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Finite Element Method Application in Computer-Aided Design for Bio-mimetic Chair Research

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Abstract. Wood is a primary material in furniture design and development. However, amid the global carbon reduction discourse, the efficient utilization of wooden resources has become a pertinent topic. Therefore, this study employed Taiwan's Laminated Veneer Lumber (LVL) made from cypress as the material. Through computer-aided design simulations and verification, we designed a Bionic Design Chair (BC) and three sets of commonly found chairs known as Traditional Modeling Chairs (TC). These were analyzed for stress and displacement using Solidworks software. The seating surfaces were categorized into two forms: strip-style and flat-style, and tested for four weight ranges – 45, 64, 81, and 100 kg, representing pressure weights based on human body weight. After Finite Element Method (FEM) analysis via Solidworks software, the BC and TC2 (strip-style) exhibited displacement between 0.9-3.0mm, outperforming TC1 and TC3 which showed displacement between 4.99-12.23mm. Stress analysis showed a range of 2.34-5.68 MPa for TC1-TC3, while the BC, due to its de-sign, could withstand a larger stress range of 4.8-10.59 MPa, superior to the three TC chair designs. In summary, furniture innovation and development are time-consuming processes. This study, by utilizing computer-aided simulations and tests, expedites the development process. The validation of BC design ensures both safety and aesthetic appeal within limited time and resources.

Keywords: Computer-Aided Design (CAD), Finite Element Method (FEM), biomimetic design, wooden material, furniture design

1 Introduction

In the contemporary era characterized by rapid product development, the realm of design heavily relies on diverse computer-aided software tools. This reliance extends to the domain of furniture design, which necessitates compliance with various factors, including aesthetics, practicality, durability, and feasibility [1]. Within the furniture design and development process, the prevalent approach involves fortifying the structural integrity and durability of furniture by leveraging material diversity, technological advancements, and hardware components. However, this developmental process often entails substantial temporal and resource investments to realize the final design.

Hence, employing the FEM for assessing structural integrity and strength and simulating diverse usage scenarios serves to expedite the processes of product design, development, and manufacturing [2-5]. FEM simulation testing encompasses a range of software solutions, among which SolidWorks emerges prominently due to its widespread application in design engineering. The software's inherent capabilities facilitate model creation and simulation of pertinent mechanical performance analyses. Consequently, harnessing SolidWorks for FEM

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simulations across various domains enables the analysis of disparate materials and conditions, thereby expediting development while ensuring the creation of products that adhere to safety standards [6, 7].

The development of furniture design has evolved to incorporate Biomimetic Design as one of the cur-rent mainstream approaches. Biomimicry integrates various biological characteristics such as the structure, principles, and behaviors of living organisms into product design. It is widely applied in industrial, interior, and architectural design fields. Presently, structural biomimicry and form-based biomimicry are the prima-ry approaches within biomimetic design. Form-based biomimicry further branches into natural, abstract, and anthropomorphic forms in the realm of aesthetic development [8, 9]. By analyzing the curve structures of DNA genetic configurations and their relationship with modern design, innovative design ideas and methodologies have emerged, incorporating organic elements into the design process [10].

Under the global carbon reduction agenda, Taiwan's forestry authorities have introduced sustainable forestry policies since 2017 [11]. However, a primary challenge persists in the effective utilization of domestically produced materials, primarily small and medium-sized thinned wood, which often exhibit low utilization rates and limited strength. LVL is manufactured through slicing and rotating veneers, producing LVL with fibers parallel to the direction of the board and perpendicular to the fiber direction of plywood. LVL veneers parallel to the fiber direction attain maximum strength and rigidity while preserving the structural properties of wood. Serving as a raw material from timber, LVL is a structural laminated compo-site material [12, 13], less constrained by volume and shortcomings (such as decay, knots, and cracks), enhancing material strength compared to solid wood of the same volume [14], thus reducing resource waste. In furniture design, using LVL as a material presents structural advantages over solid wood furniture under similar material conditions [15].

In the process of furniture design, collaborative cross-departmental development and production are common. Designers and manufacturers often strive to find suitable design solutions that balance aesthetics and safety. However, this pursuit frequently leads to the wastage of considerable human and material re-sources. This study addresses the challenge of achieving aesthetics and safety in furniture design, given the limitations of timber resources. It explores the reduction of material usage through computer-aided biomimetic furniture design and development using Cryptomeria japonica LVL as the primary material. The study focuses on biomimetic exterior design and development, comparing it with three prevalent chair types modeled using SolidWorks. These models are subjected to Finite Element Method (FEM) simulations under varying weight-bearing pressures to evaluate stress and displacement variations between biomimetic and conventional chairs. Leveraging FEM simulations, the study aims to identify optimized chair designs and offer future design directions. The ultimate goal is to effectively minimize wastage of development time and resources while achieving a harmonious balance between aesthetics and safety in design evolution.

2 Design and Methods

2.1 Biomimetic Chair Design: Element Extraction

The application of plants in biomimetic design is extensive, drawing inspiration from aspects such as plant morphology, structure, movement, and functionality. In furniture design, biomimetic chairs can en-hance functionality and practicality by better supporting the human body, reducing the strain of prolonged sitting. Additionally, biomimetic design can elevate the aesthetic value of furniture, making it more unique and visually appealing [2, 16] is shown in Fig. 1.

By observing the microscopic wood tissue elements, this study focuses on the wood rays, which contain spindle-shaped elements, serving as a crucial design element is shown in Fig. 2. The linear configuration effectively disperses pressure on the hips and enhances comfort during seating [17]. Intertwining these spindle-shaped components in two different arrangements creates a livelier and more intriguing visual effect while ensuring a smooth seating surface for enhanced comfort.

In order to achieve a stable structure, this study designed dimensions of 550 x 390 x 450mm, employing a Wood Ray biomimetic design for the external appearance, showcasing a wavy seat surface. The structure utilizes traditional mortise and tenon joints for overall assembly and connection, ensuring stability and safety for seating. Additionally, by employing lightweight materials and design, the overall weight of the seat has been effectively reduced, making it more portable compared to commercially available seats of similar size is shown in Fig. 3.

Fig. 1. Chair designed through biomimicry

Fig. 2. Wood structure and wood rays

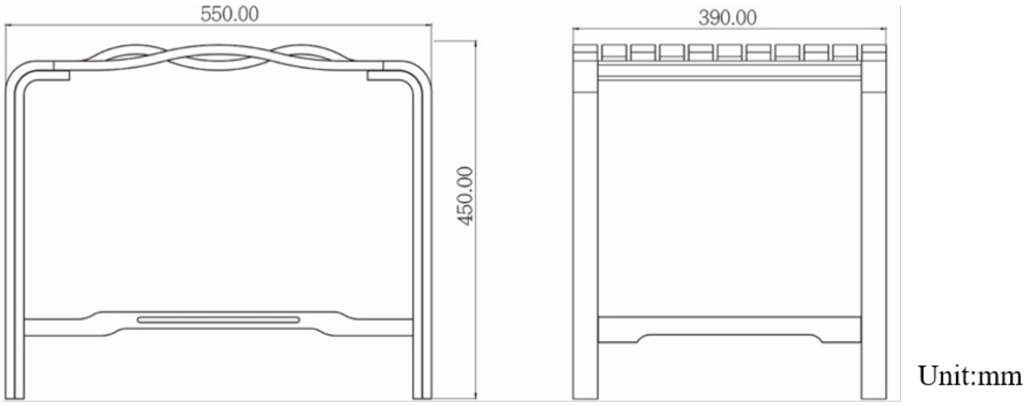

Fig. 3. Chair dimensions

Cryptomeria japonica, commonly known as Japanese cedar or sugi, has a specific gravity of approximately 0.45 when air-dried. Its soft texture, when processed into LVL, enhances mechanical performance and strength. The chemical composition of Cryptomeria japonica also imbues the resulting LVL with anti-corrosive properties [18, 19]. In the production process of LVL products, the environmental impact is less than that of solid wood products [20]. LVL, after compression molding, requires a wood strip thickness of 21mm to support a weight of 150kg, making it suitable for carrying heavy loads. Modified lightweight wood materials also enhance the physical properties of wood to meet load-bearing requirements [14, 21] is shown in Fig. 4.

Therefore, utilizing 60-year-old Cryptomeria japonica as the material and transforming it into LVL allows for the creation of laminated layered materials. The soft and distinct grain of Cryptomeria japonica presents warm reddish-yellow hues, adding a natural and inviting atmosphere. LVL demonstrates excellent strength and durability, making it suitable for long-term use in furniture, thereby contributing to environ-mental conservation and resource efficiency is shown in Fig. 5.

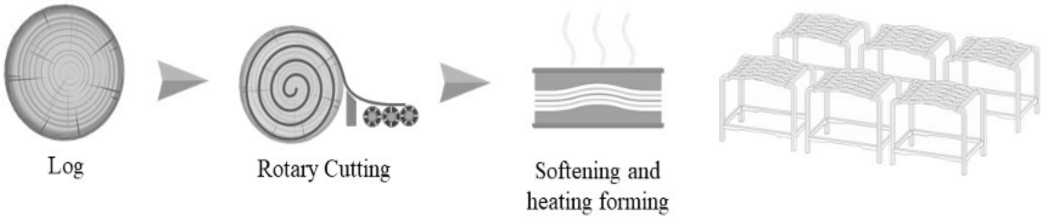

Fig. 4. LVL preparation-1

Fig. 5. LVL finish

2.2 Utilizing Three-dimensional Graphics for Finite Element Analysis

Computer-aided design methods represent a rapid and effective mode of design and development. By employing digital applications, pre-production testing of product development can be assessed, making it the primary approach in current product development. Coupled with FEM, it allows simulating stress variations and structures, effectively reducing design and development time and costs [23, 24]. The use of Solidworks for FEM verification has been widely adopted in the design industry and can also be employed for production simulations [25-27] Analyzing FEM during the 3D modeling software design process provides certain advantages such as accuracy and swift analysis [28, 29].

Furniture design and development often involve numerous issues related to ergonomics, structure, and safety. Hence, leveraging digital modeling and FEM analysis enables rapid innovation and refinement. Given the constraints of limited material resources, minimizing material waste has become a significant concern in the product development process. In summary, this study utilizes Solidworks digital modeling software to design a spindle-shaped Biomimetic chair (BC) is shown in Fig. 6. alongside three Traditional modeling chairs (TC1-3) is shown in Fig. 7 to Fig. 9. Comparative FEM analysis is conducted using Solidworks SimulationXpress.

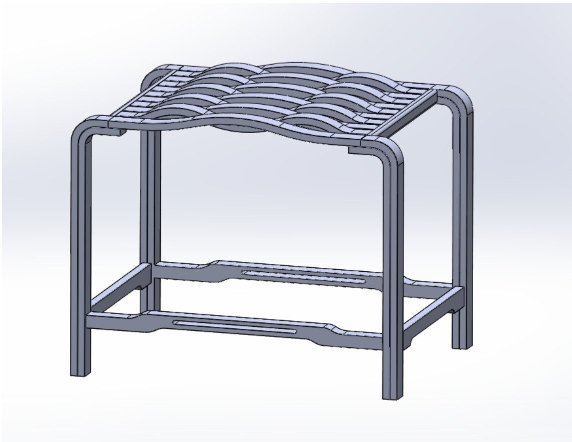

Fig. 6. Bionic design chair, BC

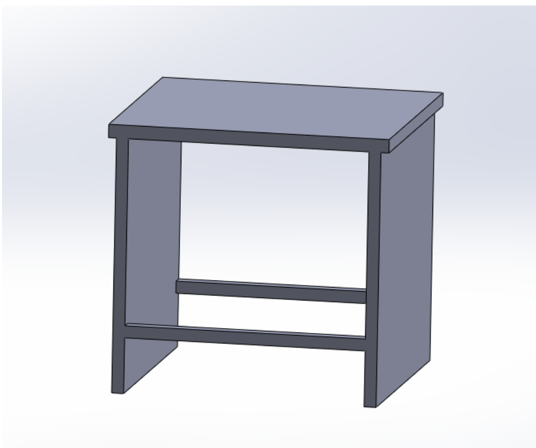

Fig. 7. Traditional modeling chair, TC1

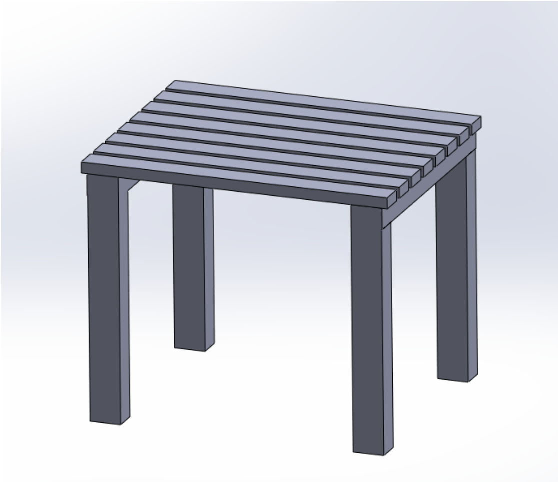

Fig. 8. Traditional modeling chair, TC2

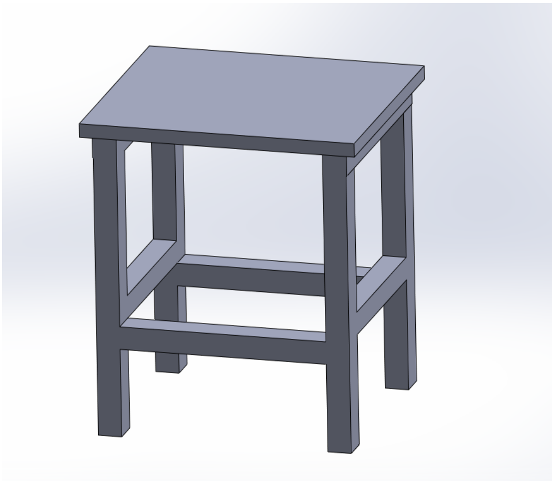

Fig. 9. Traditional modeling chair, TC3

When a user sits on a chair, the weight borne by the seat varies with the user's posture [30]. Therefore, this study considers the variation in seat loading forces and body weight while seated. Finite Element Method (FEM) simulations are conducted using 75% of the body weight of adult males and females to analyze stress and seat displacement. Four weight intervals based on normal adult male and female body weights - 45kg, 64kg, 81kg, and 100kg - are utilized for simulation calculations [31]. These weights are converted from kilograms (kg) to Newtons (N) for structural stress analysis when simulating users sitting on the chair is shown in Table 1. Additionally, pressure simulation is applied from top to bottom according to the four weight intervals, with fixed forces applied on both sides is shown in Fig. 10.

Table 1. Conversion of weight ranges from kilograms to newtons

Weight (kg)	45	64	81	100
75% weight (kg)	34	48	61	75
Newton (N)	333	470	598	735

1MPa ≒ 10.20 kgf/cm2；1N ≒ 0.10 kgf

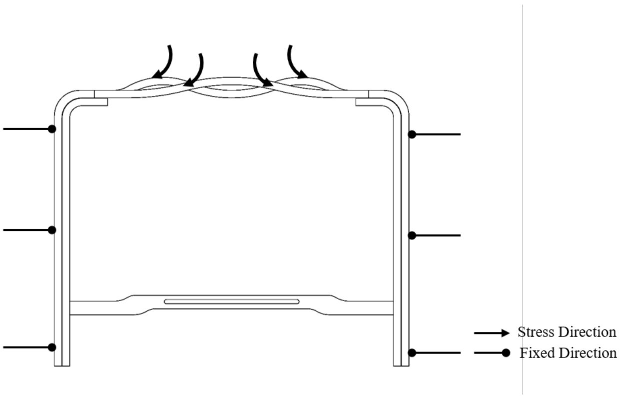

Fig. 10. Pressure release direction

3 Results and Discussion

To confirm whether stress variation and displacement differ based on different chair forms, this study compared the designed BC-shaped chair with two commonly seen flat and bar-type seat forms (TC1-TC3), referencing anthropometric dimensions [32]. Seat appearances were modeled using SolidWorks, and stress analysis and displacement calculations were conducted using Newton forces corresponding to four weight intervals for the four chair designs is shown in Fig. 11 to Fig. 14, Table 2 to Table 3.

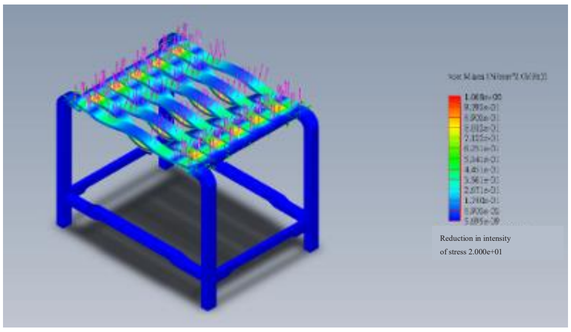

Fig. 11. BC stress distribution

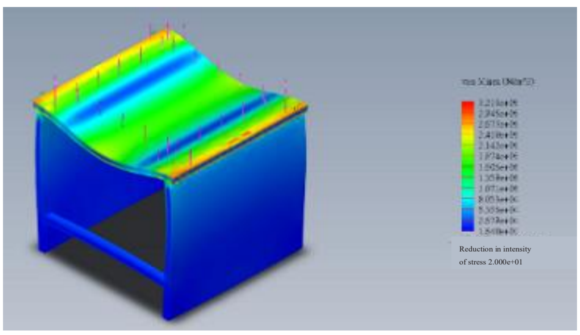

Fig. 12. TC1 stress distribution

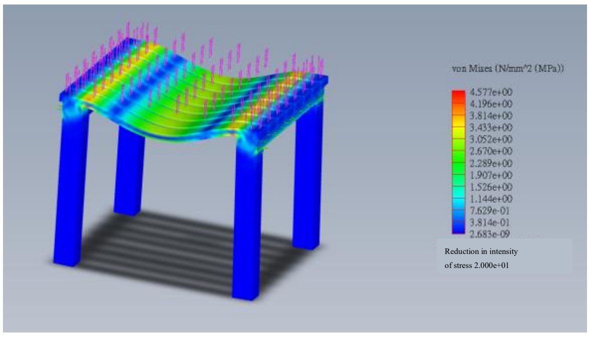

Fig. 13. TC2 stress distribution

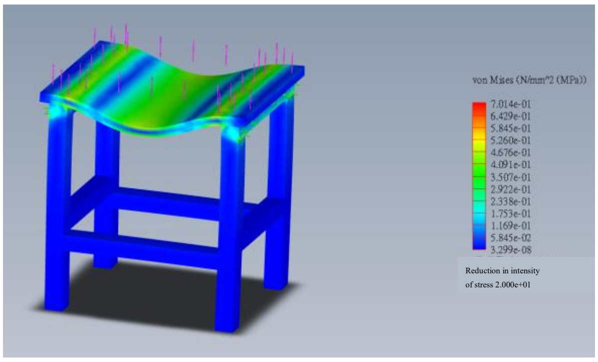

Fig. 14. TC3 stress distribution

Table 2. The stress for different Newton forces

Stress (MPa)	333 (N)	470 (N)	598 (N)	735 (N)
BC	4.8	6.77	8.61	10.59
TC1	2.45	3.46	4.40	5.40
TC2	2.57	3.63	4.62	5.68
TC3	2.34	3.30	4.20	5.16

Table 3. The maximum displacement for different Newton forces

Displacement (mm)	333 (N)	470 (N)	598 (N)	735 (N)
BC	1.36	1.92	2.44	3.00
TC1	5.54	7.82	9.95	12.23
TC2	0.90	1.11	1.41	1.73
TC3	4.99	7.05	8.98	11.03

The FEM stress and displacement simulation results indicate that the bar-type BC chair experiences stress ranging from 4.8-10.59 MPa, with displacements between 1.36-3.00 mm. TC2 stress ranges from 2.57-5.68 MPa, with displacements between 0.9-1.73 mm. The bar-type seat BC and TC2, owing to their design, distribute force per unit area smaller, with stress changing as weight increases and displacements showing a relatively moderate trend. BC, due to its curved wood design, applies greater pressure when force is exerted compared to TC2, with less noticeable changes in displacement is shown in Fig. 15, Fig. 17.

The flat-type seats TC1 experience stress ranging from 2.45-5.40 MPa, with displacements between 5.54-12.23 mm, while TC3 stress ranges from 2.34-5.16 MPa, with displacements between 4.99-11.03 mm. Compared to the bar-type seats, the flat-type TC1 and TC3, due to their larger force-bearing areas, are unable to efficiently distribute force, resulting in concentrated pressure on the seat surface and larger dis-placements with variations in pressure is shown in Fig. 16, Fig. 18.

Between the two different seat types, displacements increase with rising pressure. Notably, the largest difference in displacement occurs between TC1 and TC2 at 333N, reaching up to 4.75mm, and at 735N, the difference extends to 10.49mm. is shown in Fig. 16, Fig. 17. Comparing stress distribution between biomimetic and traditional-style seats: TC1-TC3 seat stress distribution ranges from approximately 2.34-5.68 MPa is shown in Fig. 16 to Fig. 18.

Whereas the BC-designed chair's stress distribution exceeds TC1-TC3 is shown in Fig. 15. The BC chair's textured surface allows for force dispersion across unit elements, preventing concentration on a single point and potentially relieving hip pressure during sitting. Conversely, the flat-type chairs, due to their larger contact area, concentrate pressure on a single point, allowing for higher pressure tolerance compared to the horizontal-shaped seat but potentially impacting sitting comfort [17].

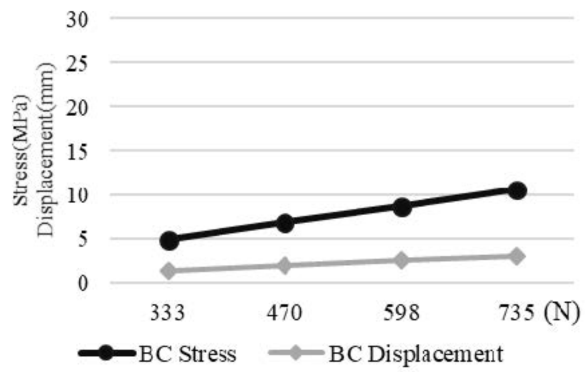

Fig. 15. BC comparison of stress and displacement

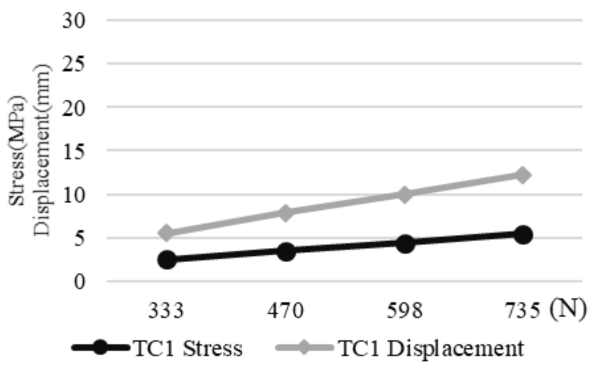

Fig. 16. TC1 comparison of stress and displacement

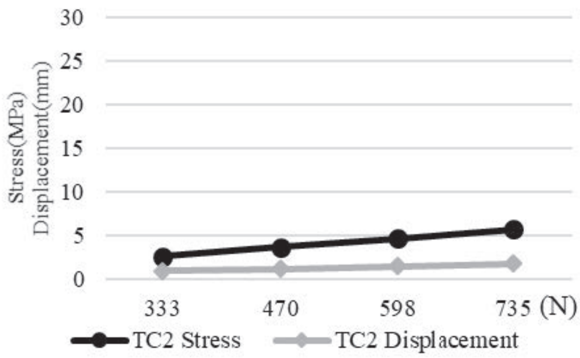

Fig. 17. TC2 comparison of stress and displacement

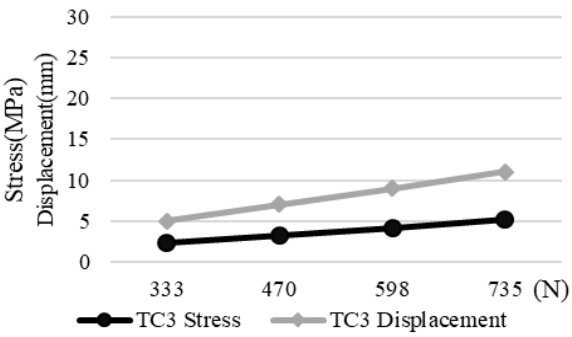

Fig. 18. TC3 comparison of stress and displacement

Through FEM simulation and testing, during the design phase, it accelerates development time and al-lows simulation of various weights and scenarios. From the aforementioned results, it's evident that the spindle-shaped fiber design elements of the BC chair exhibit design characteristics that, due to their shaping factors, enable a punctate, evenly distributed release of pressure. This feature facilitates better dispersion of pressure generated when users sit, reducing pressure points and discomfort, providing a comfortable sitting posture and alleviating body fatigue during sitting by avoiding excessive stress concentration. By alleviating stress concentration on the seat cushion, it reduces pressure on the user's buttocks. The biomimetic design featuring spindle-shaped fiber elements reduces stress loads on the chair structure, consequently lowering the risk of structural deformation and wear, thereby extending the chair's lifespan.

4 Conclusions

During the furniture design process, factors such as safety, aesthetics, and the recent focus on carbon reduction have made efficient resource usage a crucial aspect of furniture design and manufacturing. Therefore, this study utilizes the advantages of computer-aided design to create a biomimetic chair. Using Solidworks, the chair design, development, structural testing, and a series of processes are conducted. A comparison between the chair's design modeled in the current common form and the chair developed in this study is carried out through Finite Element Method (FEM) simulations to analyze variations in stress and displacement within the seat structure.

Analysis reveals several advantages of utilizing computer-aided drawing for chair design and development:

1. Reduction in design and development time and resources: Prior to formal furniture production, during the initial design phase, Solidworks facilitates designing, simulating materials, and testing usage scenarios.

This allows for the early detection of potential issues and usage conditions. Efficient adjustments and planning through computer simulations in the preliminary phase can significantly reduce design and development time and resources.

2. Stability in structural aspects: The strip-style seat is superior in distributing pressure compared to a flat surface seat. In this study, the BC chair employs a biomimetic spindle-shaped fiber structure, ensuring a more evenly distributed stress on the seat, reducing stress concentration, lowering material load, and minimizing structural damage due to stress. This decreases the risk of fractures caused by stress, thereby enhancing the chair's safety.
3. Extension of product life cycle: Through the biomimetic spindle-shaped fiber design structure, the product's life cycle is effectively extended. It reduces pressure points for users, providing superior support and improving user experience. This extension significantly prolongs the product's life cycle.

In wooden furniture design, aesthetics are as important as safety. This study, based on FEM stress and displacement variations under different body weights, examines various chair types and shapes. Through computer-aided design, designers can consider aesthetics and safety simultaneously during the design phase. This application also reduces testing time and resource consumption in the production phase effectively

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