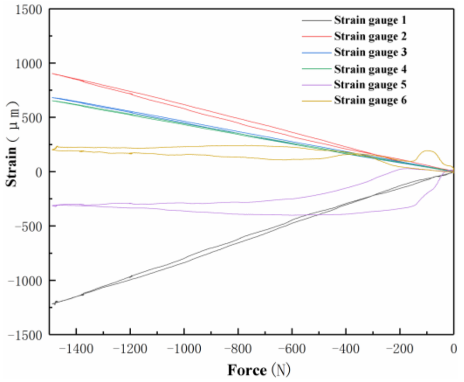

Figure 11. Relationship between loading force and strain.

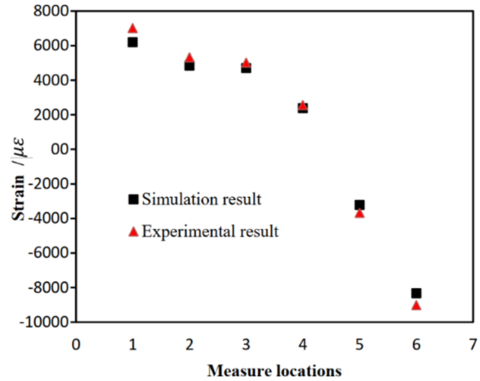

Figure 12. Comparison between test strain value and simulation value.

4. Conclusion

Aiming at a new T700 carbon fiber microsphere/epoxy composite sandwich structure proposed in this paper, the effects of face layer thickness and core layer thickness on the mechanical properties were analysed. Based on the simulation analysis and test, the following conclusions are obtained.

1) With the increase of the thickness of the core layer, the elastic modulus and shear modulus of the sandwich structure decrease in X and Y directions, but the stiffness increases. And the thickness of the core layer has an obvious effect on the initial failure stress.

2) The simulation results show that the maximum stress value of sandwich structure is 271.2MPa, and the maximum strain value is 6973$\mu\varepsilon$.

3) The change trend of the strain value obtained by the test is consistent with the that obtained by simulation, and the relative error is small, which shows that the sandwich structure designed in this paper meets the strength design requirements.

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