OPTIMIZATION OF HINGE CONFIGURATION OF FURNITURE DOORS USING FINITE ELEMENT ANALYSIS

Jianhui Zhou,[a] Chuanshuang Hu,[a,]* Shuofei Hu,[b] Hong Yun,[a] and Guifen Jiang [a]

The maximum deformation and the stress state of furniture doors with different configurations of hinges were analyzed using finite element analysis with the ultimate purpose of optimizing the hinge configuration. The results showed that the maximum deformation decreased when the end distance ratio (T_p) also decreased. It was concluded that the end distance ratio (T_p) should not be greater than 1/8 when two hinges are mounted. The maximum deformation decreased when the number of mounted hinges was more than two. It is suggested that the number of mounted hinges is three when the dimensions of a furniture door are within normal values, considering the limitations in precision of processing and location. The maximum deformation was least when the middle hinge spacing ratio (S_p) was 1/3 and the mounting hinge number was four. The von Mises stress distribution was uniform within the door, and stress concentration only occurred in the vicinity of the mounted hinges. A material with high modulus of elasticity could contribute to minimizing the maximum deformation

Keywords: Finite element analysis; Stress and deformation; Furniture doors; Hinges

Contact information: a: Dept. of Wood Science & Engineering, Faculty of Forestry, South China Agricultural University, Guangzhou 510642, P.R of China, Tel. & Fax. +86-20-85280256; b: Zhongshan Fourseas Furniture Mfg Ltd., Zhongshan 528459, P.R of China;
** Corresponding author: cshu@scau.edu.cn*

INTRODUCTION

The nonstructural application of wood-based panels, such as plywood and medium density fiberboard (MDF), for furniture has considerably increased in the last few years because of their favorable physical and mechanical properties, their ease of machining, availability, and their cost effectiveness. In the panel furniture industry, thin plywood and MDF panels are often post-processed to produce thicker or curved laminated furniture doors by means of cold or hot pressing with radio frequency heating (Zhou *et al.* 2012). About 8% of furniture doors in China encounter dimensional problems such as twisting, warping, contraction, convexity, and concavity. It has been proven that adjustments to the hinge configuration, such as the number of hinges and mounting position, is one of the most efficient ways to minimize the above-mentioned problems. However, the evidence is still empirical and has not undergone analysis for engineering purposes.

Some researchers have demonstrated that finite element analysis is a good technique for analyzing furniture construction (Eckelman and Rabiej 1984; Cai and Wang 1993; Smardzewski 1998; Colakoglu and Apay 2012). A static analysis of an office desk's construction was conducted using the finite element method to establish the mechanical behavior, especially the standing stability (Novotný *et al*. 2011). The possibility of analyzing the stress and strain state in corner joints, typically found in box-type structures was explored (Nicholls and Crisan 2002). As a result, the stress and strain state in corner joints can be accurately predicted by the developed model. However, there is no information about the effects of the hinge configuration on dimensional behavior and improving the dimensional stability of furniture doors using finite element analysis. Therefore, the objective of the present study was to determine the effect of the hinge configuration on the dimensional behavior and the stress state of furniture doors.

EXPERIMENTAL

Typical furniture doors with the dimensions 1700 mm (height) × 450 mm (width) × 18 mm (thickness) were selected because they easily encountered dimensional problems, according to the data provided by the collaborative partner Zhongshan Four Seas Furniture Ltd. The furniture door was made of medium density board (MDF). The door's moisture content, density, bending strength, and modulus of elasticity, as measured according to ASTM D1037-06a (ASTM 2006), were 9.5%, 770 kg/m^3, 31.5MPa, and 3660 MPa, respectively. The strength of MDF was assumed to be isotropic, and the Poisson's ratio was 0.33 (Ganev *et al.* 2005). The furniture door was supported by hinges with dimensions 35 mm (diameter) × 12 mm (length), which were mounted vertically along the door. A diagram showing how the furniture door was supported by hinges is shown in Fig. 1. It is of great interest to understand the effects of different numbers of hinges on the deformation and stress state of a furniture door. Therefore, doors with two, three, and four hinges were studied here.

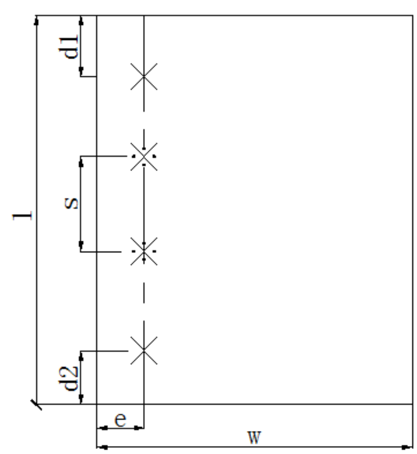

Fig. 1. Configuration of hinges along the height of the furniture door

In Fig. 1, l and w are the height and width of the furniture door, which are 1700 mm and 450 mm. × represents the mounting hinge. ※ represents a mounting hinge if the hinge number is greater than two. e is the distance from the hinge mounting central line to the nearest edge. d_1 and d_2 are the end distances, which are from the hinge mounting central point to the top and bottom edges, respectively. Here, both d_1 and d_2 are equal to d. s is the distance between the two neighboring hinges when the number of hinges was four.

The parameters end distance ratio (T_p) and the middle hinge spacing ratio (S_p) were defined to readily modify the geometry of the three-dimensional model under different conditions, as shown in Table 1.

$$T_p = \frac{d}{l} \tag{1}$$

$$S_p = \frac{s}{l-2d} \tag{2}$$

The static analysis of the deformation and stress state of furniture doors was conducted using ANSYS 12.0 finite element software. The 3D model of the analyzed furniture door was also created using ANSYS 12.0. A cylinder was hollowed out at the area where the hinges were mounted. The mesh of the model was composed of 186 solid elements using a SmartSize meshing technique with size level 1 (fine). The boundary conditions at the hinge mounting areas were simplified as simple support conditions along the height of the furniture door. All DOFs of the nodes on this area were constrained. The model was allotted with the material properties mentioned above. Acceleration of gravity was loaded on the analyzed model because there was only the inertial force during the real working conditions.

When the number of hinges was two, the maximum deformation of the furniture door was studied under different T_p values to optimize the position of the hinges. The maximum deformation of the furniture door was set as a reference when the T_p value was 1/8. The maximum deformation of the furniture door when the T_p value was not 1/8 could be expressed by the maximum deformation ratio (D_i), as given by Eq. 3.

$$D_i = \frac{the\ \max deformation\ when\ T_p\ and/or\ S_p\ \text{selected}}{the\ \max deformation\ when\ T_p = 1/8} \tag{3}$$

It is thought that the dimensional stability can be improved by using more than two hinges to support the furniture door. Therefore, the effect of the hinge configuration with different numbers of hinges on the maximum deformation of the furniture door was also studied. The middle hinge spacing ratio (S_p) was used to simulate the hinge configuration with four hinges.

The effects of different material properties on the maximum deformation of the furniture door were studied after the hinge configuration was optimized.

Table 1. Hinge Configuration with Different Numbers of Hinges and Mounting Positions

Number of hinges	Mounting positions	
	T_p	S_p
2	1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9/, 1/17	/
3	1/8	/
4	1/8	1/2, 1/3, 1/5, 3/5, 3/4, 4/5

RESULTS AND DISCUSSION

The effects of different end distance ratios on the maximum deformation radio of the furniture door when the hinge number was two are shown in Fig. 2. The maximum deformation decreased when the end distance ratio (T_p) also decreased. The maximum deformation when *Tp* = 1/8 was 0.0093 mm. The maximum deformation was 0.0172 mm when the end distance ratio (T_p) was 1/3 and was about 185.5% of the maximum deformation when *Tp* = 1/8. The maximum deformation when *Tp* = 1/17 was 0.0086 mm and was about 92.9% of the maximum deformation when T_p = 1/8. The maximum deformation did not obviously decrease when the end distance ratio (T_p) was less than 1/17. The maximum deformation greatly increased when the end distance ratio (T_p) was greater than 1/6. The effects of different end distance ratios on the maximum deformation can be described by Eq. 4, which was generated using curve fitting tools from Origin 8.5 software.

$$y = 13.98x^2 - 2.21x + 1.04 \qquad (R^2 = 0.988) \tag{4}$$

In Eq. 4, *y* represents the maximum deformation expressed by the maximum deformation ratio (D_i) and *x* represents the end distance ratio (T_p). R^2 is an index to evaluate the curve fitting performance. The curve fitting performance is satisfactory when R^2 is greater than 0.65.

It was recommended that the optimum end distance ratio (T_p) not be greater than 1/8. The maximum deformation when the end distance ratio T_p = 1/8 was used as a reference to optimize the hinge configuration below.

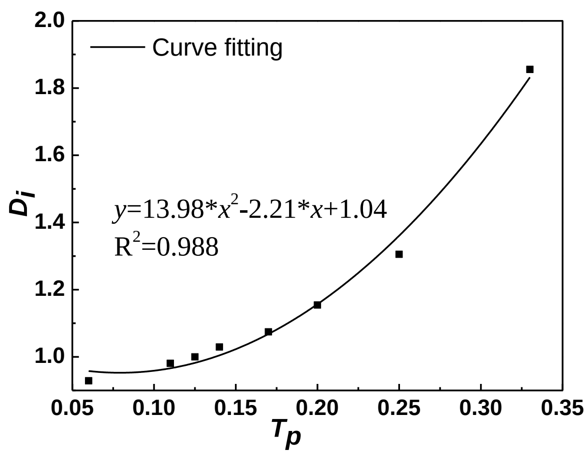

Fig. 2. Effects of the hinge mounting position on the maximum deformation of the furniture door with two hinges

The maximum deformation was 0.00053 mm when the third hinge was mounted between the two outside hinges. It was about 57.5% of the reference value. When there were four hinges, it was interesting to note how the two middle hinge mounting positions affected the maximum deformation of the furniture door. Effects of the middle hinge spacing ratio (S_p) on the maximum deformation of the furniture door with four hinges are shown in Fig. 3.

The maximum deformation of the furniture door with four hinges was 0.0045 mm when the middle hinge spacing ratio (S_p) was 1/3. It was about 48.7% of the reference value. It can be observed from Fig. 3 that the maximum deformation of the furniture door with four hinges was least when the middle hinge spacing ratio (S_p) was 1/3. The maximum deformation *versus* the middle hinge spacing ratio (S_p) could be described by Eq. 5.

$$y = 0.95x^2 - 0.58x + 0.57 \ (R^2=0.999) \tag{5}$$

where y represents the maximum deformation ratio (D_i) and x represents the middle hinge spacing ratio (S_p).

The maximum deformation decreased with an increase in the number of mounted hinges. It is suggested that the middle hinge spacing ratio (S_p) should be 1/3 when the mounting hinge number is four. However, it would be more difficult to guarantee processing accuracy if there were more than two hinges. The more hinges were mounted, the more processing accuracy was required.

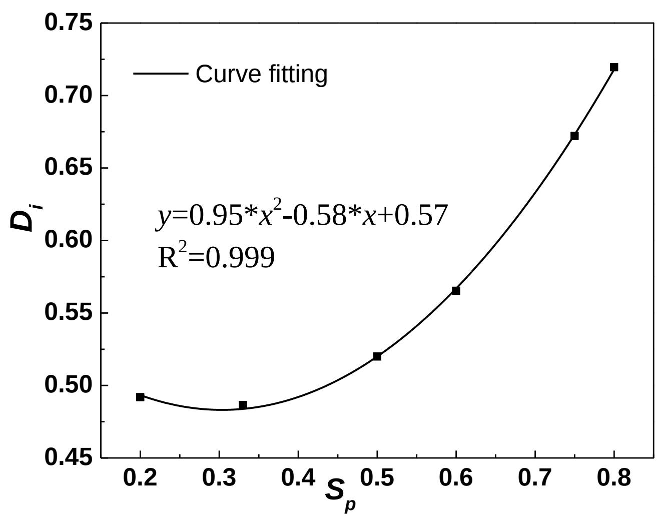

Fig. 3. Effects of the hinge configuration of four hinges on the maximum deformation

The von Mises equivalent stress and total displacement states of furniture doors with different hinge configurations are shown in Fig. 4. The stress distribution in the furniture door was almost uniform, except that stress concentration occurred near the hinges. The maximum deformation occurred at the two corners where the red color zones were.

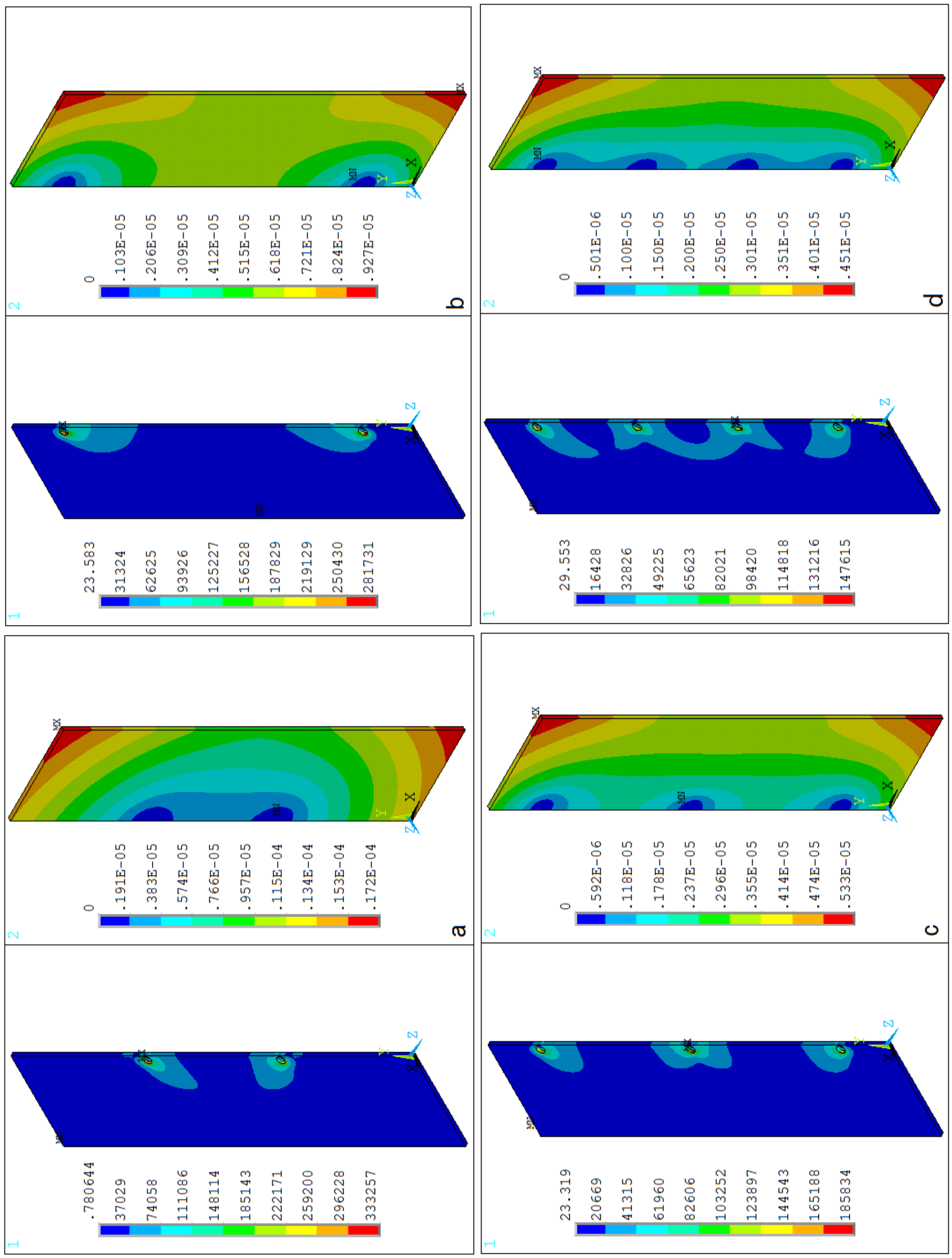

Fig. 4. The von Mises stress (Pa) and displacement (m) contours of 18 mm MDF doors with different hinge configurations, a for T_p=1/3, b for T_p=1/8, c for three hinges, d for T_p=1/8, and S_p=1/3

The maximum deformations of furniture doors with different material properties are shown in Table 2 when the hinge configuration was optimum. The analyzed furniture doors with the dimensions 1700 mm × 450 mm × 18 mm were made of MDF, plywood, and high density fiberboard (HDF). The maximum deformations were 0.00451 mm, 0.00237 mm, and 0.00339 mm for MDF, plywood, and HDF furniture doors. It can be observed that the materials with high modulus of elasticity should be used to improve the dimensional stability of the furniture door.

Table 2. Effects of Material Properties on the Maximum Deformation

Materials	Density (kg/m^3)	MOE (MPa)	Poisson's ratio	The maximum deformation (mm)
MDF	770	3660	0.33	0.00451
Plywood[1]	879	7879	0.31	0.00237
HDF[2]	900	5500	0.25	0.00339
NB: hinge configurations were T_p =1/8 and S_p =1/3. 1 refers to (Alam *et al.* 2012), 2 refers to (Ramaker and Davister 1972)				

CONCLUSIONS

1. With respect to design of the door hinge configurations, it is recommended to keep the end distance ratio (T_p) equal to 1/8 when two hinges are mounted.
2. The maximum deformation decreased when there were a greater number of mounted hinges. Three hinges should be used when the dimensions of the furniture door are within a normal size, considering the limitation of wood processing accuracy. The end distance ratio (T_p) and the middle hinge spacing ratio (S_p) should be 1/8 and 1/3 when the mounting hinge number is four.
3. Materials with high modulus of elasticity can be used to improve the dimensional stability of the furniture door.

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