Analytical Investigation into the Single Shear Performance of a Joint with a New Beech and Self-Tapping Screw Composite Dowel

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The shear capacity was evaluated for specimens connected by beech dowels and composite dowels. The bearing capacities were calculated by the shear capacity formulas of metal dowel connectors in the GB 50005 (2017), NDS (2018), and EN 1995-1-1 (2014) standards. The results showed that, except for the specimen connected by one composite dowel calculated by the GB 50005 standard (2017), the remaining calculation differences were larger. Based on the failure mode, the force analysis of the beech dowels and the composite dowels was carried out. A calculation formula for the shear bearing capacity of the beech dowels and the composite dowels was proposed. The calculated results were in strong agreement with the test results, and the margins of difference were less than 10%. Furthermore, the formulas for two and four connectors were investigated. When the number of effective connectors was calculated by the GB 50005 standard (2017), the differences between the test values and the calculated values were less than 9.36%.

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INTRODUCTION

Joints play a major role in the structural behavior of old timber frames. In a previous study, a limited number of carpentry joints, calculation rules, and possible strengthening techniques were presented (Branco and Descamps 2015). In the field of ancient timber structures restoration, the joint connected by wood dowels is an alternative connection mode (Ceraldi *et al.* 2017). For the robotic fabrication of wooden structures, the simple, quick, and tight jointing of elements can be solved using swelling hardwood dowels. Densified beech wood and compressed fast-growing poplar were used as swelling dowels in timber joints by Grönquist *et al.* (2019) and Wang (2020), and the welding properties of compressed fast-growing poplar dowels were studied by Liu (2019).

As an option to increase the strength of the joint, wood dowel welding creates a new bonding interface layer through the friction between the wood dowels and substrate holes. During this process, some wood components are softened, fused, and eventually become solidified until the friction stops (Sandberg *et al.* 2013; Zhou *et al.* 2014; Zhu *et al.* 2017).

Wooden pegs that were 10, 15, and 20 mm in diameter were tested in straight cylindrical, straight traditional, and conical traditional shapes. All the peg shapes exhibited similar maximum loads, but the straight traditional pegs exhibited greater stiffness than the cylindrical pegs due to the tight fit of the peg (Frontini *et al.* 2020). Jung *et al.* (2008) studied the application of compressed wood made from Japanese cedar by compression in the radial direction until the thickness was reduced to 30% of its original value under the condition of 130 °C for 30 min. This was done as a substitute for high-density hardwood to shear dowel. Compressed wood, with its annual ring radial to the loading direction, had a unique double shear performance characteristics with good properties as a dowel material by virtue of its strength and rich ductility. In contrast, compressed wood with its annual ring tangential to the loading direction exhibited brittle failure (Jung *et al.* 2008). In the field of new building, timber joints fastened by timber pegs are widely employed in the prefabricated timber frame industry. The contents of the design standard for those structures are also considered, especially with reference to the effective shear failure mode of the timber peg (Ceraldi *et al.* 2017). For all the wood dowels, including the compressed wood dowels, were broken suddenly during the loading process.

Self-tapping screws are widely used in the field of wood structures (Wang *et al.* 2017). The change of the angle between the self-tapping screw and the shear plane had no obvious effect on the bearing capacity of steel-wood joint under shear-compression composite stress (Lu *et al.* 2020). When the shear-compression stress was applied, it was very unsafe to calculate the ultimate bearing capacity of the shear-compression joint by the EN 1995-1-1 standard (2004). The stiffness prediction results of the EN 1995-1-1 standard (2004) and the experimental values performed very well in the shear-compressive stress zone and nailing of the vertical shear plane, but they were not able to predict the slip modulus of the shear-tension zone joints (Lu *et al.* 2020). Sun *et al.* (2018) found that destruction occurred at the mortise-tenon joints. The shape of hysteretic loops of all the joints was S-shaped, and the gathering effect got more obvious as the damage degree increased. The area of the hysteretic loops decreased as the damage degree increased. The load capacity and stiffness of the damaged joints that were not strengthened were significantly below the intact one and reduced gradually as the damage increased. The load capacity and stiffness of the damaged joints that were strengthened with steel plates and self-tapping screws were significantly higher than the damaged joints that were not strengthened, and their energy dissipation capacities were lower than before. Steel plates and self-tapping screws were suitable for the strengthening of mortise-tenon joints, the strength or rigidity of which was obviously inadequate (Sun *et al.* 2018).

On the other hand, high-strength bolts with tubes were used as fasteners in the research of He *et al.* (2016). The results showed that the initial rotational stiffness of pre-stressed tube bolted improved significantly as a result of the friction between the steel tubes and steel plate together with the tight-fitting of the tubes and the timber holes. The ultimate moment-resisting capacity and ductility of the pre-stressed tube bolted connection were also increased when self-tapping screws were applied (He *et al.* 2016).

Based on the studies above, a new composite dowel was design in this study. Self-tapping screws with beech dowels were used as composite dowel fasteners. The single shear performance of the specimens connected by beech dowels and composite dowels was tested. The theoretical analysis of the shear capacity and stiffness of the component was considered.

EXPERIMENTAL

Materials

Wood dowels were prepared using *Zelkova schneideriana* beech wood (Crownhomes, Jiangsu, China) having sample dimensions of 12 mm in diameter and 70 (100) mm in length. The density of the dowels was 703 kg/m^3 and the moisture content (MC) was 2%. The mechanical properties of six wood dowels are shown in Table 1.

Table 1. The Mechanical Properties of the Wood Dowels

Size (mm)	Tensile Force (kN)	Bending Strength (MPa)	Elastic Modulus (MPa)
12 × 70	6.31 (0.17)[1]	93.68 (8.07)	9862 (432.87)

[1]-Values in parentheses are standard deviations

Self-tapping screws (STSs) (Moregood, Shanghai, China) with 5.2 mm in diameter and 70 mm in length were selected in this study. The inner diameter of the thread was 3.4 mm. The diameters of the rod and head were 3.7 mm and 10.3 mm, respectively. The surface of the STSs were galvanized. The bending and tensile strengths were 1184.3 MPa and 1316.8 MPa, respectively.

The substrates materials were spruce-pine-fir (SPF) of grade II (Crownhomes, Jiangsu, China) having dimensions of 89 mm (width) × 38 mm (thickness) × 300 to 400 mm (length). The density was 495 kg/m^3 when the MC was 9.7%.

The composite dowels were made by two procedures as below:

1. A hole was set in the middle of the beech dowel along the length. The size of the hole was 3 mm in diameter and 70 mm in depth. A drilling machine (Proxxon TBH Typ 28 124, Proxxon, Stuttgart, Germany) was used in this procedure.

2. The STS was screwed into the pre-drilled hole in the middle of the beech dowel (Fig. 1).

Fig. 1. The composite dowels

Experimental Design

Specimen prepared

The beech dowels with length 100 mm were welded into the pre-drilled holes with the depth 70 mm in the substrates by a high-speed rotation of 1,500 rpm. After 10 s, the 30 mm of the beech dowels out of the substrates was cut off. The composite dowels were welded into the pre-drilled holes by rotating the head of the screw by a high-speed rotation of 1,500 rpm without any cutting off. The substrates connected by one or two connectors are shown in Fig. 2. In addition, the substrates connected by four connectors are shown in Fig. 3. Three specimens were prepared. All the specimens were conditioned to 12% equilibrium MC at a temperature of 20 °C and relative humidity (RH) of 65%.

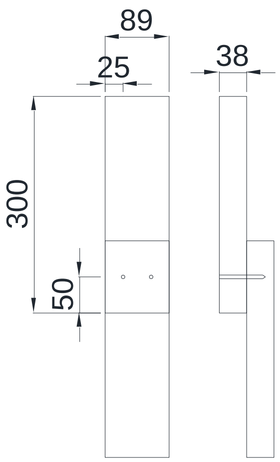

Fig. 2. The substrates connected by one or two connectors parallel to the wood grain (all units are in mm)

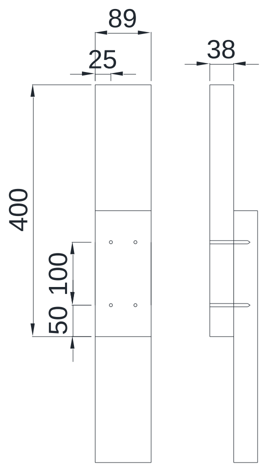

Fig. 3. The substrates connected by four connectors parallel to the wood grain (all units are in mm)

Lateral load resistance test

The universal testing machine (WDW-300E; Jinan Popwil, Jinan, China) was used to test the single shear properties. The traction speed used was 5 mm/min (Fig. 4). The force-displacement curves of the specimen connected by beech dowels (group b) are shown in Fig. 5. The curves of the composite dowels (group c) are displayed in Fig. 6. The number shown as 1, 2, and 4 in Figs. 5 and 6 is the quantity of connectors.

Fig. 4. The WDW-300E universal testing machine

Methods

Standard for the design of timber structures (GB 50005-2017)

In this study, the failure mode of all the specimens was in conformity with the yield mode IV of the GB 50005 (2017) standard for the design of timber structures. The design value of the single shear performance of a composite dowel was calculated using Eq. 1,

$$F_{GB\ 50005} = k_{IV} t_s d f_{es} \tag{1}$$

where $F_{GB50005}$ is the shear capacity of the component (kN), k_{IV} is the effective bearing length of wood embedding (mm), t_s is the width of the edge member (mm), d is the diameter of the beech dowel and composite dowel (mm), and f_{es} is the wood embedding strength when the MC was 12% (kN). Based on the GB 50005 (2017) standard, k_{IV} could be calculated by Eq. 2. However, the depth of the pre-drilled holes was 36 to 37 mm, because the shape of the end part of the drilling bit was conical. So, to simplify the calculation, t_s was 38 mm and d was 12 mm. 18 specimens of 12% MC were selected to test the f_{es}. In addition, the f_{es} value could be 28.36 MPa (Jia *et al*. 2021). The calculation for k_{IV} is shown in Eq. 2,

$$k_{IV} = \frac{1}{\gamma_{IV}} \frac{d}{t_s} \sqrt{\frac{1.647 R_e k_{ep} f_{yk}}{3(1+R_e) f_{es}}} \tag{2}$$

where γ_{IV} is the partial coefficient of resistance (mm) (according to the Table 6.2.7 in GB 50005, it could be 1.88), R_e is the ratio of the wood embedding strength between the middle member and edge member (equal to 1), k_{ep} is the elastic-plastic strengthening coefficient (equal to 1), and f_{yk} is the yield strength of the beech dowel and composite dowel (equal to 105.2 and 183.6 MPa, respectively).

National design specification for wood construction (NDS-2018)

According to the failure mode of the specimen connected by a composite dowel, the single shear performance could be calculated by Eq. 3,

$$F_{NDSWC} = \frac{d^2}{R_d} \sqrt{\frac{2 f_{yb} f_{es}}{3(1+\beta)}} \tag{3}$$

where F_{NDSWC} is the shear capacity of the component (kN), R_d is the reduction factor according to the Table 12.3.1 in the NDS standard (2018) (equal to four), and β is the ratio of the wood embedding strength between the middle member and edge member (equal to one).

EN 1995-1-1 (2004)

According to the failure mode, the single shear performance could be calculated by the EN standard 1995-1-1 (2004), as can be seen in Eq. 4,

$$F_{EC\ 5} = 1.15 \sqrt{\frac{2\beta}{1+\beta}} \sqrt{2 M_y f_{es} d} + \frac{F_{ax}}{4} \tag{4}$$

where F_{EC5} is the shear capacity of the component (kN), M_y is the bending yield moment of the beech dowel and the composite dowel (equal to 17,842.97 N·mm and 31,598.34 N·mm, respectively, and F_{ax} is the axial force of the beech dowel and the composite dowel (equal to zero).

RESULTS AND DISCUSSION

The Single Shear Performance

For both of the groups b and c, the single shear force increased with the increasing of the number of the connectors. The mean value of maximum force of group c was higher than that of group b under the same number of the connectors. Comparing Figs. 5 and 6, the curves were similar between the displacement of 0 to 10 mm, except for the mean value of maximum force. And then the curves of group b decreased sharply when the shear force reached to or exceeded the broken force of the beech dowels. The group b showed the brittle fracture at the displacement 5 to 10 mm. On the other hand, the final displacement of group c was more than 20 mm with a continuous and stable bearing stage at 10 to 20 mm. Due to this phenomenon, the ductility and energy consumption of group c were much better than that of group b.

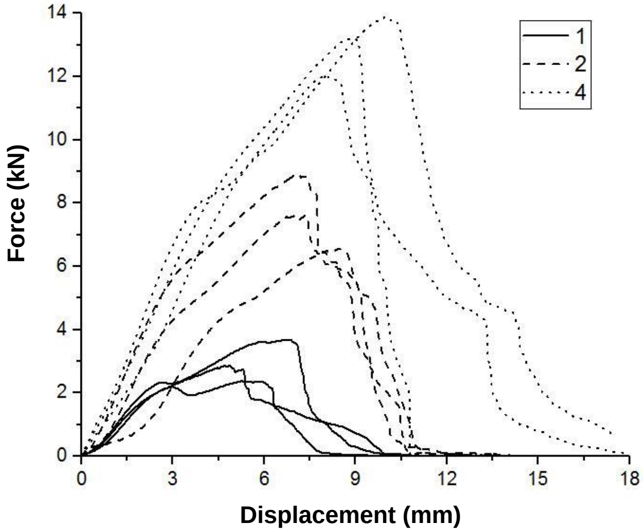

Fig. 5. The force displacement curves of the specimen connected by beech dowels

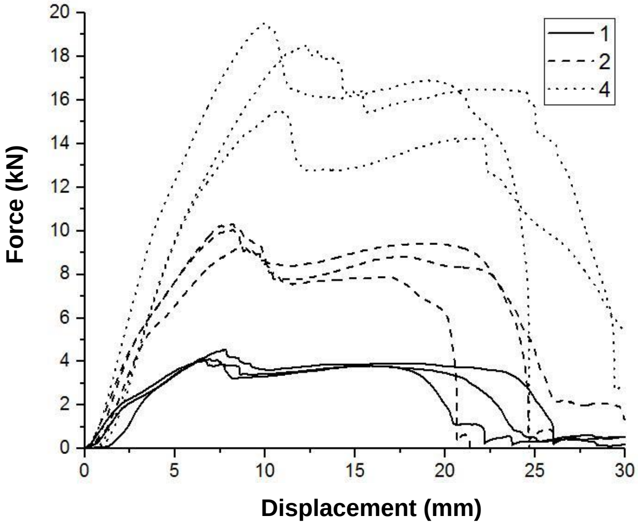

Fig. 6. The force displacement curves of the specimen connected by composite dowels

The Difference between the Test Value and the Calculated Value

As can be seen in Fig. 7, the black molten materials were covered on the surface of the dowels (Zhu *et al*. 2017). The failure mode of the specimen was hinge failure (Jia *et al*. 2021). The SPF specimen experienced extrusion failure, due to the pressing from the beech dowel and the composite dowel. On the other hand, the wood dowels were broken, and the composite dowels exhibited the bending form of breakage. The single shear loading resistance capacity was calculated according to the GB 50005 (2017), NDS (2018), and EN 1995-1-1 (2004) standards. The calculated values and test values are shown in Table 2.

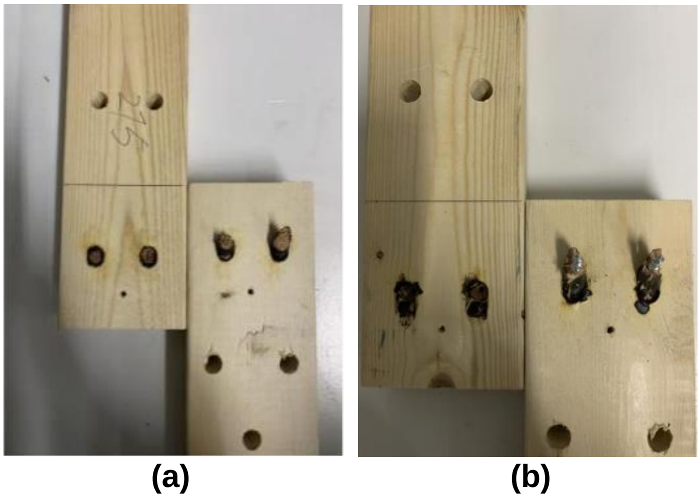

Fig. 7. The failure mode of the specimen connected by the a) beech dowel or the b) composite dowel

Table 2. The Difference between the Test Values and the Calculated Values

Method	Shear Loading Resistance Capacity of the Beech Dowel (kN)	Difference (%)	Shear Loading Resistance Capacity of the Composite Dowel (kN)	Difference (%)
Test Value	3.561	–	4.230	–
GB 50005 (2017)	2.212	-37.88	3.917	-7.40
NDS (2018)	1.135	-68.13	1.511	-64.54
EN 1995-1-1 (2004)	4.008	12.55	5.333	26.08

As can be seen in Table 2, the margin of difference of the shear loading resistance capacity of the specimens connected by the composite dowels calculated by the NDS (2018) and EN 1995-1-1 (2004) standards were more than 26.08%. The margin of difference was 7.4% for the GB 50005 (2017) standard method. However, for the specimen connected by beech dowel, the margin of difference was 37.88%. The reduction factor and partial coefficient of resistance were provided to calculate the steel pin, rather than beech dowel or composite dowel. So, these three calculated methods could not be used to estimate the shear performance directly.

Formula Correction

According to the stress distribution and failure mode of the beech dowel and composite dowel, the stress analysis of the substrate joint was carried out, as shown in Fig. 8.

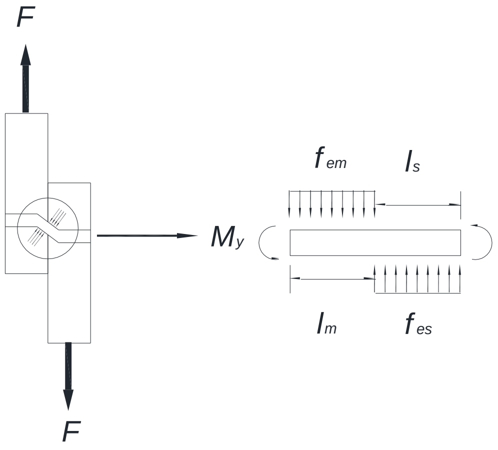

Fig. 8. The stress analysis model of the wood dowel or the composite dowel in the single shear test

Based on the stress and moment balance analysis of the beech dowel and composite dowel, two formulas (Eq. 5 and Eq. 6) could be obtained,

$$F = f_{es} l_s d = f_{em} l_m d \tag{5}$$

$$2M_y = f_{es} l_s d \frac{l_s}{2} + f_{em} l_m d \frac{l_m}{2} \tag{6}$$

Due to the use of the same substrate materials of the two layers, $f_{em} = f_{es}$, $l_s = l_m$, so Eq. 5 and Eq. 6 could be rewritten to calculate Eq. 7,

$$F = \sqrt{2M_y f_{es} d} \tag{7}$$

where F is the shear capacity of the component (kN), f_{es} and f_{em} are the wood embedding strength values of the edge member and middle member (kN), and l_s and l_m are the distances between plastic hinge and the shear plane of the edge member and middle member (mm) (Jia *et al*. 2021).

Table 3. The Difference between the Test Values and the Calculated Values

Method	Shear Loading Resistance Capacity of the Beech Dowel (kN)	Difference (%)	Shear Loading Resistance Capacity of the Composite Dowel (kN)	Difference (%)
Test Value	3.561	–	4.230	–
Eq. 7	3.485	-2.13	3.917	-7.40

As can be seen in Table 3, for both specimens connected by the beech dowel and the composite dowel, the margins of difference between the test values and the calculated values from Eq. 7 was less than 7.4%. Equation 7 was able to precisely predict the shear loading resistance capacity values of the dowels. Furthermore, to illustrate the accuracy of

Eq. 7, based on Eq. 8 of the number of effective connectors in the EN 1995-1-1 (2004) standard, the shear capacity of the component connected by two or four connectors was calculated by Eq. 9,

$$n_{ef} = n_r n^{0.9} \sqrt{\frac{a}{13d}} \tag{8}$$

$$F_u = n_{ef} F_{u1} \tag{9}$$

where n_{ef} is the number of effective connectors, n_r is the number of columns of the connectors, n is the number of every column, α is the distance between connectors along the grain direction (mm), d is the diameter of the connector (mm), F_u is the total shear capacity of the component connected by several connectors (kN), and F_{u1} is the shear capacity of the component connected by a single connector (kN).

Due to the regulations of the EN 1995-1-1 standard (2004), the transverse arrangement of the two connectors, n_{ef} was equal to two. On the other hand, n_{ef} was 3.34 for the four connectors. However, according to the appendix in the GB 50005 standard (2017), the combination coefficient of the group bolt k_g was 0.915 in this study. The number of effective connectors was 3.66 for the components connected by four connectors.

Table 4. The Difference between the Test Values and the Calculated Values

Number of Connectors	Test Value (kN)	Calculated Values from the EN 1995-1-1 Standard (2004)	Calculated Values from the GB 50005 Standard (2017)
Two Beech Dowels	7.690	6.970(-9.36)[1]	6.970(-9.36)
Two Composite Dowels	9.873	9.276(-6.05)	9.276(-6.05)
Four Beech Dowels	13.050	11.640(-10.80)	12.755(-2.26)
Four Composite Dowels	17.843	14.188(-20.48)	16.975(-4.87)

[1]-Values in parentheses are differences between the test values and the calculated values

From Table 4, based on Eq. 7, the number of effective connectors was calculated using the EN 1995-1-1 (2004) and GB 50005 (2017) standards. In addition, the shear capacity of the components connected by two or four connectors was calculated. When the n_{ef} value was calculated from the GB 50005 (2017) standard, the calculated values of the shear capacity of the components connected by two or four connectors were closer to the test values. Meanwhile, the accuracy of Eq. 7 was verified.

CONCLUSIONS

1. The single shear loading resistance capacity of the specimen connected by composite dowels, incorporating self-tapping screws, were higher than that of ordinary beech dowels. Composite dowels could be used as connector in place of wood dowels.
2. The single shear loading resistance capacity of the specimen connected by beech dowels and composite dowels was not precisely calculated by the GB 50005 (2017), NDS (2018), and EN 1995-1-1 (2004) standards.

3. A new formula (Eq. 7) was proposed to calculate the single shear loading resistance capacity of the specimen connected by one beech dowel or composite dowel. The margin of difference values for the single shear loading resistance capacity between the test values and the calculated values were less than 7.4%.
4. Regarding the specimens connected by two or four beech dowels or composite dowels, the number of effective connectors (n_{ef}) could be selected from the GB 50005 (2017) standard. The margin of difference values for the single shear loading resistance capacity between the test values and the calculated values were less than 9.36%.

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