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REINFORCEMENT OF DOWELLED JOINTS IN GLULAM

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Lund in June 1998

Hans Jørgen Larsen

Bertil Enquist

Abstract

I et tidligere projekt støttet af Byggforskningsrådet undersøgtes virkningen af at armere bolte- og sømforbindelser med glasfiber. Forsøg viste, at armeringen var meget effektiv.

I det projekt, som beskrives i denne rapport, er undersøgt armering af boltefor-bindelser belastet vinkelret på fibrene i relativt store trætykkelser (90 mm lim-træ). Der blev som armering anvendt glasfiber og også 6 mm birkekrydsfiner.

Forsøgene viste
-at både glasfiber og birkekrydsfiner er effektive armeringsmaterialer. De for-hindrer revnedannelser vinkelret på fibrene, og selv med reducerede afstande i forbindelsen kan den fulde bæreevne svarende til hulrandsstyrken nås.
-at krydsfineren i sig selv giver et væsentligt tilskud til bæreevnen.

På baggrund af disse og tidligere forsøg er opstillet praktiske beregningsmeto-der.

In an earlier project supported by Byggforskningsrådet - The Swedish Council for Building Research - the effect of reinforcing nailed and bolted joints with glass fibres was investigated. Tests demonstrated that the reinforcement is very effective.

The purpose of the project reported in this paper was to investigate the effect of reinforcing rather wide members (90 mm glulam) with glass fibres and also with 6 mm birch plywood.

The tests have shown
-that glass fibres and birch plywood are both effective reinforcing materials. They prevent splitting, and even with reduced distances in the joints, the full load-carrying capacity corresponding to the embedding strength can be obtained.
-that plywood contributes significantly to the load-carrying capacity.

Based on these and other tests, design methods for practical use are proposed.

1. Introduction

Reinforcement of joints with densified wood or with mats of glass fibres has been shown to be very effective in cases where failure is caused by tension perpendicular to the grain, see e.g. [Dahlblom et al., 1993], [Chen et al., 1994], [Larsen, 1994], [Haller, 1995], [Leijten et al., 1995], [Larsen and Enquist, 1996], and [Windorski et al, 1997].

The main effect of using glass fibre reinforcement in dowel-type joints (bolted, dowelled or nailed) is that the end distances and spacings can be reduced considerably without reduction of the load-carrying capacity. In some cases, however, the load-carrying capacity can even be increased by 10-50 per cent, see [Larsen and Enquist, 1996].

Densified veneer wood has a high embedding strength, and the direct contribution of the reinforcement to the load-carrying capacity can be essential.

Proposals for determining the necessary amount of reinforcement and its anchorage lengths are given in [Larsen and Enquist, 1996]. The proposals are, however, based on tests with rather thin members - about 45 mm - and only with glass fibre reinforcement. It was therefore decided to make further tests with wider members and also with high grade birch plywood as reinforcement. The results of these tests are reported below.

2. Tests

2.1 Materials

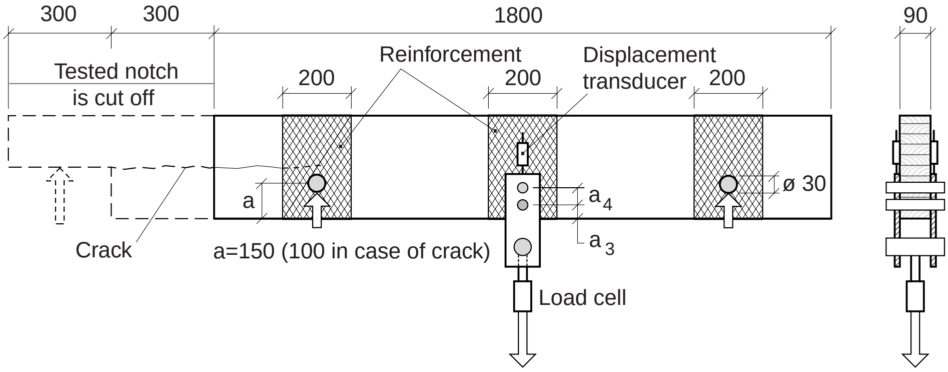

Figure 1 Test specimens and load configuration. Measurements in mm.

Wood

The test specimens were made from glulam beams of Swedish spruce (Picea abies), with cross-sections 90300 mm (9 lamination each 100/3 mm) and length 1800 mm.

The specimens were cut from beams that had previously been used for duration of load tests of notched beams, see figure 1 and [Gustafsson, 1998]. Some of the beams contained relatively large cracks in the support zone, but it is estimated that the cracks had only a marginal effect on the results, see below.

The beams had been stored for some years in an unheated barn in southern Sweden, and it is estimated that the moisture content was about 14 per cent.

The density of all specimens was determined from the mass of the beams as well as from small samples cut close to the dowel in the lamination containing the inner dowel, and close to the dowel. On average, the global density, corrected to a moisture content of 12 per cent, was 507 kg/m^3 and the local density 501 kg/m^3. The minimum value of the local density was 365 kg/m^3, the maximum value 601 kg/m^3.

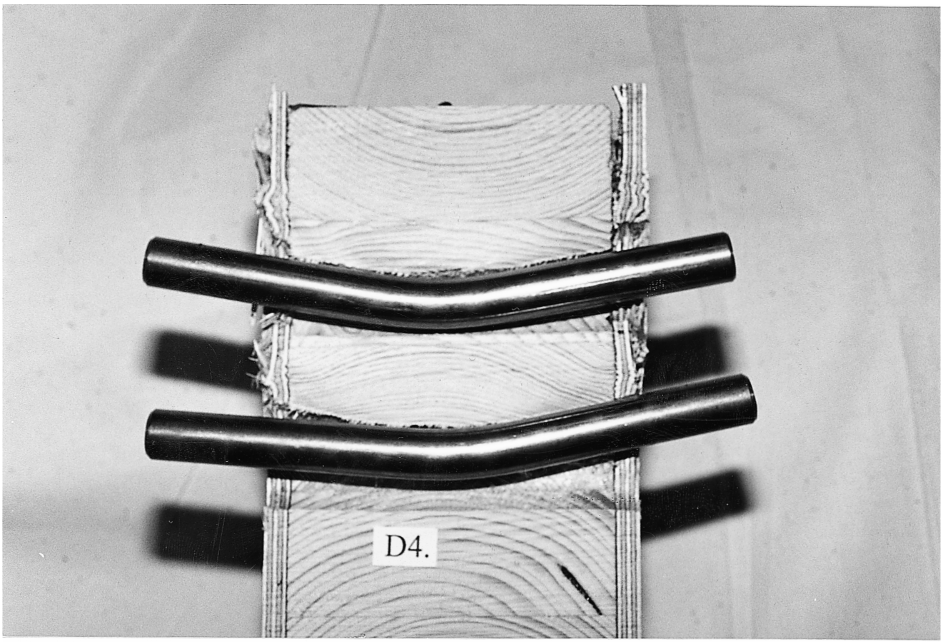

Figure 2 Specimens from test series D showing the deformed dowels after failure.

Dowels

The dowels had a nominal diameter of 14 mm. The actual diameter was 13.93 mm. Their yield moment determined according to [EN 409, 1993] was 306 Nm with a standard deviation of 4.1 Nm (coefficient of variation 1.3 per cent). The corresponding yield strength was $f_y = 6 \cdot 306000 / 13.93^3 = 679$ N/mm^2. This value was unexpectedly high and the failure mode aimed at - yield in the dowels - was not obtained. Only for series D with plywood reinforcement and ample distances was there a distinct bending of the dowel, but far from yielding, see figure 2. In the other test series the dowels remained virtually straight.

Glass fibre reinforcement

The glass fibre reinforcement was mats made of randomly oriented chopped fibres, 50 mm long, with a mass of 450 g/m^2 (Scan Glass, MK22). The mats are described in detail in [Dahlblom et al., 1993]. The strength and stiffness per unit width were 125 N/mm and 7000 N/mm, respectively.

Plywood reinforcement

The plywood reinforcement was 6.2 mm Finnish birch plywood, good two sides, delivered free of charge by the Danish firm Kristian Stærk A/S. It was of very high quality with 5 layers (1.0+1.4+1.4+1.4+1.0 mm).

The tensile strength and stiffness in the direction of the face veneer were determined from 45 mm wide strips, see figure 3. The tensile strength per unit width was 453 N/mm with a coefficient of variation of 11.7 per cent. The stiffness was 73 000 N/mm with a coefficient of variation of 9.4 per cent.

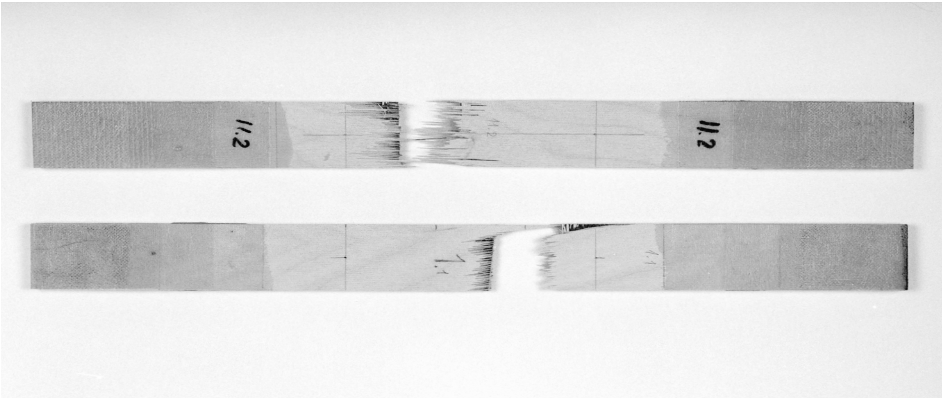

Figure 3 Plywood, failed tensile specimens. The specimens were reinforced at the ends with two layers of glass fibres, respectively 130 and 100 mm long. The grips covered 70 mm. No failures were associated with the grips.

Adhesives

The glass fibre was bonded to the wood by a normal polyester adhesive (Jotun, Norpol, 20M-80. Prior to bonding the reinforcement, the wood surface was primed with the polyester glue thinned with 30 per cent styrene. The surfaces were not sanded, which may have resulted in a slightly inferior bonding strength, see 4.1.

The plywood was bonded with an ordinary resorcinol-phenol adhesive.

2.2 Specimens

The specimens are shown in figure 1. Two dowels were tested with edge distance a_3 and spacing a_4 (notation according to ENV 1995-1-1).

The values were either the minimum distances of Eurocode 5, [ENV 1995-1-1]: $a_3 = 4d = 56$ mm and $a_3 = 3d = 42$ mm (denoted full distances), or reduced distances: $a_3 = a_4 = 2d = 28$ mm.

The reinforcement was 200 mm wide.

The specimens were supported through 30 mm dowels, normally placed 150 mm from top and bottom. In cases where a crack from the notched beam tests extended into the support area, the 30 mm dowel was placed 100 mm from the loaded side.

2.3 Test

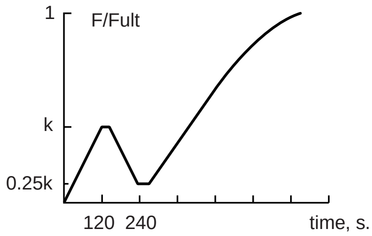

Figure 4 Load history according to EN 26981: In about 120 s, the load is increased to kF_{ult}, where F_{ult} is the (estimated) failure load. After 30 s, the load is reduced in 90 s to $0.25kF_{ult}$. After 30 s, the load is increased to failure in about 3 to 7 minutes. According to EN 26981, k should be 0.4. The actual value is given in the tables below.

The test was made in a hydraulic Mohr & Federhaft testing machine with manual steering of the oil flow. The actual load was measured with a 100 kN load cell, see figure 1. The slip in the joint was measured by translation transducers on both sides as the displacement of the steel gusset plates relative to the wood.

A loading history corresponding in principle to [EN 26981, 1983] was used, see figure 4.

3. Test results

3.1 Main results

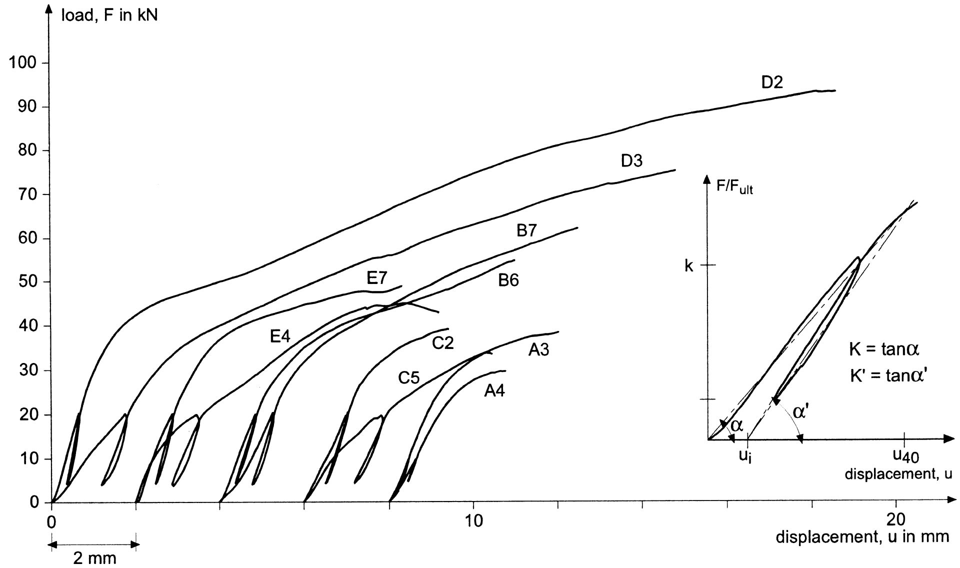

Figure 5 Typical load displacement curves. Note that the curves are offset 2 mm from the preceding curve.

Typical load displacement curves are shown in figure 5.

Table 1 gives a summary of the main results. The headings have the following meaning:

1	Test series	
Series A:	No reinforcement	Full distances
Series B:	Glass fibre reinforcement	Full distances
Series C:	Glass fibre reinforcement	Reduced distances
Series D:	Plywood reinforcement	Full distances
Series E:	Plywood reinforcement	Reduced distances

2 n Number of specimens in a series. The number aimed at was 8, but in some series one or two specimens had to be rejected because of problems with too large cracks in the glulam beams, misplacement of the reinforced zones, problems with drilling the holes, or problems during testing.

Table 1 Main results. Where more values are given, they are from the top: minimum value, mean value, maximum value and (coefficient of variation in per cent).

1	2	3	4	5	6	7	8	9
Series	n No.	Loop loads per cent	F_{ult} kN per cent	$F_{ult,cor}$ kN	u_{ult} mm	u_i mm	K' kN/mm	K kN/mm
A	8	10-5[1)]	26.4 **31.8** 37.8 (12)	 **33.2** (17)	2.5 **3.5** 5.5	0.15 **0.25** 0.35	3.5 **4.2** 4.5	5 **6.2** 8 (13)
B	7	40-10	42.1[2)] **52.0**[2)] 60.9 (12)	 **50.3** (15)	3[2)] **7** 8.5	0.25 **0.4** 0.65	4 **4.6** 6	6.5 **7.3** 8 (10)
C	7	55-15	29.2 **34.7** 39.2 (12)	 **33.8** (10)	2 **4** 5.5	0.3 **0.75** 1.3	1.5 **2.9** 4.5	4 **5.7** 7 (23)
D	6	25-6	51.9[3)] **78.6**[3)] 93.9 20[3)]	 **89.8** 	7.5 **16** 18	0.25 **0.45** 1.0	3 **5.8** 8	5 **8.1** 11 (31)
E	8	40-10	44.2 **47.5** 53.2 (6)	 **48.6** (10)	4 **6** 7	0.25 **0.6** 1.0	3 **4.2** 7	5 **8.8** 11 (26)

1) Two 60/15 per cent.

2) In this beam, failure was initiated by failure at the support. If this result is disregarded, the lowest value is 45.9 kN, the average failure load 53.6 kN and the lowest u_{ult} 6 mm.

3) The low failure load was caused by problems in the load arrangement. If this result is disregarded, the lowest value is 73.8 kN, the average failure load 84.0 kN (c.o.v. 11 per cent) and the lowest u_{ult} 13 mm.

3 k Load at top and bottom of the load loop relative to the average failure load in per cent.

4 F_{ult} Measured failure loads; minimum value, mean value, maximum value, and (coefficient of variation).

5 $F_{ult,cor}$ Failure loads corrected to a reference density of 500 kg/m^3. The

correction is made under the assumption that the failure load is proportional to the local density close to the inner dowel hole. This should be a good approximation if failure was due either to fracture at the edge of the hole or to embedding failure under the dowel. Since the correction generally leads to an increased coefficient of variation this assumption is not supported, and in the following only the uncorrected values are used.

6 u_{ult} Displacements at failure.

7 u_i Initial displacements, see insert in figure 5.

8 K Stiffness value per dowel per shear plane defined by $K = 0.25\ F_{40}/u_{40}$, see insert in figure 5.

9 K' Stiffness value per dowel per shear plane defined by $K' = 0.25\ F_{40}/(u_{40} - u_i)$, see insert in figure 5.

3.2 Series A - Unreinforced, full distances

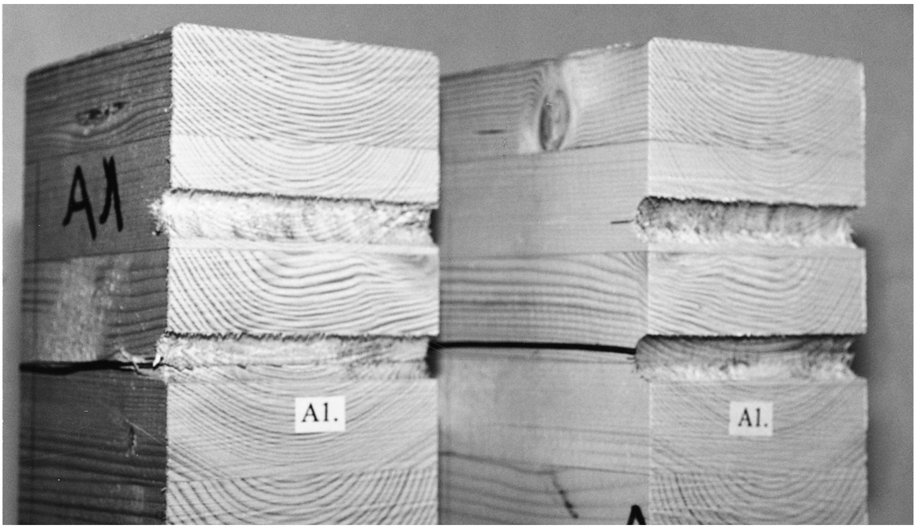

Figure 6 Series A, typical failure. The holes are slightly elongated (2 mm) and only curved corresponding to the elastic deformation of the dowel.

The dowels remained virtually straight and failure was caused by tensile failure perpendicular to the grain through the inner hole, see figure 6, showing a typical failure.

The load displacement curves are straight up to about 60 per cent of the ultimate load, after which they bend.

Failure was preceded by some noise, but was otherwise very sudden. The slip at failure was on average 3.5 mm.

3.3 Series B - Glass fibre reinforcement, full distances

The dowels were virtually straight after failure.

The load displacement curves are linear up to about 40 per cent of the ultimate load; they then bend but become again straight above 80 per cent of the failure load.

Failure was initiated by failure perpendicular to the grain as for series A but at a slightly higher load. After failure perpendicular to the grain, the total load was taken by tension in the reinforcement: the load was hanging in the reinforcement. The final failure was due either to tensile failure of the reinforcement or to shear failure (anchorage failure) between the reinforcement and the wood, see 4.1. In the latter case a gradual failure could be followed, indicated by the reinforcement becoming milky because of air between reinforcement and wood.

The slip at failure was on average 7 mm.

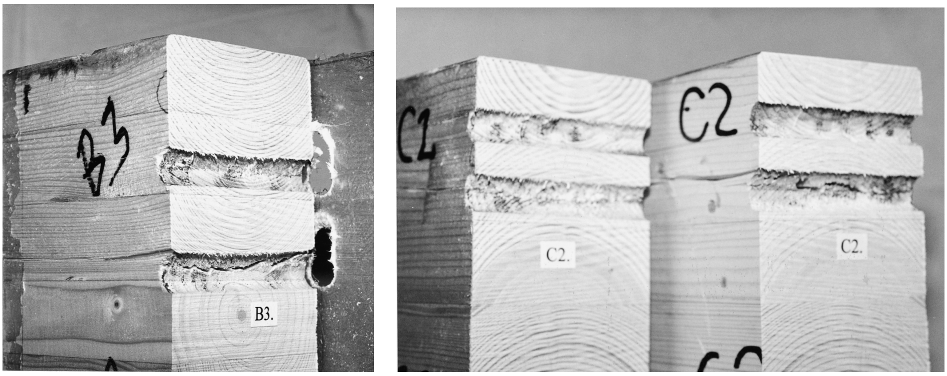

Figure 7 Series B and C, typical failures of glass fibre reinforced specimens. The holes are elongated (3-5mm) and only curved corresponding to the elastic deformation of the dowels.

3.4 Series C - Glass fibre reinforcement, reduced distances

The load displacement curves follow those of series B (the unreinforced).

Failure was initiated by tensile failure in the wood perpendicular to the grain, closely followed by either anchorage failure on both sides or by anchorage failure on one side and tension failure of the reinforcement on the other side.

The slip at failure was on average 4 mm.

3.5 Series D - Plywood reinforcement, full distances

The dowels were clearly deformed after failure. The holes were elongated and curved corresponding to the plastic deformation of the dowels plus an additional, reversible deformation.

The load-displacement curves are linear up to about 30 per cent of the ultimate load; they then bend but become again straight above 50 per cent of the failure load. The second linear part corresponds to the dowel being forced through wood and plywood. Failure was generally caused by anchorage failure, in two cases accompanied by tension failure in the plywood. A typical failure is shown in figure 8.

The displacements at failure were large 8-18 mm.

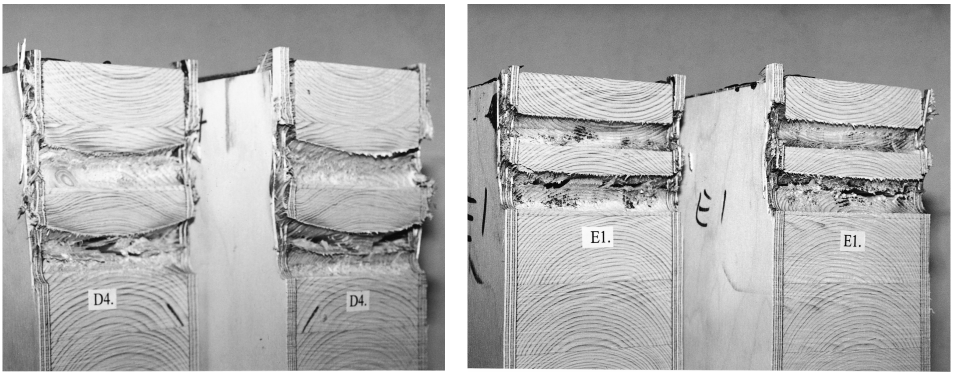

Figure 8 Series D and E, typical failures for joints with plywood reinforcement. See also figure 2.

3.6 Series E - Plywood reinforcement, reduced distances

The load slip curves follow those for series D but failure occurred at a lower load. Failure was in all cases caused by anchorage failure of the reinforcement.

The displacements at failure were on average 6 mm. A typical failure is shown in figure 8.

4. Discussion

4.1 Adherence of reinforcement

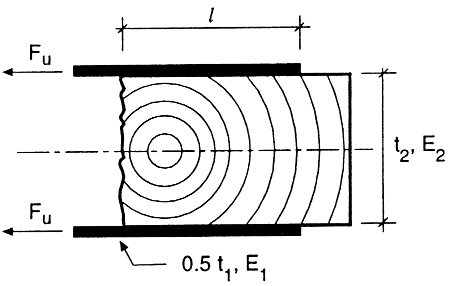

Figure 9 Situation at failure in a symmetrically loaded joint and notation.

For the reinforced specimens failure was in many cases due to anchorage failure of the reinforcement (adherence/shear failure between the reinforcement and the wood. This phenomenon has been investigated by Gustafsson [Gustafsson, 1993] and the following expressions have been proposed for the average shear stress at failure, $f_u = F_u/l$:

$$f_{u,l} = \frac{\alpha l f_a}{6}\left(1+\frac{t_2 E_2}{t_1 E_1}\right)\left(\frac{1}{\tanh\alpha}\left(\frac{\alpha^2 t_2 E_2}{6 t_1 E_1}+1\right)+\frac{1}{\sinh\alpha}-\frac{2}{\alpha}\right)^{-1}$$

$$\alpha^2 = \frac{f_a^2 l^2}{2 t_2 E_2 G_t}\left(1+\frac{t_2 E_2}{t_1 E_1}\right)$$

The following notation has been used, see also figure 9:

t_1E_1 Stiffness of the reinforcement per unit length

Glass fibres: $t_1E_1 = 2 \cdot 7000 = 14\,000$ N/mm
Plywood: $t_1E_1 = 2 \cdot 73\,000 = 146\,000$ N/mm

t_2E_1 Stiffness of the wood per unit length

For glulam a value of $E_2 = E_{90} = 350$ N/mm² is assumed, i.e.
$t_2E_2 = 90 \cdot 350 = 31\,500$ N/mm

f_a Adherence (shear strength)

For glass fibre reinforcement bonded to wood and with the load perpen dicular to the grain a value of $f_a = 2.8$ N/mm^2 has been found by Gustafsson [Gustafsson, 1993]. Since failure is in the glue or due to rolling she ar, the same value is also used for the plywood reinforcement.

G_f Fracture energy

For glass fibre glued to wood and with the load perpendicular to the grain a value of $G_f = 0.38$ N/mm has been found by Gustafsson [Gustafsson, 1993]. As for f_a, the same value is also used for the plywood reinforcement.

l Overlapping length.

Series B and D: l = 56 + 42 + 7 = 105 mm
Series C and E: l = 28 + 28 + 7 = 63 m

The maximum possible load per unit length corresponding to l = is

$$f_{u,\infty} = \sqrt{2 t_1 E_1 G_f} \sqrt{1 + t_1 E_1/(t_2 E_2)}$$

4.2 Failure load and stiffness according to Eurocode 5

The embedding strength parallel and perpendicular to the grain can be estimated from 6.5.1.2(1) in [ENV 1995-1-1]:

$$f_{h,0} = 0.082(1 - 0.01d)\rho = 0.082 \cdot (1 - 0.01 \cdot 14) \cdot 507 = 35.8 \text{ N/mm}^2$$

$$f_{h,90} = f_{h,0}/(1.35 + 0.015d) = 35.8/(1.35 + 0.015 \cdot 14) = 22.9 \text{ N/mm}^2$$

The load-carrying capacity corresponding to wood failure is

$$F_{ult,\ wood} = 2 \cdot (22.9 \cdot 14 \cdot 90) \cdot 10^{-3} = 58 \text{ kN}$$

Because of the risk of failure perpendicular to the grain, the load-carrying capacity for the joint is, however, limited by 6.1(8) in [1995-1-1]:

$$F_{ult,\ 90} = 0.667 f_v(a_3 + a_4 + 0.5d)b = 0.667 \cdot 4.5 \cdot (56 + 42 + 7) \cdot 90 \cdot 10^{-3} = 28 \text{ kN}$$

The shear strength f_v is estimated to be $0.009\rho = 0.009 \cdot 507 \sim 4.5$ N/mm^2.
The width is b = 90 mm.

The stiffness estimated by 4.2(1) in [ENV 1995-1-1] is:

$K' = 0.05\rho^{1.5}d = 0.05 \cdot 507^{1.5} \cdot 14 \cdot 10^{-3} = 8.0$ kN/mm

4.3 Series A - Unreinforced, full distances

The failure load - 31.8 kN - corresponds to the estimated load for failure perpendicular to the grain (28 kN).

The test values for the stiffness K are in the range 3.5 - 4.5, i.e. inferior to the Eurocode value of 8.0 kN/mm. The stiffness is, however, influenced by the initial slip, which is rather high because of problems with getting the dowels inserted. If the initial slip is disregarded, the test values (K') are in the range 5 - 8 kN/mm.

4.4 Series B - Glass fibre reinforcement, full distances

The anchorage strength according to 4.1 is $F_u = lf_u = 112$ N/mm, which is lower than the tensile strength (125 N/mm). Since the reinforcement under the dowel is pressed off, the effective length is $2 \cdot (200\text{-}14)$. The theoretical failure load is $0.112 \cdot 372 = 41.5$ kN. The strength corresponding to tensile failure is $0.125 \cdot 372 = 46.5$ kN.

The test value is 52 kN, i. e. slightly lower than the maximum value corresponding to wood failure (58 kN).

The joint stiffness is only marginally affected by the reinforcement.

4.5 Series C - Glass fibre reinforcement, reduced distances

The anchorage strength according to 4.1 is $F_u = lf_u = 100$ N/mm, corresponding to a theoretical failure load of 38.2 kN.

The test value is 34.7 kN, i.e. the same as for the unreinforced joints, i.e. the reinforcement had no effect because of insufficient anchorage length.

4.6 Series D - Plywood reinforcement, full distances

The initial failure load is much higher than for the other configurations. It corresponds to the full embedding strength of the wood (58 kN) and of the plywood. The latter is estimated to be $4 \cdot 0.453 \cdot 14 = 25$ kN, assuming that the embedding strength is equal to the tensile strength.

The anchorage strength according to 4.1 is $F_u = lf_a = 255$ N/mm corresponding to a theoretical failure load of $0.255 \cdot 372 = 95.0$ kN.

The test value is 84.0 kN. As mentioned in 2.1, the gluing may have been slightly inferior, which may explain the difference.

The stiffness was about 30 per cent higher than for the unreinforced beams.

Note the difference between the effect of plywood and the glass fibre reinforcement: The plywood and the wood are integral parts, whereas the glass fibres directly under the dowel cannot be regarded as fully effective; the main effect is prevention of complete failure after cracking of the wood.

4.6 Series E - Plywood reinforcement, reduced distances

The anchorage strength according to 4.1 is $F_u = lf_u = 166$ N/mm corresponding to a theoretical failure load of $0.166 \cdot 372 = 61.7$ kN.

The test value is 47.5 kN.

5. Conclusions

The tests have shown

- that Finnish Birch Plywood is a very effective reinforcing material for joints with large forces perpendicular to the grain. It ensures that the full load corresponding to the embedding strength can be obtained and that further the plywood itself can take a considerable load provided the anchorage length of the reinforcement is sufficient,

-that the design method proposed in [Gustafsson, 1993] is confirmed also for joints with large forces and for plywood as reinforcing material.

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