THE EFFECT OF DOWEL SPACING ON THE STRESS AND STRAIN OF CASE-TYPE FURNITURE CORNER JOINT

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Abstract

This paper presents stress and strain analysis of double-dowel case-type furniture corner joint. Numerical calculations are carried out with a linear elastic model for orthotropic material. The mathematical model is solved by a finite element method. The von Mises stress and displacement are calculated for the simple state of load of MDF board structure. Three dowel spacing are used in order to evaluate the effect of the distance between the centers of dowel holes. The results show that the dowel spacing and the distance between the dowel and the board edge have a considerable impact on the stress state of the face and edge member. Stress patterns obtained in planes of boards show that stress is increased in the areas of fracture zones that occur during the fracture moment tests of dowel joints. Results of the displacement calculation indicate that joint becomes stiffer when the distances between the dowels and the dowel and the board edge are rationally defined.

Keyword: case-type furniture; dowel spacing; MDF; numerical analysis; stress and strain

This Publication has to be referred as: Hajdarevic, S[eid] & Martinovic, S[andra] (2016). The Effect of Dowel Spacing on the Stress and Strain of Case-Type Furniture Corner Joint, Proceedings of the 26th DAAAM International Symposium, pp.0391-0399, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-07-5, ISSN 1726-9679, Vienna, Austria
DOI:10.2507/26th.daaam.proceedings.053

1. Introduction

Case-type constructions are one of the most common products of the furniture industry. The strength and the stiffness structures of this type are predominantly determined by properties of joints. In order to find solution that would improve the properties of the dowel joints, and indirectly, to improve the resistance of structure during service, many affecting factors are analyzed [1, 2, 3, 4, 5]. Due to efficient technology, utilization of dowel joints is the most often way used to assemble wood panels or wood-based panels. The experimental investigations focus on the factors that affect the moment capacity [6, 7, 8]. Zhang and Eckelman have developed the expressions for estimating the bending strength as a function of number of dowels used, dowel diameter, and depth of insertion [8]. Although the expressions are limited to multi-dowel corner joints within the tested range, the authors have stated that depth of insertion has a much more effect than dowel diameter. The study [9] carried out using double-dowel corner joints with various configurations indicate that the strength of dowel joints becomes higher when the member's thicknesses and/or diameter of dowels are increased. It was determined that a greatest part of joints, ~ 98 %, fails due to fracture of face member [9]. The investigation of joints produced by various wood based materials shows that the higher values of strength and stiffness are obtained for MDF joints than for PB joints and the highest values are obtained for PLY joints [10]. Failure load and optimum dowel spacing of joints, which are reinforced with glass-fibre fabric, are investigated by Yerlikaya [11, 12]. Failure loads of reinforced joints are significantly higher than failure loads of unreinforced joints. The highest strength is obtained for 96 mm dowel spacing in LMDF joints, and for 128 mm dowel spacing in LPB joints. The studies [13, 14, 15, 16] provide descriptions of the numerical approaches to analyse properties of the furniture corner joints. The study [17] provides alternative methods of numerical rigidity modelling of dowel joints using nodes of substitute linear elasticity modulus that should be determined empirically. The stiffness values obtained by numerical analysis are compared with the experimental results in the study [10]. The difference reveals that the numerical results provide more rigid behaviour of joints. The normal stress patterns to contact planes on the edge one of the boards have been analyzed by the authors [18]. The stress value reached only the half-point of maximum values in the middle of the distance between fasteners.

2. Research objective and methodology

Some of the literature provides information on the influence dowel space on the corner joint strength. Generally, the maximum strength of joints (drilling module $m=32$ mm) is obtained when the distance between the centers of dowel holes is not less than 96 mm [9, 19]. The critical distance of a dowel to the edge of a board is 50 – 60 mm. The failure mode analysis found that the weakest part of a dowel joint is the face member. Three types of joint failure that can occur are consequence of the position and the length of the fracture zone [9]. When the dowel spacing is less than 96 mm, the fractures zones are overlapping, causing the reduction of joint strength, as opposed to instances where the zones are not overlapping. The expanded fracture zone reaches the edge of the face member when the distance between a dowel and the board edge is less than critical. Also, the joint resistance depends on the joint loading scheme [8]. In the case of compression loading, the joint strength is predominantly related to the internal bond strength of the board. In the case of tension loading, the joint strength is predominantly related to the tensile strength of the board. In contrast with the experimental studies, there are shorter articles available regarding the numerical analysis of the effect of dowel spacing on the joint properties.

The aim of this study is to investigate the applicability of numerical approach in case of determining the influence of dowel spacing on the mechanical properties of case-type furniture corner joints. Since the numerical calculation was limited to a linear elastic model for orthotropic material, the study presents the analysis of the qualitative aspect of stress and strain. The objective is to evaluate the effect of the distance between the centers of dowel holes, and the distance of a dowel to the edge of a board, on the distribution of the von Mises stress, and the distribution of translation displacement. Three significant dowel spacing were used in order to assess the differences between stress patterns, as well as displacement patterns, and the stiffness of the double-dowel corner joint subjected to compression or tension loads. Calculations were performed using the Catia software package.

2.1. Mathematical model

The stress and strain of a loaded solid body in static equilibrium are described by the equation of momentum balance, expressed in the Cartesian tensor notation [20],

$$\int_S \sigma_{ij} n_j dS + \int_V f_i dV = 0 \quad (1)$$

and the constitutive relation for elastic material

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl} = \frac{1}{2} C_{ijkl} \left(\frac{\partial u_k}{\partial x_l} + \frac{\partial u_l}{\partial x_k} \right) \quad (2)$$

In the equations above, x_j are Cartesian spatial coordinates, V is the volume of solution domain bounded by the surface S , σ_{ij} is the stress tensor, n_j is the outward unit normal to the surface S , f_i is the volume force, C_{ijkl} is the elastic constant of tensor components, ε_{kl} is the strain tensor, and u_k represents the point displacement. Twelve non-zero orthotropic elastic constants A_{ij} are related to the Young's modulus E_i , the Poisson's ratio ν_{ij} , and the shear modulus G_{ij} .

The mathematical model is complete when the boundary conditions are specified. Surface traction f_{Si} and/or displacement u_S at the domain boundaries are known, i.e.

$$\sigma_{ij}n_j = f_{Si} \quad \text{and} \quad u_i = u_S. \quad (3)$$

Governing equations (1) combined with the constitutive relations (2) are solved with a numerical method based on the finite element.

General form of the von Mises stress can be expressed in terms of stress invariants I_1 and I_2

$$\sigma_{VM} = \sqrt{I_1^2 - 3I_2} \quad (4)$$

2.2. Physical model

Double-dowel case-type furniture corner joint was selected for investigation. Geometries and measurements of the joint are shown in the Fig. 1.(a). The face member and the edge member of 18 mm in thickness were joined by two 50 mm long dowels with a 10 mm diameter, Fig. 1.(b). A symmetric half of the joint was taken for the solution domain, Fig. 1.(c). The dowel was fastened to the boards without glue line. The boards were contact-connected together as were the boards and the dowel ends. The face member was fixed at the lower end. Bending moment M was applied to the end of the edge member. The imposed bending moment was -10 Nm (compression loading) and 10 Nm (tension loading).

Fig. 1. (a) Dowel joint geometries; (b) configuration of the dowel; (c) joint loading scheme

Calculation was carried out for MDF boards. Its elastic properties, for board thickness of 18 mm, density $\rho=0.787 \text{ g/cm}^3$ and internal bond strength of 0.55 MPa, are presented in Tab. 1 [18]. The dowel material was maple. Elastic properties of the maple wood, for wood density of $\rho=0.57 \text{ g/cm}^3$ and moisture content of 12%, are presented in Tab. 1 [21]. Global and local coordinate systems were applied, and numerical calculations are carried out with a model for orthotropic material.

MDF board											
Modulus of elasticity (GPa)			Rigidity modulus (GPa)				Poisson's ratio				
E_x	E_y	E_z	G_{xy}	G_{xz}	G_{yz}	ν_{xy}	ν_{xz}	ν_{yz}			
3.2	3.4	0.05	0.068	0.058	0.068	0.45	0.50	0.50			
Maple (<i>Acer saccharum</i> Marsh.).											
Modulus of elasticity (GPa)			Rigidity modulus (GPa)				Poisson's ratio				
E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}	ν_{TR}	ν_{RL}	ν_{TL}
13.810	1.311	0.678	1.013	0.753	0.255	0.46	0.50	0.82	0.42	0.044	0.025

Table 1. Elastic properties of MDF board and maple dowel

All measurements except dowel spacing l were held constant. According to the furniture 32 mm system (m x 32mm), investigations were conducted on the corner joints with three different significant distances between dowels of 160 mm, 96 mm and 32mm, Fig. 2.

Fig. 2. Three distances between dowels

3. Results

The effect of dowel spacing on the von Mises stress patterns in the width directions of boards at the board surface planes was assessed. Positions of the selected width directions are shown in Fig. 3.

Fig. 3. Width directions: (a) face member, (b) edge member

The von Mises stresses along the board width on the plane thickness of face and edge members, and for compression and tension loadings, are presented in Fig. 4. and 5. Stress patterns vary significantly and indicate that the stress increases in the areas of the dowel. For the compression loading, the von Mises stress at the plane thickness of the face member is dominantly related to the tensile stress perpendicular to board plane. The dowel insertion affects the position of the stress that cause local board delamination. Fig 4.(a) show the areas where stress values are higher than the internal bond strength of the board (0.55 MPa). The stress patterns of three dowel spacing correspond to fracture zones that occur during the fracture moment tests of dowel joints [9]. For the tension loading, the edge of the face member is less significant due to the occurrence compression stress perpendicular to board plane, Fig. 4 (b). The high stress values in the edge member are the consequence of the local geometric and material discontinuity of the edge board weakened by the dowel holes. At the distance between dowels, and distance between dowels and the edges of the boards, stress values are lower for both cases of loadings, Fig 5.

Fig. 4. The von Mises stress – face member (direction: $x = -9$ mm, $z = 0$): (a) compression loading; (b) tension loading

Fig. 5. The von Mises stress – edge member (direction: $x = 0$, $z = -9$ mm): (a) compression loading; (b) tension loading

The values of the von Mises stress along the other width directions, shown in Fig. 3., are higher and dominantly related to tensile and compression stress in the board planes. The stresses along the board width at the inner surface of face member, and for compression and tension loadings, are presented in Fig. 6. and 7. The von Mises stress along the board width, at the inner and outer surfaces of face member, and for compression and tension loadings, are presented in Fig. 8. and 9.

Fig. 6. The von Mises stress – face member (direction: $x = 0$, $z = -9$ mm): (a) compression loading; (b) tension loading

Fig. 7. The von Mises stress – face member (direction: $x = 0$, $z = -15.5$ mm): (a) compression loading; (b) tension loading

Fig. 8. The von Mises stress – edge member (direction: $x = 15\text{mm}$, $z = 0$): (a) compression loading; (b) tension loading

Fig. 9. The von Mises stress – edge member (direction: $x = 15\text{ mm}$, $z = -18\text{ mm}$): (a) compression loading; (b) tension loading

The stress patterns clearly indicate that dowel spacing affects the position and size of the high stress areas. The maximum values of the von Mises stress are obtained at the positions where dowels are inserted. The maximum values of stress are close to the MDF bending strength ($\text{MOR} > 20\text{ MPa}$) at the selected directions of the face member. For selected directions of the edge member, the maximum stresses are much lower. The effect of dowel spacing on the transition of the lower stress area between dowels is noticeable at all selected directions. When dowel spacing is 32 mm, the lower stress area between dowels is minimal. The area of lower stress stretches and the length of the area are largest when dowel spacing is at 160 mm. The effect of the dowel distance to the board edge on the von Mises stress is noticeable when the distance of a dowel to the board edge is 20 mm, and dowel spacing is at 160 mm. In that case, the areas of increased stress reach the board edges. The minimum stress values at the board edges are obtained when dowel spacing is at 32 mm and 96 mm. The areas of lower stress between dowels and between the dowel and the board edge are obtained when distance between the centres of dowel holes is 96 mm.

For compression loading, the results show that the maximum von Mises stress at the plane thickness of the face member is much higher than the internal bond strength of the board while the von Mises stress, dominantly related to the compression, at the inner surface of the face member is close to the surface strength of the board, Fig. 4.(a) and 7.(a). The inner surface of the face member is more significant in the case of tension loading, Fig. 6.(b) and 7.(b). The von Mises stress at the surface is dominantly related to the tensile stress, the maximum values of stress are higher, and the values of stress are increased at the edges of the face member, compared to the case of compressing loading. In that case, the maximum values of compression stress perpendicular to the face board are low, Fig 4.(b). As opposed to the face member, the values of stress at the surfaces of the edge member increase if the von Mises stress is dominantly related to the compression stress, Fig. 8. and 9.

Fig. 10. Total translational displacement of the free end of the edge member: (a) compression loading; (b) tension loading

The effect of dowel spacing on the total translational displacements of the free end of the edge member was assessed. Translational displacement and deformations of joint in cases of compression and tension loadings are shown in Fig. 10. and 11.

When the distance between the centers of dowel holes is 96 mm, the joint stiffness is at maximum. By increasing the dowel spacing to 160 mm, joint stiffness decreases by $\sim 8.5\%$ for both cases of loadings. When the distance is 32 mm, joint stiffness is decreased by $\sim 12\%$ for case of compression loading and $\sim 4\%$ for case of tension loading. Differences between displacement obtained for the compression and tension loadings range from $\sim 5\%$ (distances: 160mm and 96 mm) to $\sim 14\%$ (distance: 32mm).

Fig. 11. Translational displacement and deformations of joint (scale 5:1). Compression loading – dowel spacing: (a) 32mm; (b) 96 mm; (c) 160 mm. Tension loading – dowel spacing: (d) 32mm; (e) 96 mm; (f) 160 mm

The effect of dowel spacing on displacement of the boards contact zone was obtained. The components of displacement along the board width at the outer surface edge (Fig. 3.(b); $x = 0, z = 0$) of the edge member, and for compression and tension loadings, are presented in Fig. 12. and 13. Compression loading of the joint caused a lack of contact between members on the selected edge. In the case of tension loading, contact stress occurred on the edge and reduced the displacement. Displacement differences due to applied cases of loading can be noticed at the u component displacement patterns. The influence of dowel distance on the displacement is more noticeable at the w component displacement patterns. When the distance between the centers of dowel holes is 96 mm, the differences between displacements at the points along the width direction of the board are minimal and displacements are more uniform.

Generally, the numerical results indicate that the dowel spacing and the loading schemes influence the qualitative stress state and the strain in a similar way to the effect on the joint strength and stiffness obtained by experimental investigations [8, 9].

Fig. 12. Component displacement u – edge member (direction: $x = 0$, $z = 0$): (a) compression loading; (b) tension loading

Fig. 13. Component displacement w – edge member (direction: $x = 0$, $z = 0$): (a) compression loading; (b) tension loading

4. Conclusion

The study was carried out in order to obtain information concerning the influence of three dowel positions of the loaded double-dowel corner joints on the qualitative features of the von Mises stress and strain.

The results indicate that dowel spacing has an effect on the stress patterns that correspond to the fracture zones of failure mode analysis. The joint with 96 mm dowel spacing has lower value of stress and/or the larger length of lower stress areas between the dowels, and between the dowels and the board edges than those with 32 and 160 mm dowel spacing. For joints with dowel spacing other than optimal, the results show increased stress between the dowels (dowel spacing: 32mm), or between the dowels and the board edges (dowel spacing: 160mm). The joint loading schemes influence the stress state at the analyzed directions. Particularly noticeable is the significance of the free edge of the face member of the compression loaded joint. For both loading schemes, the highest joint stiffness is obtained with 96 mm dowel spacing.

Future work will include consideration of the reinforced double-dowel corner joints. In addition, numerical analysis for elastic-plastic model is needed to assess the influence of dowel spacing on the stress and strain state of the corner joint.

5. References

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