Stiffness and strength of 45x95 mm beams glued from Norway spruce using 8 different structural models

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ABSTRACT

The most common cross cut dimension for structural lumber in load bearing structures of wooden houses is undoubtedly 50x100 mm. We hypothesized that in addition to solid wood, this dimension could be successfully manufactured also by gluing from smaller lamellae. The aim of this preliminary study was to determine how the static bending properties of 45x95x2200 mm Norway spruce (*Pice abies* L.) beams vary when they are manufactured from different-sized lamellae in eight different ways. Seven of the structural models were made by gluing, and one was solid 50x100 mm reference beam. A total of 30–35 specimens were manufactured for each of the eight structural models. The lamellae were not finger jointed, i.e., they were full length pieces with knots included. The materials were relatively slow-grown and small-knotted spruce lumber. The glue applied was a single component polyuretan resin KESTOPUR 1000 E by Kiilto Ltd. After planing the lamellae, gluing and pressing the beams, and planing the final specimens into wanted dimensions, they were stressed edgewise until failure according to EN 408. The results showed only minor differences between the structural models. The average air-dry densities of the specimens varied from 437 to 456 kg/m^3. The solid reference model indicated the highest MOE and MOR values, but it also had the best knottiness quality as well as the highest density. Depending on the structural model, the average ranges for MOE and MOR were 12,500–15,200 MPa and 49–65 MPa, respectively. This study showed that small-dimensioned structural lumber with competitive mechanical performance can be manufactured by gluing from small lamellae. Further research is still needed in order to generalise the results and to define the economical restrictions of this approach.

INTRODUCTION

The load bearing structures in residential house construction are often relatively small dimensioned. Typical dimensions used in beams or columns exposed to bending, tensile or compressive stresses are 50x100 or 100x100 mm. Bending is by far the most common stress type in ceilings and floors.

If the structure appears to require stronger members, there are certain optional ways to proceed: dimensions of a solid wood member can be increased, solid wood can be replaced by more homogeneous engineered wood beams such as glulam, I-joists or LVL, or the entire material can be changed from wood into steel or concrete, for instance.

Load bearing glulam beams are often large dimensioned products that are intended for horizontal or vertical uses in big public buildings. LVL and I-joist are occasionally used in smaller residential house construction. Great majority of smaller dimensioned members are still, however, solid lumber. Nordic softwoods (Norway spruce and Scots pine) provide sufficient stiffness and strength for practically all structural members in residential construction when the dimensions are increased up to 100x100 mm. However, if the structures with equal mechanical performance could be manufactured economically using smaller dimensions, timber would be saved and the technical economical competitiveness of wood would possibly be increased in comparison to the other construction materials.

There are many commercial goods and a lot of information available concerning the manufacture of glued wood products (fibreboard, chipboard, strandboard, plywood, LVL, as well as glulam beams with large dimensions). Production of the most common structural lumber dimensions by gluing smaller boards or battens is, however, not common business and not well known from mechanics point of view, either. This is reasoned by the good competitiveness of the relatively cheap solid wood products. Still, the consumer expectations apparently shift towards construction materials with highly predictable properties and more uniform quality than in the traditional solid wood products.

The objective of this study was to manufacture small-dimensioned glued beams from smaller boards or battens of Norway spruce (*Picea abies* L.), and test their stiffness and strength in edgewise static bending according to EN 408 (1995).

MATERIALS AND METHODS

Manufacture of the lamella

Dried Norway spruce lumber originating from North Finland and North West Russia was used as a raw material in this study. Lumber was selected from a larger material with the rule that they should represent moderate growth rate (not very fast or slow grown trees) and normal knottiness. The original sawn timber available, 64x200, 44x200 and 50x100 mm in dimensions, were sawn and planed into proper numbers of lamellae with dimensions of 25x50, 50x50, 32x50, 17x100 and 25x100 mm (Table 1). These lamellae were used in eight structural models (Fig. 1).

Table 1: Numbers and dimensions of lamellae in different structural models

Dimension, mm	**25x50**	**32x50**	**50x50**	**16x100**	**25x100**	**50x100**
Structural model	Number of lamellae					
A				90		
B					60	
C	60		30			
D	120					
E			60			
F	120					
G		90				
H						30
Total number	**300**	**90**	**90**	**90**	**60**	**30**

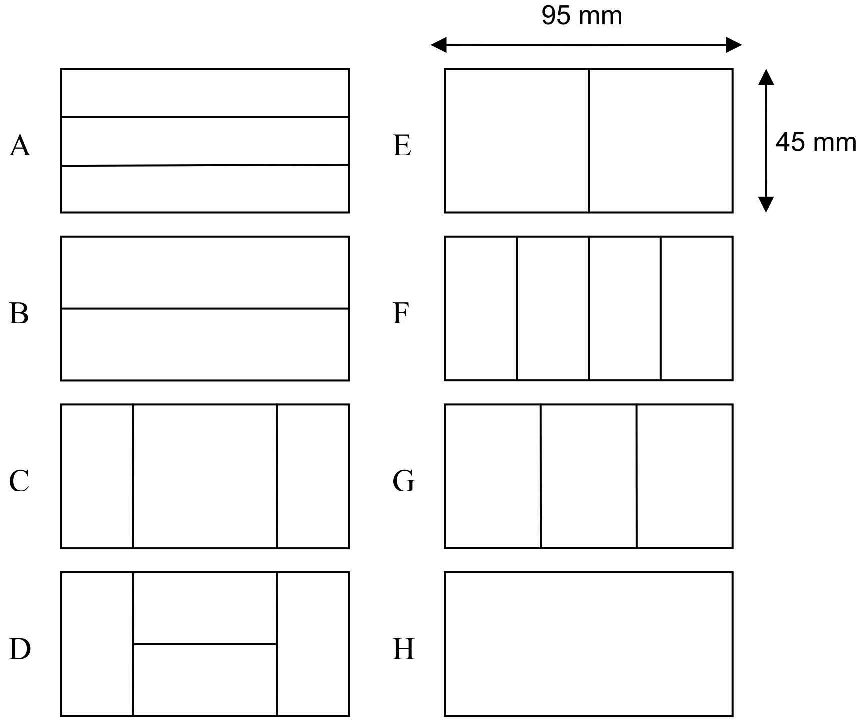

Figure 1: Structural models used in the 95x45 mm beams

Some properties of interest were measured from the lamellae before gluing. These characteristics included knot properties (size, location, type), growth rate (classification into two groups according to the annual ring width of more or less than 4 mm), resin pockets, different kinds of distortions, and whether the lamella mostly consisted of juvenile or mature wood. Knots were measured in more detail from a section of 75 cm from the mid point of the lamella towards its both ends. The measurements were done for both faces and edges. This area was expected to be the most critical from the point of view of strength and stiffness. Visually the best boards were used for structural model H as a solid wood reference group.

Manufacture of the beams

Seven glued structural models (A–G) were manufactured after all the measurements of the lamellae had been completed. The resin used was a single component polyurethane resin KESTOPUR 1000 E from Kiilto Ltd (Table 2). It fulfils the moisture resistance requirements for D4 exposure group according to standard EN 204 (2001). Roughly 200 grams of resin was used per square metre. The outermost lamellae of the beams were systematically glued so that the heart was positioned towards the surface of the beam.

In order to avoid changes in the cellular structure of wood, as well as the deformations in lamella, gluing should be done within 24 hours after planing the lamella (e.g., Limträ Guide 2007). In this study, the beams could be glued not until 3–21 day period after the planing. Thus, some of the lamellae were distorted. In the most severe cases, the distorted lamellae were changed into better ones obtained from the spare materials.

Table 2: Technical information of the resin KESTOPUR 1000 E by Kiilto Ltd

Specific gravity	1.1
Viscosity	5000 mPas (Brookfield RTV 4/20, 20 ^{o}C)
Spreading amount	100–300 g/m^2
Open time	max. 30 min, 20 ^{o}C
Press time	at least 90–120 min, 20 ^{o}C
Pressure	0.5–1.0 N/mm^2
Wood MC	8–22%

Structural models A, B, and partly E, were pressed using a horizontal plate press, whereas C, D, F, G and partly E, were pressed using a vertical press (Fig. 2). The pressing time was determined to be 1.5 to 2 hours in the temperature of 20 ˚C.

Figure 2: The vertical press used in the tests. Photo: Keijo Heikkilä

After pressing, the overflowed and dried glue foam was mechanically removed from the faces and edges of the beams before planing them into final dimensions of 45x95 mm. The beams were finally cross cut into length of 2200 mm.

Mechanical tests

The air dry densities of the beams were determined before the bending tests by measuring their masses and dimensions. Bending tests were carried out in Kymenlaakso University of Applied Sciences, using the Tiratest 28100 material testing device. The beams were bent edgewise following the standard EN 408 (1995). Modulus of elasticity (MOE) and modulus of rupture (MOR) were determined in static bending test. In order to measure MOE, an external measurement device (extensionmeter) is needed to determine the deflection as a function of force at the elastic deformation area (Fig. 3). The extensionmeter was installed in the middle of the beam, and removed as soon as the force reading was approximated to have reached a level of ca. 40% of the ultimate strength of the beam. The beams were then stressed until rupture.

Figure 3: TIRAtest 28100 material testing device with the external extensionmeter in the middle of the beam. Photo: Keijo Heikkilä

Analysis of the results

Moisture content (MC) of wood has a considerable effect on its mechanical properties. In general, strength of wood is at its highest when wood is absolutely dry (e.g., Kärkkäinen 2007). Jalava (1945) reported an increase of 100% in the longitudinal compression strength of spruce wood as the MC increased from green to air dry. In this study, the moisture content of each lamella was measured after the bending tests using a spike moisture meter. MC for a beam was calculated as the mean value of the measurements of its individual lamellae. Although the MC's did not vary too much, density (Eq. 1), MOE (Eq. 2) and MOR (Eq. 3) values were mathematically adjusted to comply with the values at 12% MC:

MC adjusted density (Kučera 1992):

$$\rho_{12} = \rho_w * \left(1 - \frac{(1-K)*(w-12)}{100}\right) \tag{1}$$

ρ_w density at the MC during the bending test, kg/m^3
K 0.5 (constant for spruce)
w Measured MC, %.

MC adjusted MOE (Boström 1994):

$$E_{12\%} = \frac{E}{1+0{,}0143*(12-u)} \tag{2}$$

u Measured MC, %.
MC adjusted MOR (Boström 1994):

$$f_{m,12\%} = \frac{f_{m,measured}}{1+0{,}0295*(12-u)} \tag{3}$$

u Measured MC, %.

RESULTS AND DISCUSSION

Density

The average air dry densities of beams varied from 380 kg/m^3 to 537 kg/m^3, the highest values being in structural models H (456 kg/m^3) and B (455 kg/m^3). The lowest densities were observed in models F (437 kg/m^3) and C (442 kg/m^3) (Table 3). In this experiment, only the mean density value for a beam was used as a predictor for the mechanical properties. However, every single lamella has different density, and the mechanical performance of the beam can be derived from the stiffness or strength of the weakest lamella. Normally, the fastest grown and lightest lamellae are placed in the middle of the member in order to maximise its performance on the compression and tensile faces, i.e., the surfaces that expose to the highest stresses. Generally, we can say that the bigger was the number of lamellae, the smaller was the standard deviation in air dry density.

Solid wood beams, i.e., structural model H, didn't have any pieces with more than 4 mm annual ring width. The other models, on the other hand, contained at least one lamella with wider rings. This has an effect not only on the density but obviously also on the mechanical properties of the beams. Some lamellae also contained small numbers of resin pockets and drying checks. These defects were analysed, but due to the relatively homogeneous material, we could not indicate any significant correlations between the mechanical properties and occurrence of defects. In addition, numbers and sizes of knots located within 75-cm-distance from the centre of the beam were recorded. Based on literature, we know that knots, especially the ones located on the tension face of a member in bending test, have considerable impact on its strength (e.g., Kärkkäinen 2007).

Table 3: Air dry densities, their standard deviations as well as min and max values for the beams in different structural models

Structural model	Mean value (St. deviation)	N of beams	Min	Max
	Air dry density, kg/m^3			
A	450.6 (24.1)	35	403.4	497.8
B	454.7 (36.1)	31	399.4	529.6
C	441.5 (23.9)	33	380.6	475.7
D	448.3 (19.7)	31	410.2	484.1
E	447.3 (29.0)	34	387.6	534.5
F	437.0 (24.4)	32	386.0	478.2
G	444.4 (26.5)	31	414.3	500.0
H	456.7 (42.8)	34	385.4	536.7

Modulus of Elasticity MOE

Structural model H (solid wood) indicated clearly higher MOE values than the glued beams. However, also the standard deviation for MOE results was the highest in case of model H (Table 4). Fig. 4 presents the frequency distributions for the MOE values in separate structural models. The smallest standard deviations for MOE values were observed in structural models A and B that did not contain any glue joints perpendicular to the applied stress.

Table 4: MOE values, their standard deviations, min and max values for the beams in different structural models, as well as the correlation coefficients between the density and MOE

Structural model	**Mean value (St. deviation)**	**Min**	**Max**	**Pearson correlation between the average density and MOE of the beam** [1)
	MOE, MPa			
A	13194 (1667)	10514	16188	0.726**
B	13249 (1751)	9776	16012	0.687**
C	12581 (2117)	8062	17361	0.496**
D	13248 (1906)	9582	17470	0.436*
E	13006 (1925)	8746	16983	0.725**
F	12926 (1936)	9183	16125	0.506**
G	13321 (2075)	8893	17976	0.479**
H	15239 (2598)	10420	20413	0.850**

1) ** significant at 0.01 confidence level, * significant at 0.05 confidence level.

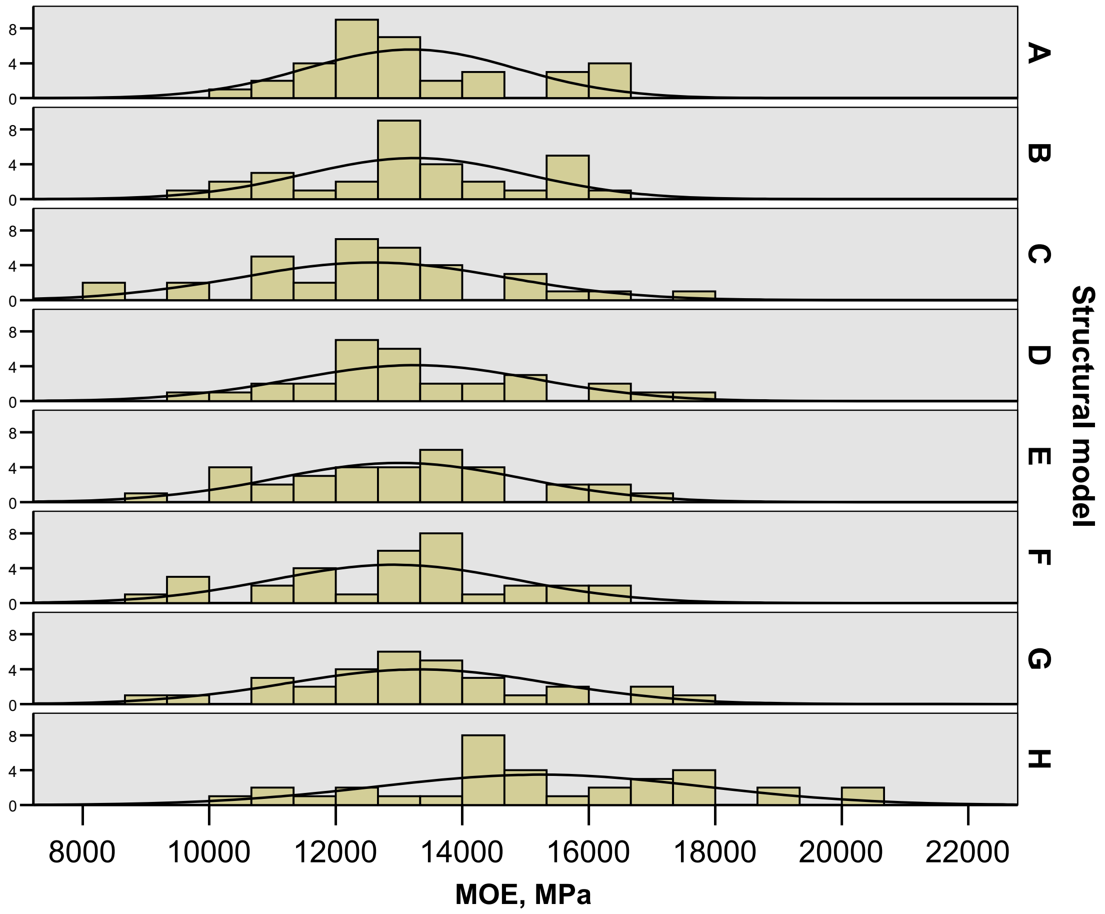

Figure 4: Frequency distributions of MOE values for structural models A–H

Modulus of Rupture MOR

The MOR values followed quite systematically the MOE results. The highest average MOR values, but also the highest standard deviations were observed in solid wood beams, structural model H (Table 5). Fig. 5 illustrates the frequency distributions for the MOR values in separate structural models. Bending strength correlated positively with the average density of the beam in case of all structural models. The highest correlation coefficients between MOR and density were observed in beams that had the highest densities.

Table 5: MOR values, their standard deviations, min and max values for the beams in different structural models, as well as the correlation coefficients between the density and MOR.

Structural model	**Mean value (St. deviation)**	**Min**	**Max**	**Pearson correlation between the average density and MOR of the beam [1)]**
	MOR, MPa			
A	55.7 (9.9)	32.6	70.4	0.551**
B	54.3 (10.9)	37.1	78.3	0.700**
C	49.1 (12.1)	27.1	72.1	0.523**
D	52.0 (8.2)	32.6	64.6	0.554**
E	51.8 (12.7)	22.4	76.2	0.444**
F	51.2 (11.9)	29.9	70.6	0.423*
G	54.5 (12.0)	32.9	75.2	0.610**
H	65.3 (14.8)	36.2	104.6	0.701**

[1)] ** significant at 0.01 confidence level, * significant at 0.05 confidence level.

In case of all structural models, the Pearson correlations between MOE and MOR were significant at 0.001 confidence level. This indicates that MOR could be rather easily predicted based on MOE measurements in actual production environment, as well (e.g., Lindgren 1996). Knot sum, as well as the diameter of the biggest knot near to the centre of the beam correlated positively with the bending strength of the beams in case of all structural models except model G. We couldn't show any clear explanation for this.

According to Kärkkäinen (2007), modulus of elasticity is roughly 50% higher near to the surface of a mature tree in comparison to its pith. Juvenile wood has lower MOE due to its different cell structure and microfibril angle. In this study, structural models B and H contained mostly juvenile wood whereas the other models were manufactured from lamellae that represented mostly mature wood. Such experimental setup suggests that models B and H should have the poorest mechanical properties, which was not the case in this material. This is explained by the fact that both in case of models B and H, the wood used had actually very narrow annual rings and high density. In addition, due to the narrow rings and close location of tree pith in models B and H, the direction of bending stress was more radial than tangential. Again, we know that the strength of wood is often higher in radial than in tangential direction (e.g., Kärkkäinen 2007).

Gluing was not carried out in optimal conditions. The recommended time between planing and gluing was clearly exceeded, and in some cases (structural model A) the open time of the glue was exceeded. Still, the glue joints did not open in bending tests, the fractures occurred in the surrounding wood material. Therefore, the glue joints were not analysed more detailed after the tests.

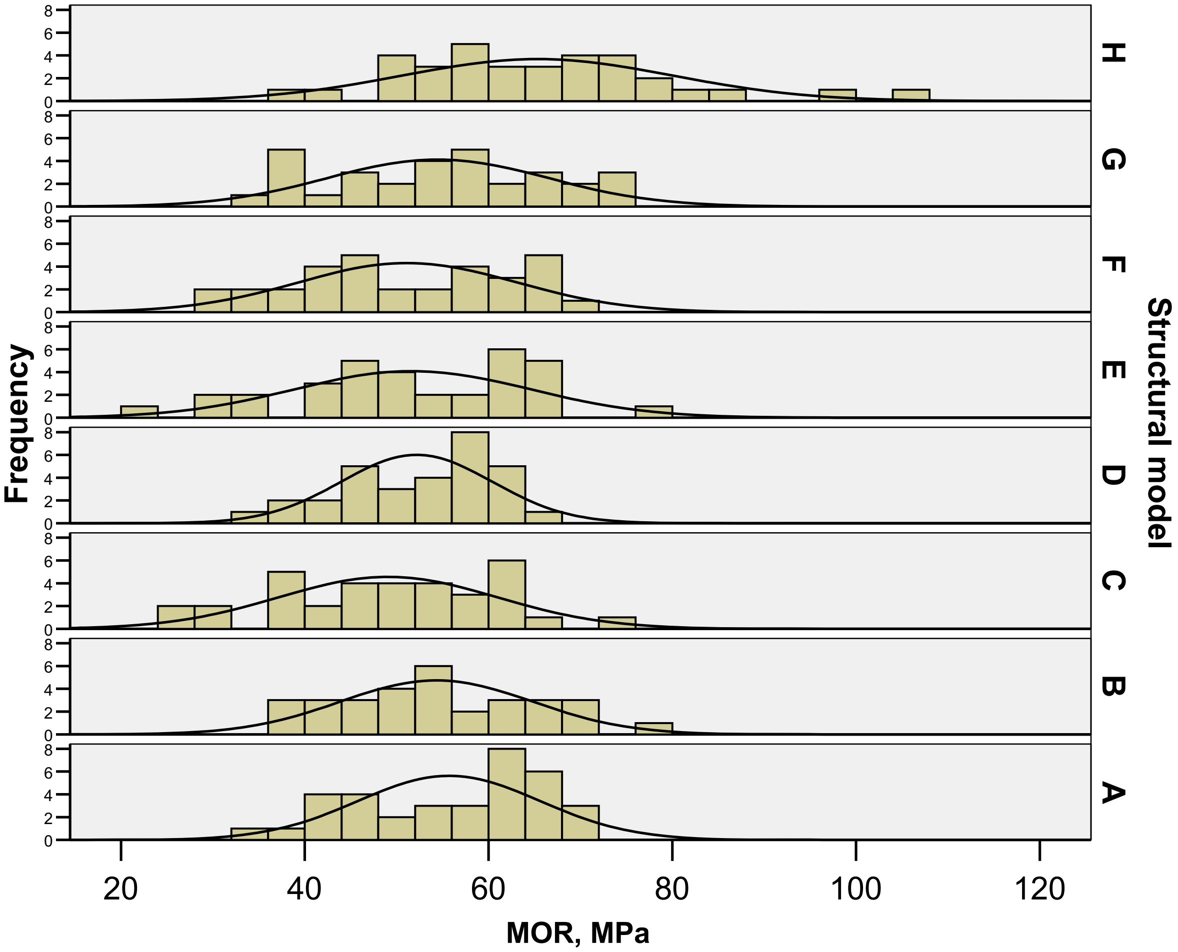

Figure 5: Frequency distributions of MOR values for structural models A–H

CONCLUSIONS

The results of this preliminary study showed that the structural model does not actually have a great effect on the bending properties of glued 45 x 95 mm wooden members. Solid wood members showed the highest MOE and MOR values, but this result was explained by the higher average density, more narrow annual rings and better knottiness structure of solid wood materials in comparison to lamellae used in the other structural models. The results indicate that further tests are required, but interesting product and production strategies might be developed based on utilisation of small-dimensioned sawn wood in glued, load carrying wooden members.

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