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Plywood frame corner joints with glued-in hardwood dowels

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Abstract This paper presents research on plywood frame corners jointed to glulam beams and columns by means of glued-in hardwood dowels. The frame corner was made of a solid block of ordinary plywood of the same width as the glulam beams and with plies parallel to the plane of the frame to avoid splitting due to stress perpendicular to the grain. Hardwood dowels with a diameter of 12mm and a maximum glued-in length of 120mm were glued into drilled holes in the plywood corner and glulam beam ends parallel to the grain direction of the beams to form a moment-resisting joint. Static bending tests were conducted of frame corners with $100 \times 200\,mm^2$ and $120 \times 420\,mm^2$ beam cross sections. Bending capacities of the joints corresponding to a modulus of rupture of the jointed glulam beams of about 30MPa were obtained for both closing and opening moments for the small cross sections, and about 22MPa was obtained for the large cross sections. Simple design models for calculation of joint strength and rotational stiffness are also presented.

Key words Frame corner · Plywood · Glulam · Hardwood dowels · Glued-in

Introduction

To date, most frame corners in timber structures have been made using dowel-type fasteners (nails, bolts, screws, drift-pins, or the like). Such joints are attractive from a construction point of view because the structure is easily assembled at the construction site. However, the moment capacity of dowel-type fastener joints is often low compared with the bending capacity of the jointed beams, and they often do not meet aesthetic requirements. Furthermore, fire resistance may be a serious problem.

Glued-in steel rods are another possible way to make frame corners in timber structures.[1] Highly efficient joints in terms of strength and stiffness may be developed but only if using some type of steel corner element.[2] Production of the steel parts is costly and the fire protection and aesthetic problems remain.

Plywood corners jointed to glulam beams using full cross-section finger joints were tested recently.[3] Corners of beech plywood resulted in opening and closing moment capacities corresponding to moduli of rupture (MOR) of 18 and 24MPa, respectively (equivalent MOR of a glulam beam cross section). Corners of fir plywood were tested for closing moments only, resulting in a MOR of 16MPa. Special plywood with only 1.2-mm veneers was needed to obtain a practical joint with reasonable strength.

In the present paper, static bending tests on frame corners of plywood jointed to glulam beams by means of glued-in hardwood dowels (Fig. 1) are reported. Models for calculating joint strength and rotational stiffness are given and compared with the test results.

Theory

Research on the pull-out of glued-in hardwood dowels has been reported previously.[4–7] For a single dowel (dowel number i) subjected to pull-out, the linear load–slip relation

$$F_i = K_i u_i \tag{1}$$

is assumed, where F_i is the pull-out force, and u_i is the pull-out slip. The pull-out failure load, F_{ui}, is given by

$$F_{ui} = \pi d l_i f_v \frac{\tanh \omega_i}{\omega_i} \tag{2}$$

and the slip modulus, K_i, is given by

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$$K_i = \pi d l_i \Gamma \frac{\tanh \omega_i}{\omega_i} \tag{3}$$

where

$$\omega_i = 2 l_i \sqrt{\frac{\Gamma}{d E_d}} \tag{4}$$

E_d is the modulus of elasticity (MOE) of the dowel; d is the dowel diameter; l_i is the glued-in length of the dowel; and f_v and Γ are bond-line properties (bond-line shear strength and shear stiffness, respectively). Note that Eqs. (1)–(3) predict that failure occurs at $u_{ui} = f_v/\Gamma$; that is, the pull-out displacement at failure is independent of dowel geometry and stiffness. Bond-line properties $f_v = 7.6$ MPa and $\Gamma = 9.9$ N/mm^3 for hardwood dowels of Japanese maple (*Acer mono*) glued into wood members of Japanese cedar (*Cryptomeria japonica*) using a polyurethane adhesive and a bond-line thickness of 0.5 mm have been reported.[10]

The theory for calculating moment capacity and rotational stiffness of the dowel joints in the frame corner is identical to the theory previously presented for moment-resisting splice joints,[8–10] and the formulas are therefore given without detailed derivations.

A frame corner as considered here contains two dowel joints: the joint between the plywood corner and the beam and the joint between the plywood corner and the column (Fig. 1). Joint number is denoted m; that is, m takes the value 1 or 2.

As indicated in Fig. 2, n_{mj} is the number of dowels in row j (N_m rows) in joint m; h_{mj} is the distance from row j to the outermost fiber in the compression side of the beam in joint m; l_{mj} is the glued-in length of the dowels in row j (all dowels in a row are assumed to be of the same length) in joint m; b is the width of the beam; and E_B is the MOE of the beam (or plywood corner).

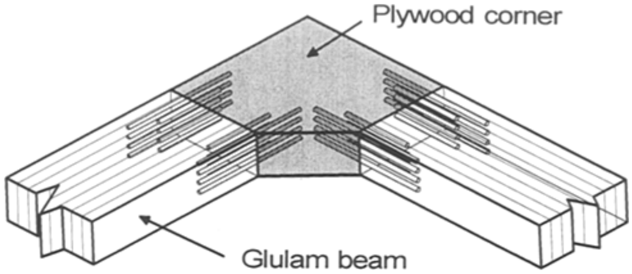

Fig. 1. Plywood frame corner jointing glulam beams by means of glued-in hardwood dowels

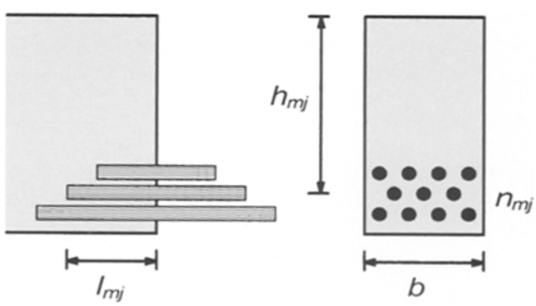

Fig. 2. Joint geometry. See text for explanation of abbreviations

The following parameters are introduced.

$$\begin{aligned} K_m &= \sum_{j=1}^{N_m} n_{mj} K_{mj} \\ l_m &= \frac{1}{K_m} \sum_{j=1}^{N_m} n_{mj} K_{mj} l_{mj} \\ h_m &= \frac{1}{K_m} \sum_{j=1}^{N_m} n_{mj} K_{mj} h_{mj} \\ h_{0m} &= \frac{K_m l_m}{b E_B} \\ h_{cm} &= h_{0m} \left(\sqrt{1 + \frac{2 h_m}{h_{0m}}} - 1 \right) \end{aligned} \tag{5}$$

The group of dowels in the tension side of joint m may be regarded as just one large (fictitious) dowel with slip modulus K_m and glued-in length l_m; h_{cm} and h_m are, respectively, the location of the neutral axis and the fictitious dowel measured from the outermost fiber in the compression side of the beam in joint m. The slip modulus, K_{mj}, of a single fastener in row j in joint m is given by Eq. (3).

The moment capacity, M_{um}, of joint m may then be given as

$$M_{um} = \nu K_m \frac{f_v}{\Gamma} \left(h_m - \frac{1}{3} h_{cm} \right) \tag{6}$$

where ν (≤ 1) is the dowel effectiveness factor.[10]

The moment-rotation relation of joint m may be written

$$M_m = R_m \Theta_m \tag{7}$$

where Θ_m is the rotation of joint m. The rotational stiffness, R_m, may be calculated by

$$R_m = \frac{1}{2} K_m \left(h_m - h_{cm} \right) \left(h_m - \frac{1}{3} h_{cm} \right) \tag{8}$$

The factor $^1/_2$ in Eq. (8) is due to the fact that the dowels pull out of both the plywood corner and the glulam beam, whereas the slip modulus given by Eq. (3) is for one-sided pull-out.

For a simple frame analysis it may be convenient to consider the whole frame corner as only one joint (spring) with rotational stiffness R.

$$\begin{aligned} M &= R\Theta \\ R &= \frac{R_1 R_2}{R_1 + R_2} \end{aligned} \tag{9}$$

Experimental

Specimens

Two specimen types, shown in Fig. 3, were tested. In all cases reported here, dowels with a diameter of 12 mm were

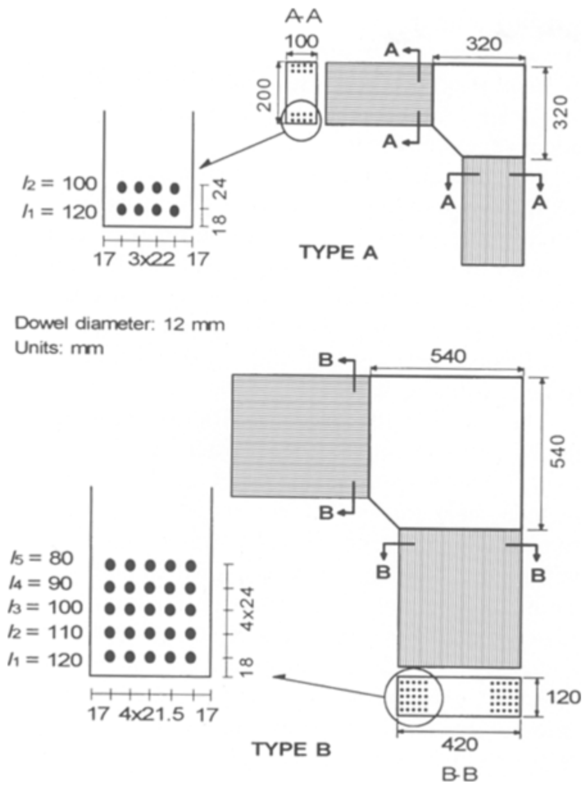

Fig. 3. Geometry of tested frame corners

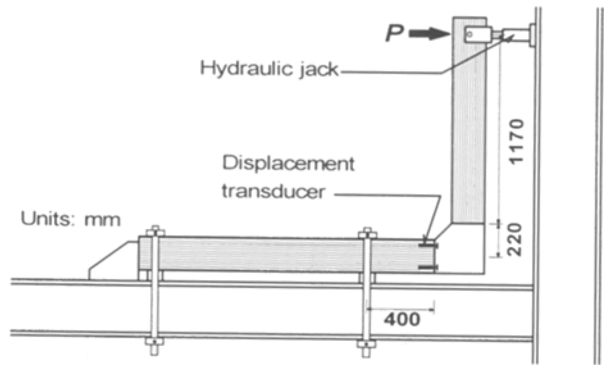

Fig. 4. Test setup for type A specimens. *P*, applied load

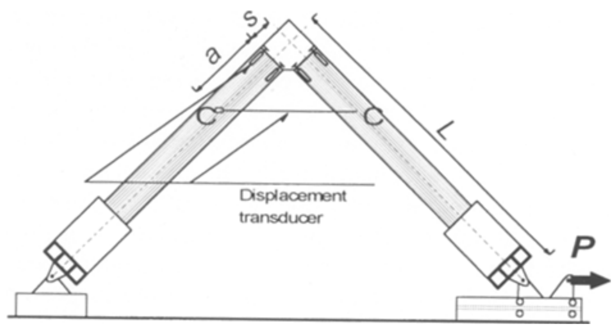

Fig. 5. Test setup for type B specimens

used. In type A specimens the dowel holes were drilled using a 13-mm drill bit, whereas a 14-mm drill bit was used in type B specimens. The influence of bond-line thickness was previously tested,[5] and only a small difference (increase) in pull-out strength was observed when the bond-line thickness was increased from 0.5 to 1.0 mm. All specimens were kept in the laboratory from fabrication to testing without controlling the temperature or humidity.

Adhesive was simply injected into the dowel holes in glulam beams and the plywood corner. Dowels were then inserted in the beams, and beams and corner were pressed together by means of manual jacks. No special injection or airing holes were used.

Materials

Materials were kept in the laboratory without controlling the temperature or humidity prior to fabrication of the specimens. Glulam beams were made of Japanese cedar (*C. japonica*). The mean MOEs of type A and B specimens were 9.0 and 10.5 GPa, respectively. The moisture content (MC) at testing was 10%–12%. Dowels were made of sugar maple (*Acer saccharum*) with a MOE of about 15 GPa and an MC of about 10%. The dowel surface was smooth without grooves.

Adhesives used were one-component polyurethanes, either C3060 from Nihon Polyurethane or 930 from Sunstar Engineering. Previous pull-out tests showed no significant difference in strength between the two adhesives. Curing time (time from gluing to testing) ranged from 4 to 7 days.

Plywood corners were made of Siberian larch (*Larix gmelinii*). The thickness of the veneer was approximately 3 mm. Corners were made by gluing plywood of standard dimensions together to achieve the desired thicknesses of 100 and 120 mm. For type A specimens the mean density of the corner was 622 kg/m^3 at 10% MC. Adhesive used in plywood for type A specimens was resorcinol. For type B specimens the mean density was 699 kg/m^3 at 11% MC. Melamin adhesive was used in the plywood for type B specimens.

Test setup and method

Type A and B specimens were tested in setups as shown in Figs. 4 and 5, respectively.

Load was applied to specimens tested to failure in opening mode as follows: $0 \rightarrow +P_{u,est}/3 \rightarrow 0 \rightarrow -P_{u,est}/3 \rightarrow 0 \rightarrow +2P_{u,est}/3 \rightarrow 0 \rightarrow -2P_{u,est}/3 \rightarrow 0 \rightarrow +P_u$, where P_u is the failure load, and $P_{u,est}$ is the estimated failure load; + indicates a positive direction (opening mode) of the applied load as shown in Figs. 4 and 5; and − indicates the opposite direction (closing mode). For specimens tested to failure in the closing mode, inversion of the signs given above apply.

Slips in the dowel joints were measured using four linear displacement transducers in each of the two joints (one in the compression side and one in the tension side on both sides of the frame) to determine the rotational stiffness of the joint. The horizontal displacement between two points (C) on the beams was also measured for type B specimens (Fig. 5).

Results and discussion

The test results for type A specimens are given in Table 1. Note that the MORs in Tables 1 and 2 do not include the axial force. Inclusion of the axial force typically results in an increase in MOR of 0.4–0.8 MPa. Failure occurred in all cases due to pull-out of the dowels in the beam side of the joint in the horizontal beam. No failure occurred in the plywood corner.

Table 2 shows the test results of type B specimens. All specimens failed in pull-out of the dowels, in some cases from the glulam beam and in some cases from the plywood corner. However, in no case was failure due to splitting of the corner or to tension failure at the end of the dowel group, as was sometimes observed in previously tested moment-resisting splice joints.[10] On all specimens except BC01, a 10-mm thick plywood sleeve ($120 \times 420\,mm^2$) was glued onto the glulam beam end surface before drilling the dowel holes to prevent splitting of the glulam beam at failure. The plywood sleeve was successful in preventing splitting.

The dowel effectiveness factor, v, is originally introduced as a reduction factor on the pull-out strength of single dowels. This is mainly motivated by the assumption that the pull-out strength per dowel in a group of dowels is lower than the strength of a single dowel joint.[6] However, the assumptions on which the present model for moment-resisting joints is based[10] result in the dowel effectiveness factor also simply becoming a reduction factor of the failure moment [Eq. (6)]. The tested/calculated MOR ratios, given in Tables 1 and 2 may thus be interpreted as the dowel effectiveness factor v.

Jensen et al.[10] found a dowel effectiveness factor of $v = 0.8$ to give good agreement between measured and calculated failure moments for splice joints with various dowel configurations. However, the results of the tested portal frame corner joints make it necessary to use different dowel effectiveness factors for the two specimen types. For type A and B specimens $v = 0.95$ and $v = 0.6$, respectively, appear to be reasonable values.

The cause of the lower MORs of type B specimens is uncertain. The previously reported tests on beam splice joints[10] and the present tests on type A specimens did not include shear forces. A few tests of splice joints subjected to combined bending and shear were conducted on beams with $100 \times 200\,mm^2$ cross sections (unpublished results). Those tests showed no significant reduction in bending strength due to the presence of considerable shear forces, and it is believed that the relatively small shear force to which type B specimens were subjected is not the main cause of the low dowel effectiveness factor. However, more tests on glued-in dowel joints subjected to combined bending and shear are needed to clarify the problem. Another possible cause of the reduction in strength of type B specimens is out-of-plane bending effects. However, simple calculations show that this effect can hardly account for the entire strength reduction.

A straight beam with a $420 \times 420\,mm^2$ plywood section at the center was fabricated from the $120 \times 420\,mm^2$ glulam beams and plywood corners already used for frame corner

Table 1. Strength of type A specimens

Specimen	Load (kN)	M_{um} (kNm)	N_{um} (kN)	V_{um} (kN)	MOR_T (MPa)	MOR_T/MOR_C
AC01	−15.1	−21.0	−15.1	0	31.5	1.00
AC02	−16.3	−22.7	−16.3	0	33.9	1.08
AC03	−12.6	−17.5	−12.6	0	26.2	0.83
Mean AC	−14.7	−20.4	−14.7	0	30.5	0.97
AO01	16.0	22.2	16.0	0	33.2	1.05
AO02	13.4	18.6	13.4	0	27.9	0.89
AO03	13.5	18.8	13.5	0	28.2	0.90
Mean AO	14.3	19.9	14.3	0	29.8	0.95

Sign convention: opening moments are positive, tensile axial forces are positive
M_{um}, moment in joint at failure; N_{um}, axial force in joint at failure; V_{um}, shear force in joint at failure; MOR_T, modulus of rupture obtained by testing; MOR_C, modulus of rupture obtained by calculation based on $v = 1$

Table 2. Strength of type B specimens

Specimen	Load (kN)	M_{um} (kNm)	N_{um} (kN)	V_{um} (kN)	MOR_T (MPa)	MOR_T/MOR_C
BC01	−29.5	−86.8	−20.9	20.9	24.6	0.66
BC02	−28.6	−67.2	−20.2	20.2	19.0	0.51
BC03	−36.2	−80.2	−25.6	25.6	22.7	0.61
Mean BC		−78.1			22.1	0.59
BO01	37.0	87.6	26.1	−26.1	24.8	0.66
BO02	38.4	87.2	27.2	−27.2	24.7	0.66
BO03	35.9	77.7	25.4	−25.4	22.0	0.59
Mean BO		84.2			23.8	0.64

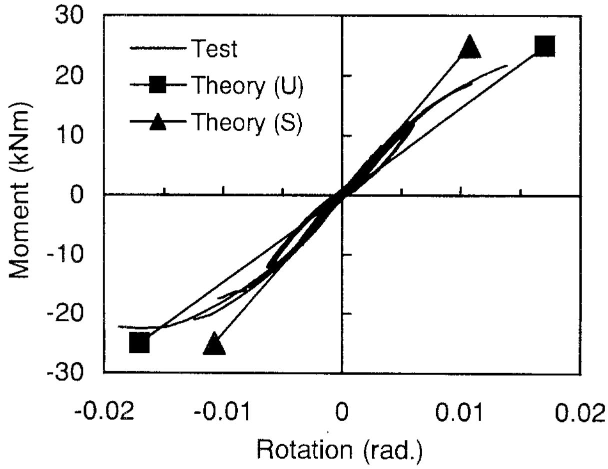

Fig. 6. Measured and calculated moment-rotation relations for type A specimens. *Theory (U)* is the calculation based on Eq. (3); *theory (S)* is the calculation based on twice the dowel pullout stiffness as given by Eq. (3)

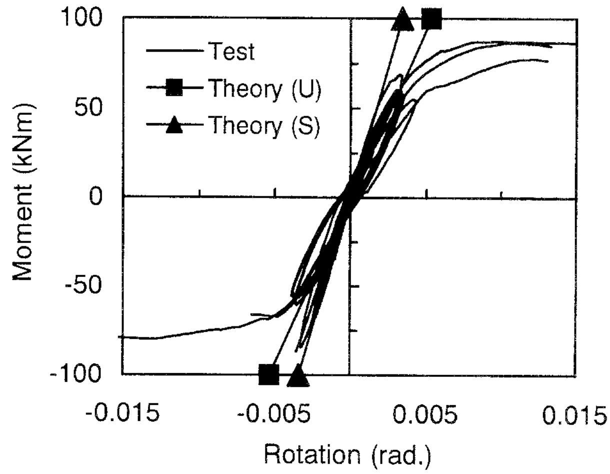

Fig. 7. Measured and calculated moment-rotation relations for type B specimens

tests. The dowel joint between plywood and glulam was the same as that used for frame corner joints of type B specimens. The joint was tested in pure bending in a four-point bending test setup (the same as the previously tested beam splice joints[10]). This test resulted in a MOR of more than 31 MPa.

Because the tested corner joints all failed due to pull-out of the dowels, the applied model for calculating joint strength is relevant here and sufficient. However, for practical applications, the model should be combined with models that consider tension and shear failure in the beam at the end of the dowel group. The model presented here may lead to a joint strength that is even more than the strength of the beams. This is the reason the dowel effectiveness factor becomes so apparently low for type B specimens (Table 2). A dowel effectiveness factor of 1.0 would result in a MOR of more than 37 MPa for type B specimens.

Figures 6 and 7 show the measured and calculated moment-rotation relations of the failing joints in type A and B specimens, respectively. It is worth noting that the models used here are all linear models, but the load–slip relation for pull-out of a single dowel is not linear. The bond-line shear stiffness, Γ,[5,10] was determined by curve-fitting of the failure loads of pull-out tests. This means that the Γ value represents the stiffness at failure; the joint rotational stiffness as calculated by Eq. (8) using this Γ value is thus representative for load levels near failure. Joint stiffness may thus be underestimated at usual service load levels. At a load level of 50% of the pull-out failure load, the pull-out stiffness of a dowel is typically about twice the stiffness at failure.[5] In Figs. 6 and 7, the calculated moment–rotation relations are therefore also shown using twice the pull-out stiffness of the single dowels as calculated by Eq. (3).

Joint rotational stiffness using the stiffness as calculated by Eq. (3) with $\Gamma = 9.9\,\mathrm{N/mm^3}$ becomes $R_m = 1466\,\mathrm{kNm/rad}$ for type A specimens and $R_m = 18\,799\,\mathrm{kNm/rad}$ for type B specimens. Using twice the stiffness, as in Eq. (3), gives $R_m = 2324\,\mathrm{kNm/rad}$ for type A specimens and $R_m = 29\,507\,\mathrm{kNm/rad}$ for type B specimens.

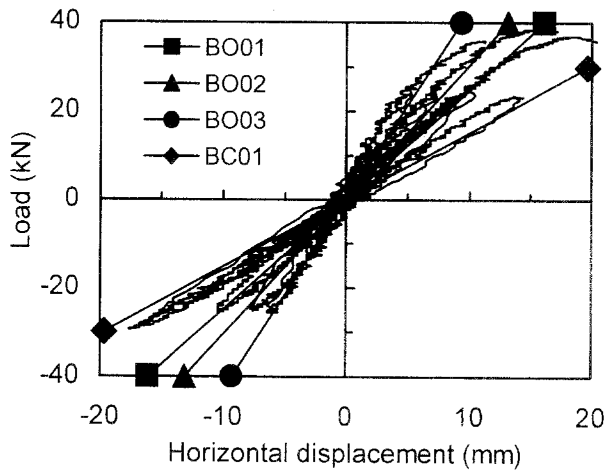

Fig. 8. Measured and calculated horizontal displacements of type B specimens

Figure 8 shows measured and calculated horizontal displacements (point C, Fig. 5) of type B specimens. The calculations are based on $R_m = 18\,799\,\mathrm{kNm/rad}$. The displacements are not the same for all specimens because the lengths of the glulam beams and the location of the measuring points (C) varied. For specimens BC02 and BC03, the lateral supports of the specimens made measurement of horizontal displacements impossible. Calculated deflections, δ, are determined by Eq. (10) (Fig. 5).

$$\delta = \left[\frac{1}{6EI}(3L - s - a)(s + a)^2 + \frac{6}{5GA}(s + a) + \frac{a(L - s)}{R_m}\right]P \tag{10}$$

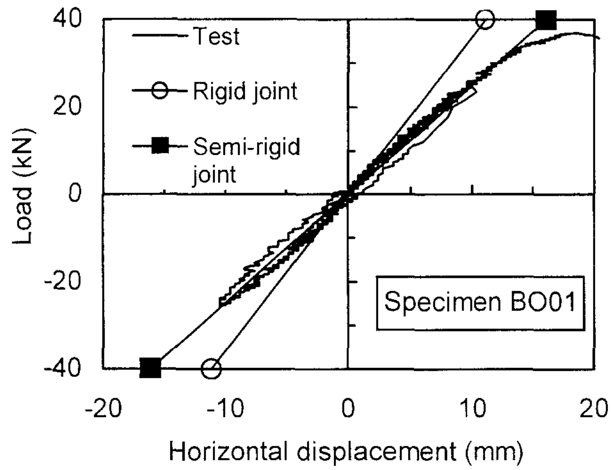

Fig. 9. Influence of semirigidity of dowel joint on horizontal displacements. Rigid joint, $R_m \to \infty$; semirigid joint, R_m = 18799kNm/rad

where I is the moment of inertia; and A is the cross-sectional area of the glulam beams. The calculated strengths and stiffness presented in tables and figures are based on the material properties noted previously in this paper and the geometry shown in Fig. 3. The shear modulus of the glulam beams, G, was not measured but was estimated to be 500MPa (E/18). For all specimens, s = 330mm. The following values of L and a, respectively, in millimeters, apply: BO01: (3680, 700); BO02: (3540, 600); BO03: (3390, 450); BC01: (4490, 900); BC02: (3650, —); BC03: (3460, —).

Glued joints are often considered fully rigid, but this is not completely true for glued-in dowel joints. An example of the influence of the semirigidity of the dowel joint is shown in Fig. 9. Here the measured horizontal displacement is compared with the calculated displacement using the theory presented in this paper (R_m = 18799kNm/rad) and fully rigid joint assumption ($R_m \to \infty$) for one of the tested specimens. Joint rotation accounts for approximately one-third of the total displacement in this example and should therefore be considered in calculations of deflections. It may also be appropriate to take into account the semirigidity of glued-in dowel joints in calculations of moment distributions in statically indeterminate structures. Taking into account the semirigidity of the joints may in some cases lead to more economical design of a structure.

Conclusions

Tests were conducted on plywood frame corners jointed to glulam beams by means of glued-in hardwood dowels. A moment capacity of the joints corresponding to a MOR of about 30MPa was obtained for small specimens (100 × 200mm^2 cross section), whereas the capacity of large specimens (120 × 420mm^2 cross section) was about 22MPa (both opening and closing moments). The test results combined with the fact that the joints are easy to produce make them alternatives to traditional dowel-type fastener joints (bolts, nails, drift pins) and to modern joints with glued-in steel rods.

In autumn 2000, a roadway timber bridge was constructed in Kochi Prefecture, southern Japan, in which beam splice joints with hardwood dowels were glued on site. The largest joints each contained 254 dowels (16mm in diameter). Even though glued-in hardwood dowel joints may be glued on site without major problems, the joint is still believed to be especially suitable for production at the factory.

The proposed models for calculating joint strength and rotational stiffness appear to be in good agreement with test results. The models may serve as tools for practical design because they are simple and, apart from joint geometry and the usual material properties, require only two bond-line material properties (bond-line shear strength and stiffness, which are easily obtained from pull-out tests on single dowel joints) as additional inputs.

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