Wet glued laminated beams using side boards of Norway spruce

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Linnaeus University

Södra

SP Trätek
Preface

The research project reported herein concerns the development of glulam beams for load bearing applications using wet glued side board laminations of Norway spruce. The work has been carried out in co-operation between the Södra Timber Company, Linnaeus University (until 1 January 2010 called Växjö University) and SP Trätek, a part of SP Technical Research Institute of Sweden. The necessary financial means have been provided by CBBT, the Centre for Building and Living with Wood Foundation.

The project, which is a continuation of two previous projects concerning wet gluing of side boards into high-value wood construction products, has been running from January 2009 to December 2010 and the work has been carried out by a project group including the following persons:

- Mr. Tomas Bengtsson, technical manager, Södra Timber,
- Mr. Johan Blixt, head of business development, Södra Timber,
- Mr. Lars Eliasson, M.Sc. and Ph.D. student, Linnaeus University,
- Mr. Bertil Enquist, research engineer, Linnaeus University,
- Mr. Bo Källsner, adjunct professor, Linnaeus University and SP Trätek,
- Mr. Jan Oscarsson, M.Sc., Ph.D. student and project co-ordinator, SP Trätek,
- Mr. Hans Petersson, professor, Linnaeus University,
- Mr. Erik Serrano, professor and project leader, Linnaeus University, and
- Mrs. Magdalena Sterley, tech. lic. and Ph.D. student, SP Trätek.

On behalf of the financing organisation, Mr. Florian Witt, operations responsible at CBBT, has participated as observer and advisor.

Växjö 29 March 2011

Erik Serrano
Project leader, Linnaeus University

Jan Oscarsson
Project co-ordinator, SP Trätek
Abstract

In a previous research project, carried out during the years 2006-2008, the possibility to manufacture wet glued laminated beams using ungraded laminations of Norway spruce side boards was investigated with very promising results.

In the project presented in this report, the performance of the wet glued beams has been further investigated and developed as regards grading of side board laminations, bond line properties and lamination finger jointing. The possibility to use scanning equipment for measurement of fibre angles and prediction of strength and stiffness of boards and beams has been studied and the procedures for technical approval and CE marking have been probed into. Studies concerning market and economy for the beams and layouts for a pilot plant and a full capacity plant, respectively, for production of such beams have also been carried out.

The possibility to grade side boards in the wet state using axial dynamic excitation was investigated with a positive result. From such excitation, a board’s stiffness (modulus of elasticity) could be determined. Accordingly, grading criteria regarding axial stiffness, and knot size, was applied to grade side board laminations into two classes; outer and inner laminations. Strength and stiffness tests of beams manufactured from such graded laminations showed that the beams actually could challenge first rate glulam and LVL products available on the market.

Regarding beam shape and shape stability, cross section cupping may need further attention. Even if this deformation was small, it was still visible to the naked eye. The problem could probably be overcome if the beams are dried to a moisture content of 12-14% before planing.

Results of shear tests show that green glued bond lines can fulfil strength requirements for glulam. However, delamination requirements for service class 3 (outdoors) were not fully met. From small scale tensile testing of glued bonds it was concluded that green glued bonds with high density wood have the same tensile strength and fracture energy as dry glued bonds. For bonds with low density wood and/or small amount of adhesive, the tensile strength could be lower than for dry glued bonds, whereas the fracture energy was on a similar level.

Strength testing of wet and dry glued finger joints demonstrated that joints glued from high density wood was significantly stronger than low density joints and that there was no significant difference between the strength of green glued joints and joints glued after drying. From X-ray measurement it was shown that the glue penetration into the wood fibres is much deeper in a green glued joint than in a joint that is glued in the dried state.

From scanning algorithms developed within the scope of this project it is possible to obtain reasonably accurate predictions of grain-angle distributions on board surfaces as well as rather accurate descriptions of knot locations and of fibre-angle disturbances around knots. From scanning of board ends, cross section characteristics with respect to radial and tangential directions and of annual ring widths could also be determined. Finally, both board and beam stiffness were predicted from this data, with an accuracy that is comparable with the one obtained from well-reputed commercial grading systems.

Key words: wet gluing, green gluing, side boards, scanning, strength grading, laminated beams.
Sammanfattning


Det arbete som redovisas i föreliggande rapport har omfattat fördjupade studier av denna typ av lamellerade balkar med särskild tonvikt lagd på sortering av sidobräderna, limfogarnas mekaniska egenskaper samt fingerskarvning av lamellerna. Möjligheten att använda skanning för att mäta fibervinklar och för att förutsäga lamellernas och balkarnas styvhet och styrka har också undersöks, liksom förutsättningarna för CE-märkning av den tänkta produkten. Marknadsaspekter och de ekonomiska förutsättningarna för produktion har också studerats.


Vad gäller balkarnas form och formstabilitet är det möjligt att sortera sidobräder genom axiell dynamisk excitering. Den utformningen var liten, men på grund av balktvärsnittens slanka form trots det synliga. Om balkarna torkas till lägre fuktkvot (12-14%) före hyvling bör dessa problem kunna undvikas.

Både skjuvprovning och delamineringsprovning av limfogar tagna från balkarna har genomförts. Dessa provningar visar att limfogarna uppfyller kraven för limträ avsedda för användning i klimatklass 1-2. De strängare kraven som ställs för konstruktioner i klimatklass 3 har däremot inte uppnåtts fullt ut. Vidare har små limfogprovkroppar provats för bestämning av hållfasthet och brottenergi i dragning vinkelrät fogen (Mod I). Provningarna visar bl.a. att de våtlimmade fogarna i trä med hög densitet har samma hållfasthet och brottenergi som torrlimmade fogar. För fogar i trä med låg densitet, och/eller för fogar med låg limmängd, var hållfastheten lägre för de våtlimmade än för de torrlimmade fogarna, medan brottenergin var ungefär densamma.


Genom de algoritmer som utvecklats i projektet visas i föreliggande rapport att det är möjligt att, med tillfredsställande noggrannhet, mäta fibervinkeln och dess fördelning över brädornas ytor. Dessutom kan man få relativt detaljerad information om kviststorlek, kvistlåge och de fiberstörningar som förekommer i närheten av kvistarna. Genom skanning av ändträytor visade det sig också möjligt att bestämma tvärsnittskarakteristik som årsringorientering och årsringbredd. Denna information användes sedan för att förutsäga styvheten i sidobräderna och i de lamellerade balkarna. Den precision som uppnåddes är i paritet med vad som idag går att få med välrenommerade kommersiella sorteringsmaskiner.

Nyckelord: våtlimning, grönlimning, sidobräder, skanning, hållfasthetsortering, laminerade balkar.
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1 Introduction

1.1 Background

Timber to be used in structural applications must possess sufficient strength, stiffness and shape stability to be able to fulfil requirements in relevant building codes and standards. For the Swedish sawmilling industry, the use of Norway spruce (*Picea abies*) in such applications is of great economical value. However, about 30% of the volume of sawn timber produced at a typical sawmill in the south of Sweden consists of side boards, *i.e.* boards of narrow dimensions sawn from the outer parts of a log. Due to their small dimensions, such boards are seldom used for load bearing purposes. Large production volumes and small dimensions imply that considerable numbers of side board pieces have to be handled in the sawmilling process and the costs for production, storage and sales are in many cases not met by the selling price on the market.

From previous research it is well known that several wood characteristics that influence the structural properties of sawn timber vary in a distinct way from pith to bark. For example, the longitudinal modulus of elasticity (MOE) in softwood trees increases significantly from pith and outwards (Wormuth 1993), and since there is a correlation between stiffness and strength in wood (Hoffmeyer 1995), this means that the strength at the bark of a log is larger than at the pith. A similar variation in the radial direction in logs has also been found for density (Steffen *et al.* 1997). Accordingly, side boards possess excellent structural properties and using such boards as laminations in engineered wood products, added value for the sawmilling industry would be achieved.

Since the year of 2004, Linnaeus University (until 1 January 2010 called Växjö University) and SP Trätek, a part of SP Technical Research Institute of Sweden, carry on research that is directed towards the development of high-value construction products based on Norway spruce side boards. This work is carried out in co-operation with the Södra Timber Company. In a pilot study performed during the years 2004 and 2005 it was shown that the performance of bond lines between flatwise wet-glued pairs of side boards was very good, and that the strength of the wet-glued side board pairs was better than for corresponding centre yield structural timber (Källsner and Petersson 2005). However, there was a potential for improvement as regards the shape stability of the glued products (Petersson *et al.* 2005). During the years 2006–2008, a comprehensive investigation concerning the possibility to use unseasoned side boards as laminations in wet-glued laminated beams for load-bearing applications was carried through (Petersson *et al.* 2009 and Serrano *et al.* 2010). Despite the fact that the beams were produced from batches of ungraded boards, their performance in terms of strength fulfilled the requirements of glulam GL32h according to the European standard EN 1194. As regards the stiffness, the performance was even better. The bond lines were found to be able to comply with requirements relevant for bond lines in (indoor) structural applications. Regarding shape stability, the cross section cup of the beams was, although small in relation to requirements stipulated in relevant standards for sawn timber (EN 14081-1), unfortunately beyond what could be assumed as acceptable on the market for a laminated product.

1.2 Objectives and goals

The overall objective of this project, which has been carried out from January 2009 to December 2010, has been to process low value sawyield in the form of Norway spruce side boards, obtained from the splitting process at a typical south-Swedish sawmill, into engineered wood products with much higher value. This could be divided into four parts:
• to demonstrate, by market analyses and investment estimations, the economical potential for manufacturing laminated wet glued beams from unseasoned finger-jointed and flat glued side boards,
• to verify, by experimental investigations, manufacturing methods and technical performance of the beams,
• to produce relevant data and documentation needed for technical approval and/or product certification of the beams, and
• to investigate and describe differences between, and pros and cons of, gluing in the wet and dried states, respectively.

The long term goal of the project has been to demonstrate the possibility to create a new market for high value wood construction products that are produced from sawyield that is often unprofitable today.

According to the project plan, the following results should be at hand at the project end:
• a product with well-documented properties,
• requirements regarding the production of the product,
• necessary documentation for the assessment of conformity of the product, leading to CE marking and/or national technical approval of both the wet glued beam itself and the glue used therein, and
• identification of a planned construction in which the product could be built-in as parts of the load bearing structure.

1.3 Manufacturing process – differences between gluing in wet and dried states

By gluing in the wet state, a much more cost efficient handling of side boards in the sawmilling process is expected, in comparison with the corresponding process used when gluing is carried out after drying. The manufacturing processes in the two states differ significantly from several points of view, see Figure 1 and Figure 2.

Figure 1. Manufacturing process: Gluing after drying (dry gluing).

Figure 2. Manufacturing process: Gluing before drying (wet gluing).

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1 In this case, the concept of “dry gluing” means gluing at a lamination moisture content below 16%.
In the dry gluing process, the boards are dried and planed before gluing. During drying, the cut fibres at board ends cause local and very fast drying in the fibre direction which incur board end cracks to appear. Occurrence of such cracks makes trimming of board ends necessary, which means a reduction of both board lengths and sawing yield. Furthermore, when water evaporates from the boards, the cross section adopts a cup shape, which necessitates planing before flat gluing of boards into beams. Since the side boards are of narrow dimensions, such planing reduces the sawing yield even further.

In the wet gluing process, the gluing is carried out using straight and flat boards for which only smoothing is needed. The last-mentioned process step means that the flat surfaces of a board are rendered plane-parallel by “careful” planing. The amount of material loss produced from smoothing is much less in comparison with the amount that is generated from planing of cupped and twisted boards after drying. Thus, by gluing in the wet state, a significant increase of the sawing yield could be obtained. Defect elimination of boards using finger jointing before drying will reduce the costs, since processing of defective boards will be avoided. Another important benefit of wet gluing of side boards is that gluing is carried out early in the process, which means that the resource consuming piece handling of the boards is heavily reduced. It should also be noted that wet gluing could imply both energy and investment savings, since gluing can be carried out at room temperature, whereas dry gluing requires preheating/warm-pressing including e.g. investments for RF (microwave) equipment. The problem regarding board end cracks discussed above could also occur when entire beams are dried, but in the last case the local drying in the fibre direction at board ends could be prevented by sealing of entire beam ends.

A disadvantage of wet gluing is that the requirements regarding logistics between the process steps splitting of logs and gluing increase, since the surfaces that are to be glued must not dry. In addition, investments in new processing and production plants are needed since the logistics in the processes of wet gluing and dry gluing, respectively, differs significantly. Regarding the performance of the products that are investigated in this project, it has been concluded that the shape stability of the beams requires further consideration. The problem could be handled either by kiln-drying of the beams to a moisture content of 12-14% before planing, or by grading of the boards with respect to fibre angle and lamination orientation in the beams in a way that minimize the shape distortion of the beams during drying.
2 Beam tests

2.1 Test methods and evaluation of results

2.1.1 Bending tests

Below, a number of test series that have been performed are presented. In these tests, the bending stiffness and the bending strength of the various beams were tested. The tests were all performed in 4-point bending, according to EN 408. Due to the limited length of the beams, the standard 18 times beam depth was not possible to use for the total span of the beams. Instead, 16 times the beam depth was used, as is also allowed according to the standard. The test set-up used is depicted schematically in Figure 3.

Two different types of deflection measurements were used, denoted $v$ and $w$ in the figure. The local deformation, $v$, includes the deformation due to bending only, since there is no shear force in the mid span. The deformation denoted $w$ includes deformation due to shear but also due to local effect at supports. Therefore, the most relevant stiffness to report is the one calculated using the deformation $v$. This stiffness is also known as local modulus of elasticity (local MOE). All tests were performed in displacement control, the loading speed set such that failure was reached within 5-10 minutes.

Prior to testing to failure, the stiffness was determined by calculating the deformation between two load levels, these being 2 and 12 kN, respectively. The 12 kN load level corresponds to approximately 30% of the ultimate load. All test results in terms of strength have been evaluated in relation to EN 14358, and EN 14080, assuming a lognormal distribution of bending strength with unknown standard deviation. The characteristic values are determined as 5-percentiles at 75% confidence level. The results are in some of the tables normalised to be representative for a beam of 600 mm depth and 150 mm width, as required by EN 1194. In the tests, 300 mm deep and 50 mm wide beams were used. This means that the actual test values were approximately 13% higher than the one reported as characteristic value for a 600 mm deep beam.

![Figure 3. Four point bending set-up used in the experimental investigations on bending behaviour.](image)

2.1.2 Shape stability

The shape stability has been evaluated by cycling the beams in various climates, as reported below. The shape of the beams was measured at delivery to the University and after completing the different climatic cycles. In those measurements a special rig as shown in Figure 4 was used, making it possible to measure twist, cup, bow, crook and cross-sectional distortion. At position A, see Figure 4, the beam is fixed to the rig in all directions ($x$-, $y$- and $z$-direction). At position B, the beam does not have contact with the rig, and at position C, the beam is again in contact with the rig.
Figure 4. Rig used to measure beam size and distortion.

### 2.2 Beam test series I and II

In previous publications (Petersson et al. 2009 and Serrano et al. 2010) a number of beam tests have been reported. These test results are summarised in the tables below. In brief, beam test series I comprised both conventionally glued and green-glued beams, all with a traditional glulam lay-up in terms of annual ring orientation of the laminations, see orientation type A, Figure 5. The beams were glued in a pressing equipment which was used only in that series, since it turned out to be difficult to accurately control the pressure. For beam test series II, a new semi-automatic adhesive application and pressing equipment was developed. In series II only green-glued beams were evaluated, the main purpose being that of investigating the influence on the shape stability of alternative annual ring orientations, see orientation type D, Figure 5. Additional details of the manufacturing and testing of the beams of series I and II can be found in Petersson et al. (2009).

#### Table 1. Summary of test results, green-glued beams without climatic cycling, series IIa and IIc. Values of bending strength, MOE and density refer to values at climate 20°C/65%RH.

<table>
<thead>
<tr>
<th>Test series</th>
<th>No. of beams</th>
<th>Orientation (lamination thickness)</th>
<th>Bending strength (MPa)</th>
<th>Bending strength (MPa)</th>
<th>MOE (local, mean values) (MPa)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIa+IIc</td>
<td>32</td>
<td>A+D</td>
<td>Mean 46.2 Char. 36.2</td>
<td>Mean 40.7 Char. 31.95</td>
<td>13850</td>
<td>501</td>
</tr>
</tbody>
</table>

#### Table 2. Test results, series I and II. Values of bending strength, MOE and density refer to values after climatic cycles. See 3rd column for final climate of each cycle.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Gluing Climatic cycling (RH)</th>
<th>No. of beams</th>
<th>Orientation (lamination thickness)</th>
<th>Bending strength (MPa)</th>
<th>MOE (local, mean values) (MPa)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>Dry No¹</td>
<td>15</td>
<td>A (21 mm)</td>
<td>Mean 43.9 Char. 35.2</td>
<td>14210</td>
<td>495</td>
</tr>
<tr>
<td>Ib</td>
<td>Green No¹</td>
<td>12</td>
<td>A (21 mm)</td>
<td>Mean 44.8 Char. 35.8</td>
<td>13860</td>
<td>498</td>
</tr>
<tr>
<td>Ic</td>
<td>Green 50-90-50</td>
<td>13</td>
<td>A (21 mm)</td>
<td>Mean 42.6 Char. 31.4</td>
<td>13750</td>
<td>504</td>
</tr>
<tr>
<td>IIa</td>
<td>Green No⁶</td>
<td>16</td>
<td>A (25 mm)</td>
<td>Mean 45.5 Char. 36.2</td>
<td>13680</td>
<td>495</td>
</tr>
<tr>
<td>IIb</td>
<td>Green 65-35-65</td>
<td>16</td>
<td>A (25 mm)</td>
<td>Mean 45.5 Char. 31.8</td>
<td>13800</td>
<td>492</td>
</tr>
<tr>
<td>IIc</td>
<td>Green No⁶</td>
<td>16</td>
<td>D (25 mm)</td>
<td>Mean 46.8 Char. 35.1</td>
<td>14030</td>
<td>507</td>
</tr>
<tr>
<td>IId</td>
<td>Green 65-35-65</td>
<td>16</td>
<td>D (25 mm)</td>
<td>Mean 50.4 Char. 42.7</td>
<td>14510</td>
<td>504</td>
</tr>
</tbody>
</table>

¹ Beam tests carried out after conditioning at climate 20°C/50%RH.
² Beam tests carried out after conditioning at climate 20°C/65%RH.
Table 3. Test results, series I and II: Mean values of shape stability. Values were measured after each step of the conditioning cycle (for series II also after kiln drying, prior to conditioning).

<table>
<thead>
<tr>
<th>Test series</th>
<th>Climatic cycling</th>
<th>Number of beams</th>
<th>Orientation (lam. thickness)</th>
<th>Twist&lt;sup&gt;a&lt;/sup&gt; (degrees)</th>
<th>Bow&lt;sup&gt;a&lt;/sup&gt; (mm)</th>
<th>Crook&lt;sup&gt;a&lt;/sup&gt; (mm)</th>
<th>Cup (mm)</th>
<th>Distortion (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic Kiln</td>
<td>50</td>
<td>13</td>
<td>A (21 mm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td></td>
<td></td>
<td>1.2</td>
<td>1.9</td>
<td>1.2</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td></td>
<td></td>
<td>0.6</td>
<td>1.0</td>
<td>1.1</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>IIb Kiln</td>
<td>65</td>
<td>16</td>
<td>A (25 mm)</td>
<td>0.5</td>
<td>2.2</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td>0.8</td>
<td>2.4</td>
<td>0.7</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td></td>
<td></td>
<td>1.5</td>
<td>3.3</td>
<td>0.6</td>
<td>1.5</td>
<td>0.6</td>
</tr>
<tr>
<td>IIId Kiln</td>
<td>65</td>
<td>16</td>
<td>D (25 mm)</td>
<td>0.4</td>
<td>1.8</td>
<td>1.1</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td>0.9</td>
<td>1.4</td>
<td>1.1</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td></td>
<td></td>
<td>1.7</td>
<td>1.4</td>
<td>1.0</td>
<td>1.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

<sup>a</sup> Measured along a length of 3.72 m

2.3 Beam test series III

2.3.1 Introduction and overview of beam manufacturing

One purpose of conducting the third test series was to evaluate possible alternatives for the orientation of the laminations within the beam (orientation of annual rings). Another purpose was to evaluate the possibility of grading the laminations in the wet state and to use that grading information to optimise the beam lay-up by placing high quality laminations in the outer parts of the beam, similar to how combined glulam is produced.

In beam test series III, side boards 120 mm wide, 21.5 mm thick and 5400 mm long were used. Each board was split into two halves, approximately 58 mm wide, and 15 split boards were stacked on top of each other to form the beam cross section, approximately 320 mm deep and 58 mm wide in the wet state. The beams were kiln dried and planed after curing, the final dimensions of the beam cross section being approximately 50×300 mm. Out of the 15 laminations of the beam, the outer 3 on both sides were high-quality “outer laminations”, the remaining 9 being lower-quality “inner laminations”. The grading used for classifying the boards into the correct lamination type is described below.

The beam tests performed included both static bending tests to evaluate strength and stiffness and evaluation of the shape stability of the beams. In the latter case, the beam dimensions were measured after kiln drying and planing, and after the beams had been stored at different climates.

2.3.2 Design of beam lay-ups

In general, the annual ring orientation is known to influence the shape stability of timber. Thus, in order to minimise the cup in the beam cross-section, finding an optimal annual ring orientation is of great concern. The laminations used here were cut such that the pith was located approximately along the edge of the lamination. Four different principles for orienting the laminations within the beam cross-section were considered, see Figure 5.
These four orientations, denoted A-D, were discussed during the design of test series III-beams. Orientation of type A is a traditional orientation used for glulam, and was also tested in test series I, as reported above. The orientation of type D was tested in series II, and should in principle lead to less distortion of the cross-section than type A. Note that in series II, orientation of type A was used as reference, see Table 2 and Table 3.

A theoretical investigation using linear elastic finite element analyses was performed to get a qualitative indication of the influence of the annual ring orientation, see Figure 6. Following the finite element analyses, it was decided to investigate orientation type B in test series III since it was concluded that orientation B would lead to less distortion of the cross-section. Note that beam lay-ups B and C rely on the laminations being split to their final width before gluing the laminations together to form the beam cross-section. Beam lay-ups A and D can be manufactured by splitting the beam after gluing has the advantage of minimising waste, since only two sides have to be planed, and generally the waste from the saw cut is less than the waste from planing.

It was decided to include in test series III not only annual ring orientation B, but to also include, as a reference, annual ring orientation D. By comparing the distortion between these two orientations for pairs of beams with matched laminations the variability could be kept at a minimum. The matching procedure was realised by first splitting wider boards into two
halves, one such half being used as a type D-lamination in a type D-beam, the other half being used as a type B-lamination at the same position in the corresponding type B-beam. Therefore, test series III included pairs of beams, each pair being one type B-orientation beam and one type D-orientation beam. Each lamination in a type B-beam was thus matched as close as possible with the lamination at the corresponding position of the type D-beam.

Before gluing the beams, the laminations were also graded, as described below. This meant that not all laminations could be used, since there was a constraint that both halves should be placed at the same position in corresponding beams. Thus, if one half was graded (based on either stiffness or knot size) as being an outer lamination and the other as an inner lamination (see chapter 2.3.3 below), both halves had to be rejected. However, it turned out that a slight relaxation of this requirement was necessary, see chapter 2.3.3 below).

The above described, somewhat complicated, procedure was used in order to minimise variability, and thereby simplify the evaluation of the results. In production, clearly this approach cannot be used, for practical reasons.

2.3.3 Grading of boards and beam manufacturing

After splitting the original boards of dimension 21.5×120×5400 mm into two halves, the split boards were graded. It was decided to use two grading criteria in order to classify the boards into inner laminations, outer laminations and rejects. First, a visual grading was performed, in which maximum knot size was checked. For outer laminations, the maximum wide face knot size was set to 25 mm. No criterion on maximum knot size was set for inner laminations.

Following the visual grading, an MTG hand-held timber grader was used in order to determine the MOE of each lamination. The grader is a wireless measuring instrument for strength grading of structural timber (Brookhuis Micro-Electronics BV 2009). It is approved as a machine grading system with settings listed in EN 14081-4 and the approval concerns timber with mean moisture content between 10 and 25%. A grading set includes grader, balance and computer software and hardware, see Figure 7 (right).

The MTG grader measures the first axial resonance frequency, see Figure 7 (left), which is excited by a blow of a metal piston built into the grader. The frequency is related to the member length L [m], density \( \rho \) [kg/m\(^3\)] and average dynamic MOE [Pa] in the axial direction (E\(_{An}\)) of the board, according to Equation 1 (e.g. Ohlsson and Perstorper 1992)

\[
f_{An} = \left( \frac{n}{2L} \right)^2 \frac{E_{An}}{\rho}
\]

in which \( n \) denotes the mode number. Since MOE is a material property that varies along the length of a board, E\(_{An}\) is an apparent MOE that reflects a mean MOE value in a board. The described method is today used for strength grading of structural timber in the dried state, i.e. typically timber with a moisture content of about 16-18%. It has also been shown (Oscarsson et al. 2010a-c) that this grading method can be used for boards in the wet state. As an example from that investigation, the coefficient of determination between the dynamic MOEs measured in wet and dried state, respectively, was found to be \( r^2=0.92 \). In this context, it should be noted that grading systems using axial resonance frequency have recently been approved for wet state grading of structural timber (e.g. CEN/TC124/TG1 2010). In this investigation, the board’s weight and the first natural frequency were obtained from the balance and the grader, respectively, and density and MOE were calculated manually, the last property by reformulation of Equation 1.
For outer laminations, the MOE-criterion was 12 000 MPa. Boards with MOE-values between 7 000 and 12 000 MPa were used as inner laminations and boards with MOE less than 7 000 MPa were rejected. However, the laminations were produced from a batch of boards of excellent quality which implied that it was actually difficult to find a sufficient number of inner laminations. Due to this, for a minor number of lamination pairs comprising one outer and one inner lamination (with respect to MOE), both laminations were graded to be inner laminations. For pairs comprising laminations with MOE>12 000 MPa, but with maximum knot size being >25 mm in one of the laminations, both laminations were rejected.

A total of 2×183 halves, in total 366 laminations, were graded for final use in beams. The MOE-matching between these pairs of laminations is depicted in Figure 8. Of the 183 lamination pairs, 72 pairs were graded as outer laminations and 108 pairs as inner laminations in manufacturing 12 beams type D and 12 beams type B, see Figure 5. The cumulative density functions of the MOE of the different types of laminations are shown in Figure 9. Obviously the different lamination types were well separated into two groups.
All beams were manufactured using the same equipment as described above, using the same type of adhesive (Dynea Prefere 6000). The nominal spread was 200 g/m² and the nominal curing pressure was 0.9 MPa, which was applied during approximately one hour.

The test plan comprised 12 pairs of beams B1-B12 and D1-D12. However, due to malfunction of the beam press, and also due to uncontrolled drying of the beams, leading to large end cracks, the final test plan comprised only 7 pairs of matched B- and D-beams (B3/D3, B4/D4, B5/D5, B6/D6, B7/D7, B10/D10 and B11/D11). In addition to these, 3 beams of type B or D, but without any “partner” were available (D1, B2, D12) and 2 pairs of beams with larger end cracks (B8/D8 and B9/D9). This makes a total of 21 out of the planned 24 beams, according to Table 4. After gluing, the beams were kiln dried to target moisture content of 16-18% by including them in a standard drying batch with large dimension lumber (75 mm thickness) at the sawmill. After drying, the beams were planed to target size, 50×300 mm, and finally transported to the University for conditioning in a climate chamber with the standard climate 20°C/65%RH. The test plan for the 21 beams is summarised in Table 5. According to the plan, 7 beams were to be tested to failure in the first series (as indicated by the notation $E, f_{m}$ in the fourth column of Table 5). Of these 7 beams, 2 were not included in the evaluation of the test results (B9 and D8) due to large drying cracks at the ends of the beams.

Table 4. Overview of beams for testing in series III.

<table>
<thead>
<tr>
<th>Beam pair</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>-/D1</td>
<td>B1 not available due to press malfunction</td>
</tr>
<tr>
<td>B2/-</td>
<td>D2 not available due to press malfunction</td>
</tr>
<tr>
<td>B3/D3</td>
<td>OK</td>
</tr>
<tr>
<td>B4/D4</td>
<td>OK</td>
</tr>
<tr>
<td>B5/D5</td>
<td>OK</td>
</tr>
<tr>
<td>B6/D6</td>
<td>OK</td>
</tr>
<tr>
<td>B7/D7</td>
<td>OK</td>
</tr>
<tr>
<td>B8/(D8)</td>
<td>D8 has large drying crack</td>
</tr>
<tr>
<td>(B9)/D9</td>
<td>B9 has large drying crack</td>
</tr>
<tr>
<td>B10/D10</td>
<td>OK</td>
</tr>
<tr>
<td>B11/D11</td>
<td>OK</td>
</tr>
<tr>
<td>-/D12</td>
<td>B12 not available due to press malfunction</td>
</tr>
</tbody>
</table>
Table 5. Overview of planned testing in series III. $E$ and $f_{m}$ denote testing of bending stiffness and bending strength, respectively. The columns represent the various tests being performed.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Initial shape</th>
<th>20°C/65% RH</th>
<th>Shape</th>
<th>Bending test</th>
<th>20°C/35% RH</th>
<th>Shape</th>
<th>20°C/85% RH</th>
<th>Shape</th>
<th>20°C/65% RH</th>
<th>Shape</th>
<th>Bending test</th>
</tr>
</thead>
<tbody>
<tr>
<td>-/D1</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B2/-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B3/D3</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
</tr>
<tr>
<td>B4/D4</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
</tr>
<tr>
<td>B5/D5</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
</tr>
<tr>
<td>B6/D6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
</tr>
<tr>
<td>B7/D7</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
</tr>
<tr>
<td>B8/(D8)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(B9)/D9</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B10/D10</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
</tr>
<tr>
<td>B11/D11</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
</tr>
<tr>
<td>-.D12</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$E_f_m$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2.3.4 Bending tests

Beam bending tests were performed after having stored the beams in standard climate 20°C/65%RH for approximately 5 months. After this time period, the moisture content (MC) of the beams was found to be approximately 14.5% at the surface and approximately 16.5% in the centre, these values being obtained with a pin-type (resistance) moisture meter.

The tests were performed as 4-point bending, with the loading points being located such that the zone of constant bending moment was equal to 6 times the beam depth, as given in the standard EN 408. The MOE of the beams was evaluated both as local MOE and global MOE, the former being based on measuring the deformation (curvature) in the zone with constant bending moment. The results from the tests are summarised in Table 6.
Table 6. Overview of first bending tests of series III, after conditioning at climate 20°C/65%RH. The characteristic strength value is calculated according to EN 14358, but is of course very uncertain due to the small number of specimens.

<table>
<thead>
<tr>
<th>Beam</th>
<th>MOE Local (MPa)</th>
<th>MOE Global (MPa)</th>
<th>Bending strength (MPa)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>13750</td>
<td>12600</td>
<td>49.8</td>
<td>509</td>
</tr>
<tr>
<td>B3</td>
<td>13450</td>
<td>12240</td>
<td>-</td>
<td>483</td>
</tr>
<tr>
<td>B4</td>
<td>14570</td>
<td>12950</td>
<td>-</td>
<td>508</td>
</tr>
<tr>
<td>B5</td>
<td>15200</td>
<td>13260</td>
<td>-</td>
<td>484</td>
</tr>
<tr>
<td>B6</td>
<td>14210</td>
<td>12420</td>
<td>-</td>
<td>493</td>
</tr>
<tr>
<td>B7</td>
<td>14500</td>
<td>12800</td>
<td>-</td>
<td>507</td>
</tr>
<tr>
<td>B8</td>
<td>14020</td>
<td>12180</td>
<td>47.7</td>
<td>491</td>
</tr>
<tr>
<td>B9 (excluded)</td>
<td>13910</td>
<td>12090</td>
<td><strong>34.9</strong></td>
<td><strong>509</strong></td>
</tr>
<tr>
<td>B10</td>
<td>14810</td>
<td>12920</td>
<td>-</td>
<td>495</td>
</tr>
<tr>
<td>B11</td>
<td>14350</td>
<td>12920</td>
<td>-</td>
<td>491</td>
</tr>
<tr>
<td>D1</td>
<td>14160</td>
<td>12180</td>
<td>52.7</td>
<td>464</td>
</tr>
<tr>
<td>D3</td>
<td>13290</td>
<td>12050</td>
<td>-</td>
<td>484</td>
</tr>
<tr>
<td>D4</td>
<td>14390</td>
<td>13050</td>
<td>-</td>
<td>509</td>
</tr>
<tr>
<td>D5</td>
<td>13840</td>
<td>12440</td>
<td>-</td>
<td>481</td>
</tr>
<tr>
<td>D6</td>
<td>13080</td>
<td>11690</td>
<td>-</td>
<td>485</td>
</tr>
<tr>
<td>D7</td>
<td>14600</td>
<td>13020</td>
<td>-</td>
<td>507</td>
</tr>
<tr>
<td>D8 (excluded)</td>
<td>13690</td>
<td>11070</td>
<td><strong>22.4</strong></td>
<td><strong>494</strong></td>
</tr>
<tr>
<td>D9</td>
<td>13710</td>
<td>12620</td>
<td>50.0</td>
<td>510</td>
</tr>
<tr>
<td>D10</td>
<td>14420</td>
<td>12710</td>
<td>-</td>
<td>495</td>
</tr>
<tr>
<td>D11</td>
<td>14630</td>
<td>12810</td>
<td>-</td>
<td>485</td>
</tr>
<tr>
<td>D12</td>
<td>13630</td>
<td>12540</td>
<td>52.8</td>
<td>506</td>
</tr>
</tbody>
</table>

Mean, B-beams 14320 12700 48.7 496
Mean, D-beams 13970 12510 51.8 493
Mean, all beams 14140 12600 50.6 494

Characteristic value 44.7

h=600 mm, b=150 mm:
Mean value 44.7
Characteristic value 39.5

2.3.5 Evaluation of shape stability

After drying and planing at the sawmill, the beams were delivered to the University where their shape was measured using the same equipment as that described above, see Figure 4. At delivery, the MC of the beams was approximately 18% in the inner parts of the beams and approximately 14% at the surface. The beams were then stored at standard climate 20°C/65%RH for approximately five months. At that time the MC was found to be 16.5% and 14.5% in the inner parts and at the surface of the beams, respectively. In Table 7, the measured distortions for this period of time are presented. In general, the distortions are small, although in some cases (e.g. cupping of a few mm:s) visible to the naked eye. The same results are also shown in Figure 10 – Figure 15, to facilitate the comparison between different beams, and between different beam lay-ups.
Table 7a-d. Test results, series III (as of November 2010). Values measured at delivery to the University (after planing) and after storage five months in 20/65.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Twist (degrees)</th>
<th>Gamma (degrees)</th>
<th>Bow (mm)</th>
<th>Crock (mm)</th>
<th>Cup (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>-0.6</td>
<td>-0.1</td>
<td>0.8</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>B3</td>
<td>-0.8</td>
<td>0.5</td>
<td>-1.7</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>B4</td>
<td>-1.4</td>
<td>-0.2</td>
<td>-0.5</td>
<td>0.4</td>
<td>-0.7</td>
</tr>
<tr>
<td>B5</td>
<td>-1.2</td>
<td>0.0</td>
<td>-1.1</td>
<td>0.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>B6</td>
<td>-0.1</td>
<td>-0.3</td>
<td>3.5</td>
<td>0.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>B7</td>
<td>0.5</td>
<td>-0.2</td>
<td>1.3</td>
<td>0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>B8</td>
<td>-0.6</td>
<td>0.5</td>
<td>-0.2</td>
<td>0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>B9</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.4</td>
<td>0.1</td>
<td>-0.3</td>
</tr>
<tr>
<td>B10</td>
<td>-0.1</td>
<td>-0.2</td>
<td>2.1</td>
<td>0.3</td>
<td>-0.7</td>
</tr>
<tr>
<td>B11</td>
<td>-0.9</td>
<td>0.0</td>
<td>1.4</td>
<td>0.6</td>
<td>-0.2</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.6</td>
<td>0.0</td>
<td>0.2</td>
<td>0.3</td>
<td>-0.4</td>
</tr>
<tr>
<td>Max</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>0.9</td>
<td>-0.5</td>
</tr>
<tr>
<td>Min</td>
<td>-1.4</td>
<td>-0.3</td>
<td>-1.7</td>
<td>-0.2</td>
<td>-2.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam</th>
<th>Twist (degrees)</th>
<th>Gamma (degrees)</th>
<th>Bow (mm)</th>
<th>Crock (mm)</th>
<th>Cup (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>-1.5</td>
<td>-0.1</td>
<td>0.8</td>
<td>-0.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>B3</td>
<td>-0.9</td>
<td>0.4</td>
<td>0.7</td>
<td>-0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>B4</td>
<td>-1.7</td>
<td>-0.1</td>
<td>-0.9</td>
<td>-0.4</td>
<td>-0.8</td>
</tr>
<tr>
<td>B5</td>
<td>-1.4</td>
<td>-0.1</td>
<td>0.2</td>
<td>-0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>B6</td>
<td>-0.3</td>
<td>-0.3</td>
<td>1.8</td>
<td>0.3</td>
<td>-2.3</td>
</tr>
<tr>
<td>B7</td>
<td>0.7</td>
<td>0.0</td>
<td>0.8</td>
<td>-0.3</td>
<td>-0.5</td>
</tr>
<tr>
<td>B8</td>
<td>-0.7</td>
<td>0.1</td>
<td>0.5</td>
<td>0.0</td>
<td>0.7</td>
</tr>
<tr>
<td>B9</td>
<td>0.0</td>
<td>-0.1</td>
<td>-0.5</td>
<td>0.6</td>
<td>-0.6</td>
</tr>
<tr>
<td>B10</td>
<td>0.0</td>
<td>-0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>-1.0</td>
</tr>
<tr>
<td>B11</td>
<td>-1.1</td>
<td>-0.1</td>
<td>1.5</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.7</td>
<td>-0.1</td>
<td>0.7</td>
<td>-0.1</td>
<td>-0.7</td>
</tr>
<tr>
<td>Max</td>
<td>0.7</td>
<td>0.4</td>
<td>2.0</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Min</td>
<td>-1.7</td>
<td>-0.3</td>
<td>-0.9</td>
<td>-0.6</td>
<td>-2.3</td>
</tr>
</tbody>
</table>

Figure 10. Twist measured at delivery and after storage in 20/65. Measuring length is 3.72 m.
Figure 11. Distortion (deviation from right angle) measured at delivery and after storage in 20/65.

Figure 12. Bow measured at delivery and after storage in 20/65. Measuring length is 3.72 m.
Figure 13. Crook measured at delivery and after storage in 20/65. Measuring length is 3.72 m.

Figure 14. Cup measured at delivery and after storage in 20/65.
2.4 Comparison of results from series I/II and series III

2.4.1 Strength and stiffness

As reported above, see Table 1, the strength values obtained in the series II tests (for beams without climatic cycling) was 40.7 and 31.95 MPa at the mean and characteristic level, respectively (normalised to h=600 mm and b=150 mm). The corresponding values from the 5 beams tested so far in series III are 44.7 and 39.5 MPa, respectively, see Table 6.

The mean strength thus has increased by 10% by use of the simple grading criteria used in series III. At the characteristic level (5-percentile) the strength increase is about 24% although this value is very uncertain, due to the small number of beams tested so far in series III. However, one would expect the influence on characteristic strength to be more pronounced than at the mean strength level, due to the fact the very low-strength laminations (i.e. in practice the decisive ones for determining the characteristic value) have been rejected in the outer parts of the beam. Bearing in mind that the visual grading rules applied here allows the use of laminations with large knots (25 mm), the results obtained could most probably be improved considerably.

Regarding the stiffness, the average local stiffness for green glued beams without climatic cycling in series I and II was 13 850 MPa, see Table 1 and Table 2, and the corresponding value for series III was 14 140 MPa, see Table 6. Thus, a slight increase, probably due to the grading of laminations, was obtained. This confirms results from previous projects (Petersson et al. 2009) that the stiffness in wet glued laminated beams manufactured from Norway spruce side board laminations is equal to the one found in high quality glulam (GL32-GL36 with MOE of 13700-14700 MPa) or LVL (Laminated Veneer Lumber) products that are available on the market today.

2.4.2 Shape stability and distortion

The measured shapes at different instants in time after various climatic changes gave a possibility to estimate the distortion of the beams, and also a possibility to estimate the influence of the various orientations of the laminations used. Comparing the results from series I/II with those from series III it seems that no general trend can be seen. The reason for this is most probably that the distortions are small in comparison to the variability in distortion, this variability being due to the variability of the material in general.
The general conclusion – and indeed an important conclusion – is that the shape stability of the beams is good, and should not be of any major problem in practise. Cupping, visible to the naked eye, could probably be eliminated if, for example, the beams are dried to a moisture content of 12-14% before planing.
3 Gluing parameter tests; Shear and delamination

3.1 Laboratory study

For investigation of different gluing parameters, green glued block shear specimens were manufactured and tested according to ASTM D905. A specimen tested according to this standard is shown in Figure 16. Results were compared with requirements according to EN 386 for dry glued bonds in glulam. Two levels of pressure in the glue press, two levels of spread rate of the adhesive and two different wood densities were tested. The different parameters are listed in Table 8. Shear strength and wood failure percentage (WFP) were determined. The number of specimens tested for each group varied between 10 and 14.

Figure 16. Block shear specimen according to ASTM D905.

Table 8. Different gluing parameters and results from block shear tests according to ASTM D905 of green glued bonds (standard deviation in parenthesis).

<table>
<thead>
<tr>
<th>Beam number</th>
<th>Spread rate (g/m²)</th>
<th>Pressure (MPa)</th>
<th>Density (kg/m³)</th>
<th>MC at gluing (%)</th>
<th>Shear strength (MPa)</th>
<th>WFP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>135</td>
<td>0.33</td>
<td>340</td>
<td>160</td>
<td>8.59 (0.66)</td>
<td>91 (9)</td>
</tr>
<tr>
<td>2</td>
<td>135</td>
<td>0.33</td>
<td>430</td>
<td>110</td>
<td>9.09 (1.08)</td>
<td>93 (12)</td>
</tr>
<tr>
<td>3</td>
<td>135</td>
<td>1</td>
<td>310</td>
<td>150</td>
<td>7.12 (1.55)</td>
<td>73 (22)</td>
</tr>
<tr>
<td>4</td>
<td>135</td>
<td>1</td>
<td>440</td>
<td>100</td>
<td>8.37 (1.08)</td>
<td>86 (20)</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>0.33</td>
<td>350</td>
<td>160</td>
<td>9.37 (0.83)</td>
<td>86 (13)</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>0.33</td>
<td>430</td>
<td>110</td>
<td>10.55 (1.13)</td>
<td>90 (13)</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>1</td>
<td>310</td>
<td>150</td>
<td>7.78 (1.05)</td>
<td>82 (14)</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
<td>1</td>
<td>430</td>
<td>110</td>
<td>10.92 (1.21)</td>
<td>89 (10)</td>
</tr>
</tbody>
</table>

Densities referred to in chapters 3-5 are based on green volume and absolutely dry weight.
Results from block shear test according to ASTM D905 are shown in Table 8 and Figure 17. The different parameters were tested in order to examine if extreme cases in production of green glued products involving low adhesive spread rate and lack of pressure in combination with different timber densities can cause unacceptable and weak bonds.

The mean strength of high density wood bonds was higher than low density bonds. WFP did not differ between beams and failure occurred mainly in the wood with the exception of Beam 3, which failed partially in the adhesive layer. The highest strength was obtained in the bonds in Beam 8 with high density, spread rate of 200 g/m² and conventional pressure of 1 MPa. The lowest bond strength was found in Beams 3 and 7, both characterized by a combination of low spread rate, conventional pressure and lower density. Beam 3 had the lowest WFP of all beams. As shown in Figure 17, bonds in Beam 3 did not fulfill the requirements in EN 386 for glulam. This result was obtained for both individual values (3 of 13 values) and average value. The poor performance of this beam was probably caused by weak low density wood (310 kg/m³) and lack of adhesive. Beam 7 had also bonds which did not fulfill the requirements (2 of 13 values) which in that case could be explained by low density of wood (310 kg/m³) in combination with conventional pressure. However, the relatively high values of WFP (73% for Beam 3 and 82% for Beam 7) show also that the adhesive bond was partially stronger than the wood which means that even if unfavourable combinations of adhesive spread rate and low pressure would occur, the bond can be stronger than the weakest wood. Totally 94 specimens were tested and 5 of them did not fulfill requirements for strength and WFP according to glulam standard EN 386 (see Figure 17). It should be noted that the investigation performed here is based on the use of the ASTM-specimen cut from the beams glued in the laboratory, and not based on cutting of specimens directly from the laminated beams in the industrial production, as assumed in the standard EN 386.

### 3.2 Industrial study

For assessment of adhesive bonds in industrially manufactured beams, shear strength and WFP were determined according to the European standards EN 392 and EN 386, respectively. The delamination of the bonds according to EN 391 was also measured. The procedure is based on cutting a slice of the full cross-section of the laminated beam. Such a slice is then either used to evaluate the strength of the individual bond lines in shear tests, or exposed to varying wetting and drying cycles to evaluate the delamination of the bond lines. In a first test series, specimens for shear and for delamination tests were taken from four beams from series II (two of type A and two of type D according to Figure 5) that had been tested in bending
Eight cross sections were cut from the type A beams and four cross sections were cut from the type D beams. Twelve bond lines were included in each specimen. Thus, 48+48 bonds from the type A beams and 24+24 bonds from the type D beams were tested for shear strength and delamination, respectively.

A second test series was performed by taking additional specimens from two type A beams which had not been tested in bending, but were manufactured especially for the shear and delamination tests. These beams had two different spread rates: 150 and 200 g/m². Here, two cross sections were cut from each beam and thus 24+24 bonds with each spread rate were tested for shear strength and delamination, respectively.

A third test series was realized by cutting specimens from beams that had been tested in bending after climatic cycling. These specimens were used only for delamination tests.

Results from all of the above described test series for shear and delamination are shown in Table 9.

<table>
<thead>
<tr>
<th></th>
<th>Mean shear strength (MPa)</th>
<th>Mean wood failure (%)</th>
<th>Delamination (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green glued beam type A (bend tested without climate cycl.)</td>
<td>9.3 (1.4)</td>
<td>94 (12)</td>
<td>3.4</td>
</tr>
<tr>
<td>Green glued beam type D (bend tested without climate cycl.)</td>
<td>10.3 (1.4)</td>
<td>91 (13)</td>
<td>5.1</td>
</tr>
<tr>
<td>Green glued type A beam, 150 g/m² (without bend test)</td>
<td>9.5 (1.86)</td>
<td>86 (13)</td>
<td>5.2</td>
</tr>
<tr>
<td>Green glued type A beam, with 200 g/m² (without bend test)</td>
<td>9.9 (1.2)</td>
<td>93 (10)</td>
<td>3.3</td>
</tr>
<tr>
<td>Green glued type A beam, 200 g/m² (bend tested after climate cycling)</td>
<td>-</td>
<td>-</td>
<td>19 (9)</td>
</tr>
<tr>
<td>Green glued type D beam, 200 g/m² (bend tested after climate cycling)</td>
<td>-</td>
<td>-</td>
<td>17 (7)</td>
</tr>
<tr>
<td>Requirements for average according to EN 386</td>
<td>6</td>
<td>Min. 90</td>
<td>Max 5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Min. 72</td>
<td></td>
</tr>
<tr>
<td></td>
<td>≥11</td>
<td>Min. 45</td>
<td></td>
</tr>
</tbody>
</table>

The results from the first series of tests (beams that had been tested but not exposed to climatic cycling) indicate that the bonds in the type A beams show slightly better performance compared with bonds in the type D beams in terms of average delamination, see Table 9. The type A beams fulfil requirements while the type D beams do not (5.1% delamination, maximum value is 5%). As regards the WFP versus strength performance, two specimens from the type A beams did not fulfil the requirements of individual test values as given in EN 386, see Figure 18. However, the averages of WFP versus strength for both beam types fulfilled the requirements of the standard (the requirements for the averages are given in Table 9). Apart from the different annual ring orientation, another difference was that the average density of the type A beams was 485 kg/m³ and of the type D beams was 515 kg/m³. The higher density could cause higher deformation of wood during delamination testing and this would in turn lead to the bonds in the type D beams being subjected to higher stresses during testing. High density wood generally shows a more pronounced shrinkage, inducing higher drying stresses compared to low density wood and delamination testing is known to be sensitive to wood density. Therefore results may not be comparable when density varies between specimens.
As shown in Figure 19, two of 24 specimens with low spread rate included in the second series (beam that had not undergone bend tests) did not fulfil the requirement for glulam adhesive bonds according to EN 386. The delamination for the low spread rate bonds was 5.2% and exceeded the required value of maximum 5%. The spread rate 200 g/m² appeared to be enough to obtain both sufficient mechanical strength and to obtain adequate resistance to delamination, the average value being 3.3%. Both average shear strength and average WFP fulfil the requirements in EN 386 for both spread rates. These results agree with the laboratory block shear test in which low strength was obtained for low adhesive amount in combination with low density. The timber used in the industrial tests was not graded and the density of the individual side boards thus varied considerably (density was determined on the slice cut from the beam, and thus comprising several laminations). For the individual boards, the variation in density was between 290 and 510 kg/m³. The results from both tests indicate that grading of timber before gluing should be carried out in order to guarantee good quality of green glued bonds. Boards with low density should be excluded and control of the adhesive spread rate should be carried out.
The results from delamination tests with specimens cut from beams subjected to climatic cycles are shown in Table 9. The delamination tests were carried out with the delamination procedure A according to EN 391 which is a method required for products to be used in service class 3. The results show severe delamination, too high for those requirements. Only three of totally 32 beams fulfilled the requirements for the outdoor service class 3. Since the beams used in this test series had been subjected to climatic changes already before the delamination test it is however difficult to assess whether they would have passed the requirements if the tests had been performed on “virgin” beams – which is assumed to be the case in the standard. It is known that wood subjected to climatic fluctuations regarding relative humidity have residual internal stresses even when the moisture gradient is levelled out and those stresses could influence delamination results.

The general conclusions drawn from the shear tests performed is that green glued bonds can fulfil the strength requirements for glulam. The delamination tests have shown, however, that the bonds in some cases did not fulfil the requirements for products to be used in service class 3. Those requirements imply the hardest delamination procedure. For service class 1 and 2, only shear tests are required.

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3 For structures of service class 3, delamination tests shall be made in conformity with method A of EN 391. For structures of service class 1 or 2, the testing shall be either delamination tests in conformity with method A of EN 391 or block shear tests in conformity with EN 392. For routine quality control the test methods specified may be substituted by the following: Delamination method A may be substituted by delamination method B of EN 391:2001. For members to be used in service class 1 or 2 block shear tests may be substituted by delamination method C of EN 391:2001.
4 Fracture properties of green glued adhesive bonds

As presented in the previous chapter, testing of standardised specimens often results in large share of wood failure. This means that the strength results obtained from such testing describe glued wood strength more than the mechanical properties of the adhesive bonds. In order to find the mechanical properties of green glued bonds, a special testing procedure was developed with small scale tensile specimens (see Figure 20). The aim of this study was to determine strength, fracture energy and brittleness of both dry glued and green glued adhesive bonds.

A number of 8 types of small tensile specimens were prepared: two types of solid wood specimens with 12% MC, two types of dry glued specimens (i.e. glued at 12% MC) and four types of green glued specimens from boards with two densities and two adhesive spread rates, all specimen types are described in Table 10. The specimens were prepared from the same beams as for ASTM D905 block shear tests.

Small tensile notched specimens with dimensions 4×10×12 mm and with a bond line length of approximately 4 mm in the longitudinal direction of the boards were manufactured from the side boards. The notches were cut through the bond line with a cutter tool of 0.3 mm thickness until the teflon wire was reached (Figure 20). The area of the tested adhesive bond was thus approximately 40 mm².

The tensile specimens were glued into the grips of the testing machine before testing. The tests were run in a servo-hydraulic MTS testing machine under displacement control. The displacement used for controlling the test speed was measured with an external extensometer. For some specimens, the deformation was also measured by the optical system ARAMIS™. This was done in order to compare the two different methodologies and to investigate what additional information could be obtained with optical deformation measurement. For optical measurements, one side of the specimen was covered with a pattern applied by spraying of black paint. The pattern applied deforms along with the specimen during loading and is continuously registered by the cameras of the contact free measurement system used. The set-up used for testing of small tensile specimens is shown in Figure 21.

Figure 20. Tensile specimens: a) raw specimen cut from the laminated boards with in-glued teflon wires, b) finished notched tensile specimen.
Figure 21. Set-up for small tensile specimen. Both extensometer and one of the cameras of the optical system for deformation measurement (ARAMIS™) are shown.

An example of the type of curves that were obtained in the tests is shown schematically (for clarity) in Figure 22. After the maximum load has been reached, the tested bond line starts to fail. Thus, the descending part of the curve describes the progressive failure of the bond line: after peak stress the bond line still has a load bearing capacity, although this capacity gradually diminishes.

From the curves strength, stiffness and fracture energy can be estimated. Here, the area below the stress-deformation curve represents the fracture energy of the bond line. In addition to the total fracture energy also the effective fracture energy has been calculated by the following procedure: From the curve measured in the test (solid curve of Figure 22) the elastic deformations are subtracted. The resulting curve is shown in Figure 22 as a dashed curve. The steepest part of the descending curve is then used to make a linear approximation (the thin dashed-dotted line in Figure 22). The effective fracture energy is then the shaded area shown in Figure 22. In Figure 23 one example from an actual test is shown, and in Table 10 all results from the tests are presented.

The slope of the linear approximation to the steepest part of the descending curve (here denoted –K) represents the brittleness of fracture of the bond together with a parameter called the brittleness ratio, ω. Both parameters are presented in Table 10.
Figure 22. Principle for calculating the effective fracture energy (the shaded area).

Figure 23. Example of stress-deformation curves: dashed line is the originally recorded curve, solid thin line represents the curve without elastic deformation and solid thick line illustrates the negative slope used to approximate the descending part.
Table 10. Tensile strength $f_t$, fracture energy $G_f$, and brittleness ratio $\omega = (f_t)^2 / G_feff$ of dry glued bonds, green glued bonds and solid wood at 12% MC (mean values and standard deviation in parenthesis). Results are obtained with deformation measured with extensometer between two grips of the testing machine.

<table>
<thead>
<tr>
<th>Type</th>
<th>Beam Spread</th>
<th>Density $\rho$ kg/m$^3$</th>
<th>MC at gluing</th>
<th>No $G_f$ Nm/m$^2$</th>
<th>$G_feff$ Nm/m$^2$</th>
<th>$f_t$ MPa</th>
<th>$f_t^2 / G_feff$ K GPa/m</th>
<th>$\omega$ GPa/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid wood</td>
<td>- 430</td>
<td>6</td>
<td></td>
<td>471 (55)</td>
<td>308 (56)</td>
<td>5.20 (0.54)</td>
<td>89 (15)</td>
<td>65 (11)</td>
</tr>
<tr>
<td>Solid wood</td>
<td>- 310</td>
<td>4</td>
<td></td>
<td>347 (45)</td>
<td>231 (74)</td>
<td>4.48 (1.55)</td>
<td>104 (72)</td>
<td>74 (60)</td>
</tr>
<tr>
<td>Mean solid wood</td>
<td>370</td>
<td>10</td>
<td></td>
<td>421 (80)</td>
<td>278 (72)</td>
<td>4.91 (1.05)</td>
<td>95 (44)</td>
<td>69 (36)</td>
</tr>
<tr>
<td>Dry glued</td>
<td>200 430</td>
<td>12 4</td>
<td></td>
<td>494 (109)</td>
<td>382 (119)</td>
<td>4.16 (0.62)</td>
<td>52 (28)</td>
<td>37 (30)</td>
</tr>
<tr>
<td>Dry glued</td>
<td>200 310</td>
<td>12 4</td>
<td></td>
<td>452 (56)</td>
<td>276 (10)</td>
<td>4.87 (0.30)</td>
<td>86 (12)</td>
<td>58 (3)</td>
</tr>
<tr>
<td>Mean dry glued</td>
<td>200 370</td>
<td>12 8</td>
<td></td>
<td>473 (83)</td>
<td>329 (97)</td>
<td>4.52 (0.59)</td>
<td>69 (28)</td>
<td>48 (22)</td>
</tr>
<tr>
<td>Green glued</td>
<td>135 430</td>
<td>110 5</td>
<td></td>
<td>466 (70)</td>
<td>356 (135)</td>
<td>3.31 (0.81)</td>
<td>36 (17)</td>
<td>25 (11)</td>
</tr>
<tr>
<td>Green Glued</td>
<td>135 310</td>
<td>150 6</td>
<td></td>
<td>441 (92)</td>
<td>317 (76)</td>
<td>3.60 (0.49)</td>
<td>42 (26)</td>
<td>27 (8)</td>
</tr>
<tr>
<td>Mean green glued</td>
<td>135 370 130</td>
<td>11 11</td>
<td></td>
<td>452 (80)</td>
<td>335 (103)</td>
<td>3.46 (0.64)</td>
<td>40 (15)</td>
<td>26 (9)</td>
</tr>
<tr>
<td>Green Glued 8</td>
<td>200 430</td>
<td>110 5</td>
<td></td>
<td>571 (126)</td>
<td>398 (81)</td>
<td>5.95 (1.01)</td>
<td>92 (29)</td>
<td>68 (27)</td>
</tr>
<tr>
<td>Green Glued 7</td>
<td>200 310</td>
<td>150 6</td>
<td></td>
<td>386 (103)</td>
<td>306 (76)</td>
<td>3.66 (1.38)</td>
<td>46 (26)</td>
<td>31 (13)</td>
</tr>
<tr>
<td>Mean Green glued</td>
<td>200 370 130</td>
<td>11 11</td>
<td></td>
<td>470 (145)</td>
<td>348 (88)</td>
<td>4.70 (1.67)</td>
<td>67 (35)</td>
<td>48 (27)</td>
</tr>
<tr>
<td>All green glued</td>
<td>170 370 130</td>
<td>22</td>
<td></td>
<td>461 (115)</td>
<td>341 (93)</td>
<td>4.09 (1.39)</td>
<td>53 (30)</td>
<td>40 (23)</td>
</tr>
</tbody>
</table>
Figure 24. Stress vs. deformation curves representing $G_{eff}$ for a) solid wood, b) dry glued 200 g/m², c) green glued 135 g/m², d) green glued 200 g/m² adhesive. Low density (LD) 310 kg/m³, high density (HD) 430 kg/m³.

Figure 24 shows average curves representing the effective fracture energy obtained for all 8 groups of small scale tensile specimens.

Moreover, fractured surfaces were examined with electron microscopy (SEM) studying also the penetration of the adhesive into the wood. Comparison between ARAMIS™ and extensometer curves was also carried out. Examples of such analyses and the results obtained can be seen in Figures 25-27. Details from these investigations will be published in Magdalena Sterley’s doctoral thesis which will be defended in 2011.

Figure 25. Stress vs. deformation measured with external extensometer (red curves) and using ARAMIS™ (blue curves). The straight lines are the linear approximations used to approximate the post-peak part of the curves.
Figure 26. Strain fields obtained with ARAMIS™. Left: At peak load. Right: Post peak stage (50% of peak load).

Figure 27. Examples of microscope pictures. Left and centre: Fracture surfaces. Right: Cross-cut showing the penetration depth of the adhesive to be approximately 5-6 cells.

From the small scale tensile testing of glued bonds the following conclusions can be drawn:

- Green glued bonds have the same average tensile strength and fracture energy as dry glued bonds. Green glued bonds with high density wood have even higher tensile strength in comparison with dry glued bonds.
- Green glued bonds with small amount of adhesive and/or lower density can have lower strength compared with dry glued bonds, but this difference is not significant. Fracture energy is on the same level.
- Fracture obtained with specially designed small scale tensile specimen occurred in the bond, either in the adhesive or in the interphase (the volume of wood impregnated with adhesive), which make results obtained from this testing representative for mechanical properties of the bonds.
- The fracture in dry glued bonds occurred either in the adhesive layer or in the interphase. In contrast, fracture in green glued bonds always occurred in the interphase.
5 Finger jointing – comparative study

5.1 Tensile testing of finger joints

Gluing of undried timber was used more than 20 years ago with finger jointing technique and was successfully tested by many researchers. In this project, finger jointing was investigated in order to compare the mechanical behaviour of green and dry glued polyurethane joints (with the same one component polyurethane adhesive). A further aim was to compare brittle and ductile adhesives in dry glued finger joints. As brittle adhesive a conventional structural PRF (Phenol Resorcinol Formaldehyde) adhesive was used and as ductile adhesive the same one component polyurethane adhesive was used. Side boards with dimensions 25×70 mm were selected with respect to density. Two separate side board groups were chosen: a high density group with an average density of 445 kg/m³ and moisture content of 90% and a low density group with an average density of 360 kg/m³ and moisture content of 115%.

Each board was divided into three parts: 1) for green gluing with polyurethane adhesive, 2) for dry gluing with polyurethane adhesive, and 3) for dry gluing with PRF adhesive. Both densities were included in all three groups of joints. Boards for green gluing were cut and glued immediately after cutting. Boards for dry gluing were kiln dried in a sawmill with other side boards of the same dimensions to an average moisture content of 14%. Dry glued finger joints were manufactured thereafter.

Finger joints were cut in the laboratory with a profile for finger joints for structural use: 15×3.8×0.42 mm according to EN 385. Fingers were visible on the flat side. A laboratory press was used for pressing the finger joints. The nominal end pressure was for the green joints 5 MPa and for the dry glued joints 10 MPa.

The finger joints were planed before test specimen preparation. Exactly 14 fingers were included in each specimen. The test set-up for the tensile testing of finger joints is shown in Figure 28. The tensile strength was determined for each finger joint group. Results are shown in Table 11.

![Set-up for tensile test of finger joints](image1)
![Example of fracture path in PRF dry glued finger joint](image2)
![Green glued finger joint](image3)

Figure 28. a) Set-up for tensile test of finger joints, b) example of fracture path in PRF dry glued finger joint with the fracture within the finger joint, and c) green glued finger joint with fracture in the wood near the finger joint.
Table 11. Tensile strength of finger joints.

<table>
<thead>
<tr>
<th></th>
<th>High density</th>
<th>Low density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry glued PRF</td>
<td>Dry glued PUR</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>Std.dev (MPa)</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>COV</td>
<td>13%</td>
<td>13%</td>
</tr>
</tbody>
</table>

Generally, it could be seen that the strength of high density joints was significantly higher compared with low density joints, the average strengths being 74 MPa and 54 MPa, respectively. This was valid for all three types of joints. There were no significant differences between the strength of the green glued and dry glued joints. However, there were some differences in terms of fracture path for the different joints, cf. Figure 28. High density PRF joints failed mainly within the finger joint itself, high density dry glued PUR joints failed partially in the surrounding wood and partially in the finger joint area and high density green glued joints failed mainly outside of the joint area, often in the wood under the steel plates at the specimen ends, and also partially in the vicinity of the finger joint area (see Figure 28). Low density PRF joints failed partially in the finger joint area and partially in the wood, low density dry glued PUR joints failed to a lesser extent in the finger joint area but also in the wood outside the finger joint area while the low density green glued joints failed mainly in the wood outside the joint area, no finger joint failure was observed.

The analysis of the full strain field in the loaded finger joints was carried out using the optical system ARAMIS™. Figure 29 shows an example of such an analysis. The strains in the finger tips can be determined and shear strains along the finger joint bond can be analysed. The aim with this analysis is to find out if there are differences in the mechanical behaviour between brittle and ductile adhesives and to examine how strains are distributed in the joint under loading. Detailed results from the finger jointing tests will be published in 2011.

![Figure 29. Strain field on the surface of loaded finger joint, dry glued PUR joint.](image)
The penetration of the adhesive in three different finger joint types was determined with Microtomography, an X-ray non destructive method. Figure 30 shows the penetration of the adhesive within a finger joint. This investigation shows that green glued polyurethane finger joints show deeper penetration of the adhesive. The adhesive is seen inside the cell lumen at a depth equal to several cell rows from the bond, the size of the bubbles in the bond is lower in comparison with the dry glued joints. The dry glued PRF adhesive has a penetration at the same level as the dry glued PUR adhesive.

![Dry glued PRF, Dry glue PUR, Green glue PUR](image)

Figure 30. Pictures across fingers illustrating adhesive penetration.

### 5.2 Durability testing of finger joints

Finger joints were tested according to ASTM D4688 which is an American standard for structural finger joints. At present, there is no European standard for testing of the durability of finger joints. Three types of joints were tested:

1) Green glued with polyurethane adhesive (G) and dried thereafter.
2) Dry glued with polyurethane joints (D).
3) Dry glued with PRF adhesive (PRF).

In total 14 side boards were used for manufacturing of finger joints. Both high and low density wood was included. From each board all 3 types of joints were manufactured. From each joint three specimens of dimensions 6×30×300 mm were cut. Three groups of specimens were composed for testing:

1) Testing in dry state as dry reference (R).
2) Testing in wet state after vacuum/pressure impregnation with water as wet reference (V).
3) Durability testing in wet state after 6 cycles of boiling and 5 cycles of drying (B).

This resulted in the following groups:

<table>
<thead>
<tr>
<th>RG</th>
<th>RD</th>
<th>RPRF</th>
<th>reference tested in dry state</th>
</tr>
</thead>
<tbody>
<tr>
<td>VG</td>
<td>VD</td>
<td>VPRF</td>
<td>reference tested in wet state after impregnation</td>
</tr>
<tr>
<td>BG</td>
<td>BD</td>
<td>BPRF</td>
<td>wet testing after boiling/drying treatment</td>
</tr>
</tbody>
</table>

14 specimens in each group were tested and the results are shown in Figure 31.
The results show that there are no significant differences between green glued joints and dry glued joints with polyurethane adhesive.

Joints with PRF adhesive show higher strength after boiling cycles than both green and dry glued polyurethane joints. The PRF adhesive was thus more resistant to boiling and water treatment than the polyurethane adhesive. This difference in behavior resulted in different fracture paths: The PRF joints failed mostly in the wood and the polyurethane adhesives failed in the joint and adhesive which resulted in lower strength.

However, the results show for all three adhesives that the respective wet reference strength values (specimens tested in wet conditions) is on the same level as the corresponding strength after boiling (i.e. no significant difference exists for a certain combination of adhesive type and moisture content during gluing) which in turn means that boiling did not affect the strength but instead, strength is only affected by the (high) moisture content at testing.
6 Property predictions by scanning of structural timber and glued laminated beams

6.1 Introduction
Grading is for a modern sawmill an important and integrated part of the production process by which the value of the sawn products can be increased. Grading means a classification of the timber with respect to the requirements from the end-user. For structural timber the strength, the stiffness and the shape stability are of most importance. These properties can be measured by use of scanning techniques. The potential of using scanning for property predictions is treated in this chapter. In an ongoing study the potential of quality grading of timber by use of modern scanning techniques is investigated. The two approaches employing fluorescent lighting and lighting from a large number of laser point sources are assessed. Tests have been performed using wood-scanning equipment from one of the major manufacturer for face scanning while conventional technique was employed for scanning of end surfaces of boards and glue-laminated beams produced of side boards (Petersson 2010a and Petersson 2010b).

6.2 Scanning for fibre angles
A WoodEye scanner equipped with four sets of multisensor cameras as well as dot and line lasers was used for face and edge scanning, see Figure 32. In scanning for research purposes so called live images along the length of the scanned board were produced. Considerable efforts were directed at finding ways of improving the measurement of wood properties by laser scanning, making use of the so-called tracheid effect, where one of the principal axis of the light intensity distribution around a laser spot is oriented in the direction of the wood fibres. This provides a practical method for measuring variations in grain angle on a wood surface.

![Figure 32. WoodEye scanner and overview of the WoodEye system with lasers, light and multisensor cameras. The notation “IN” marks the cross section of a scanned board.](image)

The sizes and longitudinal distribution of the knots on a board are often of considerable interest. A knot indicator or knot index can be introduced for each separate face or edge, based on the measured grain angles, or alternatively, a single weighted index taking account of all sides of the board. The standard deviation of the measured fibre angles at a fixed length coordinate has often been found to be a good knot indicator.

A test series of 105 boards having the cross sectional dimensions of $45 \times 145$ mm were scanned. For selected graded spruce timber with and without rejects the quality varied markedly. Results obtained for a low-quality board are illustrated in Figure 33.
Figure 33. Above: Knot indicators for a 3.6 m long board of low quality (Board no. 19). The green curve refers to the inner face and the blue one to the outer face. Below: Measured fibre angles and knots on inner and outer faces are shown for a small part of the board (length 0.7 m).

6.3 Scanning for cross sectional properties

Scanning the end surfaces of boards provides valuable information on cross sectional properties that can be used for grading of timber. It is often remarkable in comparing the two ends of a board of Norway spruce how little they differ in their properties. Thus, the average properties obtained from scanned images of the two end surfaces of a board usually provide representative values for the stiffness of the board. Since strength and stiffness are rather closely correlated, this observation is also of interest in strength grading.

6.3.1 Solid wood

An ordinary office scanner was used for the scanning of the end surfaces, 300 dpi resolution being used most. The scanned surfaces were automatically divided into various sub-areas within each of which the most representative radial direction was determined. Combining information on the radial directions of the different sub-areas allows the most likely location of the pith to be determined.

Figure 34. Automatic material characterization of a cross section subdivided into two rows and four columns of sub-areas.
For the example shown in Figure 34, the grey scale input image of the end cross section is shown at the top. The lower part of the figure shows the radial directions of the sub-areas, the location of the pith, and a bar indicating the light intensities of the image on a coloured scale.

Much more detailed information can be obtained for each subarea as illustrated in Figure 35, the middle subfigure of which shows variations in light intensity in the radial direction. The minimum values for the light intensity, marked by red dots, correspond to the boundaries between late wood and early wood. The distances between these minimum values indicate the annual ring widths, shown in the lower part of Figure 35.

As indicated in the upper part of Figure 35, changes in mean value for density and the longitudinal modulus of elasticity (MOE) between early wood and late wood can be estimated. The changes in light intensity can be mapped to other variables of importance from a micro-mechanical standpoint. The major input values used for the results reported here are given below. For an annual ring width of 3 mm the following served as ends values for each annual ring interval:

- Early-wood density = 200 kg/m$^3$
- Late-wood density = 1200 kg/m$^3$
- Early-wood MOE = 8000 MPa
- Late wood MOE = 30000 MPa

Knowledge of the variations in density and in MOE within each sub-area allows integration over the whole cross section area to be performed. The average values obtained for the cross section shown in Figure 34 was 433 kg/m$^3$ for density and 12101 MPa for stiffness (mean MOE at axial loading). The mean annual ring width was about 2.7 mm.

![Figure 35. Property characterization of a sub-area. Above: density and MOE differences between early wood and late wood. Centre: radial variations in light intensity. Below: variations in annual ring width.](image-url)
Results obtained from end-scanning of 105 boards are compared with experimentally obtained values in Figure 36. Obtained $R^2$-values for MOE at edge-bending and for density were 0.67 and 0.71, respectively.

An interesting feature of the computer code developed is that the cross sectional data for any of the tested boards can be reached interactively from the diagram. For example, when pointing at the board with the lowest test-values for strength in the diagram, corresponding board data will be shown on the screen according to the right part of Figure 36.

6.3.2 Glued laminated beams

The approach suggested for solid wood can also be applied for determining the properties of laminated beams. In the computer analysis the glue-lines of the cross section were first identified automatically. Each lamination, which consisted of one of the two split halves of a side board, could then be analysed separately as described for individual boards earlier. The properties of the laminations were integrated finally to provide cross sectional data concerning the glued laminated beam. The average values for the two end cross sections were assumed to be representative for the whole beam. An example will be used to illustrate how the results finally can be presented in form of a data sheet.

The beam chosen is a type D beam from test series IIc, see Figure 5 and Table 2. In this series, the beam was denoted LB14B. The results obtained for this beam, using the micromechanical material parameters cited earlier, are shown in Figure 37. The results agree rather well with the experimentally obtained values for density and stiffness at edgewise bending. Up to now 32 glued laminated beams have been analysed from the test series II.
<table>
<thead>
<tr>
<th></th>
<th>First end</th>
<th>Second end</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board thickness (in mm)</td>
<td>290.2</td>
<td>292.4</td>
<td>291.3</td>
</tr>
<tr>
<td>Board width (in mm)</td>
<td>48.9</td>
<td>49.3</td>
<td>49.1</td>
</tr>
<tr>
<td>Distance from top to reference axis (in mm)</td>
<td>147.9</td>
<td>147</td>
<td>147.4</td>
</tr>
<tr>
<td>Distance from left side to reference axis (in mm)</td>
<td>24.3</td>
<td>24.8</td>
<td>24.6</td>
</tr>
<tr>
<td>Annual ring width (mean value in mm)</td>
<td>2.13</td>
<td>2.25</td>
<td>2.19</td>
</tr>
<tr>
<td>Density (mean value in kg/m^3)</td>
<td>536</td>
<td>544</td>
<td>540</td>
</tr>
<tr>
<td>Modulus of elasticity (for axial loading, in MPa)</td>
<td>14763</td>
<td>14768</td>
<td>14766</td>
</tr>
<tr>
<td>Modulus of elasticity (for edgewise bending in MPa)</td>
<td>14038</td>
<td>14130</td>
<td>14084</td>
</tr>
<tr>
<td>Modulus of elasticity (for flatwise bending in MPa)</td>
<td>14903</td>
<td>14845</td>
<td>14874</td>
</tr>
<tr>
<td>Improved modulus (for edgewise bending in MPa)</td>
<td>15773</td>
<td>15576</td>
<td>15674</td>
</tr>
<tr>
<td>Improved edgewise bending stiffness in per cent</td>
<td>12.4</td>
<td>10.2</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Figure 37. First end (left) and second end (right) of a 5.4 m long glued laminated beam from test series IIc (denoted LB14B in that series), see Table 2, having a 50×300 mm cross section.

6.3.3 Concluding remarks

The results obtained so far in the ongoing study appear promising, especially in providing reasonably accurate predictions of grain-angle distributions on the wood surfaces, as well as rather accurate descriptions of knot locations and of fibre-angle disturbances around knots. A close characterization of end cross sections with respect to radial and tangential directions alike and of annual ring widths has also been obtained. Characterization of the growth within the annual rings from early wood to late wood was so successful that the properties of laminations could be integrated finally to provide cross sectional data concerning the glued laminated beams tested experimentally.
7 Procedure for technical approval and/or CE marking

7.1 Overview of procedure for CE-marking

In order to be able to affix the CE-mark on a construction product, normally either a so-called European harmonised standard, or a so-called ETA (European Technical Approval) describing the product must be available. An ETA is not – in contrast to the name – an approval of the product in a traditional sense. The ETA does not mean that the product is “approved” to be used in construction in all European countries – or even in the country were the ETA was issued. Instead, an ETA is a document describing some (but not necessarily all) of the properties that the product possesses (e.g. strength, stiffness, fire resistance etc.), how these properties were evaluated and, finally, the intended use of the product. If seen as descriptive documents, the difference between a harmonised standard and an ETA is of little importance4. The ETA certifies that an evaluation has been done under a set of given circumstances, and that the product possesses the properties as given in the ETA (the declared properties), no matter if these properties are good or bad. The ETA does not certify that a product fulfils the requirements of e.g. national building regulations. Instead the user of the product should make sure that the declared properties are such that national regulations are met. According to the rules of the free market, it is however possible to put the product on the market, and free trade with CE-marked products within the EU is guaranteed. The definition of what an ETA should include is given in a so called ETA-guideline (ETAg).

However, for innovative products such as the green-glued laminated beams dealt with here, no harmonised standards or ETAg’s exist – otherwise the product would hardly be possible to classify as being innovative. In such cases, an ETA can be issued following a so called CUAP (Common Understanding of Assessment Procedure): The producing company applies for an ETA at one of EOTAs member organisations (in this case e.g. Sitac in Sweden). Sitac and the producing company will then together develop a work plan for the assessment of the product. The result of the assessment, including the description of how the assessment was done, is then circulated among the European EOTA-members. After this circulation changes and/or additional assessments might be necessary, and after completing these, the ETA can be issued – giving the producer the right to affix the CE-mark. Note that an ETA can only be issued when there is a product being placed on the market by a producer (otherwise there is no product or production facility to assess). An initial inspection of the production facilities, sampling of specimens for evaluation and agreements regarding third part inspection on a regular basis are all integral parts of the ETA. The initial sampling and testing of the product is called ITT – initial type testing.

7.2 National approval

If the product in question is to be put on the market only in Sweden, it could be of interest to apply for a national approval since, at the moment, it is not compulsory to use the CE-marking for construction products put on the Swedish market. Such a national approval consists basically of a document were the issuing organisation (in Sweden: Sitac) certifies that the product has the properties declared in the document – i.e. the same type of content as in the case of an ETA. However, and this is an important difference, it is possible also in a national approval to set the “requirements” such that national building regulations are met. Thus, a user of the product can rely on the fact that the product fulfils the requirements given in the national building regulations (for the intended use) – this is not the case with an ETA.

4 Issuing of ETAs is the responsibility of EOTA, European Organisation for Technical Approvals, while harmonised standards are the responsibility of CEN, European Committee for Standardization.
The practical procedure to issue a national approval can be the same as for an ETA, with the important exception that the approval does not have to be circulated among other institutes in Europe. Thus, the procedure should be much faster.

### 7.3 A possible approach

For the present case it would of course be natural to assume that a certification procedure should be relatively similar to that of traditional glued-laminated timber, glulam (irrespective if a CE-marking is aimed at or if a national approval is the goal). This has also been the general assumption in the work with describing a possible procedure for certification.

The harmonised standard covering glulam has been under revision during recent years. In upcoming versions, that harmonised standard (EN 14080), will be a single document with references to test standards and material standards (structural timber). EN 14080 contains a number of definitions of what glulam is (e.g. lay-up and orientation of laminations), materials to be used in the production of glulam (adhesives and timber), the various requirements put on these materials (timber strength class, adhesive type), requirements put on finger joints and general production requirements. In addition to this the standard includes general requirements on the production (temperature, pressing during curing etc).

A possible approach to formulate a CUAP would then be to include the same aspects as those given in EN 14080. Since the adhesive used in the tests has already been approved for the case of conventional gluing, the idea has been that the adhesive itself need not to be approved, merely the product itself.

As the producer is free to define the product and its performance, things like material strength, timber quality etc. can be chosen rather freely. These parameters should of course be chosen with great care, taking into account both economical and technical aspects and risks. The key points are that all materials and procedures used in the production of the beams should be well-defined, and thus it should be possible to produce similar products with similar properties during a long period. Third party audits will assure that the requirements of the ETA (which is based on the results of the initial inspection and ITT) are met. Such audits could typically include taking samples for testing (e.g. finger joints) and audits of the records of the internal quality procedures used. The producing company would typically need to sign agreements with an inspection body for this type of audits. The ETA typically involves the requirement that such agreements are signed. In general an ETA is issued for a period of validity of five years. Within the project several draft versions of a possible ETA have been formulated.
8 Market and economy

8.1 Market
From Södra Timber’s point of view, two main applications of wet glued side boards are forseen. They could be used for production of either high end studs (structural timber) or laminated structural beams. The entire stud market is approximately 40 million m³/year in Europe of which 6 million m³ are high end studs. The total potential for glued beams in residential housing in Europe, including Sweden, is estimated to about one (1) million m³/year. In Sweden, the use of wood as structural material in residential housing construction amounts to approximately 45% of the market, whereas the corresponding figure for Europe is only about 10%. The market price for glued beams varies between 2000-5000 SEK/m³. High end studs have a lower price, about 2000 SEK/m³, but the market for such products is much larger.

In what way the wet glued beams studied in this project will be received by the market is still difficult to say as long as the full specification about quality and dimensions is not decided and the performance is not fully verified.

The sales department at Södra Timber have surveyed the potential market for the beams. Several customers, mainly Swedish truss manufacturers, have been contacted and their response is very positive. However, to be able to give definite answers regarding to what extent they are interested in buying laminated beams of wet glued side boards, they need more information about price and product features. For use in load bearing structures, a national or European certificate/approval is also needed.

8.2 Economy
As described in the introduction, about 30% of the volume of sawn timber produced at a typical sawmill in the south of Sweden consists of side boards. Such products are considered as so called consequence products which appear in divergent production processes, e.g. sawing of logs. The production cost per m³ after the sawing process is dependent on board sizes. The capacity in grading and planing mills is defined as the number of pieces or total length that is processes per time unit. For example, the production cost, per piece or length, for a side board with dimensions 22×100×4000 mm is equivalent to the cost for a centre board with dimension 47×150×4500 mm, although the volume of the centre board is 3.6 times larger. This means in turn that if the average processing cost for grading or planing is e.g. 100 SEK/m³, the corresponding production cost for the side board is 227 SEK/m³ and for the centre board 63 SEK/m³.

Clearly, the production costs between different sawmills vary depending on the product range. However, if the production cost per m³ is calculated, the difference in volume per piece has a great impact on the planing and grading cost.
Figure 38. Products from sawing of a log (left) and relation between production costs and volume (right).

The production costs for sideboards are of importance when the economical potential of production of products based on wet glued sideboards is evaluated. If the side boards are wet glued, the costs for grading and planing will be reduced when the volume per piece increases, see Figure 38. The following costs have been estimated for a wet glued beam with dimensions 45×300 mm, produced from 22 mm thick sideboards:

- Glue: 450 SEK/m³.
- Production cost: 550 SEK/m³ (after sawing).
- Waste: 200 SEK/m³.
- Investment: 100 Million SEK in a full capacity line (50-100 000 m³ annually).

These figures are of course dependent on what type of product is produced and on the side board quality and dimensions.
9 Planning of a pilot plant and a full capacity line for production of wet glued beams.

Together with Ledinek, which is a manufacturer of machines for glulam production, Södra Timber has investigated the conditions for planning and building a pilot plant and a full capacity line for production of wet glued beams.

9.1 Full capacity line
The machine layout suggested for the full capacity line is based upon a production flow that could be described as follows:
1. Input of side boards from the saw line.
2. Scanning and grading for different qualities.
3. Finger jointing of boards up to 16 meters length.
4. Glue application.
5. Pressing.
6. Stacking for the kiln-drying process.

With the outlined full capacity line it would be possible to produce about 50 000 m³ wet glued beams annually.

9.2 Pilot plant
Before a full capacity line is designed and put into operation, it is necessary to evaluate the production costs more thoroughly. For such an evaluation, a pilot plant that imitates the industrial production conditions is needed. To investigate how such a plant could be installed at one of the Södra Timber’s sawmills, a diploma work (Eriksson 2010) was carried out. The result of this work shows how existing and available equipment could be used in combination with new machinery to achieve a pilot plant for wet glued beams using side board laminations. The results of the diploma work were used by Ledinek to make an offer regarding delivery and assembly of such a line. The cost of the pilot plant was estimated to 300 000 €.

The conclusion from the diploma work reads as follows (extract and translation of summary in Swedish):
The new machine equipment was assembled to different concepts which were drawn up in CAD. The first four concepts, which included finger jointing and green gluing in the same process, were deemed to be too complicated to enable a good flow in the factory. The winning concept was the alternative combining the finger jointing process with the process of splitting the wooden beams. That alternative had to have other prerequisites than the other four concepts but was assessed, on the basis of the requirements specified for the plant, to be the best alternative for the layout of the factory.
10 Dissemination of results

Professional journal articles that include presentations of or references to the project:

1. Additional processing requires new sawmill models (In Swedish: Ökad förädling kräver nya typer av sågverk). Interview with project leader Erik Serrano, professor at Växjö University. Södra Kontakt, no. 1, February 2009.


Scientific papers based on results from the project:


Lectures, speeches and oral presentations related to the project:

2. Glafo Glass Research Institute, Växjö, October 12, 2009. Project presentation, 10 listeners (Jan Oscarsson, SP Trätek).

Seminars, work shops and days devoted to particular themes:

11 Future work

The results of this project will serve as a basis for a subsequent two year research project starting in January 2011 and financed through CBBT and The Foundation for Forestry and Wood Research in the South of Sweden. The new project will include continued studies of wet glued bond lines and finger joints, properties of wet glued products, requirements regarding strength grading of laminations and grading of beams and boards based on scanning techniques. An important new research area is the optimization of drying programmes for wet glued products of considerable size.

A successful market introduction of the wet glued laminated beams would be promoted by a pilot construction project in which the beams could be included and exposed as parts of the structure. At the time of writing (March 2011), the planning of a new tennis stadium in Växjö is in progress and the possibility to apply the beams in the described manner is presently investigated.
12 References


