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REINFORCEMENT FOR COMPRESSION PERPENDICULAR TO THE GRAIN BY MEANS OF ADHESIVELY BONDED BIRCH TIMBER PRODUCTS

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ABSTRACT: The strength of timber when loaded perpendicular to the grain is significantly lower than when being loaded parallel to the grain. For softwoods, the compression strength perpendicular to the grain is approximately one-tenth of the strength parallel to the grain. Typical methods to increase the bearing strength of a timber beam at the supports include enlarging the support length and/or inserting reinforcing screws at the beam's support. In this study, two new methods of reinforcement for stress perpendicular to the grain are investigated through laboratory tests and analytical methods. The proposed methods utilize birch timber products which are adhesively bonded to the beam at the supports, i.e., where high bearing stresses occur. The adopted birch products: plywood with varying thicknesses and rods with a diameter of 19 mm. The laboratory test results show that the bearing capacity of softwood beams can be significantly increased if reinforced either by means of birch plywood plates or glued-in birch rods. The results pave the way for a new eco-friendly reinforcement technique. A simple analytical model to predict the load-bearing capacity for stress perpendicular to the grain of beams reinforced with the proposed technique is also suggested.

KEYWORDS: compression perpendicular to the grain, reinforcement, birch plywood, glued-in birch rod.

1 – INTRODUCTION

For structural members mainly stressed in the direction parallel to the grain, timber has an excellent strength-to-weight ratio, which among other things makes the material remarkably suitable for long-span applications. On the other hand, it is well known that timber is anisotropic, with significantly lower strength when loaded perpendicular to the grain direction than when being loaded in the direction parallel to the grain [1]. Timber's anisotropy sometimes gives rise to problems, e.g., when sizing a long-span beam; here the high bearing stresses at the supports in combination with timber's low strength for stresses perpendicular to the grain might be a challenge for the designer [2].

Various reinforcement methods have been investigated in the past few years, e.g., glued-in steel rods, wooden rods, steel screws, nails, etc. [3, 4]. One of the typical ways of increasing the compressive strength perpendicular to the grain is to insert self-tapping screws [5, 6]. Bejtka and Blaß [7] proposed the load-bearing capacity calculation models for timber components reinforced with fully threaded screws based on the observed three possible failure modes, i.e., (a) screws being pushed into the timber, (b) buckling

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of the screws, and (c) timber failure within a distributed area at screw tips. The analytical models have been further modified and included in the next generation of Eurocode 5 (prEN 1995). Nevertheless, through a recent experimental campaign conducted by Tomasi et al. [8], it was found that the last type of failure mode at screw tips can hardly occur although the analytical model in prEN 1995 predicted its occurance, implying the necessity of further investigation on this reinforcmenet method.

A drawback of using steel reinforcement within the timber is the risk of problems with introducing additional screws for fastening the beam to the supporting structure. To reduce the carbon footprint and avoid collisions with the inserted screws, new reinforcement methods by using birch timber products, i.e., birch plywood plates or glued-in birch rods, are proposed in this study. Birch (*Betula spp.*) has a wide natural distribution area in Scandinavian and Baltic countries [9]. Moreover, it also possesses superior mechanical properties, i.e. strnegth and stiffness, compared with commonly used softwood species [10]. The analytical models for this reinforcement approach using wooden products are not addressed in either the current or the next generation of Eurocode 5 [11]. Only few research works in this topic are available in the literature. Ed and Hasselqvist [12] investigated several reinforcement methods against compression perpendicular to the grain (CPG). One of the methods comprised wooden rods with a diameter of 19 mm glued into the glulam beam. It was found that all the studied methods can improve the strength and stiffness significantly. However, the deformation measuring system was not installed in a consistent way since different types of supporting materials were utilized in their study. Conway et al. [4] evaluated a reinforcement method using densified wood dowels (DSDs), which usually possess higher mechanical and physical properties, e.g., strength, elastic modulus, density, etc., but, on the other hand, need to undergo more complicated manufacturing process, meaning that DSDs are more energy comsuming and costly compared to pure wooden dowels.

This paper focuses on utilizing birch timber products, i.e., birch plywood and birch rods, to enhance the strength and stiffness of timber in compression perpendicular to the grain (CPG). Some preliminary results are presented in a thesis work [13]. Although various loading cases exist in real applications [14], this study has a limited scope that only one loading case is analyzed, following the standard testing method described in EN 408 [15], where both ends are fully compressed. Analytical models serving the purpose to predict the load-bearing capacity of the reinforced timber element are proposed and the predictions are further compared to the test results.

2 – MATERIALS AND METHODS

2.1 – MATERIALS

The timber material to be reinforced in this study is spruce glulam with a strength class of GL30c and a height of 270 mm. The cross section is either 90 mm×90 mm or 90 mm× 120 mm. The reinforcement materials cover 9 mm-thick and 12 mm-thick birch plywood plates and birch rods with a diameter of 19 mm. Density and moisture content of each type of timber component were measured on smaller samples that were stored in the same indoor environment as the tested specimens. Moisture content was determined by using oven-dry method following the standard EN 13183-1 [16]. The mean density and moisture content of each type of timber material are presented in Table 1.

Table 1: Mean density and moisture content of timber materials

Timber materials	Density (kg/m^3)	Moisture content (%)
Spruce glulam	443	10.0
9 mm-thick birch plywood	688	7.2
12 mm-thick birch plywood	663	6.5
Birch rod	605	7.7

Table 2: Some technical features of the employed adhesives

Properties	Adhesive 1 (XEPOX-G)	Adhesive 2 (XEPOX-F)
Stoichiometric volume ratio (A/B)[a]	100:50	100:50
Pot life 23 ± 2° (min)	60-70	50-60
Viscosity (mPa·s)	A=450000 B=13000	A=14000 B=11500

[a]: A and B represent adhesive and hardener respectively.

Two types of adhesives were employed, namely, XEPOX-G (gel) and XEPOX-F (fluid). Both are two-component epoxy adhesives but with different viscosities. XEPOX-G with a high viscosity was used for surface-to-surface adhesive bonding between spruce glulam and birch plywood. XEPOX-F with a lower viscosity is more suitable to be used for filling the gap between the predrilled holes and the wooden rods. The technical features are outlined in the producer's technical data sheet and summarized in Table 2.

For the specimens reinforced by plywood plates, screw-gluing pressing method was adopted. Different types of screws were utilized based on the specific reinforcement methods. Screw type 1 was used for the case with two birch plywood plates glued to the sides of the glulam element, while screw type 2 and 3 were used for the case with a single plywood plate in the middle, mimicking the situation with one slotted-in plywood plate. The diameter and the length of screw type 1, 2, and 3 are Ø4.5×45 mm, Ø3.5×35 mm, and Ø3.5×60 mm, respevtively.

2.2 – ASSEMBLY PROCESS

CPG Reinforced by Birch Plywood Plates

Fig. 1 displays the assembly process of a specimen reinforced by two plywood plates. Adhesives and hardener were poured in a container with the correct amount and then mixed together by using a paint mixer mounted in a screwdriver. After the adhesives being mixed to be homogenous, they were spread on glulam surface with an application amount of around 400 g/m^2. Plywood and glulam elements were predrilled prior to the assembly and screw-gluing pressing method was employed to glue plywood plates and glulam together. No close assembly time is required.

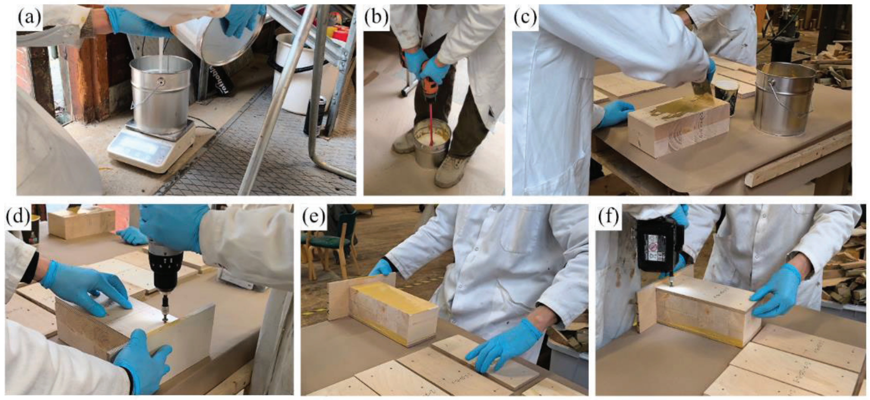

Figure 1. Assembly process for CPG reinforced by two plywood plates: (a) pouring adhesives and hardener in a container; (b) mixing adhesives and hardener; (c) applying adhesives; (d) screw-gluing; (e) applying adhesives on the other side of glulam; and (f) screw-gluing the other plywood plate.

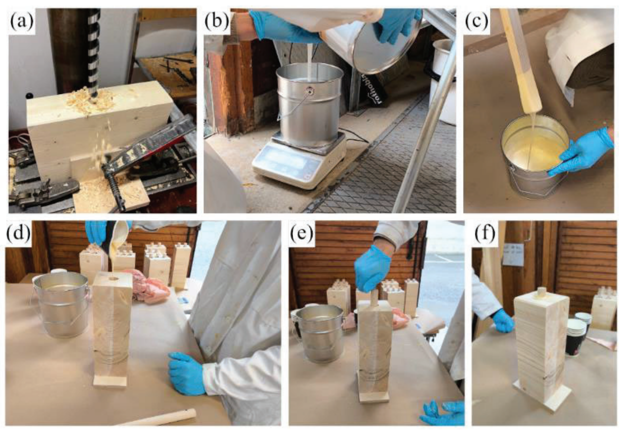

Figure 2. Assembly process for CPG reinforced by birch rods : (a) predrilling; (b) pouring adhesives and hardener in a container; (c) mixing adhesives and hardener; (d) pouring mixed adhesives into the predrilled hole; (e) twisting and pressing birch rod into the hole; and (f) assembled specimen.

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CPG Reinforced by Birch Rods

In this study, birch rods with a diameter of 19 mm were utilized. The assembly process is presented in Fig. 2. As can be seen in Fig. 2(a), glulam was predrilled for the insertion of the birch rod. The predrilled diameter is 22 mm, leading to a bond line thickness of 1.5 mm. Glulam element was then cut into the desired shape. For glued-in wooden rod application, epoxy adhesive XEPOX-F was used. This adhesive has lower viscosity than XEPOX-G and it is possible to mix by hand (see Fig. 2(c)). The mixed adhesives were poured into the predrilled hole and the birch rod was twisted and gently pushed down at a moderate speed until it reached the bottom. Any excess adhesive was squeezed out from the top, implying adequate adhesive application. A plate, shown in Fig. 2(d)-(f), was mounted at the bottom of the specimen to prevent the leakage of adhesive during assembly.

All the specimens were cured in a fume hood for 12 days. After curing, the bottom plate and the birch rod at the top were cut off, which was the final preparation step before the compressive test.

2.3 – TEST SERIES AND CONFIGURATIONS

Formal Tests

Ten test series with different reinforcement methods were carried out and have been summarized in Table 3. Fig. 3 illustrates the specimen configuration of each test series. Test series (a)-(d) utilize birch plywood as reinforcement plates while test series (e)-(j) employ different numbers of glued-in birch rods for CPG reinforcement. Among test series (a)-(d), test series (a) and (b) use plywood plates with a thickness of 9 mm and 12 mm, respectively, and glue to the side surfaces of glulam. In test series (c), glulam element was cut into two halves in thickness direction. One plywood plate was glued in between these two halves, representing the situation that the plywood plate could be possibly inserted into a slot. In test series (d), plywood plates were only screw-connected to the glulam element with no adhesive applied on the surface.

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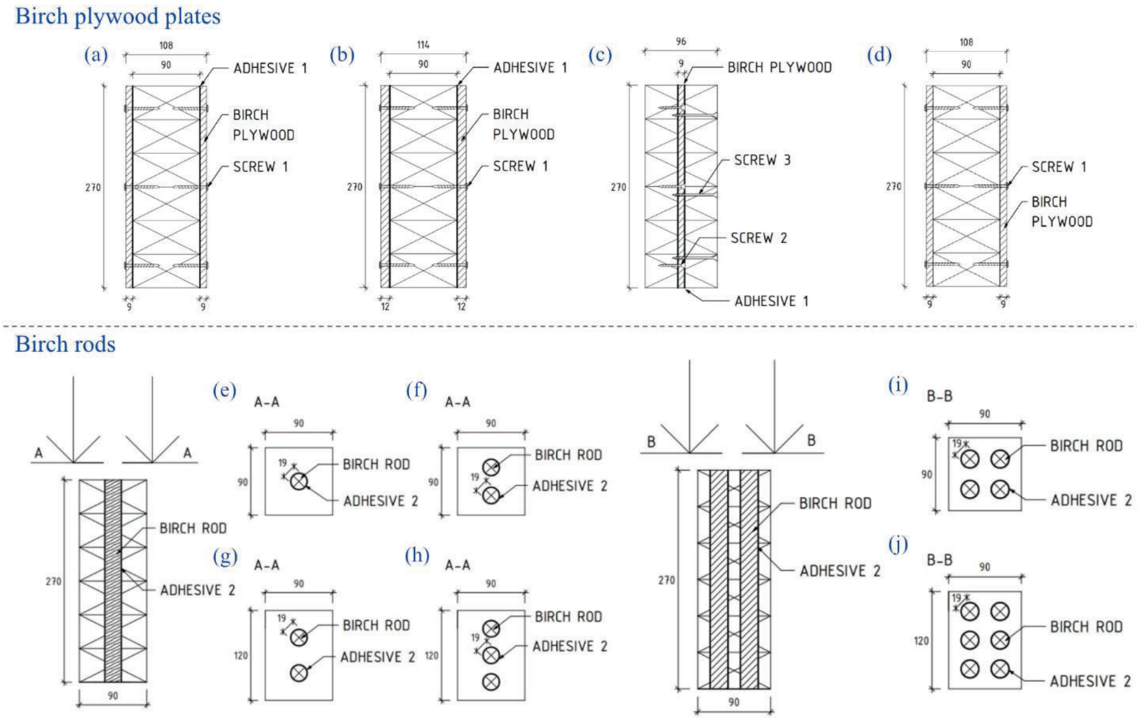


Figure 3. Specimen configuration in test series (a)-(j)(unit in mm).

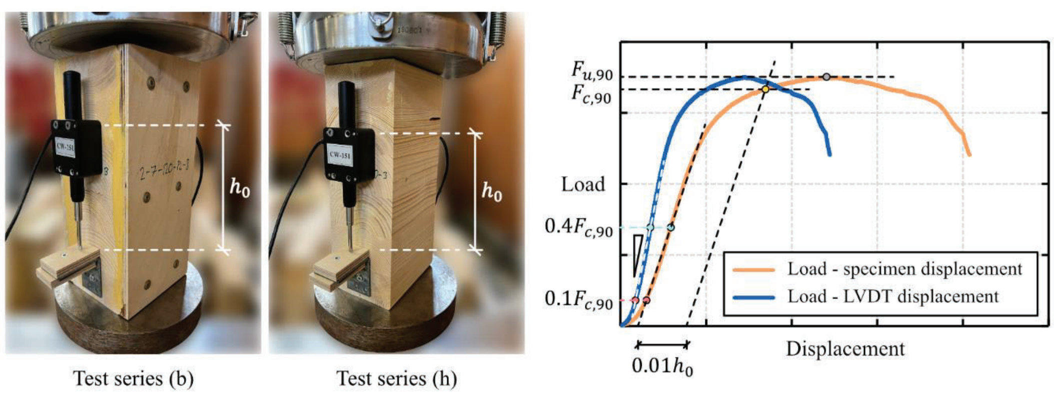


Figure 4. Illustration on the test set-up and force-displacement curves.

All the specimens were loaded in compression with a load cell capacity of 200 kN following the standard testing method EN 408 [15]. As shown in Fig. 4, a round bearing plate was mounted on the test machine to ensure a full contact with the specimen. Two linear variable differential transformers (LVDTs) were installed on the side surfaces. The measured range (h_0) is 170 mm, which is around 60% of the total height of the specimen, i.e., 270 mm. The loading rate was controlled to be 1 mm/min so the the maximum load could be reached within a relatively short time. Definitions of the strength and stiffness properties are illustrated in Fig. 4. The strength values can be determined from the orange curve (load in relation to the specimen displacement) by first connecting the points representing 10% and 40% of the estimated capacity and then offsetting this linear line with a distance of $0.01h_0$. If the intersection point between the offset line and the test curve is within 95-105% of the estimated capacity, this value is considered to the compressive capacity perpendicular to the grain ($F_{c,90}$). The maximum load is defined as the ultimate capacity ($F_{u,90}$). Dividing the capacity by the cross-sectional area, the corresponding strength values ($f_{c,90}$ and $f_{u,90}$) can be obtained. The elastic modulus perpendicular to the grain ($E_{c,90}$) is supposed to be obtained by analyzing the blue curve (load in relation to the LVDT displacement) (see (1)).

Table 3: Information regarding the formal test series.

Test series	Reinforcement configuration	Adhesive	Specimen cross-section (mm)	Replicates
(a)	9 mm-thick birch plywood (2 pcs)	Yes	120×108	
(b)	12 mm-thick birch plywood (2 pcs)	Yes	120×114	
(c)	9 mm-thick birch plywood (1 pcs)	Yes	120×96	
(d)	9 mm-thick birch plywood (2 pcs)	No	120×108	3
(e)	Birch rod (1 pcs)	Yes	90×90	
(f)	Birch rod (2 pcs)	Yes	90×90	
(g)	Birch rod (2 pcs)	Yes	120×90	
(h)	Birch rod (3 pcs)	Yes	120×90	
(i)	Birch rod (4 pcs)	Yes	90×90	
(j)	Birch rod (6 pcs)	Yes	120×90	

$$E_{c,90} = \frac{(F_{40} - F_{10}) \cdot h_0}{(w_{40} - w_{10}) \cdot A} \tag{1}$$

where F_{40} and F_{10} are 40% and 10% of $F_{c,90}$; w_{40} and w_{10} are the corresponding LVDT displacements at 40% and 10% of $F_{c,90}$.

Supplementary Tests

Apart from the formal test series, four supplementary tests were conducted and summarized in Table 4. Test series (1)-(3) serve the purpose to characterize the compressive strength of glulam perpendicular to the grain, compressive strength of birch plywood and birch rod parallel to the grain, respectively. The experimentally determined strength properties can be used as input values for predicting the load-bearing capacities of the specimens. Test series (4) is a calibration test that the upper round plate was pushed to the lower steel plate to capture the machine compliance, which would be further removed from the loading head motion so as to derive the ''real'' displacement of the specimem. The test set-up and configuration of each supplementary test are displayed in Fig. 5.

Table 4: Information regarding the supplementary test series.

Test series	Specimen	Loading direction	Specimen dimension (mm)	Replicates
(1)	Unreinforced glualm	Perpendicular to the grain	120×90×270	4
(2)[a]	Birch plywood	Parallel to the face grain	50×21×100	12
(3)	Birch rod	Parallel to the grain	Ø19×50	5
(4)	Steel plates	-	-	1

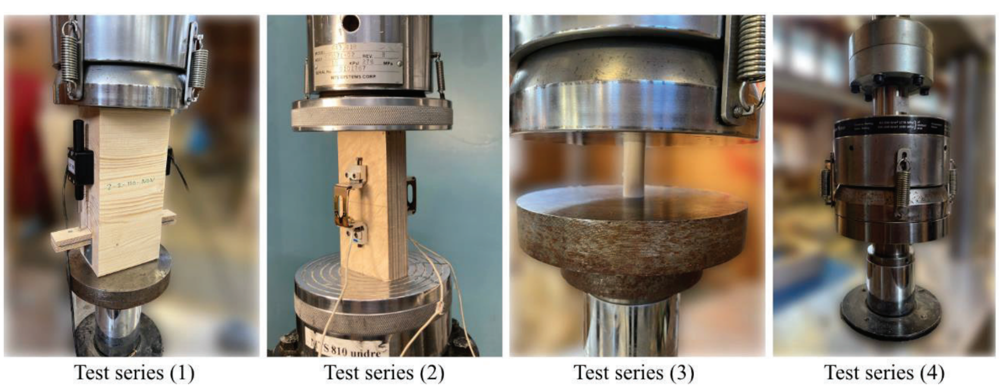
[a]: Test series (2) has been carried out in a previous study [17], where the mechanical properties of birch plywood have been summarized.

2.4 – STRENGTH PREDICTION MODEL

In the next generation of Eurocode 5 (prEN 1995), a design model is proposed to calculate the capacity of the reinforced timber element in compression perpendicular to the grain. The reinforcement method covered in prEN 1995 contains the usage of steel screws or steel rods. In this study, this design model is employed for glulam elements reinforced by timber products, i.e., birch plywood or birch rod (see (2)).

$$f_{c,90,ana} = \frac{k_{mat} \cdot k_{c,90} \cdot A_{GL} \cdot f_{c,90,GL} + n \cdot F_{c,r}}{A_{tot}} \tag{2}$$

where $f_{c,90,ana}$ is the analytically predicted compressive strength; k_{mat} is the factor accounting for the material behaviour and degree of compressive deformation perpendicular to the grain. In most design situations, k_{mat} is considered to be 1.4 for softwood glulam. $k_{c,90}$ is the stress spreading factor. For the loading case studied herein with both ends fully compressed, $k_{c,90}$ should be set equal to 1. A_{GL} and A_{tot} are the cross-sectional areas of the glulam element and the total specimen, respectively. $f_{c,90,GL}$ is the compressive strength of glulam perpendicular to the grain, which can be experimentally determined from supplementary test (1). n is the number of the reinforcement elements. $F_{c,r}$ is the capacity of each reinforcement element in compression.



Test series (1) Test series (2) Test series (3) Test series (4)

Figure 5. Supplementary test set-up and configuration.

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For all the cases with adhesives applied between glulam and reinforcement materials, buckling is not an issue because of the low slenderness of the reinforcement material and its lateral movement is strongly restrained by the surrounded timber and adhesive layer. $F_{c,r}$ is thus:

$$F_{c,r} = A_r \cdot f_{c,r} \tag{3}$$

where A_r and $f_{c,r}$ are the cross-sectional area and compressive strength of each reinforcement element. It is worth noting that, for the case that the birch plywood was only screw-connected to glulam, i.e., test series (d), buckling failure could happen. $F_{c,r}$ is thus:

$$F_{c,r} = \min(F_{buckling,r}, A_r \cdot f_{c,r}) \tag{4}$$

$$F_{buckling,r} = k_c \cdot A_r \cdot f_{c,r} \tag{5}$$

where $F_{buckling,r}$ is the buckling capacity of birch plywood; k_c is the instability factor, which can be calculated based on the formulas in Section 6.3.2 in the current Eurocode 5 [11].

3 – RESULTS AND DISCUSSION

3.1 – EXPERIMENTAL RESULTS

The experimental curves illustrating compressive stress in relation to the specimen displacement are displayed in Fig. 6. The CPG strength ($f_{c,90}$) of the unreinforced glulam is approximately 3 MPa. It is evident that all the reinforcement methods are able to enhance the CPG capacity significantly. Among the test series using birch plywood for reinforcement, test series (b), with 12 mm birch plywood glued on both sides, exhibited the highest compressive strength $f_{u,90}$ and $f_{c,90}$. It is not surprising, considering its highest reinforcement ratio, defined as the cross-sectional area of the reinforcement over the total area. It is worth noting that test series (a) and (d) have the same reinforcement ratio, both reinforced by two 9 mm-thick plywood. However, test series (a) yielded over 30% higher compressive strength than test series (d). This is attributed to the different methods that, in test series (a), plywood plates were glued to glulam while in test series (d), plywood plates were just screw-connected to glulam. Furthermore, comparing test series (d) with test series (c), although the reinforcement ratio in test series (d) was doubled, they yielded nearly the same compressive strength.

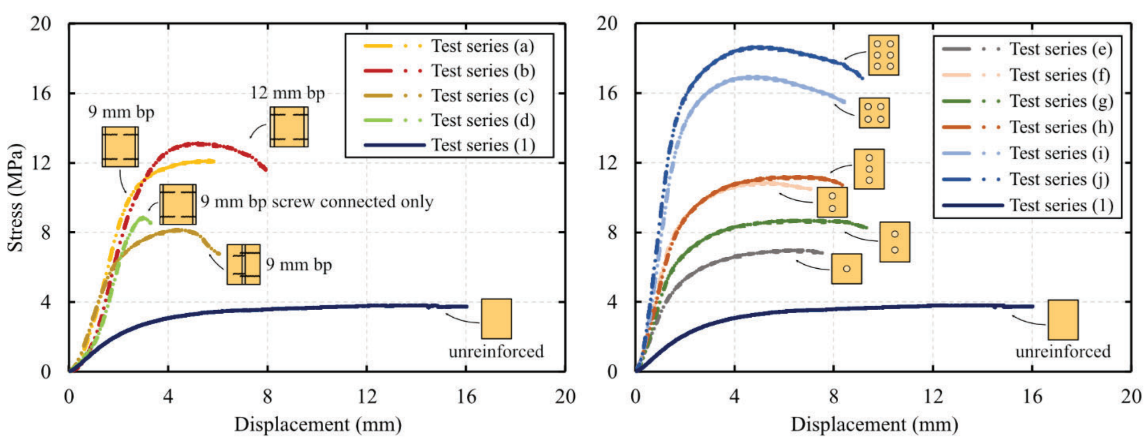
The failure modes further support these findings. All the test series with birch plywood glued to glulam showed plywood compressive failure while test seires (d) showed buckling failure of plywood (see Fig. 7). To further enhance the capacity of the screw-connected specimen, it could be beneficial to insert more screws in order to reduce the buckling length.

The detailed experimental results are summazied in Table 5. It is noted that no $f_{c,90}$ value is presented for test series (d). This is due to that, according to the definition illustrated in Fig. 4, the intersection point between the experimental curve and the offset line occurred after the peak. No $f_{u,90}$ is presented for test series (1) since the unreinforced glulam material was kept compressed and the force did not drop even with large deformation.

Table 5: Experimental results.

Test series	$f_{u,90}$ (MPa)	$f_{c,90}$ (MPa)	$E_{c,90}$ (MPa)	Reinforcement ratio (%)
(a)	12.1 (4.1)	11.9 (4.0)	1439 (18.9)	17.0
(b)	13.2 (1.5)	12.9 (3.1)	1852 (20.4)	21.4
(c)	8.2 (1.1)	8.0 (1.2)	1462 (6.9)	9.4
(d)	9.1 (8.9)	-	884 (24.0)	17.0
(e)	7.0 (8.9)	6.4 (7.0)	1110 (13.3)	3.5
(f)	11.0 (9.1)	10.4 (14.1)	2134 (5.2)	7.0
(g)	8.7 (7.7)	8.3 (11.7)	1598 (16.9)	5.3
(h)	11.2 (3.2)	10.6 (2.0)	2260 (8.5)	7.9
(i)	17.0 (7.6)	16.5 (6.8)	3614 (16.6)	14.0
(j)	18.7 (1.6)	17.9 (1.7)	3716 (7.0)	15.8
(1)	-	3.1 (5.0)	319 (8.6)	0.0

Note: The numbers in parenthese indicate the coefficient of variation (CoV) values for each property.



Note: birch plywood (bp) plates in test series (a)-(c) were screw-glued to glulam while bp plates in test series (d) were screw connected only.

Figure 6. Compressive stress in relation to the specimen displacement .

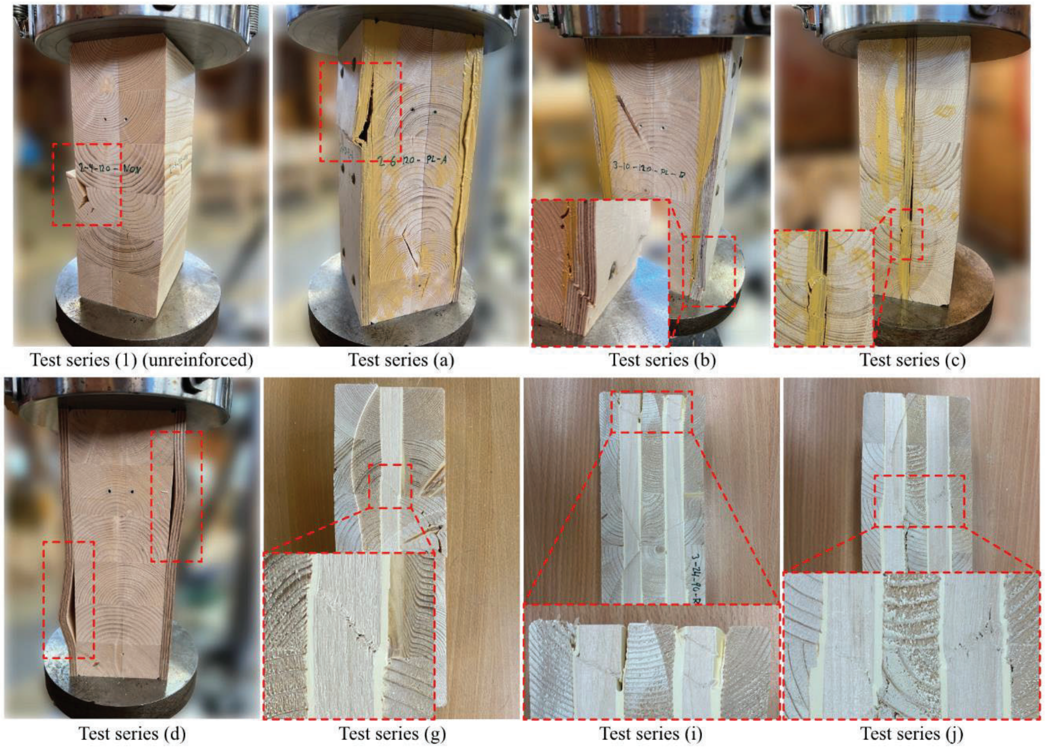


Figure 7. Typical failure modes.

Test series (e)-(j) employed glued-in birch rods for CPG reinforcement. Both elastic modulus and compressive strength perpendicular to the grain are enhanced with the increased number of inserted wooden rods. Test series (j), with six birch rods glued in glulam, resulted in the highest compressive strength perpendicular to the grain (approximately 18 MPa) among all the test series. However, its reinforcement ratio is lower than that of test series (a), (b), and (d) with two plywood plates glued on the side surfaces. This is due to that birch rods have all the materials loaded parallel to the grain while birch plywood possesses nearly half of the veneers loaded perpendicular to the grain. It is aforementioned in Section 2.3 that supplementray tests were conducted to characterize the compressive strength of birch rod and birch plywood. As a result, the mean compressive strength of birch rod is 67.8 MPa (CoV=5.9%) while the mean compressive strength of birch plywood parallel the face grain is 31.3 MPa (CoV=4.0%). Hence, glued-in wooden rods are considered as a more efficient reinforcement material than birch plywood when it comes to compression perpendicular to the grain.

Typical failure modes of the specimens with glued-in birch rods are shown in Fig. 7. All specimens show a shearing type of compressive failure in birch rods. Buckling was not observed after the tests, which may be due to the low slenderness ratio of the rods associated with the restrained lateral movement.

3.2 – ANALYTICAL PREDICTIONS

Having conducted supplementary tests to determine the compressive strength of each timber material, i.e., spruce glulam, birch plywood, and birch rod, it is possible to employ the analytical model proposed in the next generation of Eurocode (prEN 1995) (see (2)). The predicted compressive strengths perpendicular to the grain are compared to the experimental results and summazied in Table 6 and Fig. 8.

Table 6: Comparison between experimental and predicted compressive strength perpendicular to the grain ($f_{c,90}$).

Test series	$f_{c,90}$ **(MPa)**		Exp./Pre. (%)
	Experiment al results	Predictions	
(a)	11.9	8.9	133.4
(b)	12.9	10.1	127.5
(c)	8.0	6.9	116.5
(d)	9.1	8.6	105.8
(e)	6.4	6.6	97.6
(f)	10.4	8.8	118.5
(g)	8.3	7.7	108.2
(h)	10.6	9.3	113.6
(i)	16.5	13.2	124.9
(j)	17.9	14.3	125.0

Note: $f_{c,90}$ can not be determined for test series (d). Hence, the ultimate strength value ($f_{u,90}$) is presented for test series (d) in this table.

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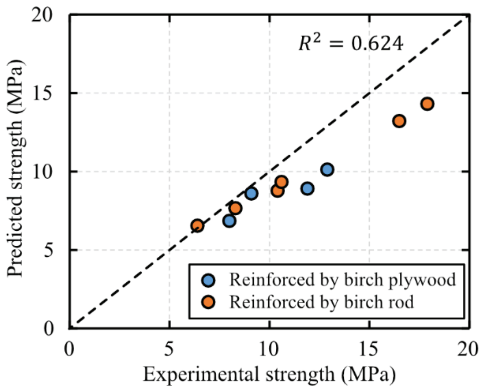

Figure 8. Comparison between experimental and predicted compressive strength perpendicular to the grain.

As can be seen in Table 6 and Fig. 8, the predicted strength for test series (e) with one single rod glued in glulam closely matches the tested strength while for all the other test series, the predictions are slightly lower than the experimental results. The discrepancy between predicted and experimental results varies from approximately 5% up to over 30% and it tends to increase as the number of birch plywood plates or birch rods increases. In other words, the prediction model is more conservative when the reinforcement ratio increases.

4 – CONCLUSION

This paper proposes two novel reinforcement methods using wood products, namely birch plywood and birch rod, to reinforce glulam in compression perpendicular to the grain. The mechanical behaviours of the reinforced specimens were examined by conducting laboratory tests. The experimentally investigated parameters comprise the number of birch plywood plates or birch rods, the thickness of plywood, and the connection methods between plywood and glulam (screw-glued or screw-connected only). The first two parameters are related to the reinforcement ratio. The conclusions are as follows:

- The proposed reinforcement methods can significantly enhance the strength and elastic modulus in compression perpendicular to the grain. The degree of strength and stiffness improvement is highly related to the reinforcement ratio.

- Glued-in wooden rods are considered as a more efficient reinforcement material than birch plywood for compression perpendicular to the grain. This is attributed to the fact that birch rods are entirely loaded parallel to the grain while birch plywood possesses nearly half of the veneers loaded perpendicular to the grain.

- All specimens with birch plywood or birch rod glued to glulam exhibited compressive failure in the reinforcement materials. While the specimens with birch plywood only screw-connected to glulam showed buckling failure of birch plywood. The capacity of the screw-connected specimens can be further enhanced by inserting more screws so as to reduce the buckling length.

- The analytical model in the next generation of Eurocode (prEN 1995) were utilized to predict the compressive strength perpendicular to the grain. The predicted strength is approximately 5%-30% lower than the experimental results, with the prediction model becoming more conservative as the reinforcement ratio increases.

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