Requirements for wood based lightweight panel intended for furniture and interiors

Jonaz Nilsson
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Licentiate Thesis
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REQUIREMENTS FOR WOOD-BASED LIGHTWEIGHT PANELS
INTENDED FOR FURNITURE AND INTERIOR USE
Licentiate Thesis, Department of Forestry and Wood Technology,
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Abstract

Introduction: Throughout many parts of the world, forests exist in one form or another. And for the timber from these forests to be used, it must be processed by, for example, sawing into planks and dried. Studies have shown that profits for the forest owners increase from beneficial processing of these raw materials. An efficient use of this raw material is to process it into lightweight panels. Some general incentives for using lightweight constructions are: economical, technical and environmental. Some general weaknesses with sandwich constructions are more sensitive to impact and bumps, risk for delamination, harder to make fastenings, and more sensitive to the concentration of point loads. This work aims to increase the knowledge of properties and design of wood based lightweight panels used for interiors and furniture. The intention with this knowledge is that it can contribute to the development of lightweight panels. Material and method: A lightweight panel of cross glued sandwich type and a cross-glued multi-layered panel with densified face sheets have been used as an example to investigate and understand which parameters are crucial for a lightweight panel, made of wood. The lightweight panel of sandwich construction has been studied to consider the changes of shape brought about by moisture, as well as which mechanical properties this panel has, with a focus on creep deformation. Two methods for reducing the moisture-generated shape changes so as to increase the shape stability of the panel have also been studied. The methods are cross-gluing and thermal treatment of the wood material. In the investigations of the panels, primarily quantitative methods in the form of empirical tests have been used. Some numerical simulations describing the moisture-generated shape changes and stresses that arise in the investigated lightweight panels were also made. Results and discussion: Cross-gluing of a multi-layered panel and also for the lightweight panel used in this study is a way to reduce the movement in the panel, generated by moisture. The drawbacks with this method are that stresses occur in the panels when the moisture change, and this can lead to a decrease in the shape stability of the panel. Thermal treatment can also be used to decrease the moisture-generated movement in wood, and in this way increase the shape stability of the product. In those cases where the empirical experiments were combined with numerical simulations, there was good agreement between the experimental and the numerical results. With the lightweight panels a weight reduction was achieved from 307 to 540 kg/m³ compared with a solid beech wood panel. The creep deformation of the lightweight panel was better or comparable for 6 of the 8 studied groups, compared to solid beech wood panel. The study also show that is possible to adapt the mechanical properties through its design of this lightweight panel.
Acknowledgement

This research work has been done at the Linnaeus University on the department of Forestry and Wood Technology. As author for this work, I would like to thank Professor Dick Sandberg together with Associate Professor Jimmy Johansson who offered me to do this work. Initially Dick was my main supervisor, while Jimmy was assistant supervisor. After Dick finished his employment at Linnaeus University, become Jimmy my main supervisor. I would also like to thank my co-authors for help and good advice in the work. As well as all other colleagues and friends who have been supporting me in this work. Finally, I especially thanked Professor Ove Söderström and Assistant Professor Lars Eliasson, for many rewarding conversations related to research and developments. Lars became my assistant supervisor after Jimmy.
List of papers


Contribution to the included papers

Paper 1  The authors initiated, planned and wrote the article together. Nilsson prepared the sample and performed the experimental work.

Paper 2  Nilsson and Johansson initiated and planned the study. Ormarsson planned and performed the simulations, based on requirements and data from Nilsson and Johansson. Nilsson performed the experimental work. The authors wrote the paper together.

Paper 3  Nilsson and Johansson initiated and planned the study. Nilsson performed the experimental work and wrote large parts of the article.

Paper 4  The authors initiated, planned and wrote the article together. Nilsson planned and performed the experimental work.
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1 Introduction

1.1 Background

Forests and thus wood of various kinds and qualities are found throughout large parts of the globe (Keenan et al., 2015; Nilsson, 2017; Streyffert, 1957). If the timber produced in the world’s forests is to be used, it must be processed in some way. Even for the simplest uses wood is not useful as it is. For example, even when wood is only to be used as fuel, a breakdown is required, and usually a drying process. For many areas of use, advanced technology and a knowledge of the material is required; for example, when it is used as construction timber it most often requires cutting into planks and/or boards which are then processed through a number of steps. The use of wood for the production of paper pulp in turn requires a different type of processing, one which also requires extensive knowledge and access to advanced technology. In those parts of the world that do have forests, wood is an important, old and common construction material both for buildings and furniture. Niemz et al. (2015) shows that beech wood has better mechanical properties in form of tensile, bending and compression strength compared with the usually used wood from spruce. Boutelje and Rydell (1995) also show that there are large differences in mechanical properties between different wood species. Hoadley (1990) describes how it is possible, with the guidance of anatomical and visual differences, to identify wood of different species. Pakarinen (1999) has investigated consumer attitudes to wood in furniture. The study shows that most consumers see great advantages in using wood for furniture in form of environmental friendly, good-looking and trendy material. Nordvik and Broman (2005) investigated how five Swedish furnishings and interior magazines described wood. Their study showed that wood was an important factor to create the images that the magazines depict of different indoor environments. These factors together make wood to be one of the most important construction materials for buildings, interiors and furniture. Grönlund (2004) also shows that wood in relation to many other materials is relatively easy to process, shape and join.
The key factors that in future will allow wood to remain one of the main construction materials for buildings, interiors and furniture, is that there is ongoing work on the development of new products and new forms of processing for this natural material.

For interiors and furniture it is often a combination of technical and aesthetic characteristics in combination with fashion trends that determine how these products are designed and constructed. Interiors and furniture made of solid high density wood and with designs having dimensions larger than necessary from a mechanical point of view result in a very heavy product. This type of product is often very durable against wear and external impact. Usually, this type of product is also much more expensive, and not always so trendy. One way to create interiors and furniture with a “powerful” design, and without the weaknesses that greater weight and unnecessary material consumption can lead to, is to use light weight panels (LWP). In addition to attaining less weight, the advantage of an LWP is that it offers greater possibilities for adapting properties to the areas for which it’s intended use.

1.2 General notes about lightweight materials

A very common way of achieving lightweight construction is to use a sandwich construction. A sandwich construction is built up of two thin, stiff and strong face sheets with a light core material between them. Commonly occurring, and relatively inexpensive face sheet materials, are aluminium alloy, steel and plywood. Other common but more expensive face sheet materials are composites. Between these face sheets there is a core material; common core materials are aluminium, polymers, wood and composites. Common to all is that the core is a foam, a honeycomb, or of a corrugated construction. The function of the core is to separate the face sheets from one another. The most common way to connect the core material to the face sheets is to glue them together. The reason why this design is so common for lightweight construction is that it provides a very advantageous strength-to-weight ratio (Petras, 1999).

It seems difficult to find a clear definition of what a lightweight material is. Needless to say there are different ways to describe what is meant by a lightweight material.
Lightweight materials and lightweight constructions are such materials and constructions that have a high performance by weight. Thus they help to reduce the weight of industrial products and components (Vinnova, 2016).

A lightweight construction can be defined as an integrated construction technique that uses all available means of design, material science and manufacturing technology in combination to reduce the mass of a structure and each individual element, while still increasing the functionality of the structure and its elements (Kleiner et al., 2003).

A classification of materials and constructions can also be made based on its density. Such classification could be as follows: Heavy material > 500 kg/m³, lightweight material density ≤ 500 kg/m³, extra lightweight material density ≤ 300 kg/m³, ultra-lightweight material ≤ 200 kg/m³ (FPInnovations, 2009).

Two other alternative methods that can be used for categorizing a material or construction as lightweight are: **Weight controlled lightweight**, which in short means that lighter materials are used to reduce the weight of the construction. **Demand controlled lightweight** which means that weight loss is achieved through alternative solutions to meet predetermined requirements. The methods require that there are well-formulated requirements, and that these requirements are strictly followed (Edvardsson et al., 2013).

### 1.3 LWP from the forest owner’s perspective

Much of the timber from some species of wood that are produced in the forests (in Sweden) and, almost certainly, even in other parts of the world too, has a very low degree of processing. One possible reason for this may be that such timber does not have suitable properties necessary for further processing. In this context, it should also be noted that a certain amount of dead wood left in the forest is important for the conservation of biodiversity (Fridman and Walheim, 2000). Trying to predict and chart how an industry will develop in the future is always associated with a fairly high level of uncertainty. This is because development is governed by a wide variety of parameters, and it may be difficult to identify some of these in order to determine the significance they may have for the industry’s future operations. Holmberg (2013) has through interviews and workshops for the Swedish wood mechanical industry tried identified objectives for the period 2020, 2030 and even visions up to 2050. In this agendum it is stated that the Swedish wood mechanical industry is the base of forest economics. That is because it is the industry that processes the raw material from the Swedish forests into sawn timber, panels, packaging, furnishings and furniture. A rough schematic overview of the
distribution of the volumes processed in Sweden shows that 20% will be used as sawn timber and for different types of panel, 30% for paper pulp and 50% for energy purposes. The profit for the forest owner between the turn of the centuries from 1900 to 2000 was in principle the opposite compared with the distribution shown for the forest’s raw material. 82% of the forest owner’s profit came from the volumes used as sawn timber, 18% from that used for pulp, and less than 1% used for energy purposes. This indicates that processing the forest’s raw material is necessary in order to preserve the Swedish forests. If further processing is done on the forest’s raw material after it has been sawn, the value added processes will increase its value further. There is a big difference between the value added processes, depending on which industry is finalizing it into a product. Figures from (Holmberg, 2013) indicate value-added processes for raw forestry material used in the construction industry to be approximately 1.5 times, furnishings to approximately 15 times, and furniture approximately to 30 times of the sawn timber processed values. Furthermore, the figures also from the agenda state that only 30% of the timber used in the Swedish wood mechanical industry will be products with a processed value that exceeds the costs of the raw material. With this in mind there are great benefits to be achieved if the processing of the low-processed timber could be increased.

1.4 Incentive for weight reduction and LWP

During the period 2003-2007 light materials and lightweight constructions were one of Vinnovas (Verket för Innovationssystem) 18 priority growth areas. It was considered as a growth area, due very much to the interest in Sweden for environmentally sustainable solutions. It was also mentioned that there was a need for qualified development and manufacturing environments for developing these materials and products. The description of the area to be developed was “the material, in itself or in combination with construction and manufacturing concepts for a given application, is aimed at reducing weight with retained performance or increased performance as well as retained weight” (Äström et al., 2017).

Reduction of weight for a product has no eigenvalue in itself. But for many products, a low weight is a prerequisite for the product’s function. Even with enormously large and heavy equipment like an oil tanker, with a deadweight of thousands of tons, it can be somewhat surprising when considered as an extremely lightweight construction. The incentive to construct oil tankers as light as possible is to be able carry a greater load in relation to their own weight, and in that way create more efficient transportation costs. This means that there are similarly strong economic incentives for lightweight constructions for all cargo vessels. A similar reasoning applies to an aircraft,
more easily understood as a lightweight construction compared with a large cargo vessel. Just as for ships, the weight of a plane will be quite crucial to its performance. A lower weight plane results in a longer range, less fuel consumption and increased load capacity. If a longer range and less fuel consumption are related to technical factors, there will be technical factors in addition to economic ones as incentives for lightweight construction. Wojciechowski (2000) shows that 1 kg saved weight on an aircraft reduces fuel consumption by more than 2900 l per year. Such a saving will not only be positive from an economic perspective; there is also an important incentive for lightweight constructions from an environmental perspective. A growing world population in combination with shrinkage natural resources is yet a further strong incentive for more efficient material use (Haberl et al., 2007; Pimentel et al., 1999).

The incentives mentioned here for the use of lightweight constructions are of a general nature and may be valid for different types of products and operations. In summary they are:

- Economic
- Technological
- Environmental
- Efficient use of materials

Feifel et al. (2013) mean that LWP can contribute to the reduction of air emissions from the wood industry. Overall, the listed incentives make LWP into a very interesting area for the wood industry to develop further in the future.

For a long time, various panel materials have been, and are still, a very important “raw material” in the manufacture of interiors and furnishings. Effective material utilisation and efficient manufacturing methods are always important factors for the manufacturing industry. One way to improve material utilisation may be to use LWP. Such a choice not only produces positive effects in terms of lesser costs due to better material utilisation, but also requires a need for increased knowledge of the properties for LWP in terms of strengths and weaknesses, Table 1 shows a compilation of references for the five factors shown below Table 1. Several of the weaknesses identified are of a general character for panels of sandwich design. The areas were considered as weak or in need of being taken in comparison with conventional solutions.
Table 1. Compilation of references for the five factors been assessed as weak for LWP. The table also shows certain assessed interactions of these factors.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Factor (1)</th>
<th>Factor (2)</th>
<th>Factor (3)</th>
<th>Factor (4)</th>
<th>Factor (5)</th>
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<td>x</td>
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<td>Song et al., 2008.</td>
<td>x</td>
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<td>Rammerstorfer et al., 2006.</td>
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<td>x</td>
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<tr>
<td>Kim and Lee, 2008.</td>
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<td>x</td>
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<tr>
<td>Bozhevolnaya and Lyckegaard, 2005.</td>
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<tr>
<td>Goswami and Becker, 2001.</td>
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<td>x</td>
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<tr>
<td>Fatt and Park, 2001.</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Schubel et al., 2007.</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>Heimbs et al., 2010.</td>
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<td>Jiang and Shu, 2005.</td>
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<td>McElroy et al., 2015.</td>
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<td>Sargianis et al., 2013.</td>
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<tr>
<td>Wen-chao and Chung-fai, 1998.</td>
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<td>Denli and Sun, 2007.</td>
<td>x</td>
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<td>Hohe and Librescu, 2008.</td>
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<td>Shengchun et al., 2010.</td>
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<tr>
<td>Ng and Hui, 2008.</td>
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<tr>
<td>Kawasaki and Kawai, 2006.</td>
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<td>x</td>
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</table>

- (Factor 1) Minor overload limits, damages give greater impact.
- (Factor 2) More sensitive to knocks and shocks.
- (Factor 3) Risk of delamination between face layers and core.
- (Factor 4) Sound and thermal isolation.
- (Factor 5) Increased difficulty for fastening. Sensitivity to the concentration of loads.

The LWP of sandwich construction which has been studied in this work consists of wood both in the faces sheets and the core. The choice of materials
and the construction of the panel, in combination with knowledge of the characteristics of wood, known since long time ago, have parameters other than those considered as general for sandwich constructions been studied in this work.

The following three main areas were studied:

- Moisture generated deformation in ordinary wood and moisture generated deformation in densified wood.
- Mechanical properties with an emphasis on creep deformation.
- Methods for reducing deformation generated by moisture in densified wood.

Three of the more prominent properties that wood has are that it is an orthotropic, hygroscopic and porous material. These three properties will largely determine the method of future processing. The design will then affect the factors mentioned in Table 1 and in that way even the design of any future product.

1.5 Aim and objective

The aim of this work is to increase the knowledge of the properties for a LWP made of wood and intended for furnishings and furniture. The objective is to learn how this LWP should be designed so as to have a stable shape, but also gain knowledge of its mechanical properties and ways for adapting of these.

1.6 Research questions

- How is shape stability of LWPs affected by varying moisture conditions? And is there a way for improvement of the shape stability?

- What mechanical properties do these LWPs have? And is it possible to adjust the mechanical properties to a predetermined value?
2 Material and method

The objective setting of the numerical and experimental method used was to create a tool to provide a new knowledge about what could be investigated. The particular LWP used in this work has been an excellent product to investigate and understand the issues and areas that are critical for a wood-based LWP. Numerical studies have been performed in most of the investigated areas and the tests have been done as empirical attempts. The test layout was in certain parts based on the so-called PDCA-cycle (plan-do-check-act). Figure 1 shows the principle for the PDCA-cycle. In this work, the last step in the PDCA-cycle that is used has been in the form of suggestions for improvements, and the writing of articles as an evaluation of those improvements. At a later stage these evaluations have led to new proposals for improvements and the need for new studies for the evaluation of these new proposals.

![PDCA-cycle diagram](image)

*Figure 1. Illustrates how the work was intended to be performed according to the PDCA-cycle.*

The thesis is based basically on two research questions as noted in chapter 1.6. Figure 2 shows how the written papers have been distributed on these
questions. That just these questions were studied depends on the fact that wood material is orthotropic, hygroscopic and porous.

The way in which varying humidity conditions in terms of relative humidity (RH) variations affect the panels was studied by exposing them in a climate chamber to different levels of RH. The RH was determined both by the temperature and the water content in the air (Nevander and Elmarsson, 1994). The chosen levels of moisture and temperature were based on the levels of temperature and moisture that could be expected to occur in a “normal” indoor climate in the southern parts of Sweden (Socialstyrelsen, 2005; Wern, 2013). Below is an overview of the material and the methods used in each paper.

**Paper 1** studies how moisture variations affect shape stability (cupping) of a modified cross-laminated 3-layer solid panel made of radially sawn pine (*Pinus sylvestris* L.). The face sheet consisted of a 4 mm thick layer of radial densified wood (modified), Figure 3 shows the densification in the radial direction. The sample was densified to 60% of the original size.
The middle layer consisted of a 6 mm thick layer of radially sawn pine (unmodified). The bottom layer also consisted of radial sawn pine (unmodified) in thicknesses of 2, 4 and 6 mm. This resulted in three groups of samples with four replicates in each group. The size of the panel samples was 500 * 500 mm².

The temperature during the test was 20° C, and the RH varied between 40 and 85%. The time for the test was 388 days, plus 35 days of conditioning the sample before the test started (measurements of cupping). The cupping was measured in X and Y directions at least once a week. Figure 4 shows the panel and the jig which was used for the measurements.

**Paper 2** studies how moisture variations affected the shape stability of a wood-based LWP of sandwich type. This sandwich construction in both the struts/webs and the two face sheets were made of wood. The face sheets
consisted of beech-wood (*Fagus sylvatica* L.) and the struts/webs consisted of pine wood (*Pinus sylvestris* L.). The wood material both in the face sheet and struts/webs was sawn radially. The face sheets and the struts/webs were glued in a cross-wise direction in relation to each other, Figure 5 shows the design of the LWP.

![Figure 5. The directions in the LWP, global (X, Y, Z). And the directions for the components, local (L, R, T).](image)

The dimensions of the samples were 500 * 500 * 40 mm³ (X, Y, Z). Five groups of panels with three replicates in each group were tested, in total 15 samples. Two distances between struts/webs, 96 and 160 mm and two thicknesses of face sheets, 3 and 6 mm, were tested. The test was conducted for 36 weeks. The temperature was 20° C and 30° C and the RH was 65, 85 and 20%.

The study was based on the assumption that the shape of the samples will change in some way when the ambient temperature and the relative humidity change. To study this, twist and bow of the panel samples were measured. In a second step some numerical simulations of the studied samples was made. The simulation results were compared with the experimental findings. For more detailed description of the modelling work, see Ormarsson, 1999.

**Paper 3** the creep deformations of the same LWP as described in paper 2 was studied. The only differences were the sizes and numbers of the samples. All these tests were experimental. As basis for testing creep deformation it was necessary to test some mechanical properties. For this reason, the experiment was initiated with a four-point bending test. In a panel of this type, there are at least two directions, here called X and Y-direction. Figure 6 shows these two main directions.
Figure 6. The difference between samples taken along the X-direction compared to samples taken along the Y-direction and the fibre directions for the components.

The loads for the creep tests were based on 30% of the maximum load from the bending tests. The test took place over a period of 117 days. Figure 7 shows schematically the test setup and the measurements of the creep deformation.

Figure 7. (a) Schematic view of the test rig used for the creep tests. (b) Show the equipment that was used for measurements of the creep deformation.

**Paper 4** thermal treatment (TT) was studied to see if it could be a way of reducing moisture-related re-swelling of densified wood. The light weight panel was as same type as had been used in papers 2 and 3, with the difference that the Struts/webs were of hour-glass shape and both face sheets and struts/webs were made of pine. The study consisted of four groups with three replicates in each group, in total 12 samples. The sizes of the samples were 400 * 200 * 36 mm³. The thickness of the face sheet was 6 mm and the
distance between the struts/webs was 96 mm. The TT consisted of heating the samples under a pressure of 1 MPa in 160° C for 180 minutes in an open system. Figure 8 shows the pressure that been used for TT of the wood samples. The climates used in the study were 20° C/20% RH and 20° C/85% RH.

Figure 8. The TT material after it has been treated and the hot plates in the hydraulic press that been used for the treatment.
3 Results

This whole work is based on two questions. These are described in the form of research questions in chapter 1.6. But to give some kind of answer to these questions requires more than two investigations. Based on these two questions four studies have been done, reported in four papers. Below is a review and summary of the results from these four papers. The reason why the results have been divided into sub-chapters is primarily to facilitate an overview of the areas that have been studied. The results considered as general for this work, are compiled in sub-chapter 3.1. While moisture-related results are to be found in sub-chapter 3.2 and mechanical-related results in sub-chapter 3.3.

3.1 General results of LWP

In papers 2, 3 and 4, a LWP of sandwich construction has been studied. The density of the studied LWPs varied from 165 to 398 kg/m³. For comparison, it should be mentioned that a solid panel of beech wood has a density of about 705 kg/m³. In this comparison a weight saving from 307 to 504 kg/m³ in favour to the LWP is given.

A LWP of this type, made of face sheets and webs/struts, lies in two main directions. If a panel or material with anisotropic or orthotropic properties, such that this LWP has, is used in a construction, this must be considered. If this is not done, at the worst this could contribute to the mishap.

An LWP provides more efficient material utilisation compared to the use of a solid wood panel. Thus an LWP provides benefits to the consumer in the form of a lower weight and, in the best scenario, a cheaper product. The lower weight makes it easier to move and transport products. The weight and material reduction will not only have a positive impact on consumers, but may even be a positive factor throughout the product’s entire logistic chain. In the latter case, the savings of material and weight will also have a positive effect on the environment.
3.2 Moisture

In those cases where the empirical experiments were combined with numerical simulations (paper 2), there was a good match between the experimental and the numerical results.

Paper 1 showed that it is possible to reduce the moisture-related cupping (an improvement of the shape stability) in a cross-laminated 3-layer solid panel with the face sheet made of densified pine, by adapting the thickness of the bottom layer.

As expected, the LWP swelled and shrank less than a solid wood panel (paper 2). This is because the panel was based on a crosswise-glued sandwich construction. To divide a panel of wood (lightweight or solid) into a number of layers, usually an odd number, and at a later stage glue these layers together crosswise, not only means a reduction of the moisture-related movement (swelling and shrinking); it also means that moisture-related stresses will arise in the panel when the surrounding climate changes (papers 1, 2 and 4). If drastic changes to the climate occur in a short period of time, it may cause such high stresses in the panel that damage occurs. Typical damages are cracks, and/or a separation of the webs/struts from the face sheets. The highest risk for damage to arise is when the climate goes from a high level of humidity to a low level of humidity, because then tensile stresses arise in the panel.

In the LWPs studied, the LWP with the thin face sheet and short distance between webs/struts showed less risk for damage compared with the LWP with thick face sheets and a greater distance between webs/struts.

At extreme moistening there may be some risk for the face sheet on panels buckling of the with thin face sheets (in this study 3 mm) in combination with long distance between webs/struts. The reason for this possible buckling is that compression stresses arise in the material when the moisture is increased.

The Thermal Treatment (TT) of wood (see paper 4) can be a way of reducing the moisture-related movement in wood. Figure 9 shows the different between a face sheet which is both densified and TT and a face sheet that only had been densified.
Figure 9. Difference of re-swelling in the radial direction, between densified untreated face sheet to left and densified TT face sheet to right.

3.3 Mechanical properties

The initial bending tests to the creep tests gave some product properties for the LWPs, which was then used for the creep tests. In Table 2 these properties are summarized along with unpublished results of the measurement of hardness in some species of densified wood. The lightweight panels exhibited equivalent or smaller creep deformations for 6 of the 8 studied groups compared with a solid beech wood panel.
Table 2. Overview of the mechanical properties for LWP, from tests performed in this work, along with unpublished results of hardness measurements performed on densified wood. For reference, solid wood has been used both for the test of LWP and the tests of hardness.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
<th>Reference value</th>
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<tbody>
<tr>
<td>$F_{\text{max}}$ (N)</td>
<td>1476 — 4638</td>
<td>19273</td>
</tr>
<tr>
<td>Deflection at $F_{\text{max}}$ (mm)</td>
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<td>71</td>
</tr>
<tr>
<td>$F_{\text{max}} / \text{Deflection at } F_{\text{max}}$ (N/mm)</td>
<td>45 — 237</td>
<td>272</td>
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<tr>
<td>E-modulus (GPa)</td>
<td>1.79 — 6.29</td>
<td>20.59</td>
</tr>
<tr>
<td>Bending strength (MPa)</td>
<td>3.71 — 11.06</td>
<td>93.17</td>
</tr>
<tr>
<td>Densified pine (Brinell$_{\text{radial surface}}$)</td>
<td>2.90</td>
<td>1.59</td>
</tr>
<tr>
<td>Densified pine (Brinell$_{\text{tangential surface}}$)</td>
<td>2.93</td>
<td>1.85</td>
</tr>
<tr>
<td>Densified aspen (Brinell$_{\text{radial surface}}$)</td>
<td>2.42</td>
<td>1.33</td>
</tr>
<tr>
<td>Densified aspen (Brinell$_{\text{tangential surface}}$)</td>
<td>3.43</td>
<td>1.55</td>
</tr>
<tr>
<td>Densified alder (Brinell$_{\text{radial surface}}$)</td>
<td>1.90</td>
<td>1.41</td>
</tr>
<tr>
<td>Densified alder (Brinell$_{\text{tangential surface}}$)</td>
<td>2.05</td>
<td>1.28</td>
</tr>
<tr>
<td>Densified oak (Brinell$_{\text{radial surface}}$)</td>
<td>5.23</td>
<td>3.08</td>
</tr>
<tr>
<td>Densified oak (Brinell$_{\text{tangential surface}}$)</td>
<td>5.92</td>
<td>3.14</td>
</tr>
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</table>
4 Discussion

The aim of this work has been to increase knowledge about the properties of a LWP made of wood. The objective has been to learn how this LWP should be designed to be stable in shape, and characterise its mechanical properties. In the discussion that follows, the studied areas have been divided into the two main areas; moisture and mechanical properties, and a general discussion about LWP. The purpose of this division was not to inadvertently intertwine with the various issues raised in this discussion. A possible weakness of that breakdown may be the difficulty of identifying the issues that interact between the aforementioned areas.

4.1 Moisture

During real conditions, more extreme levels of both temperature and moisture other than those selected in this study may occur. It is mainly the changes in the RH of the indoor air between summer and winter that may affect interiors and furniture made of wood. It is not only the level of RH that will affect the panels, but also at what rate the RH changes. The rate of change of the RH used during these tests was appreciated to be faster when compared to the real changes of the RH that occur in a house between summer and winter. Other reasons for the fast changes of RH that should be considered are if the production occurs in places with large differences in RH compared with the place of sale/use of the product.

The problem that moisture generates stresses and movements, which in turn lead to changes in the shape of the LWP, should not be related to the LWP; instead it is a property which should be related to the wood material itself. The problem with movement, mainly the retardation of the swelling, becomes even more apparent when densified wood is used. In this work, two methods have been used to reduce the problem of moisture-related swelling and shrinkage.
• Cross-gluing of the wood.
• Thermal treatment (TT) of the wood.

The advantage of these two methods is that they reduce the moisture-generated motion in the wood material, without more chemicals than those present in the glue being added to the product.

But there are also drawbacks. The main drawback with cross-glued constructions is that they automatically produce stresses in the construction when the moisture ratio changes. This requires the product (in this case a panel) being designed so that the stresses that arise in the construction are in balance with each other. If this not done there is a high risk that the product will have a moisture-generated change of shape and be considered to have poor shape stability. In the worst scenario these stresses can lead to a burst in the gluing between the pieces of wood.

Two drawbacks which may be mentioned in this context about TT wood are, first, that the TT process gives the processed wood a darker colour. This does not have to be a drawback in all contexts; in some contexts it can prove to be a positive side effect of the TT process. And secondly, wood processed by thermal treatment can get a slightly smoky smell.

There are also other ways to reduce the moisture-generated movement in wood other than those considered in this work. One method that is the acetylation of wood (Rowell, 2005).

4.2 Mechanical properties

Cross-gluing of a multi-layered wood made panel will cause a drastic reduction of the wood’s orthotropic properties. An example of such, which has been in use for many years, is plywood, an ever popular product. But the LWP studied in this work, based on a sandwich construction consisting of face sheets in combination with a core of webs/struts, the strength properties are received from dependent direction. A possible way of reducing this directional dependent property could be to use as a homogeneous and isotropic core material as possible. Commonly occurring core materials with these properties, or in any case close to them, are foam cores. If the face sheet consists of a relatively thin solid wood panel, as it does in the studied LWP, then the core material must be able to withstand the forces that arise when this face sheet swells or shrinks, depending on differences in moisture content. But if a thinner variant (3-8 mm) of the panel type studied in paper 1 has been used as face sheet, the majority of the stresses generated by moisture would “stay” in the face sheet, without affecting the core. If this were possible it
would mean the LWP with a more anti-abrasion resistance would retain a more stable shape: it would also mean new uses for low density wood, like aspen.

As shown in Table 2, all the LWPs studied have lower values for the investigated mechanical properties, compared to the reference panels of solid wood. This is not surprising, nor a weakness for LWPs; they should not be compared with solid panels, but instead considered as separate products with the appearance of solid wood panels.

As can be seen from Table 2, dispersion is high between the mechanical properties of the studied LWPs. This spread is due to differences in the distance between webs/struts and differences in the thicknesses of the face sheets. A greater distance between webs/struts in combination with thin face sheets gives a low density LWP, but with lower $F_{\text{max}}$ values in bending compared to a LWP with shorter distance between the webs/struts combined with thicker face sheets. To vary the distance between the webs/struts and the thickness of the face sheets gives greater possibilities for adapting the mechanical properties to predetermined requirements.

An experience gained from this work is that TT wood is perceived as more brittle and with poorer mechanical properties compared with untreated wood. How this perceived deterioration of the mechanical properties may affect the mechanical properties of the studied LWPs as a whole has not been investigated in this work.

4.3 Generally about LWP

For the use of wood in an LWP, as well as for other uses, the wood properties will get a major impact on the properties of the end product. Properties that are mentioned are juvenile wood versus mature wood, compression wood, fibre aberration, fibre angle and branches. The importance of these and similar properties have long been known. More about this large area of research can be found, amongst others in (Bergkvist and Fröbel, 2013; Dinwoodie, 2004). In this work, various defects in the wood have been reduced by selecting and sorting, in combination with the cutting of wood with defects.
5 Conclusions

The results of this work have primarily increased the knowledge in the area of wood-based LWP. Furthermore, the knowledge of cross-glued multilayer solid wood panels with densified face sheets has increased.

The LWP was a sandwich construction made of face sheets and webs/struts, with densities of 165 to 398 kg/m³. Cross-gluing reduced the swelling and shrinking for the both the LWP and the multilayer panel. One drawback with the cross-gluing design is that stresses are formed in the panels when the moisture changes. The stresses that thereby form can have an effect on the shape stability of both the LWP and the multilayer panels.

A way that has been used in this study of reducing the swelling is cross-gluing of the multilayer panel with densified face sheets, in combination with the adjustment of the thicknesses of the bottom layer to increase the overall shape stability of the panel. For the LWP the swelling of the densified face sheet was reduced by thermal treatment.

With the LWP that has been studied in this work a weight reduction was achieved from 307 to 540 kg/m³ compared with a solid beech wood panel. The creep deformation of the lightweight panel was better or comparable for 6 of the 8 studied groups, compared to solid beech wood panel. The study also show that is possible to adapt the mechanical properties through its design of this lightweight panel.
6 Suggestions for future work

During working with this study, new issues related to LWP and wood have arisen. The issues that might be appropriate to investigate further, and to get answers to in a future work, are:

- Development of methods for reducing the effects of the forces and movements that occur in the wood materials when the temperature and the relative humidity of the environment change. A possible idea for this could be to study the weakening of the wood material in one direction only.

- What kinds of components/products are suitable for producing in the form of LWPs? And how should any production plant be designed to enable efficient production?

- What products do consumers consider to be attractive for lightweight solutions? And are these products the same that the sales organizations consider suitable for lightweight solutions?

- Development of numerical models for optimizing structural behaviour of LWPs used for interiors and furniture products with the aim of achieving an efficient material product with neutral, or in the best case, a positive environmental impact.
References


