STUDY ON STIFFNESS COEFFICIENTS UNDER BENDING TEST OF END CORNER DETACHABLE JOINTS OF STRUCTURAL ELEMENTS MADE OF PLYWOOD

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ABSTRACT
In this study are given the results from investigation into stiffness of end corner detachable joints of structural elements made of beech veneer plywood. The stiffness coefficients under compression bending test have been determined. The highest stiffness is characteristic of joints with universal connector and screw for wood ø 6 x 90 and ø 6 x 80 mm while the lowest stiffness is typical of joints with Minifix with bolt, mounting in metal sleeve and direct mounting. The parameters of the screw joints have considerable impact on the stiffness characteristics of the joints.

It is recommended that the comparative data of bending strength be taken into consideration when selecting the type of joints in the construction of furniture made of plywood.

Key words: furniture construction, plywood, joints, stiffness.

INTRODUCTION
Plywood is preferred material in furniture production. The advantages it has in terms of form complexity, line and uniqueness have stirred the interest of both designers and architects from all over the world for many years. The choice made by modern consumers is based on two key factors – product design and quality. Undoubtedly, both factors play a very important role. Design as such is a very dynamic factor and experimenting with design is compulsory if the aim is to create interesting and attractive furniture. Quality, on the other hand, is a factor which has to be constantly improved. Therefore, trying to achieve the optimum construction and reliable strength and deformation sizing are compulsory.

Determining the strength and deformation characteristics of the most common end corner detachable joints of structural elements made of plywood in furniture construction poses a question of both practical and theoretical importance.

The studies, carried out in Bulgaria do not present data concerning the experimental data of strength and deformation characteristic features of end corner joints made of plywood. There are considerably more data concerning the strength and deformation characteristics of joints of structural elements made of solid beech and chestnut wood which can be used in comparative analysis (Jivkov et al., 2000; Kyuchukov, G., et al, 2009; Kyuchukov, G., et al, 2011; Kyuchukov, G., et al, 2012; Kyuchukov, G., et al, 2013).

The foreign scientific literature provides data concerning the study on stiffness and deformation characteristics of end corner joints of structural elements made of plywood. It presents data about bending strength and some of it contain data about the stiffness of joints. There are data about strength under tensile, shear and torsion loading.

A number of these publications focus on studies of joints connected with dowels (Zhang et.al. 2001; Erdil and Eckelman 2001; Eckelman et.al. 2002; Jensen and Koizumi 2002).
Since plywood is widely used in the construction of upholstered furniture, there are studies focusing on joints with metal staples and metal plates in framework constructions of upholstered furniture made of plywood and other wood materials. A number of publications present comprehensive experimental studies of the strength characteristics of the corner joints under tensile, shear, static and cyclic loading (Zhang et al. 2002; Zhang et al. 2002; Erdil et al. 2003; Zhang et al. 2005). With the exception of Erdil, Zhand and Eckelman’s publication (2003), which contains results from a study on tensile strength and bending strength of structural elements made of plywood, joint through connector with cross dowel, there is almost no information about studies on the stiffness and deformation behaviour of the detachable joints of structural elements made of plywood.

On the basis of the study we can draw the conclusion that the data about the deformation behaviour of joints made of beech veneer plywood are insufficient. That is why it is advisable to set specific and exact values of the strength and deformation characteristics of joints made of plywood which would facilitate both the scientific research into this relatively new in furniture production material and the manufacturers from the furniture industry.

**MATERIALS AND WORKING METHOD**

For the purpose of the study test samples were made of plywood from rotary cut beech veneer, manufactured by “Nikrom-Veneer” Ltd, Petkovo. For the needs of the study it is made entirely from ‘A’ quality veneer. The thickness of the plywood was 20 mm and 21 mm, respectively. Veneer panels were produced in size of 920 by 500 mm. Two-component urea formaldehyde adhesive manufactured by “DINEA” – Hungary, with a quantity of 150 g/m² was used. Plywood manufacturing was carried out on “Vecciato VALTER” multi-storey pressing machine. Pressing temperature was 110 °C, while the continuity was 15 min, and pressure was 1.3 N/mm².

The plywood panels are cut out to make test samples for testing strength and deformation characteristics of various types of corner joints. BDS EN 636, Plywood: specifications’ have been met.

The physical and mechanical characteristics of the panels are as follows (Jivkov et al):

- Density – 760.1 kg/m³;
- Bending strength under loading perpendicular to panel layers – 55.58 N/mm²;
- Bending strength under loading parallel to panel layers – 63.16 N/mm²;
- Modulus of elasticity in bending under loading perpendicular to the veneer layers – 5286 N/mm²;
- Modulus of elasticity in bending under loading parallel to the veneer layers – 6650 N/mm².

Eight series of test samples with cross section 50 x 20 mm were made. For the purposes of the study have been selected some of the most common detachable joints, made with hardware produced by „Häfele” – Germany. The following types of detachable end corner joints have been tested:

1 – screw M6 with cross metal dowel; 2 – wood screw ø 6x90 mm; 3 – wood screw ø 6x80 mm; 4 – bolt and nut with external and internal thread; 5 – one-piece connector Confirmat ø 7x70 mm; 6 – one-piece connector Confirmat ø 7x50 mm; 7 – Minifix with M6 metal sleeve ø 8x15 mm; 8 – Minifix for direct mounting in ø 5 mm hole.

The type and sizes of the test samples are shown in figure 1.
The test samples were loaded under bending in arm compression test as shown in Fig. 2.
Testing was carried out in the scientific and research laboratory at the Institute of Mechanics and Biomechanics, BAS, Sofia on a TIRA test 2000 testing machine.

The load speed was selected so that the destruction of the test samples occurs between 30 s and 120 s after the start of loading.

To measure the force a sensor with range up to 10 kN with 1 % accuracy, appropriate for over 100N force was used. The testing was carried out at temperature of 22 ± 1 °C, humidity: 63 ± 5 %.

For 10 and 40 % of the maximum loading forces the change in the distance between the application points was recorded and the changed arms of bending and the changed angle between the arms of the joints were determined. Previous studies have found that this area of loading corresponds to the linear section from the “loading – deformation” correlation.

More data were recorded – the maximum force, the deformation under the maximum force, the force and deformation at the destruction of each test sample.

The theoretical and experimental studies on the strength and deformation characteristics of the corner joints illustrate that the key criteria for their evaluation are the maximum bending moment and the coefficient of stiffness.

The deformation of the joints under the compression bending test gives as a result changes in both, the right angle between the joint arms and the bending arms $l$ of the forces. The linear displacement $f_i$ of the application points of the forces $F_i$ is recorder for each test sample at each loading level. It represents a sum of displacement resulting from turning the joint arms and additional displacement $\Delta_i$ resulting from bending of the arms. To find out the displacement $\Delta_i$ we use the following formula:

$$\Delta_i = \frac{F_i a^3}{3 E I},$$  \hspace{1cm} (1)

where: $F_i$ is the value of the loading force, $N$;

- $a$ – axial length of the joint arms, $m$;
- $E$ – modulus of elasticity of the plywood parallel to the layers, $N/mm^2$;

- $I$ – axial moment of inertia of the cross section of the joint arms, $m^4$,

which is worked out with the formula:

$$I = \frac{b \delta^3}{12},$$  \hspace{1cm} (2)

where: $b$ is the width of the arms, $m$;

- $\delta$ – thickness of the arms, $m$.

The distance between the force application points at each level of loading is determined with the formula:
STUDY ON STIFFNESS COEFFICIENTS UNDER BENDING TEST OF

\[ L_i = L - f_i + \Delta_i, \]  

(3)

The angle \( \gamma_i \) [rad] changed under loading between the joint arms is worked out with the formula:

\[ \gamma_i = 2 \arcsin \frac{L_i}{2a} = 2 \arcsin \frac{L - f_i + \Delta_i}{2a}. \]  

(4)

The changed bending arm \( l_i \) is determined with the formula:

\[ l_i = a \cos \frac{\gamma_i}{2}. \]  

(5)

The result from the deformation under compression bending test is the semi rigid rotation of the joint arms in [rad]:

\[ \alpha_i = \frac{\pi}{2} - \gamma_i. \]  

(6)

For certain values of the loading force \( F_i \) the bending moment [N.m] is determined with the formula:

\[ M_i = F_i l_i. \]  

(7)

Stiffness coefficient \( c_i \) [N.m/rad] under compression bending test is determined with the formula:

\[ c_i = \frac{\Delta M_i}{\Delta \alpha_i}, \]  

(8)

In (8) the following designations are used:

\[ \Delta M_i = M_i - M_0, \]

\[ \Delta \alpha_i = \alpha_i - \alpha_0, \]

where: \( M_i \) and \( \alpha_i \) are determined under (7) and (6) for the value of force \( F_i \), equal to 40% of \( F_{\text{max}} \), while \( M_0 \) and \( \alpha_0 \) – under (7) and (6) for the value of force \( F_0 \), equal to 10% of \( F_{\text{max}} \).

The stiffness coefficient \( c \) as a deformation characteristic of the corner joint under compression bending test is defined as the arithmetic mean of the result of (8) numbers for each test sample when loaded in the section which corresponds to the linear section on the curve of the correlation between the bending moment and the corner deformation of the joint.

The testing of each test sample lasts until the maximum loading is reached and then – until complete destruction. The maximum bending moment is determined with formula (7) for the maximum strength of the loading. In this way, by testing the test samples under one and the same pattern of loading, we determine both the stiffness and strength characteristics of the joint.

RESULTS AND ANALYSIS

The objects of the study are eight types of detachable end corner joints at right angle under compression bending test. Table 1 and Figure 3 present the data related to the mean values of the stiffness coefficients of the studied detachable end corner joints.

The data in table 1 and figure 3 show that the results related to the stiffness of the studied end corner joints of the components made of beech plywood can provisionally be divided into three groups. The highest stiffness is typical of the joints with a connector with cross metal dowel (5167 Nm/rad) and screw \( \phi 6 \times 90 \text{ mm} \) (4931 Nm/rad), average stiffness is typical of the joints with screw \( \phi 6 \times 80 \text{ mm} \) (4565 Nm/rad), bolt and nut (4310 Nm/rad) and Confirmat \( \phi 7 \times 70 \text{ mm} \) (4124 Nm/rad), and the lowest stiffness is typical of joints with screw \( \phi 6 \times 80 \text{ mm} \) (4565 Nm/rad), bolt and nut (4310 Nm/rad) and Confirmat \( \phi 7 \times 50 \text{ mm} \) (3392 Nm/rad), Minifix with metal sleeve (2596 Nm/rad) and bolt for direct mounting (2398 Nm/rad).
**Table 1: Stiffness coefficient**

<table>
<thead>
<tr>
<th>Type of the corner joints</th>
<th>No of the series</th>
<th>No of the test samples</th>
<th>Average, N.m.rad</th>
<th>Minimum, N.m.rad</th>
<th>Median, N.m.rad</th>
<th>Maximum, N.m.rad</th>
<th>Standard deviation, N.m.rad</th>
<th>Coefficient of variation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw M6 with cross metal dowel</td>
<td>1.</td>
<td>10</td>
<td>5167</td>
<td>4593</td>
<td>5295</td>
<td>5473</td>
<td>336</td>
<td>6,5</td>
</tr>
<tr>
<td>Countersunk screw for wood ø6x90 mm</td>
<td>2.</td>
<td>13</td>
<td>4931</td>
<td>4453</td>
<td>4916</td>
<td>5559</td>
<td>273</td>
<td>5,5</td>
</tr>
<tr>
<td>Countersunk screw for wood ø6x80 mm</td>
<td>3.</td>
<td>15</td>
<td>4565</td>
<td>3875</td>
<td>4508</td>
<td>5431</td>
<td>406</td>
<td>8,9</td>
</tr>
<tr>
<td>Screw with metal sleeve</td>
<td>4.</td>
<td>12</td>
<td>4310</td>
<td>3619</td>
<td>4525</td>
<td>5122</td>
<td>745</td>
<td>11,7</td>
</tr>
<tr>
<td>Confirmat ø7x70</td>
<td>5.</td>
<td>15</td>
<td>4124</td>
<td>2190</td>
<td>4251</td>
<td>5149</td>
<td>847</td>
<td>20,5</td>
</tr>
<tr>
<td>Confirmat ø7x50</td>
<td>6.</td>
<td>13</td>
<td>3392</td>
<td>2226</td>
<td>3232</td>
<td>5122</td>
<td>752</td>
<td>22,2</td>
</tr>
<tr>
<td>Minifix for metal sleeve</td>
<td>7.</td>
<td>15</td>
<td>2596</td>
<td>1768</td>
<td>2661</td>
<td>3172</td>
<td>486</td>
<td>18,7</td>
</tr>
<tr>
<td>Minifix for hole ø5</td>
<td>8.</td>
<td>12</td>
<td>2398</td>
<td>1437</td>
<td>2442</td>
<td>3313</td>
<td>571</td>
<td>23,8</td>
</tr>
</tbody>
</table>

The difference between the highest (with cross metal dowel) and the lowest (Minifix for bolt with direct mounting) value is more than two times. The difference between the stiffness coefficient of the two types of screw connectors is 8,0 %; between the two types Confirmat – 21,6 %; between the two Minifix types – 8,3 %. The difference between the screw with cross dowel and the screw ø 6 x 90 mm is 4,8 %.

![Figure 3: Stiffness coefficients of the studied detachable end corner joints under compression bending test](image)

The difference between the stiffness coefficients of the connector with cross dowel and ø 6 x 90 screw is insignificant and statistically negligible. The choice between the two connectors which are characterised with
identical stiffness has to be made on the basis of their technological manufacture and/or its aesthetic characteristics.

All values of the stiffness coefficient of the joints with the same type of connector (screw, Confirmat and Minifix) are grouped in pairs within a relatively narrow range. The only exception is the one-piece connector Confirmat.

The mounting of all types of connectors and screws comply with the recommended diameters and sizes which are intended mostly for materials such as Particleboard and MDF, which have different structure and physical and mechanical properties. When they have to be fitted in a material with considerably higher stiffness and density, such as plywood, certain internal stress occurs in the connector itself when tightening up, which affects its own stiffness indicators and the labour-intensity of the screwing process. The results clearly show that the parameters of the individual types of joints play a key role for their stiffness. For example, the bolt in the connector with cross metal dowel passes through one of the components and is screwed vertically in a metal nut in the other component, thus providing considerable stiffness of the joint. In the case with screw joints the bigger length of the part of the screw which enters along the axis of the component results in higher stiffness. For the one-piece connector “Confirmat” the greater depth of the hole where the head of the screw enters leads to considerably reduce of the stiffness (more than 25%). Eccentric connectors exhibit relatively low stiffness since their construction and material are mostly designed for softer materials such as Particleboard and MDF.


CONCLUSION
The analyses of the results show that the following important conclusions can be drawn:

1. Of the studied end corner detachable joints the ones with the highest stiffness are the joints with connectors with cross dowel and screw Ø 6 x 90 and Ø 6 x 80 mm.
2. The lowest stiffness is observed in joints with Minifix with bolt for mounting in sleeves and Minifix with bolt for direct mounting.
3. The parameters of the screw connectors play an important role for the stiffness of the joint.
4. The stiffness of the joints of components made of beech plywood is comparable with the stiffness of the same type of joints made of solid beech wood and chestnut wood.
5. The results from the current study can be used for the strength design of furniture and to be used by constructors as a guideline with respect to the stiffness of the selected joints.

REFERENCES
1. BDS EN 636 „Plywood: specifications”.