GREEN-GLUED LAMINATED BEAMS – HIGH PERFORMANCE AND ADDED VALUE

Erik Serrano¹, Jan Oscarsson², Bertil Enquist³, Magdalena Sterley⁴, Hans Petersson⁵ and Bo Källsner⁶

ABSTRACT: The work presented in this paper deals with the use of green gluing (also known as wet gluing) as a mean to overcome the difficulties in making use of side boards for structural applications. By manufacturing laminated beams from unseasoned side boards several advantages are obtained. Beams were manufactured from side boards of approximately 25 mm thickness. The board width was 120 mm. The boards were glued together with a 1-component polyurethane adhesive to form a beam cross-section of approximately 120×315 mm². After curing, the beams were split into two halves, each approximately 55 mm wide. These 55×315 mm² beams were then dried in a conventional kiln dryer. Finally, the beams were planed to target size, 50×300 mm². Tests performed included beam bending tests for strength and stiffness, tests of the shape stability of the beams, tests of the integrity of the adhesive bond lines (delamination) and tests on the strength and fracture energy of the adhesive bond lines. The main results obtained show that there is a potential for the production of green-glued laminated beams with good technical performance.

KEYWORDS: green gluing, laminated beams, bending strength, shape stability

1 INTRODUCTION

1.1 BACKGROUND

For the Swedish saw milling industry, the use of Norway Spruce (Picea abies) in structural applications is of great economical value. However, it is estimated that around 30% of the production at a typical south-Swedish saw mill are side boards of narrow dimensions of 20-25 mm thickness. These side boards are not used for structural applications today. Although the cost for producing and handling the side boards at the saw mill is high, their price on the market is typically only half of the price for structural timber. Thus if it would be possible to upgrade the side boards to structural use, much would be gained in terms of increased added value for the saw mills.

1.2 OVERVIEW OF PRESENT WORK

1.2.1 Green-gluing of side boards

The basic idea behind the research project presented here is to make use of spruce side boards as laminations in glued-laminated products. Since the side boards are of narrow dimensions, there thickness being typically only 20-25 mm and their width being 70-150 mm, it is imperative to reduce the amount of planing in the processing after cutting the boards from the logs. Using green gluing, this can be achieved since gluing the boards together before drying them considerably reduces the amount of planing needed. Normally, green gluing of unseasoned timber is a method which is not primarily aiming at replacing traditional gluing of dried wood, but is used to facilitate the upgrading of low quality timber with an efficient process. This upgrading is typically in terms of defect elimination (knots) and finger joining. In this case, however, the upgrading is in terms of using side boards of narrow dimensions, which are difficult to use in structural applications, to form large structural components. In previous studies of flat wise green glued timber, promising results have been obtained see e.g. [1], [2] and [3]. An extensive state of the art for green gluing is also available in the Core Document of the COST E 34 action 2008 [4].

1.2.2 Research idea

Although the side boards are difficult to use in structural applications due to their dimensions, these boards have some appealing properties. It is well-known that the mechanical properties of spruce timber vary within the stem, and that several properties show a consistent dependence on the distance to the pith. It has been shown that for example the coefficient of shrinkage and the longitudinal modulus of elasticity (MOE) vary considerably with the distance from pith, [5]. Thus the longitudinal MOE in the outer parts of a stem could be at least twice as high as close to the pith (for a log of “normal” age - 60-80 years). We are thus faced with the
following contradicting facts: in normal production, large dimension structural lumber is cut from the central parts of the log where the MOE is low. This timber is then used as e.g. floor joists, where typically the stiffness governs the dimensions of the joists. Thus, by using the stiff side boards as laminations and produce large size products the “low grade” material is upgraded, optimising the use of the material and increasing the economical potential for the saw mills.

In order to fully take advantage of the idea described above, the production of green glued products should be viewed in a large scale perspective. By the use of green-gluing (edgewise gluing, flatwise gluing, defect elimination and finger jointing), possibly in combination with traditional gluing, basic principles of today’s production chain could change. For example, in today’s production of sawn timber in Sweden, logs are cut to lengths being multiples of 300 mm. With the use of a process based on green-gluing, this would not have to be the case. Thus, logs of any length can be handled by the saw mill, logs that are cut to boards and planks which in turn are finger jointed to continuous products and cut to length before kiln drying. It is estimated that this independence of length alone would increase the yield of a typical south-Swedish saw mill by 5-8%.

2 MATERIALS AND METHODS

The basic principle used in the current work is to use freshly cut side boards, face-gluing these to form a beam with rectangular cross-section, and after curing, splitting the beam (if this is desired) to half width. After splitting, the beams are kiln-dried in a traditional manner, together with structural timber of similar size (the thickness of the timber being approximately equal to the beam width). The current work has so far included the following steps:

- Design of beam lay-up
- Choice of adhesive system
- Design of semi-industrial production equipment
- Production of laminated beams
- Evaluation of beam properties – stiffness, strength and shape stability
- Evaluation of interlaminar bonds – strength, fracture energy and integrity (delamination tests) in relation to some production parameters (adhesive amount, clamping pressure, wood density)
- Design of preliminary procedure for CE-marking

2.1 TIMBER AND BEAM LAY-UPS

The raw material used was ungraded spruce side boards, saw falling quality. Two different beam lay-ups have been tested so far, and during spring 2010, additional lay-ups will be tested. The basic idea behind the choice of lay-ups has been to test the traditional lay-ups used in normal glued-laminated beams, and also to test other lay-ups in order to minimise possible distortion and risk of cracking during drying. In Figure 1 the different lay-ups are depicted. The average density of the beams was 499.5 kg/m³, measured at an MC of approximately 15%.

2.2 ADHESIVE SYSTEM

The specific adhesive system to use has not been the main aim of the current research. In [1] a number of possible candidates are mentioned, these being more or less available on the market. As the project has an ambition to give practical recommendations for the industry on the basic principles to be used in the production of green-glued products, the choice was made to use an adhesive system available on the market today. Thus, a 1-component moisture curing polyurethane adhesive was chosen. The adhesive used is not specifically designed for green-gluing, but is in fact an adhesives approved for structural gluing according the European standards.

2.3 PRODUCTION EQUIPMENT

All beams were produced in a press which was designed especially for the current project. The press includes also equipment for application of adhesive, Figure 2, and is capable of clamping simultaneously three beams of 300 mm depth, and of length up to approximately 6 m.
2.4 PRODUCTION OF LAMINATED BEAMS

So far a total of 64 (approximately 60×300×5400 mm$^3$) beams were produced and evaluated. All beams had the target depth 300 mm, produced with ungraded (saw falling) spruce laminations of 25 mm thickness. The beams were produced with laminations of full beam-length. In upcoming work within the project, finger-joints will be included.

The gluing of beams was done using a target clamping pressure of 0.9 MPa and an adhesive spread of 200 g/m$^2$. After gluing, and keeping the pressure for approximately 90 minutes, beams were kept for curing and, following this, additional processing at the saw mill was undertaken. As indicated in Figure 1, the beams were split in two halves, and these halves were then dried in a conventional kiln. After drying, (target moisture content of 16% average obtained was 18%) the beams were finally planed to target size, 50×300 mm$^2$.

In addition to the full size beams, a total of 16 smaller beams were produced for evaluation of adhesive bond line properties: strength and fracture energy.

2.5 EVALUATION OF BEAM AND BOND LINE PROPERTIES

The beams have been tested in terms of bending stiffness, bending strength and shape stability. The bending tests were performed according to EN 408 [6]. After production of the beams (including kiln drying), all beams were stored at standard 20°/65%RH climate for four months. After this, half of the beams were tested with respect to bending stiffness and bending strength. The remaining beams were kept at 20°/65%RH for another month, and had at that time reached a moisture content of 14 to 16% (surface and interior). After this the beams were moved to a climate of 20°/35%RH, and were kept in this climate for three months. Finally, the beams were moved back to the climate 20°/65%RH and kept in that climate for seven months. Finally, the beams were tested for bending stiffness and bending strength. The beams that were exposed to the varying climate were measured in order to monitor the shape stability. Thus beam twist, bow, crook, cupping and the change of cross-sectional shape (deviation from right angle) were determined.

The adhesive bonds were evaluated and tested according to European standards for glued-laminated timber EN 386, [7], EN 391, [8], and EN 392. [9]. Thus shear strength, wood failure percentages and delamination values were determined. The specimens used for shear and for delamination tests were taken from two type A beams and from two type B beams after the bending tests and a total of 48 bonds from the type A beams and 24 bonds from the type B beams were tested for shear strength and delamination. Additional specimens were taken from type A beams that were manufactured especially to study the influence of spread rate. Thus, within these beams, two spread rates were used: 150 and 200 g/m$^2$. These beams are denoted A*.

The delamination cycles applied were according to method A of EN 391, involving the use of a pressure vessel. One cycle involves submerging the test pieces in water (10-20°C), lowering the pressure to obtain a vacuum, and, finally, increasing the pressure again. This is done twice, each time in a 65 minutes cycle. Following this the specimens are dried in an air duct at 60-70°C, for 21-22h at a relative humidity of maximum 15%. The delamination was measured after two cycles only. If the values obtained after two cycles do not meet the requirements (delamination ≤ 5%), the standard suggests an additional cycle, and evaluation of results instead after three cycles (delamination ≤ 10%). The strength and integrity tests performed correspond to those of structural adhesives Type I, service classes I-III.

In addition, also small-scale specimens for testing the fracture properties of the adhesive bond in Mode I was developed. The complete force versus deformation curve, including both the ascending and the descending parts could be obtained with these small-scale specimens. The deformation field of the small-scale specimen was measured with a contact-free technique, based on two cameras and white light. This equipment made it possible to register the strain in and along the bond line and in the wood with a high spatial resolution (0.2 mm). Detailed information about the methods used for testing the bond line fracture properties can be found in [10]. Figure 3 shows the test specimens used for the evaluation of tensile strength and fracture energy. For these specimens also tests on dry glued bond lines and on solid wood specimens were performed.
3 RESULTS AND DISCUSSION

3.1 BEAM STIFFNESS AND STRENGTH

Table 1 summarises the results from the tests in 4-point bending according to EN 408. All strength values refer to a beam depth of 600 mm and to a beam width of 150 mm, using the size factors according to the current European glulam standard EN 1194, [11]. The beam dimensions are in the current case 50×300 mm², and thus the size factor applied in the evaluation was

\[ k_{size} = \left( \frac{50}{150} \right)^{0.05} \left( \frac{300}{600} \right)^{0.1} = 0.88 \]

which implies that the strength of the beams actually tested was approximately 13% higher than reported below.

Table 1: Main test results – beam bending strength (5% value according to EN 14358, [12]) and stiffness. All series comprised 16 beams.

<table>
<thead>
<tr>
<th>Series (4 series with 16 beams in each)</th>
<th>Mean strength [MPa]</th>
<th>Characteristic strength [MPa]</th>
<th>MOE [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – No climate cycling</td>
<td>40.2</td>
<td>31.9</td>
<td>13 700</td>
</tr>
<tr>
<td>A – Climate cycling</td>
<td>40.1</td>
<td>28.1</td>
<td>13 800</td>
</tr>
<tr>
<td>B – No climate cycling</td>
<td>41.3</td>
<td>30.9</td>
<td>14 000</td>
</tr>
<tr>
<td>B – Climate cycling</td>
<td>44.4</td>
<td>37.6</td>
<td>14 500</td>
</tr>
<tr>
<td>All</td>
<td>41.5</td>
<td>32.2</td>
<td>14 000</td>
</tr>
</tbody>
</table>

The results do not indicate any consistent influence of the climatic cycling nor of the orientation of the laminations. Thus, evaluating all tests as one group, the beams fulfil the strength and stiffness requirements of European glulam standard EN 14080, [13]. It is emphasised that all beams were produced with ungraded boards, and that no finger-joints were included.

3.2 SHAPE STABILITY

The shape stability was measured for 32 of the total 64 beams produced. The evaluation was performed before, during and after the climatic cycling as described above. There are currently only rules regarding dimensional tolerances for glulam available in the European standards, and thus no obvious comparison can be made regarding the fulfilment of any criteria. According to a draft for a new version of the glulam standard, EN 14080, values of maximum crook and bow are suggested to be 4 mm for a measuring length of 2 m. In the same draft, a value of 1.15° is given as the recommended maximum deviation from right angles within the rectangular cross-section. The results obtained for the current beams are given in Table 2. The twist, bow and crook were here determined for a measuring length of 3.7 m. Generally speaking, the dimensional stability of the beams is quite good. However, to the naked eye, it turns out that the cupping of a few millimetres (maximum value measured was 2.4 mm) over the rather slender cross-section is clearly visible. Although this is not problematic from a structural point of view, for aesthetical reasons and for marketing reasons when introducing a new product, it is important to improve the shape stability.

Table 2: Test results in terms of shape stability. The table gives average absolute values for the initial state and after three consecutive climatic cycles. A⊥ refers to the deviation from right angles within the cross-section.

<table>
<thead>
<tr>
<th>Series</th>
<th>Initial (1)</th>
<th>20°/65% 5 months</th>
<th>20°/35% 3 months</th>
<th>20°/65% 7 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twist</td>
<td>0.5°</td>
<td>0.8°</td>
<td>1.5°</td>
<td>1.2°</td>
</tr>
<tr>
<td>Bow</td>
<td>2.2mm</td>
<td>2.4mm</td>
<td>3.3mm</td>
<td>1.9mm</td>
</tr>
<tr>
<td>Crook</td>
<td>0.6mm</td>
<td>0.7mm</td>
<td>0.6mm</td>
<td>0.6mm</td>
</tr>
<tr>
<td>Cup</td>
<td>0.3mm</td>
<td>0.9mm</td>
<td>1.5mm</td>
<td>1.3mm</td>
</tr>
<tr>
<td>Δ⊥</td>
<td>0.3°</td>
<td>0.4°</td>
<td>0.6°</td>
<td>0.5°</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twist</td>
<td>0.4°</td>
<td>0.9°</td>
<td>1.7°</td>
<td>1.4°</td>
</tr>
<tr>
<td>Bow</td>
<td>1.8mm</td>
<td>1.4mm</td>
<td>1.4mm</td>
<td>1.2mm</td>
</tr>
<tr>
<td>Crook</td>
<td>1.1mm</td>
<td>1.1mm</td>
<td>1.0mm</td>
<td>1.0mm</td>
</tr>
<tr>
<td>Cup</td>
<td>0.2mm</td>
<td>0.5mm</td>
<td>1.3mm</td>
<td>1.0mm</td>
</tr>
<tr>
<td>Δ⊥</td>
<td>0.4°</td>
<td>0.4°</td>
<td>0.4°</td>
<td>0.3°</td>
</tr>
</tbody>
</table>

3.3 BOND LINE STRENGTH AND INTEGRITY

In Table 3 a summary of the bond line test results is given. The average shear strength and corresponding wood failure percentage, determined according to the test method of EN 392, fulfil the requirements of Type I adhesives for use in service class I-III. The delamination results are close to fulfilling these requirements using the spread rate of 200 g/m². The possibility of performing a third test cycle in delamination was not used and it is therefore possible that the adhesive would fulfil that requirement (max 10% delamination).

Table 3: Test results from bond line tests. Values in parenthesis are standard deviations.

<table>
<thead>
<tr>
<th>Beams type</th>
<th>Mean shear strength (MPa)</th>
<th>Mean wood failure (%)</th>
<th>Delamination (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9.4 (1.5)</td>
<td>94 (12)</td>
<td>3.4</td>
</tr>
<tr>
<td>B</td>
<td>10.3 (1.4)</td>
<td>91 (13)</td>
<td>5.5</td>
</tr>
<tr>
<td>A* (150 g/m²)</td>
<td>9.5 (1.9)</td>
<td>86 (13)</td>
<td>5.9</td>
</tr>
<tr>
<td>A* (200 g/m²)</td>
<td>9.9 (1.2)</td>
<td>93 (10)</td>
<td>3.1</td>
</tr>
</tbody>
</table>

3.4 BOND LINE FRACTURE PROPERTIES

The recorded normal stress (i.e. force divided by nominal bond area which is 40 mm², see Figure 3) was
plotted against calculated deformations obtained from the contact free deformation measurement system (Aramis™). An example is given in Figure 4. This curve represents the deformation across the adhesive bond line and additional deformation of the adjacent wood. The elastic response during the test is represented by the initial linear part. The fracture energy, \( G_f \), is defined as the area below the stress versus deformation curve and was evaluated by subtracting the elastic deformations from the measured curve. Thus only inelastic deformations were included in the evaluation of \( G_f \), see Figure 4. The non-linear deformation of the ascending part of the curve includes most likely some plastic deformation of the adhesive and probably some micro-cracking of the bond line or of the wood material. After reaching maximum load, the descending part of the curve represents the progressive failure of the specimen.

The results from the bond line fracture tests are given in Table 4, showing that the strength of the green glued bonds was higher than that of dry glued bonds. The fracture energy, \( G_f \), was lowest for solid wood and higher for the green- and dry-glued bonds.

Table 4: Test results from bond line fracture properties tests. Values in parenthesis are standard deviations.

<table>
<thead>
<tr>
<th>Type of specimen</th>
<th>Tensile strength (MPa)</th>
<th>Fracture energy, ( G_f ) (Nm/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid wood</td>
<td>5.26 (0.70)</td>
<td>302 (41)</td>
</tr>
<tr>
<td>Green glued</td>
<td>5.85 (0.56)</td>
<td>323 (100)</td>
</tr>
<tr>
<td>Dry glued</td>
<td>3.88 (0.33)</td>
<td>489 (65)</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

The following main conclusions are drawn from this research:

- With a new view on timber processing, there is a possibility for today’s saw mills to produce products with a high degree of added value.
- The product type evaluated here shows excellent properties, especially bearing in mind that the raw material was ungraded, saw falling quality.
- The continued research within the current area will address
  - grading of unseasoned side boards, (optical and dynamic methods)
  - finger joints
  - optimisation of beam lay-ups for optimum stiffness, strength and shape stability

ACKNOWLEDGEMENTS

The financial support, from CBBT – Centre for building and living with wood, which made this research possible, is gratefully acknowledged.

REFERENCES

[12] EN 14358 Timber structures – Calculation of characteristic 5-percentile values and acceptance criteria for a sample.