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STUDY ON BENDING CHRACTERISTICS OF FAST GROWING EUCALYPTUS BOOKCASE SHELVES BY USING BURGERS MODEL

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ABSTRACT

This paper used fast-growing eucalyptus wood to prepare three shelf structures as solid wood puzzle, frame panels, and flat puzzle plus metal wear belt, respectively, and then, a creep tests was examined. After fitting the examined results by Burgers creep model, the long-term creep tendency was predicted from the short-term creep behavior of the three structures. Based on the Burgers creep model analysis, an optimized structure that can alleviate the bending problem on bookcase shelf was obtained. The results also provide practical reference for fast-growing eucalyptus wood for furniture design. During comparative analysis of the bending creep and strain, the results show that the flexural creep properties of frame panel and flat puzzle plus metal wear belt were superior to those of solid wood puzzle. After considering the aesthetics, frame panel was the best structure. Furthermore, the fitting results show that using the Burgers model to analyze the creep process of furniture is a very effective method and has strong theoretical and practical significance.

KEYWORDS: Bookcase shelves, bending structure, Burgers model, fast-growing eucalyptus.

INTRODUCTION

At present, the timber consumption is increasing with the rapid development of the furniture industry. Unfortunately, natural forest resources are limited (Utsugi et al. 2007), which promotes the planting and use of fast-growing wood. Because fast-growing eucalyptus wood grows faster and correspondingly needs to absorb more water and various nutrients (Jacobs 1938), it was easy to crack and warp during being dried and processed (Tian 1994). Moreover, the diameter of eucalyptus wood is relatively small (Lu et al. 2018) restrict its high value-added utilization (Ren and Li 2013). However, due to a fast-growing wood with fast growing speed, cheap price, hard texture, and strong anti-corrosion ability, eucalyptus was usually used in high and/or middle grade furniture, and some case also was used as architectural decoration (Guan 2006).

For an ordinary home or office environment, bookcases usually play an important role in the book storage, document preservation and protection, decorative ornaments, and space cleanliness. However, the shelf of the bookcase may be bent due to the long-term load bearing. The reason can be attributed to the creep behavior of the plate. At present, Chinese researchers usually focus on the perspective of furniture support and jointing methods to reveal the creep reasons (Dong and Shao 2007), while other countries researchers pay more attention to practical application (Kotas 1958, Eckelman and Kwiatkowski 1987). There is not an appropriate and normative standardized result so far. There are two common ways to relieve the creep of shelves by thickening the shelves or adding a vertical partition under the shelves. However, both of the two methods should affect the aesthetic appearance of the furniture. Therefore, this paper focus on the bookcase shelf structure to study the creep characteristics and the shelf structure with excellent creep resistance was predicted with Burgers four-element model analysis.

MATERIAL AND METHODS

The fast-growing eucalyptus wood used in this study was produced in Guangxi plantation forest. The moisture content of the final material after drying was 13%. The air-dry density was 0.536 g·cm^{-3} and the dry density was 0.476 g·cm^{-3}. Before the experiment, the dried material should be covered with plastic wrap to reduce the influence of the temperature and humidity. The experiment was performed in 47 % relative moisture content at room temperature (~24°C). According to "the main dimensions of furniture cabinets" (GB/T 3327-2016) as well as the results from market research, this study used the panel size as length × width × thickness = 750 × 300 × 20 mm, and the three shelf structures of solid wood puzzle, frame panels, and flat puzzle plus metal wear belt were shown in Fig. 1.

Because the thickness is only 20mm, M-shaped milling cutter slotted was used to customize all panels and then glue and fixed with puzzle clip after processing. Removed the glue after drying and wrapped with plastic wrap to prevent from temperature and humidity change (Roszyk and Molinski 2003, Gril 1996)). All panels were used to examine the creep characteristics after storage for one week.

Fig.1: Three structures of bookcase shelf.

Each structure was examined for seven samples and removed a maximum and a minimum, then averaged the remaining 5 values. Shimadzu universal testing machine was used for testing (Shimadzu, Japan). The testing method using three-point bending load as shown in Fig. 2.

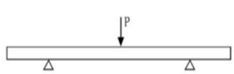

Fig. 2: Schematic diagram of three points bending loading method.

The width of the custom loading head was 80 mm. Placed the sample on a support with a span of 300 mm, and the test machine was loaded at a speed of 5 $MPa \cdot s^{-1}$ at the beginning and then slowly increased to reach the final set load of 500 Newton and kept constant. The experimental procedure was to set the data to be collected from the moment when the loading head touches the sample, and the data was collected every 1 s, collected 20 times; And then collected data every 10 s, collected 20 times; finally collected data every 120 s, collected 60 times; collected a total of 100 data, which lasted 7.420 s (Jiang et al. 2009).

RESULTS

The creep test of the three kinds samples were examined for about 2 hours in order to obtain the viscoelastic parameters and the results were summarized in Tab. 1. The suspicious values, a maximum and a minimum values (drawn offline in Tab. 1), were removed through arithmetic average error detection (Pan and Chen 2008).

Tab. 1: Results of creep test.

Sample name / Entries No.	Solid wood puzzle	Frame panels	Flat puzzle plus metal wear belt
1	1.21	0.79	0.58
2	0.92	1.33	0.86
3	1.73	0.91	0.87
4	1.06	0.54	1.27
5	1.04	1.00	0.92
6	0.95	0.88	0.93
7	0.77	0.89	0.97

The strain analyzed results were summarized in Tab. 2.

Tab. 2: Results of strain analysis.

Sample Name / Entries No.	Solid wood puzzle	Frame panels	Flat puzzle plus metal wear belt
1	6.04	3.95	2.90
2	4.61	6.70	4.29
3	8.70	4.55	4.36
4	5.32	2.70	6.40
5	5.22	5.00	4.61
6	4.74	4.38	4.64
7	3.90	4.43	4.86

After removing a maximum and a minimum values (drawn offline in Tab. 2), the remaining five data were used for strain analysis. In order to more intuitively observe the strain difference between different samples, the results were shown in Fig. 3.

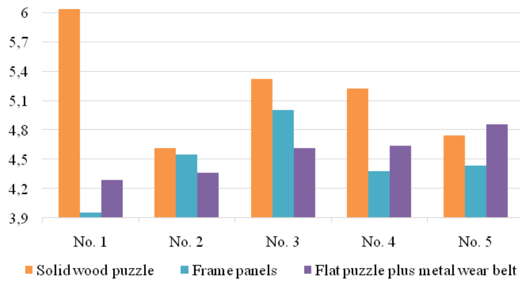

Fig. 3: Strain results of the three structures.

It can be observed from Fig. 3 that the three structures have the highest strain at 4.5%-4.8%. Among them, the solid wood puzzle structure strain range was relatively large from 3.9%-6.1%, and the strain value of flat puzzle plus metal wear belt was mainly settled at 4.2%-4.8%, showed a most stable change, followed by the frame panel structure change at 4.0%-4.9%.

After substituting the data in Tab. 2 into Origin software to plot a curve, Fig. 4 was obtained.

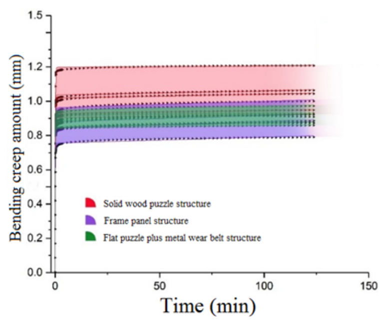

Fig. 4: Creep deformation curves of three structures.

It can be found from Fig. 4 that after two hours of short-term creep tests, the bending behaviors increased rapidly with increased the initial load from 0 N to 500 N, when kept constant in 500 N load, a slow creep was observed in all the three shelves structures. The flat puzzle plus metal wear belt structure has a maximum of 0.35 mm bending improvement and frame panel structure has a maximum of 0.42 mm improvement compared with the solid wood puzzle structure. The bending creep arithmetical average value of the solid wood puzzle structure was 1.04 mm, of the frame panel structure was 0.89 mm, and of the flat puzzle plus metal wear belt structure was 0.91 mm, respectively. There was a 0.29 mm difference between the maximum bend and the minimum bend of the solid wood puzzle structure. The frame panel structure also has a gap of 0.21mm, and only the flat puzzle plus metal wear belt structure showed 0.11 mm difference between the maximum bend and the minimum bend. Therefore, from the analytical results with Burgers model, it can be concluded that in the anti-bending creep performance, the frame panel and the flat puzzle plus metal wear belt structure are better than those of the solid wood puzzle structure, and the structure with metal wear belt was more stable.

DISCUSSION

Burgers model is based on the mechanism of molecular motion and suitable for describing the creep of linear polymers (Chen 2003). Burgers model also was used to study the creep behavior in rock and composite materials. Burgers model is a four-element model, which is composed of Maxwell model and Kelvin model and usually can be used to simulate the instantaneous elastic deformation, delayed hysteresis deformation, and plastic deformation of wood during creep. According to the rheological theory, the Burgers model constitutive equation is as follow.

$$\varepsilon = \sigma\left[\frac{1}{E_e}+\frac{1}{E_d}\left(1-e^{-\frac{E_d}{\eta_2}t}\right)+\frac{1}{\eta_1}\right] \quad (1)$$

where: ε - the amount of creep (mm),
σ - the loading stress (Pa),
E_ei - the instantaneous elastic deformation coefficient in the Maxwell model,
E_d - the delayed elastic deformation coefficient in the Kelvin model,
η_1 - the viscoelastic coefficient in the Maxwell model,
η_2 - the viscosity coefficient ($N \cdot min \cdot mm^{-1}$) in the Kelvin model,
t - the loading time (min), respectively.

In order to apply the formula more conveniently and process the subsequent data, the above equation (1) can be transformed into the following Eq. 2.

$$Y(t) = A + B\,[1 - \exp(-Ct)\,] + Dt \quad (2)$$

where: t - the creep time,
Y(t) - the mathematical function that change over time,
$A = \sigma/Ee$, $B = \sigma/E_d$, $C = E_d/\eta_2$, $D = \sigma/\eta_1$, respectively.

Among them, A and D reflect the elastic deformation and viscous deformation, B and C reflect the viscoelastic deformation (Xu et al. 2009).

Use Eq. 2, through the curve fitting, the parameters of A, B, C, and D were calculated and summarized in Tab. 3.

Tab. 3: Fitting parameter values.

Sample	Entries No.	A	B	C	D	R^2
Solid wood puzzle	1	0.71	0.49	8.25	1.0×10^{-4}	0.97
	2	0.54	0.37	10.87	0.2×10^{-4}	0.98
	3	0.61	0.42	9.52	2.4×10^{-4}	0.98
	4	0.60	0.42	9.63	2.3×10^{-4}	0.98
	5	0.55	0.38	10.60	1.6×10^{-4}	0.98
Arithmetic average value		0.60	0.42	9.78	1.5×10^{-4}	0.98
Frame panels	1	0.45	0.30	12.32	3.4×10^{-4}	0.98
	2	0.57	0.39	9.96	5.4×10^{-4}	0.98
	3	0.53	0.36	10.90	3.5×10^{-4}	0.98
	4	0.50	0.34	11.39	2.8×10^{-4}	0.98
	5	0.50	0.34	11.49	4.0×10-4	0.98

Arithmetic average value		0.51	0.35	11.21	3.8×10^{-4}	0.98
Flat puzzle plus metal wear belt	1	0.50	0.34	11.53	1.4×10^{-4}	0.98
	2	0.51	0.35	11.37	2.0×10^{-4}	0.98
	3	0.53	0.36	10.85	3.2×10^{-4}	0.98
	4	0.55	0.37	10.64	0.6×10^{-4}	0.98
	5	0.56	0.39	10.28	2.4×10^{-4}	0.98
Arithmetic average value		0.53	0.36	10.94	1.9×10^{-4}	0.98

In Tab. 3, Burgers model fitting coefficient R^2 was 0.98, which indicated that the fitting curve fitted well with the test curves and can well describe the creep behavior of the three shelves structures (Wu 2015).

The parameters A, B, C and D represent the different stages of creep. Fig. 5 showed the comparison of the four parameters corresponding to the three structures.

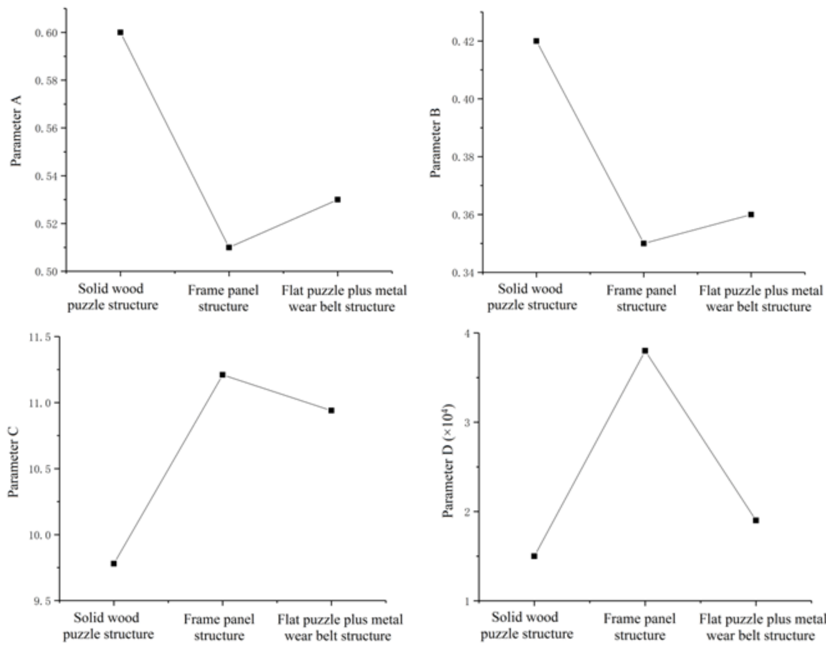

Fig.5: Four parameters corresponding to three structures.

Parameter A is the instantaneous elastic deformation. From Fig. 5a, the instantaneous elastic deformation were, solid wood puzzle >flat puzzle plus metal wear belt > frame panel structure. Parameter B is the time delay elastic deformation, which reflects the material creep increases with time (Xu and Li 2007). From Fig. 5b, the creep of the solid wood puzzle structure increases rapidly with time, next was flat puzzle plus metal wear belt structure, and the frame panel structure was the minimal. Parameter C is the change of strain. From Fig. 5c, frame panel structure has more strain change than other two structures during the stress increase. Parameter D is the sticking deformation, which is an irreversible plastic deformation due to the material molecular chain and the segment (Smulski and Ifju1987). From Fig. 5d, the sticking deformation of the frame panel structure was the largest, suggesting that frame panel structure is very easy to make the substrate molecular chain micro-displacement.

CONCLUSIONS

In this study, a short-term bending creep test of three fast-growing eucalyptus wood bookcase shelves structure was carried out. The results shown that in the average amount of bending creep, solid wood puzzle structure was 1.04 mm, flat puzzle plus metal wear belt structure was 0.91 mm, and frame panel structure was 0.89 mm, respectively. In strain rate, solid wood puzzle structure showed average value of 5.2%, flat puzzle plus metal wear belt structure of 4.6%, and frame panel structure of 4.5%, respectively. It can be seen that flat puzzle plus metal wear belt and frame panel structures are better than solid wood puzzle structure. The difference between the maximum bend and the minimum bend for each structure was examined separately. The results shown that solid wood puzzle structure was 0.29 mm, frame panel structure was 0.21 mm, and flat puzzle plus metal wear belt was 0.11 mm, respectively, meaning that the flat puzzle plus metal wear belt structure has a stable creep resistance. However, when consider from the aesthetics and structural bending performance, the frame panel structure is the best. When fitting the experimental results with Burgers model, the fitting correlation coefficient was maintained at 0.98 suggesting that Burgers model can be used to analyze the creep of furniture. Structural optimization can take the initiative to ease the problem of bookcase shelf compression and bending.

As a continuous research topic, we are conducting comparative experimental research to reveal whether the frame panel structure can further increase its flexural creep resistance by adding wear belt. This study using fast-growing eucalyptus wood was also want to reduce the waste of natural forest resources. If the short puzzle plus metal wear structure can ensure the structural strength, it should become a good method to make full use of wood resources, especially the fast-growing wood.

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