Computing, Performance and Communication Systems (2022)
Clausius Scientific Press, Canada

DOI: 10.23977/cpcs.2022.060202
ISSN 2371-8889 Vol. 6 Num. 2

Structural Strength Optimization Design of Composite Furniture Based on Particle Swarm Optimization Algorithm

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Keywords: Particle swarm optimization, Combination furniture, Structural strength, Mechanical load, Optimized design

Abstract: In the process of using composite furniture, some parts are easy to loosen or damage, so it is necessary to optimize the structural strength of furniture to avoid affecting the quality of furniture products. Therefore, based on particle swarm optimization algorithm, this paper proposes a strength optimization design method of composite furniture structure. The same furniture material, different parts of the shape and joint mode, in the case of bearing the same load, the strength performance is also different. Carry out finite element analysis of the composite furniture entity, impose constraints on the model with reference to the real test scenario, and calculate the stress load of the key structure to obtain the maximum impact force borne by the entity. Within the range of allowable tensile, extrusion and shear stresses, aiming at maximizing the structural strength of composite furniture, particle swarm optimization algorithm is used to solve the structural strength, and the optimal design scheme is obtained. Experiments show that this method can improve the maximum static load and bending strength of composite furniture in the tensile direction, make the overall stress distribution of the structure uniform, reduce the loosening and damage of parts in use, and have better application performance.

1. Introduction

With the continuous improvement of living standards, when people pursue the use of natural materials and advocate the green health brought by nature, wood resources are constantly decreasing. The composite furniture needs to ensure that it will not shake in the process of use, and will not collapse under impact during normal use. At the same time, it needs to conform to the characteristics of ergonomics, will not appear inconvenient, uncomfortable and other phenomena, and try to reduce the fatigue when sitting for a long time. Composite furniture is widely used in daily life. During the use of composite furniture, there are many factors that affect the quality or damage of furniture, such as furniture materials, size of parts, use environment, etc., which further affect the quality of furniture products [1]. In the process of use, composite furniture is likely to have problems such as loose parts or damage of individual parts, which are related to structural strength. Experienced designers can quickly find the cause of the problem by relying on their own experience. They can remake the sample and pass the experimental test through one or two modifications. The process of structural strength optimization design of composite furniture is basically based on the designers' existing historical experience, putting forward design schemes according to user needs, and then analyzing the structure [2]. However, some composite furniture may pass the structural strength test after a long period of structural design and repeated modifications, which not only prolongs the design cycle of composite furniture products, but also causes a waste of design material resources. Check the strength, stiffness, steady state, vibration frequency, etc. of the structure. If there is a situation that does not meet the standard requirements, the original design scheme needs to be modified, analyzed and checked again. At present, the frame structure design of domestic composite furniture is still based on the experience of craftsmen, and there is a lack of systematic design theoretical basis and scientific basis to guide the design of composite furniture. The structural design of complex composite furniture becomes difficult to achieve. The same furniture material, different parts of the shape and joint mode, in the case of bearing the same load, the strength performance is also different. For example, wood is an anisotropic and heterogeneous material, and the mechanical strength of different texture directions are significantly different. Only by fully understanding the mechanical properties of wood in different texture directions and considering the texture direction and stress form of each component in the stress analysis of specific furniture, can we truly solve the strength problem in the structural design of composite furniture [3]. The design safety factor of combined furniture is too large, which does not save raw materials to the greatest extent, resulting in a waste of resources, increasing production costs and reducing the market competitiveness of products. These make the combined furniture in the market have great differences in quality and comfort, which greatly limits the development of China's furniture industry and hinders the improvement of international competitiveness. Based on particle swarm optimization algorithm, it optimizes the structural strength of composite furniture, so that the composite furniture has good mechanical properties, improves stability and durability, and makes it more in line with the laws of ergonomics.

2. Finite Element Analysis of Composite Furniture Structure

The structure is a frame shape that bears external loads. It can prevent the shape of the whole from changing when it is subjected to external forces. Finite element analysis is realized by element features. The shape and force characteristics of the structure need to be considered in the element mode. The selection of elements depends on the number of model digits and analysis conditions [4]. According to the properties of the selected materials, select the appropriate unit type. There are multiple different types of units in the unit library of the analysis software platform. Researchers can choose according to the specific requirements of the test. In the processing stage, we first need to define the element type, which is divided into three types: solid element, beam element and shell element. The element type used in this paper is a mixed definition of solid element and beam element. Composite furniture is composed of various parts connected. If all solid units are used for analysis, too many units will be generated, and the construction of model mesh will take a lot of time. In this analysis, hybrid grid elements are used, beam elements are used for the upper and lower seat frames, and solid elements are used for the connecting parts. The three-dimensional structure of composite furniture can be simulated by Solid186 in ANSYS element type. Composite furniture materials can be regarded as orthotropic materials approximately, so the three directions of the unit body need to have different properties and can be deformed. It is a durable element with three high-order positions and 20 knots. The entity is defined by 20 nodes, each of which has 3 degrees of freedom to move in the X, Y and Z directions, with any spatial anisotropy. It is full of advantages in analyzing incompressible Elastoplastic Materials and completely Incompressible

Hyperelastic Materials [5]. Use meshtool to control mesh parameters to expand mesh division, and set the number of meshes to 20. The main body of the device can perform ductility, hyperelasticity, creep, stress, high deformation and high tensile capacity, and can also use mixed mode to simulate elastic plastic materials and hyperelastic materials. Then complete the selection of unit type, and then need to define the unit material properties, which are determined by the materials actually used in the combined furniture [6]. Considering the relationship between mesh accuracy and operation time, this paper uses curvature based mesh generation to simulate the three-dimensional solid of orthotropic materials. First, the hexahedral mesh is converted to the surface mesh of the quadrilateral core, and then the triangular surface mesh must be added. Then, hexahedral mesh generation is performed on the 3D graphics with large internal capacity and sweepable area, and wedge-shaped or tetrahedral elements are used to fill the parts that cannot be swept. However, it is best to prevent wedge-shaped and tetrahedral elements. After the material model of the test piece is established and imported into the ANSYS finite element software, and the pretreatment material attribute definition and grid division are carried out, the load with the vertical downward Y axis of the extended coordinate axis needs to be applied in the middle of the upper end of the material according to the requirements of the national standard to simulate the vertical positive pressure generated by the loader on the material [7]. Hexahedral meshing method is usually used in curved or deformed structures and structural features with large deformation. With the same accuracy, a small number of hexahedral elements can be used for calculation. At the same time, the degrees of freedom in the X, Y and Z directions at the bottom of the material are constrained. The correl function is used to investigate the correlation between the material entity and the simulation analysis curve. The formula is as follows:

$$\gamma(a_1,a_2)=\frac{\sum_m (a_1-\bar{a}_1)(a_2-\bar{a}_2)}{\sqrt{\sum_m (a_1-\bar{a}_1)^2 \sum_m (a_2-\bar{a}_2)^2}} \tag{1}$$

In formula (1), γ represents the correlation coefficient; m represents the total number of samples; a_1 and a_2 correspond to the real shape variable value and the simulated maximum shape variable data set respectively; $\bar{a}_1$ and $\bar{a}_2$ represent the average value of the sample. This paper needs to analyze the nonlinear static load of composite furniture. In order to make the model simulation more close to the test results of real products, the corresponding material parameters are selected for different material parts of the model. The constraint conditions are imposed by referring to the real test situation, and the degree of freedom of the model with 3D space is given by referring to the real test situation.

3. Stress Load Calculation of Key Structures

The joint connection of furniture structure is the weak link that is most likely to cause damage in furniture structure, and has become an important research object of structural design. After meshing the composite furniture entity, add loads and constraints to the model. Select the static analysis module to conduct static load test on the composite furniture to test the mechanical compressive strength of its structure [8]. The purpose of response surface structural analysis of composite furniture is to find out the internal relationship between stress load and equivalent stress, deformation and safety factor under the conditions of meeting the allowable stress value, safety factor and deformation of materials. This paper takes the solid wood chair as an example to analyze the stress of the composite furniture. In the use of composite furniture, the free falling body impacts the base part, and the calculation formula of impact time is as follows:

$$t = \sqrt{\frac{2D}{g}} \tag{2}$$

In formula (2), t represents the time from free fall to seating surface; D refers to the height of the loader from the seat surface; g represents gravitational acceleration. In the process of use, the influence of components with different texture directions on the stress and strain of the overall structure. To apply a vertical downward static force to the seating surface, it is necessary to set the size, direction and action point of the load according to ergonomics and national standards [9]. The member does not undergo major deformation and meets the requirements of stiffness and strength. The expression of the impact force borne by the member is as follows:

$$P = c\left(g + \sqrt{2gD}\right) \tag{3}$$

In formula (3), P represents the impact load when the loader reaches the seat plate surface; c indicates the mass of the loader. During the static pressure simulation of the upper seat, base, TR components and FRP spring sheets, the maximum equivalent stress did not exceed the allowable stress of their respective materials, so it met the strength requirements, and the total deformation of the frame was small, and the structure did not change significantly [10]. When the chair is stressed as a whole, it can be seen from the schematic diagram of the chair components and the equivalent stress diagram after the chair is stressed that the stressed load components are mainly the chair legs. Under the condition that the thickness of the seat panel remains unchanged, this paper selects a pair of legs of the solid wood chair for force analysis. Divide the force equally into four chair legs, and calculate the load in the vertical direction as shown in formula (4):

$$w = \frac{1}{4w_y} \tag{4}$$

In formula (4), w represents the load borne by a single chair leg; w_y represents the total load in the Y-axis direction. The maximum equivalent strain and stress on the chair leg are mainly distributed at the lower end of the contact between the chair back and the chair leg, and the minimum safety value during use is greater than the maximum equivalent stress. A fixed support is applied to the vertices, edges, or surfaces of the model to facilitate limiting all mobility. For the movement in the direction of the coordinate axis restricted by the entity, and the degree of freedom in the direction of the coordinate axis restricted by the surface and line body, the four legs of the combined furniture are in contact with the ground, and the static pressure downward from the vertical sitting surface is applied at the center point of the sitting surface [11]. Taking the chair leg diameter, stress width and loading load as input variables, the relationship between them and the deformation, strain and safety factor after stress is solved. It can be seen from the three-dimensional response surface and contour map of stress and safety factor that the maximum deformation and stress of the chair leg under stress show a downward and then upward trend with the increase of the transverse brace width under the condition that the chair leg diameter remains unchanged. The safety factor of chair legs showed a trend of rising first and then declining. Apply the vertical load at the center of the gasket, and the load is consistent with the load value obtained from the bending strength test of the solid material. The stress concentration of the component of composite furniture materials is located at the contact position between the loader and the component, which is consistent with the most vulnerable position under the actual bending load test, and is relatively close to the actual stress situation. When the cross brace width is unchanged, the deformation and maximum stress of the chair leg show a downward trend with the increase of the chair leg diameter. And the deformation of the chair leg when it is stressed is mainly related to the width of the transverse brace, and the maximum stress and safety condition are mainly related to the diameter of the chair leg. To prevent stress concentration and additional deformation. The displacement of the gasket centerline in the Y-axis direction is constrained, and the gasket can still rotate freely along the Z-axis. This reduces the constraint of the spacer from the support on the wood, and can well simulate the hinge connection of the support.

4. Optimization of Structural Strength of Composite Furniture Based on Particle Swarm Optimization

The task of furniture structure design is to study the cross-sectional changes, composition, connection and assembly of various parts of furniture according to the overall design goal of furniture. Considering the processing technology, mechanical strength, modeling aesthetics and economic cost, the structural engineering drawings are drawn to reflect the required modeling and functions and guide the furniture production and manufacturing. The connection structures of composite furniture mainly include bolt connection, glue connection and glue screw hybrid connection. Hybrid connection is widely used because it combines the advantages of high reliability of bolt connection, large load transmission and high efficiency of rubber connection. For the strength check of bolt connection structure, it is divided into the check of composite laminate and the check of fastener bolts. When the width diameter ratio of the connecting plate is small, it is easy to break, so its tensile strength check formula is:

$$\delta_1 = \frac{P}{(b-s)h} \tag{5}$$

In formula (5), δ_1 represents the tensile strength of the plate; b indicates board width; s refers to aperture; h indicates the thickness of the plate. The extrusion strength during the extrusion failure of the plate is the basis of the connection design, and the extrusion strength δ_2 is checked according to the following formula:

$$\delta_2 = \frac{P}{sh} \tag{6}$$

In the case of the same materials and the same span of the combined furniture, the sectional area of the main beam structure determines its self weight. According to the principle of selecting design variables, the width and thickness of the upper and lower flange plates of the main beam and the thickness and height of the web are selected as design variables, ignoring other factors with less influence. If the ratio between the end distance of the connecting plate and the hole diameter is small, the fastener may have shear failure, and its shear strength is checked according to the following formula:

$$\delta_3 = \frac{P}{2kh} \tag{7}$$

In formula (7), δ_3 represents the shear strength of the plate; k refers to the end distance of connecting plate. Bolt connection is selected for the fastener of composite connection joint. Therefore, the shear strength δ_4 of the bolt is checked according to the following formula:

$$\delta_4 = \frac{4P}{\pi s^2} \tag{8}$$

The structural strength optimization design of composite furniture refers to a method to optimize the structural form, layout and size of composite furniture under the condition of meeting various constraints (such as strength, stiffness, frequency, weight, etc.), so as to optimize the objective function value (such as weight or stress change). To optimize the structural strength of composite furniture, generally, the optimization problem is first transformed into a mathematical model, and then solved by the corresponding optimization algorithm. Within the range of allowable tensile, extrusion and shear stresses, aiming at maximizing the structural strength of composite furniture, particle swarm optimization algorithm is used to solve the structural strength.

Initialize the population randomly, generate the speed and position of particles, calculate the fitness of each particle, and update the historical optimal values of individuals and populations. In each iteration, a certain number of particles are allowed to enter the crossover area according to the hybridization rate. The particles in the crossover area perform crossover operation according to the crossover operator in genetic algorithm to generate new offspring particles [12]. In the update of particle velocity, the first part reflects that the particle is affected by the current velocity and associated with the current state of the particle, so as to balance the global search and local development capabilities. The second part reflects the self-learning part of particles, that is, the displacement vector of particles to the optimal position of individuals. The third part is the social cognition part, which shows the influence of population information on individuals, that is, the displacement of particles to the optimal position of the population [13]. The learning factor is an important parameter in the speed state equation of the algorithm, which is used to adjust the historical movement of particles to individual and population extreme values. In this paper, a linear decreasing learning factor is designed to enhance the convergence of individuals and avoid premature convergence to local extremum.

$$\begin{cases} \beta = \beta_1 + \left(\beta_2 - \beta_1\right)\dfrac{\tau}{T} \\ \varphi = \varphi_1 + \left(\varphi_2 - \varphi_1\right)\dfrac{\tau}{T} \end{cases} \tag{9}$$

In formula (9), β represents self cognitive learning factor; φ refers to social cognitive learning factor; Subscripts 1 and 2 correspond to the initial value and the final value respectively; τ and T represent the current and maximum iterations. PSO algorithm uses the cooperation and competition between particles in the optimization process. In the early stage of algorithm evolution, the optimization speed is fast, the accuracy is high, and the operation is simple and easy to realize [14]. It does not have the complex operations of encoding, decoding, selection, hybridization and mutation in genetic algorithm, which makes the algorithm simple and less expensive. Especially in the field of evolutionary computing, there have been many theoretical achievements. Inertia weight is introduced, and the time relationship between the maximum and minimum weight coefficients and the number of iterations is used to ensure the optimization performance of the algorithm. As the program runs and the number of iterations increases, the weight decreases. Through the dynamic change of weight, the particles can continuously expand the search space at the initial stage of operation, which is conducive to the global optimization of the algorithm. At the later stage of the algorithm, most particles are concentrated near the optimal solution, and more attention is paid to the local development ability of the algorithm and the discovery of accurate solutions [15]. The parameters of the optimization scheme obtained by particle swarm optimization algorithm are taken as the lower limit of the design space. By substituting the optimized design variables into the finite element model, the real response of the structural strength optimization scheme of composite furniture is obtained.

5. Experiment

5.1 Experimental Preparation

In order to verify the effectiveness of the structural strength optimization method of composite furniture based on particle swarm optimization algorithm proposed in this paper, load tests are carried out. The composite sofa is randomly selected as the research object. The main material parameters of the sofa are shown in Table 1.

Table 1 Main Material Parameters of Combined Furniture

Material	Density (kg/m^3)	Modulus of elasticity (N/m^2)	Poisson's ratio	Yield strength (MPa)
Elm	6700	4.26	0.62	672
Pine	5500	5.96	0.58	563
Poplar	5600	3.55	0.42	253
FRP	1900	6.25	0.41	431
T5	2600	6.29	0.32	142
45 steel	8000	2.18	0.28	358
PA66	1200	2.38	0.36	06

In the process of using the sofa, the main damage form is the damage of the connecting node, and the damage parts are concentrated in the front and rear baffles of the armrest and the left and right baffles of the backrest. Therefore, the experimental specimen is designed according to the easily damaged parts. When the sofa armrest is normally used for leaning, the transverse connection node between the front and rear baffle of the armrest and the armrest is mainly subject to shear force. When the backrest is leaning, the transverse connection node between the left and right baffle plates of the backrest and the backrest is mainly affected by bending force. In the durability experiment of sofa, these two kinds of joints are also subject to tensile force. Therefore, the experimental load test mainly includes tensile and bending directions.

In the setting of PSO algorithm, select 300 iterations, increase the population size n, and take n=100. The initial and final values of self cognitive learning factors are 0.7 and 0.3 respectively, and the initial and final values of social cognitive learning factors are 0.3 and 0.7 respectively. The maximum and minimum values of inertia weight coefficient are 0.9 and 0.4 respectively, and the hybridization probability is 0.5. PSO algorithm is used for iterative calculation, and the structural strength optimization scheme of composite furniture is obtained.

5.2 Experimental Results and Analysis

Test the maximum static load and bending resistance of the joint of the combined furniture in the tensile direction. In order to test the structural strength optimization method of composite furniture designed based on particle swarm optimization algorithm in this paper, the performance of composite furniture is tested from the maximum tensile static load and bending stiffness. The test results are compared with the structural strength design methods based on genetic algorithm and fuzzy clustering. The experimental results are shown in Table 2.

Table 2 Comparison of Structural Strength of Combined Furniture

Test serial number	Structural strength optimization design method of composite furniture based on particle swarm optimization algorithm		Structural strength design method of composite furniture based on genetic algorithm		Structural strength design method of composite furniture based on fuzzy clustering	
	Tensile maximum static load (N)	Bending stiffness (N m^2)	Tensile maximum static load (N)	Bending stiffness (N m^2)	Tensile maximum static load (N)	Bending stiffness (N m^2)
1	724.65	3.15	594.09	2.46 528.49	2.37	
2	865.58	2.99	625.56	2.16	669.24	2.65
3	636.79	3.46	586.62	2.55	536.68	2.84
4	805.46	3.65	575.35	2.68	603.35	2.98
5	717.80	4.17	648.27	2.34	527.56	2.62
6	851.62	3.22	657.54	2.22	691.87	2.56
7	885.35	3.55	664.78	2.55	684.61	2.25
8	693.53 4.68	592.46	2.89	760.54	2.34	
9	762.86	2.93	620.83	2.64	652.72	2.61
10	755.63	3.51	598.62	2.73	675.25	2.42

In the tensile test, the average maximum static load of the structural strength optimization design method of composite furniture based on particle swarm optimization algorithm is 769.93N, which is 153.52N and 136.9N higher than the methods based on genetic algorithm and fuzzy clustering. Under the optimized structure, the maximum limit load of the joint increases, indicating that the structure becomes more difficult to destroy and the strength value is also larger. Under the same load, the structural deformation of the design method is smaller, and the ability to resist deformation is improved. In the bending test, the average bending stiffness of the combined furniture structure strength optimization design method based on particle swarm optimization algorithm is 3.53N m2, which is 1.01N m2 and 0.97N m2 higher than the methods based on genetic algorithm and fuzzy clustering. Therefore, the design method in this paper can improve the structural strength of composite furniture, make the overall stress distribution of the structure uniform, increase the surface stress value, and reduce the deformation of furniture structural stiffness.

6. Conclusion

In the process of using composite furniture, there are many factors that affect the quality or damage of furniture, among which the structural strength affects the stability, durability, safety and comfort of the whole composite furniture. In the process of use, the parts of the combined furniture may become loose, or a single part may be damaged. Therefore, this paper combines particle swarm optimization algorithm to optimize the structural strength of composite furniture. Taking the maximum structural strength of composite furniture as the goal, the particle swarm optimization algorithm is used to solve the structural strength within the allowable tensile, extrusion and shear stresses. The test results show that this method can improve the structural strength of composite furniture and reduce the shape variable of furniture structural stiffness.

However, due to the limitation of time, the research on the structure of composite furniture in this paper still needs to be improved, such as the molding process and mold design of composite furniture need to be further optimized. In the future research, starting from the actual working conditions of composite furniture, we will discuss the stress condition of furniture structure, and provide some technical guidance and theoretical support for the structural design of composite furniture.

References

[1] Yang Dandan, Li Xiaofei. Simulation Analysis of Repairing Damaged Traditional Furniture Based on 3D Virtual[J]. Computer Simulation, 2020, 37(4):419-423.

[2] Falheiro Mizael S., Sato André K., Bigon Christophe B., et al. Smart Configurator to Integrate Customized Furniture Design and Fabrication[J]. IFAC PapersOnLine, 2022, 55(2):205-210.

[3] Zor Mustafa, Kartal Murat Emre. Finite Element Modeling of Fiber Reinforced Polymer-Based Wood Composites Used in Furniture Construction Considering Semi-Rigid Connections[J]. Drvna Industrija, 2020, 71(4):339-345.

[4] Huang Pengfei, Li Fangfei, Zhang Lei. Improvement of Structural Strength of Furniture Based on Finite Element Analysis[J]. Journal of Bamboo Research, 2021, 40(4):13-21.

[5] Caeiro Carlos, Calado Jorge S., Sarraipa João, et al. Framework for Validation of Furniture Smartification Processes[J]. IFAC PapersOnLine, 2022, 55(2):499-504.

[6] Yang Dandan. 3D modeling design model of modular furniture based on fuzzy clustering[J]. Modern Electronics Technique, 2020, 43(4):142-144,148.

[7] Kasal Ali, Kuşkun Tolga, Smardzewski Jerzy, et al. Experimental and Numerical Study on Withdrawal Strength of Different Types of Auxetic Dowels for Furniture Joints.[J]. Materials, 2020, 13(19):4252-4252.

[8] Shang Lina, Wang Tianlong, Shen Yang, et al. Analysis and Research of Slide Rail Connection Strength of Panel Furniture Based on Finite Element Method[J]. China Forest Products Industry, 2022, 59(3):36-40, 48.

[9] Abhinesh Prabhakaran, Abdul-Majeed Mahamadu, Lamine Mahdjoubi, et al. The effectiveness of interactive virtual reality for furniture, fixture and equipment design communication: an empirical study[J]. Engineering Construction and Architectural Management, 2021, 28(5):1440-1467.

[10] Demirel Samet, Bas Seda. Evaluation of Creep Characteristics of Single- Staple Furniture Joints Made of Different Wood Species[J]. Drvna Industrija, 2021, 72(2):179-186.

[11] Hu Wengang, Guan Huiyuan. Review of Study on Application of Finite Element Method in Panel Furniture Structure Design[J]. World Forestry Research, 2020, 33(2):68-71.

[12] Xie Zixuan, Huang Xueyu, Liu Wenwen, et al. Domain Learning Particle Swarm Optimization With a Hybrid Mutation Strategy[J]. Journal of Social Science and Humanities, 2022, 13(1):1-27.

[13] Yadav Ravi, Ganguli Ranjan. Reliability based and robust design optimization of truss and composite plate using particle swarm optimization[J]. Mechanics of Advanced Materials and Structures, 2022, 29(13):1892-1902.

[14] Flori Arnaud, Oulhadj Hamouche, Siarry Patrick. QU Antum Particle Swarm Optimization: an auto-adaptive PSO for local and global optimization[J]. Computational Optimization and Applications, 2022, 82(2):525-559.

[15] Besbes Mariem, Zolghadri Marc, Costa Affonso Roberta, et al. Performance Comparison of Particle Swarm Optimization and Genetic Algorithm Combined with A Search for Solving Facility Layout Problem[J]. Journal of Integrated Design and Process Science, 2022, 24(34):121-137.*