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Shape Stability and Effect of Enhanced Formability on Bond-Line Strength

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Laminated Veneer Products: Shape Stability and Effect of Enhanced Formability on Bond-Line Strength
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Abstract

Blomqvist, Lars (2016). *Laminated Veneer Products: Shape Stability and Effect of Enhanced Formability on Bond-Line Strength* Linnaeus University Dissertation No 247/2016, ISBN: 978-91-88357-13-7. Written in English with a summary in Swedish.

This thesis concerns two aspects of the manufacture of laminated veneer products (LVPs). The first aspect is related to the possible improvement of the shape stability of LVPs, and the second has its starting point in the modification of the veneer for enhanced formability as well as the question of whether and how these modifications affect the bond-line strength.

LVPs are veneers bonded with adhesive into predetermined shapes, mostly for the production of furniture and interior fittings. Since any deviation from the intended shape is a problem for both manufacturer and customer, various studies have sought to evaluate the influence of different materials and process parameters on shape stability. Parameters studied have included wood species (beech and birch), an adhesive system based on urea formaldehyde, the adhesive distribution on the veneer, climate, moisture content and fibre orientations of the veneers, as well as the orientation of the individual veneers in a multi-ply.

Manufacturers of LVPs must consider some basic facts about wood in orders adequately to provide shape-stable LVPs to customers. Wood emits and absorbs moisture in relation to the surrounding climate, and this can lead to shrinkage and swelling. Such moisture induced movements differ in the wood's different directions, and the magnitude is specific for the species. A thorough understanding of this is the basis for achieving shape-stable LVPs.

Symmetry is defined in this thesis such that the veneer properties are balanced in the laminate. This means that opposite veneers on either side of the centre veneer have similar characteristic. An LVP will become distorted if the veneers are asymmetrically oriented before the press. Deviation from the desired shape can be small immediately after the pressing, but it may increase significantly with moisture content (MC) variations. Asymmetry may result when veneers with different fibre orientations are included in the laminate or when the veneers are placed asymmetrically. It may also occur if veneers with different MCs are bonded together asymmetrically. One aggravating factor is that the lathe checks that are introduced when the veneers are peeled or sliced from the log affect the shape stability. In 3-ply crosswise-oriented plywood, the veneer surfaces on which the lathe checks occur should be oriented in the same way for high shape stability.

Based on existing knowledge, the production of shape-stable LVPs requires that the veneers are conditioned to a uniform MC and sorted with regard to fibre orientation and the side with lathe checks before bonding. End-user climates should govern the MC of the veneers and the moisture added with the adhesive during the process. Straight-grain veneers and symmetry should always be the goal.

Moulding can cause stretching, i.e. strain, of the veneers depending on the curvature of the mould. To prevent the veneers from rupture, there are various ways to strengthen the veneers particularly in the transverse direction in which the veneer is weakest. However, tests have shown that these pre-treatments of veneers for enhanced formability can prevent the adhesive from penetrating the wood surface. It is therefore important to confirm that the pre-treatment does not affect the bond-line strength.

Sammanfattning (in Swedish)

Denna avhandling berör två områden inom tillverkning av plan- och formpressade fanerprodukter. Det första avser formstabiliteten hos dessa och om det är möjligt att förbättra densamma. Det andra har sin utgångspunkt i modifiering av faner för ökad formbarhet och huruvida dessa modifieringar påverkar limfogens styrka.

Plan och formpressade fanerprodukter består av faner som sammanfogats med lim till en förutbestämd form. Metoden används främst för tillverkning av möbler och inredningar. Avvikelse från avsedd form hos produkterna är ett stort problem för både tillverkare och kunder. Orsakerna till avvikelser i form kan relateras till både materialet och processen men också till hur produkten används. Studier har genomförts för att utvärdera inverkan av olika material- och processparametrar på formstabiliteten hos några utvalda produkter. De undersökta parametrarna var träslag (rödbok och björk), limsystem (baserade på urea-formaldehyd), limspridning, klimat, jämviktsfuktkvot, fiberorintering hos faner samt orienteringen av faner i den specifika produkten.

För att kunden till skiktlimmade produkter ska erhålla en formstabil vara krävs att tillverkarna tar hänsyn till grundläggande fakta om trä. Detta material avger och tar upp fukt i förhållande till omgivande klimat, vilket innebär att trä krymper och sväller. Detta sker dessutom med varierande magnitud i olika riktningar av träet. Denna variation är även träslagsspecifik. Att ha en förståelse för detta beteende är grunden för tillverkning av formstabila träprodukter.

Symmetri definieras i denna avhandling med att faneregenskaperna är balanserade i laminatet. Detta innebär att det motsatta faneret på vardera sidan av det mittersta faneret i laminatet har liknande egenskaper. Om faneren sammanläggs och pressas på ett asymmetriskt sätt blir produkterna skeva eller kupade. Avvikelsen från önskad form kan vara liten direkt efter pressningen men kan öka avsevärt i samband med fuktkvotsvariationer. Asymmetri kan uppstå genom att faner med avvikande fiberorientering ingår i sammanläggningen eller att faneren läggs asymmetriskt. Det kan även uppstå om faner med olika jämviktsfuktkvot sammanlimmas på ett icke symmetriskt sätt. En försvårande faktor är att även de sprickor som uppstår när faneren tillverkas genom svarvning eller knivskärning inverkar på formstabiliteten. I en korsvis limmad tre-lagers plywood ska fanerens sida med sprickor vara orienterad åt samma håll för hög formstabilitet.

För att uppnå formstabila produkter bör faneren vara konditionerade till en enhetlig jämviktsfuktkvot och vara rätfibriga, dvs. att fiberriktningen sammanfaller parallellt med ytornas kanter. Som nämnts tidigare bör även fanerets sida med sprickor beaktas. Slutanvändarens, det vill säga kundens, klimat bör styra fanerens måljämviktsfuktkvot som tillsammans med tillförd fukt från limmet påverkar produktens jämviktsfuktkvot i tillverkningsprocessen. Dessutom ska läggningen vara symmetrisk.

Vid formpressning kan faneren utsättas för sådana sträckningar, dvs. töjningar, att bristningar uppkommer. Därför finns det olika sätt att förstärka faneren främst i transversell riktning där faneren är som svagast. Detta kan ske genom olika bearbetningar och/eller pålimningar. Dessa förbehandlingar av faner för förbättrad formbarhet kan dock hindra limmet från att tränga in i träytan vilket tester visat. Därför är det viktigt att kontrollera att förbehandlingen inte påverkar limfogens styrka.

Preface

The work described in this thesis has been carried out at the Department of Forestry and Wood Technology at Linnaeus University in cooperation with the wood manufacturing industry. The projects that are the basis for this thesis were financed by the industry, the Knowledge Foundation and Linnaeus University. Cost Action FP0904, The Frans and Carl Kempe Memorial Foundation 1984, and Linneaus Academy have supported international cooperation. Professor Dick Sandberg initiated my doctoral studies and has been active in the planning and development of the various papers upon which this thesis is based. Associate Professor Jimmy Johansson has been an integral part of my studies and has helped me with the framework of this thesis. Professor Hans Petersson, who came later to the supervisory group, has also helped me with the framework and has been a discussion partner within wood research both before and during my time as a doctoral student. In addition to this group of supervisors, Professor Ove Söderström contributed to the development of the structure of my studies, Dr Magdalena Sterley, the faculty examiner for my licentiate degree, helped me in the area of adhesion and testing methods, University Lecturer Jan Oscarsson contributed with constructive criticism and helpful comments during the preparation of the framework, and Associate Professor Anthony Bristow carried out linguistic revisions. Collaborations with Dr Sterley and her employer, SP Technical Research Institute of Sweden, made possible the investigation that led to the appended Paper V. Others who contributed to my research are reviewers and editors, people I have met at different conferences and courses, and those I have interacted with in the industry. I would like to thank all those who have contributed to my work. I have been encouraged in my work through Tore Danielson's Scholarship Fund for technology research with the promotion of local development, for which I am very grateful.

Växjö, May 2016

Lars Blomqvist

Appended papers

This doctoral thesis is based on the following papers, which are referred to in the text by their roman numerals:

Paper I	Blomqvist, L., Johansson, J., Sandberg, D. (2013). Shape stability of laminated veneer products – an experimental study of the influence on distortion of some material and process parameters. *Wood Material Science & Engineering*, 8(3), 198–211. DOI:10.1080/17480272.2013.803501
Paper II	Blomqvist, L., Johansson, J., Sandberg, D. (2013). Shape stability of laminated veneer products – How to decrease the negative effects of fibre deviation? In: *Forest Products Society (FPS) 67th International Convention*, Austin, Texas, USA.
Paper III	Blomqvist, L., Sandberg, D., Johansson, J. (2014). Influence of veneer orientation on shape stability of plane laminated veneer products. *Wood Material Science & Engineering*, 9(4), 224–232. DOI:10.1080/17480272.2014.919022
Paper IV	Blomqvist, L. (2015). Shape stability of laminated veneer products – a review – defining and achieving shape stability. *International Wood Products Journal*, 6(2), 89–95. DOI: http://dx.doi.org/10.1179/2042645315Y.0000000004
Paper V	Blomqvist, L., Sterley, M., Sandberg, D., Johansson, J. (2015). The effect of veneer modification on the bond-line strength in laminated veneer products. *Pro Ligno*, 11(4), 43–49. http://www.proligno.ro/en/articles/2015/4/Jamaaoui_final.pdf/

Author's contribution to the work in appended papers with divided authorship

Paper I	Blomqvist and Sandberg initiated the work, collected the material and performed the analysis. The authors wrote the paper together.
Paper II	Blomqvist and Sandberg initiated the work, collected the material and performed the analysis. The authors wrote the paper together.
Paper III	Blomqvist initiated the work, collected the material and performed the analysis. The authors wrote the paper together.
Paper V	Blomqvist and Sterley initiated the work, collected the material and performed the analysis. The authors wrote the paper together.

Contents

Introduction

The main materials used in the production of laminated veneer products (LVPs) are veneers[1] which are bonded together with an adhesive under high pressure into a predetermined shape (Figure 1). This process is, in general, carried out under a raised temperature to shorten the curing time of the adhesive (Paper IV). The processes used to manufacture such products can be divided into the following groups depending on the intended shape: plane pressing, laminated bending (shaping of the veneers in a single direction), and moulding (shaping of the veneers in a multi-curved shape).

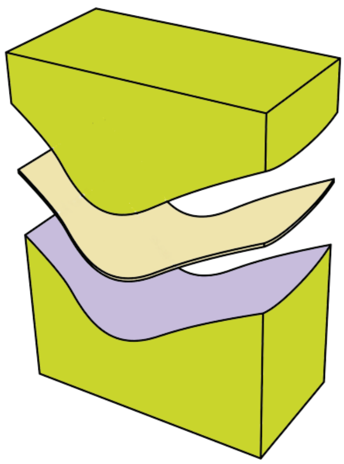


Figure 1 A two-piece mould with laminate between.

LVPs are commonly used for both exterior and interior purposes. Depending on their use, many of these products are sensitive to variations in shape. Shape instability can be a significant problem in the manufacture and use of the assembled product, as any distortion may cause problems such that the products fail to meet the product requirements (Blomqvist 2013).

[1] A veneer is a thin sheet of wood. Veneers can be rotary-cut (peeled), knife-cut (sliced) or sawn from a log or a part of a log. The majority, ca 90%, of veneers are rotary cut (Paper IV).

An example of a typical distortion is shown in Figure 2. Shape stability can be defined, in a broad sense, as how well the shape of a product is preserved in use, *i.e.* in the face of time-related changes in the mode of distortion (Paper IV).

Wood properties limit the formability of wood (Anderson and Earle 1972). Because of its anisotropy, it is difficult to bend wood in more than one direction (Marra 1992). Moulding can cause stretching of the veneers as a result of the mould's curvature (Navi and Sandberg 2012). In laminated bending, the smallest radius of curvature and the choice of wood species in relation to veneer thickness affect the possibility of bending the wood without problems (Stevens and Turner 1970). Formability can be defined as a material's ability to undergo plastic deformation without rupture.

The adhesive must lock the LVP in the desired shape and not soften or flow under heat or be deformed by loads. Therefore, the development of thermosetting adhesives has contributed to the development of LVPs (Forest Products Laboratory 2010; Paper IV). Excellent bond-line strength can be defined as a bond which is as strong as the materials which have been bonded together (Forest Products Laboratory 2010).

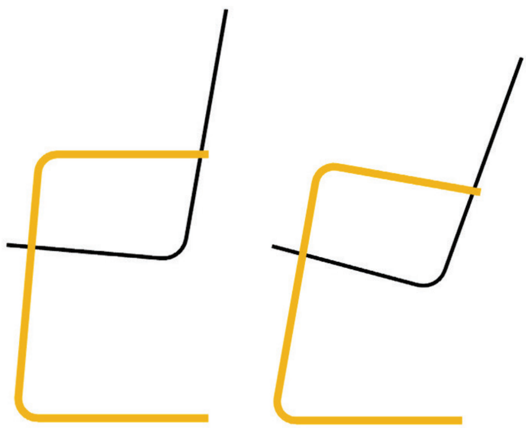


Figure 2 *LVPs are in general sensitive to variations in shape. The figure on the right has changed its shape relative to the figure on the left. This can be due to dehydration, which causes the wood to shrink.*

Many different material and process parameters interact and are relevant for the end result. Several of these parameters, necessary for reaching a high shape stability and an understanding of the effect on the bond-line strength of enhanced formability, are investigated in this thesis. The work was done in close cooperation with the industry, and the different parameters have been sifted out from the various issues that have arisen. Climate tests have been designed to imitate the customer's environment. The hope is that the results will contribute to decision-making in both product development and production technology. Lowering the amount of rejects reduces the resources used per delivered unit produced. Thus, productivity is increased as more of the units produced can be delivered. Reducing the resources used and enhancing the productivity separately or together enhances the profit margin. Moreover, it is a way of being responsible with regard to natural resources.

Within the framework of this thesis, the following parameters have been studied in the area of adhesive systems and veneers: water content of the adhesive, type of hardener, adhesive filler, adhesive distribution; moisture content of the veneers, fibre orientation of the veneers, veneer orientation, loose side versus tight side, veneer orientation, parallel versus perpendicular, beech versus birch (two common species used in the industry), and the effects of different veneer modifications on the bond-line strength.

Background

The technologies to produce LVP follow the industrial revolution. The steam engine and other technical innovations made it possible to efficiently produce rotary-cut (peeled) and knife-cut (sliced) veneer (Shaykett 2012) in a material-saving manner without chip forming, which even today appeals to the desire to better utilize natural resources. However, laminated wood has a longer history and remains have been found in the tombs of the pharaohs, showing the earliest evidence of veneer production with sawn veneers (Knight and Wulpi 1927). Canoes and boats had been built with laminated veneers before 1920s. However, the scarcity of steel during the Second World War demanded new forms of LVP, especially for boats and aeroplanes (Shaykett 2012). The intense pre-war application of wood engineering resulted for example, in the British Mosquito aeroplane constructed of LVP (Figure 3). The planning of the Mosquito started in December 1939, and the first prototype flew in November 1940. Approximately 7 785 Mosquito units were manufactured, and this is considered to be one of the most successful aeroplanes built during the Second World War (Yorkshire Air Museum 2015). The development of the moulding process enabled more advanced forms, of which radar domes with their paraboloid form and plywood tubes are examples (Meyer 1947). This inspired many furniture designers such as the American designers Charles and Ray Eames. The Eames couple are probably best known for the Eames Lounge chair constructed of two pieces of LVPs joined by stainless-steel tubing (Encyclopaedia Britannica 2015a) (Figure 4). LVP furniture had its heyday during the 1940s and 1950s. From the beginning of the 1990s, mid-century design has gained renewed interest, which has contributed to a revival of LVP furniture (Shaykett 2012).

Figure 3 *De Havilland Mosquito DH98 NFII. Photos by courtesy of Yorkshire air museum (2016).*

Figure 4 *The Eames Lounge chair designed by Charles Eames and Ray Eames. Photos by courtesy of Herman Miller, Inc. (2016).*

The technology of producing LVP has high economic value, evidenced by the large volume of popular chairs made with laminated veneers. For example, more than 5 million units of the “Seven” chair designed by Arne Jacobsen and produced by Fritz Hansen, Ltd., have been sold since 1955 (Figure 5), and more than 60 million units of the “Poäng” or “Poem” chair designed by Noburo Nakamuro for IKEA of Sweden Ltd., have been sold since 1977 (Blomqvist 2013) (Figure 6). LVPs combine strength, lightness and durability (Meyer 1947), and their use has extensive possibilities for designs beyond what would be possible with solid wood (Stevens and Turner 1970; Blomqvist 2013). In addition, the wood material is perceived to be climate-smart (Rowell 2013; Bergman *et al.* 2014).

Figure 5 The Seven chair designed by Arne Jacobsen. Photos by courtesy of Republic of Fritz Hansen (2016).

Figure 6 The Poäng chair designed by Noburo Nakamuro. Photos by courtesy of IKEA (2016).

Parameters

Symmetry is defined in this thesis such that the veneer properties are balanced in the laminate. This means that opposite veneers on either side of the centre veneer have similar characteristic.

A stable moisture content (MC) is an important parameter in shaping stable wood (Suchsland 2004). Changing the wood's MC is also a trigger for low shape stability in combination with divergent fibre orientation and other asymmetries (Paper I, and II). The wood should therefore stay in a stable climate to be shape-stable. According to Eliasson (2014), high shape stability is also a prerequisite for more automated production.

The relative humidity (RH) indoors can vary from 15 to 80% in southern Sweden through the year (Paper IV). Since wood strives to achieve an MC in balance with the surrounding climate, it will swell and shrink (Suchsland 2004). Swelling of the cells is dependent on the wood's fibre saturation point (FSP), and shrinkage begins just below the wood's FSP. The FSP is the state when the cell wall is saturated with water, but no free water exists in the cell. Since the water above the FSP is free water in the voids, the free water does not contribute to further expansion (Kollmann and Côté 1968).

Wood can be described, in chemical terms, as a three-dimensional biopolymer[2] composite consisting of a network of cellulose, hemicellulose and lignin with minor amounts of extractives and inorganic material. Cellulose, hemicellulose and lignin are all thermoplastic and they are the building blocks of micro-fibrils, which in turn are the basic components of the cell wall layers forming the wood cells. The underlying reason why wood changes dimensions with changing MC is that the cell wall polymers contain hydroxyl and other oxygen-containing groups, which attract moisture through hydrogen bonding (Rowell and Ellis 1984).

The directions in wood are (see Figure 7): longitudinal (parallel to the axis of the stem), radial (perpendicular to both the growth rings and the axis of the stem), and tangential (tangential to the growth rings). This anisotropy also affects wood surface wettability, although different types of wood exhibit differences in this property (Rowell 2013). Wood has different properties in its different directions, with respect to for example shrinkage, swelling, stiffness, strength and elasticity. These properties are also affected by the level of MC (Kollmann and Côté 1968). The addition or removal of water below the FSP has a pronounced effect on almost all wood properties, whereas the addition or removal of water above the FSP has almost no effect on any wood properties (Kollmann and Côté 1968). The mechanical properties are influenced by the glass transition temperature (*Tg*) (Van de Velde and Kiekens 2002), which

[2] A biopolymer is a polymeric substance occurring in living organisms (Oxford Dictionaries 2016a). A polymer is a macromolecule that is formed by polymerisation of smaller units (Oxford Dictionaries 2016b).

marks the border between the brittle glassy state (below *Tg*) and the soft rubbery state (above *Tg*) (Navi and Sandberg 2012). Above the *Tg,* the mechanical properties can degrade considerably. Below the *Tg,* the flexibility of indefinite polymers is low as no segmental motion can occur in the polymer (Van de Velde and Kiekens 2002). In wood, the *Tg* occurs in the vicinity of 180 to 200°C in the dry state (oven-dry), but it is significantly lower in the moist state. This makes it possible to shape moist wood at temperatures between 90 and 120°C (Navi and Sandberg 2012). Softening for the peeling and slicing of veneers is often done at temperatures around 90°C with moist logs.

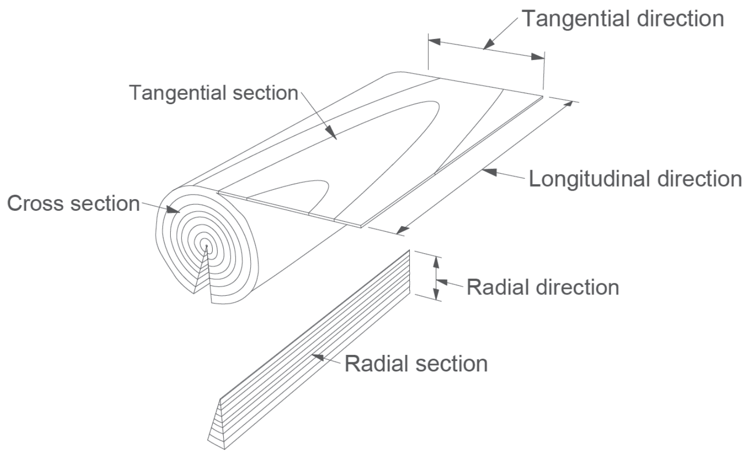


Figure 7 *The principal directions and principal sections of wood (Blomqvist 2013; Paper IV).*

In LVP bonding, the target temperature is often 90–110°C with dried veneers. When resistive heating is used, it is relatively easy to achieve a uniform temperature. When dielectric heating (high-frequency heating) is used, such uniformity is however not easy to achieve, since the heating can be uneven with peaks and a smoothing period after the high-frequency heating is turned off is required to equalize the temperature and ensure that the temperature is sufficiently high in the entire bond-line for curing. This means that the LVP may have achieved relatively high temperatures in some regions in time for bonding.

When wood is bonded with an adhesive, the wood is also wetted (River *et al.* 1991). This means that the wood's ability to absorb moisture is utilized in the gluing process. Although the absorption ability is problematic, the gluing process is dependent on the wood's ability to absorb moisture. According to the Forest Products Laboratory (2010) and Marra (1992), the wood surface must be both wetted and penetrated by the adhesive to achieve a strong bond-line. The purpose of the adhesive is to transmit and distribute the load between the components to be joined. If the adhesive has either dried or cured too much before pressing it does not wet the opposite surface, and this results in a thick and weak bond-line. However, the adhesive layer has to be thick enough to avoid over-penetration when pressure is applied. If the surface is over-penetrated, the bond-line becomes meagre and weak (Forest Products Laboratory 2010).

The properties of wood can be modified to reduce the total volume of shrinkage and swelling. This can be done both mechanically and chemically. In the first case, cross-bonding layers of wood are used. This technique is applied in for example plywood (Suchsland 2004). In the second case, wood can be modified by, for example, a reaction with the polymer hydroxyl groups (Hill 2006). After chemical modification of the three-dimensional biopolymer composite, *i.e.* wood, a new biomaterial is achieved. Heat treatment (which can be considered to be a thermal modification), furfuralation (wood + furfural alcohol), epoxidation (wood reaction with oxiranes), and acetylation (wood reaction with acetic anhydride) are examples of chemical modifications (Rowell 2013). These chemical modifications alter and reduce the wood's ability to absorb moisture. In the case of heat-treated wood, this is achieved at the expense of a loss of strength (Hill 2006; Rowell 2013). Acetylation of wood makes it more water repellent (hydrophobic), but this impedes bonding (Rowell 2013). Epoxidation also reduces the bond strength, due to the wood's lower moisture uptake capacity (Rowell and Ellis 1984).

Research questions

The foci in this thesis are the shape stability of LVPs and how measures to enhance formability can affect the bond-line strength. The work has been based on the following research questions:

- What is the underlying reason for distortion and poor shape stability?
- Is it possible to identify factors that have a particularly strong impact on shape stability?
- Is it possible to limit the problems of poor shape stability under industrial conditions, and if so, how is it possible to achieve this in practice?
- Is the bond-line affected by methods to strengthen the veneer from rupture by enhancing the formability, and if so, how does it work?

Aim and objective

The aim of the thesis has been to understand what causes rejected LVPs with low shape stability, as well as how pre-treatments for enhanced formability affect bond-line strength. By extension, the objective has been to rank parameters with the greatest impact and describe how they can be adjusted and adopted to contribute to reducing the occurrence of unacceptable products.

Limitations

Only selected material and process parameters were studied (see the introduction), and this means, of course, that there is a risk that some important parameters have been missed. For instance, it is well known that distortion and shape stability differ between species, but in the work described in the appended papers only beech and birch have been studied.

When the veneer's fibre angle has been controlled, this has been done only in the plane of the veneer. Conical angles in the thickness direction of the veneer and the angle of the S2 layer in the cell wall have not been considered.

The applied pressure has been calculated from oil pressure, piston area and surface area. The applied pressure was controlled by sensors for tests reported in Paper III. The reason for not using these sensors in all the tests was due to the sensors' inability to withstand the temperature used for the other tests or to handle the high-frequency heating used in the tests reported in Paper II.

Climatic cycling has been done by varying the relative humidity (RH) in combination with a constant temperature. This means that the influence of temperature variations has not been investigated.

The climates chosen for the climate cycling are based on measurements made in southern Sweden (Paper IV) regarding low and high target moisture contents (MC).

The shape measurements were made on unloaded products.

Overview of appended papers

Paper I is based on underlying studies found below, under heading: Reports in Swedish. Results from research projects regarding adhesive systems gave input to subsequent investigations of veneer-related properties. The work was based on practical experiments the purpose of which were to reduce the number of rejects. Discussions on the results of one test led to the next test. Paper I focused on how material and process parameters influence the shape stability of LVPs. Four aspects were investigated: (1) choice of adhesive system, (2) adhesive distribution, (3) moisture content of veneers, and (4) fibre orientation of veneers. The distortion of the product, a seat shell of beech or birch, was determined in production and after the shells had been subjected to alternating relative humidity to simulate conditions that may arise when the final product is in use.

The results show that both material and process parameters have a clear influence on the shape stability, and that it is possible on an industrial level to influence the degree of distortion and the shape stability by controlling some key parameters.

This study concludes that the key parameters for good shape stability of LVPs are fibre orientation in the veneers and between veneers, in combination with moisture content variations. This was especially evident when the principle of symmetry was not followed.

In the tests where species were compared, beech showed a poorer shape stability than birch.

Paper II expands on the part of Paper I which examines the impact of the fibre orientation of the veneers on the shape stability.

The distortion of the product, a shelf of birch, was determined in production and after the tested shelves had been subjected to alternating relative humidity to simulate conditions that could arise when the final product is in use.

The results show the well-known fact that differences in fibre orientation of the veneers in the laminate influence the shape stability of the product and that it is possible to reduce the degree of distortion and improve the shape stability by controlling the fibre orientation. The results of this study also show how the abnormal placement of veneers in the LVPs influences the degree of distortions, that two similar abnormally oriented veneers are better than one abnormal veneer, and that two opposing abnormally oriented veneers are the worst. Using this basic knowledge, some improvements in the production of LVPs are suggested.

Paper III is based on laboratory studies together with literature studies and discussions with researchers. It was developed from the hypothesis that lathe checks, which occur when a veneer is peeled or sliced, change the swelling and shrinking in the veneers. An underlying unpublished preliminary study of the influence of different surface pressures gave support to the idea for this study. In both studies the outcome was that the result was affected by the orientation of the lathe checks.

The paper is a study of how the orientation of one veneer in relation to the orientation of the other veneers in a laminate influences the shape stability of a three-layer, plane-laminated panel. The orientation of the veneer in this case may be: (a) in-plane rotation, *i.e.*, all three veneers in the same direction or the middle veneer cross-wise, or (b) out-of-plane rotation, *i.e.* orientation of the loose side of the veneers.

During peeling, one side of the veneer becomes much more cracked than the other as a result of the peeling process (*e.g.* Koch 1964). The cracked side of the veneer is called the ‘loose side’ or ‘back’ and the opposite side is the ‘tight side’ or ‘face’. Paper III presents an understanding of how the orientation of an individual veneer in the laminate affects the shape stability. The tests were carried out on plane-pressed laminates of beech. The results showed clearly that the orientation of the veneers influences the shape stability.

The conclusion of the study is that a 3-ply cross-laminated plane-pressed veneer product should have all the veneers oriented in the same direction according to the processing of the veneer (loose or tight side) in order to achieve a good shape. This is not the orientation commonly used in the industry today.

Paper IV, which is a review article, combines the results from Papers I, II and III with more extensive literature studies. It identifies several important factors that influence shape stability. The conclusions from Papers I, II and III are included in the study.

Based on existing knowledge of how to produce shape-stable LVPs, the veneers should be conditioned to a uniform moisture content (MC) and sorted with regard to fibre orientation and to the loose or tight side of the veneer before bonding. End-user climates should govern the veneers’ MC taking into consideration moisture added through the adhesive during the process. Straight grain veneers and symmetry should always be sought.

The review reveals several areas that need to be further clarified in order to achieve a shape-stable LVP, for example the influence of adhesive, the distribution of pressure, temperature, stresses and strains during moulding, and the development of numerical methods to better predict the final shape.

Paper V deals with the effect of enhanced formability on bond-line strength. The lack of formability of wood materials is a problem, as mentioned in the introduction. An initial study to enhance the formability and thereby mitigate cracking was carried out. Samples of a multi-curved seat shell were moulded, and regions with high stretching were visually checked for ruptures and cracks (Blomqvist *et al.* 2014a). That study (see Figure 8) combined with a study of how different modifications affect the bond-line strength and a smaller study concerning adhesive penetration were carried out and presented (Blomqvist *et al.* 2014b). The bond-line strength was tested by a tensile shear strength test (Figure 9). Adhesive penetration was tested on a shelf with recurrent shapes and visually checked, as shown in Figure 10 (Blomqvist *et al.* 2014b). The study that focused on the adhesive bond strength was deepened by climate cycling of samples and light microscopy studies to gain an understanding of the cause of failure with time in the tensile shear strength test (Blomqvist *et al.* 2014c).

The three conference reports, Blomqvist *et al.* (2014a, b and c), laid the foundation for the development of Paper V regarding bond-line strength. The study by Blomqvist *et al.* (2014c) was followed up in Paper V by a statistical analysis, and a more dependable analysis of the cause of failures. Scanning electron microscopy (SEM) was used to study the micro-structure of the bond-line zone. Paper V explores how different methods of increasing the formability of veneers affect the veneer-to-adhesive bond strength.

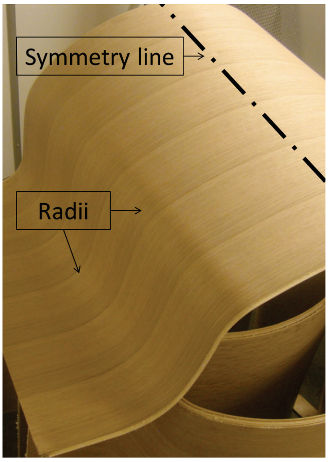


Figure 8 *Surface veneer of the tested seat shell. The symmetry line indicates the region with extensive stretching of the surface veneer (oak) during moulding.*

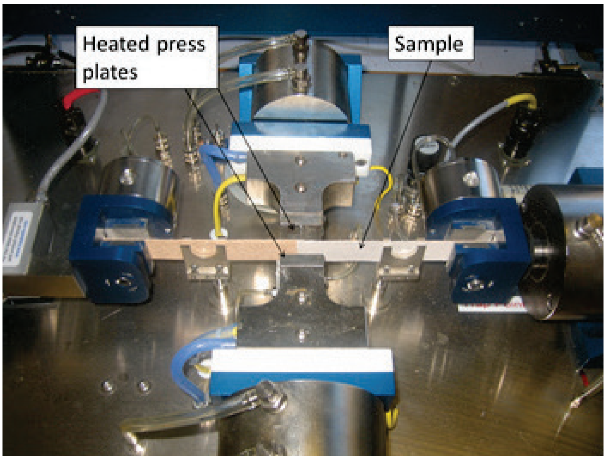
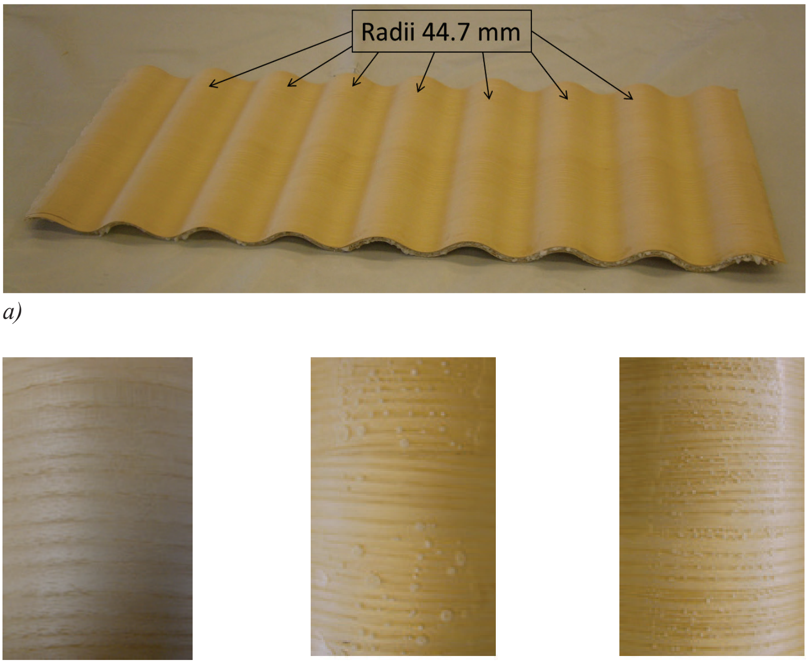


Figure 9 *Automated bonding evaluation system testing machine.*



a)

b) *c)* *d)*

Figure 10 *a) The tested shelf, with arrows indicating where the stretching of the veneer was critical. Examples of the tested shelf with: b) pre-pressed surface veneer, c) densified surface veneer, and d) unmodified surface veneer—all made of ash.*

A major problem in the manufacture of three-dimensional LVPs is damage due to stretching and/or buckling of the veneer. To reduce or eliminate this problem, veneer densification or the addition of a strengthening layer to the veneer can be a possibility. To study how veneer modification influences the veneer-to-adhesive bond strength, three methods of modification were studied in relation to an unmodified reference veneer: (1) densified veneer, (2) veneer pre-bonded with paper and hot melt adhesive (HMA), (3) veneer pre-bonded with non-woven polypropylene (NW) fabric glued to the veneer with (a) a urea formaldehyde (UF) adhesive, (b) a mixture of UF and polyvinyl acetate (PVAc) adhesive, and (c) a PVAc adhesive.

Densification, pre-bonding with paper, and NW with a UF/PVAc adhesive mixture resulted in a slight or no decrease in strength of the bond-line compared to the reference. NW glued with UF or PVAc adhesive showed a considerable reduction in the strength of the bond-line. Climatic cycling had no significant influence on the bond strength.

Materials and methodologies

The main materials used in the production of LVPs are veneers and adhesive, as already mentioned in the introduction.

Adhesive

Today, most LVPs produced industrially are bonded together by adhesive systems which involve chemical hardening. This means that chemical processes bond the adhesive molecules in chains (interlinked) and that the adhesive cannot re-emulsify. In all the tests included in this thesis, a urea formaldehyde (UF) adhesive system from Casco Adhesives, Inc., Sweden, was used.

Urea is a solid crystal obtained from ammonia and formaldehyde is produced from methane. Formaldehyde is a highly reactive gas with toxic emissions. An adhesive based on urea and formaldehyde, which was transparent, thermosetting, and hard, was patented in the early 1920s by German and British chemists (Encyclopaedia Britannica 2015b).

In the investigations presented in Paper V, a polyvinyl acetate (PVAc) adhesive, which dries physically, and a hot melt adhesive were also used for pre-bonding of samples.

Beech versus birch

In the various studies included in this thesis veneers from either beech (*Fagus silvatica* L.) or birch (*Betula pubescence* Ehrh.) have been used. The reason for this is that these wood species are the most prevalent in the industry which was studied. One significant difference between these two wood species is that beech shrinks more than birch in the tangential direction (Thunell and Perem 1952), Table 1. This is of interest since the degree of distortion is affected by shrinkage and swelling (Suchsland 2004).

Table 1 Shinkage properties of beech and birch (Perem and Thunell 1952).

	Shrinkage from Fibre Saturation Point to 0 % MC (%)		
	Radial	Tangential	Longitudinal
Beech	5.8	11.8	0.3
Birch	5.3	7.8	0.6

To carry out simulations of moisture-induced shape distortions, values of material properties influencing such distortions are required. However, for birch such values are not easily available. Blomqvist *et al.* (2015) used stiffness parameters based on data presented by Dinwoodie (2000), shrinkage parameters based on data presented by Boutelje and Rydell (1995), and mechano-sorption values based on data presented by Ormarsson (1999) for Norway spruce since data was limited for birch.

Enhanced formability of veneers

The formability of veneers can be enhanced. Veneers can be formatted by removing “unnecessary parts” of the veneer in areas prone to stretching and/or buckling while moulding. A fabric, mesh, paper, or other material can be pre-bonded to the back of the veneer to strengthen it in the transverse direction, a method often used for the visible, outermost veneers of thin or brittle veneers (Paper V). A ‘3-D veneer’ can be formed three-dimensionally. The most well-known way to produce 3-D veneer was developed by Reholz GmbH and later introduced onto the market (Müller 2006). Veneers can be modified either chemically or thermally (Navi and Sandberg 2012). Traditionally, the use of heat and moisture has been the most common way to soften wood and make it more amenable to shaping (Paper V).

There are interesting approaches in the area of veneer modification for enhanced formability. Pfriem and Herold (2015) have described a one-sequence method in which veneers are impregnated with a mixture of furfuryl alcohol and maleic anhydride, and are then moulded, bonded, and fixed by polymerisation at the end of the sequence.

Methodology to study shape stability

In this work, three different types of products have been studied regarding shape stability: a seat shell (Paper I), a shelf (Paper II) and a plane construction (Paper III). Different modes of distortion have been defined and determined based on future use and the consumer environment.

For the shell, position and twist were used to define the shape of the product (Figure 11).

Position was defined according to the mould. If the shell was wider, *i.e.* the angle between the seat and back was greater than that of the mould, the distortion was positive (+) and if the angle was smaller, the distortion was negative (-).

Twist is the situation when the four corners of a quadrangle are no longer in the same plane (Forest Products Laboratory 2010). A gauge was constructed to measure the position and twist of the seat shell. The shell was placed on three reference points in the gauge, these points being positioned in the seat area of the shell, and measurements were made at two points 235 mm apart on the back of the shell (Figure 12). For each of the two measurement points, the distance to the gauge was determined. The position was calculated as the average of the two distances, whereas the twist was determined as the difference between them. The accuracy in the deformation measurements was about ±0.1 mm.

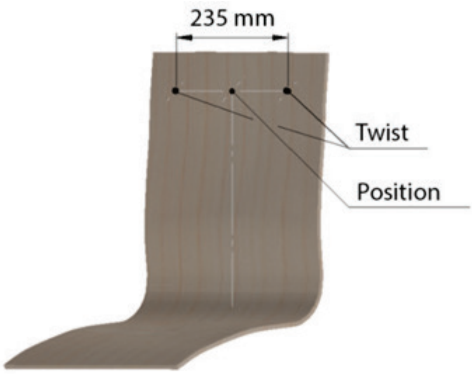


Figure 11 Definition of distortion of a moulded seat shell.

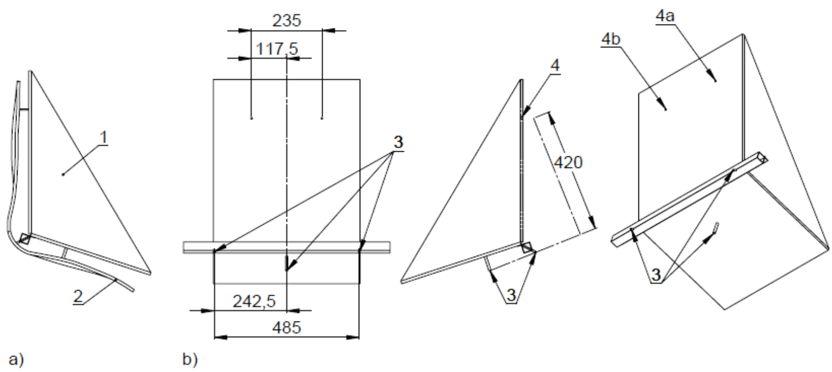


Figure 12 *Determination of distortion of seat shells. a) Side view of the gauge (1) in position for measuring the seat shell (2). b) Back, side and a free view of the gauge showing the positions of the fix points (3), and locations for position and twist measurement (4a and 4b). Length measurements in mm.*

In the case of the shelf, position, twist and cup were used to define the shape of the product (Figure 13). Cup is the name given to the phenomenon where there is a deviation from a straight line across the width of a surface (Forest Products Laboratory 2010). A gauge was constructed to measure the position, twist and cup of the shelf. Position and twist was calculated in the same way as for the seat shell, using two measurement point positioned at a distance of 567 mm from each other (Figure 13). Cupping was determined as the distance between a straight line drawn between the two earlier mentioned measuring points and a third measuring point between them (Figure 14) The accuracy in the deformation measurement was about ±0.1 mm.

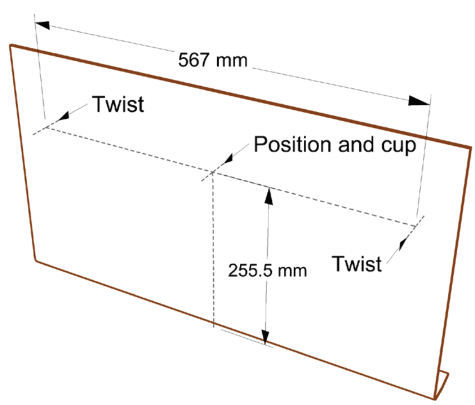


Figure 13 *Definition of distortion of a moulded shelf.*

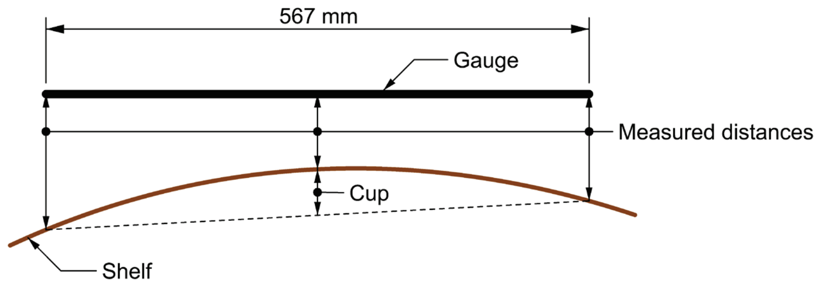


Figure 14 Definition of measuring of cup.

For the plane construction, cup and twist were used to define the shape of the product. Cup was measured as the height of the arc at the centre of the construction. Twist was measured as the difference between two points (Figure 15). The twist of the plane construction was measured by holding down two corners and measuring the difference in height between the two free corners. This method was chosen to reduce the influence of cupping on the measure of twist. Typically three corners would be held down to measure the twist at the fourth free corner. The accuracy in the deformation measurement was about ±0.1 mm.

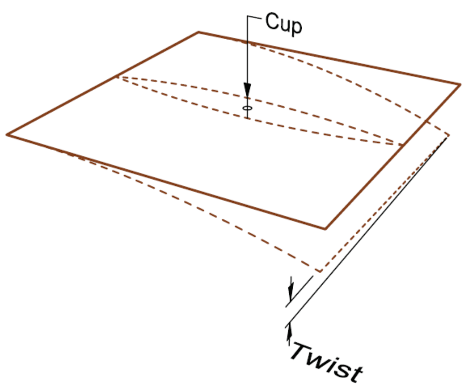


Figure 15 Definition of distortion of a plane-pressed laminate.

To simulate the shape stability of products in an end-user environment, the tested samples were exposed to variations in relative humidity, where the low and high humidity levels were chosen to simulate the levels to which the product can be subjected in use. The samples were weighted to confirm that the equilibrium moisture content (EMC) in relation to the surrounded climate had been reached.

Methodology to study the effect of enhanced formability on the bond-line strength

To be able to produce more advanced LVP shapes, the formability of veneers needs to be enhanced. This can be done in several ways, and the way in which this affects the adhesive bond must be taken into consideration in the choice of method. In Paper V, a tensile shear strength test was used to study the bond-line strength in samples where one of the two veneers was modified to increase its formability. The test was a single lap-joint test according to EN 205 (2003), but with modified dimensions (Figure 16). To avoid failure in the wood material during the test, the unmodified parts of the samples were strengthened with paper glued onto the outer parts of the samples with hot-melt adhesive.

The test was performed in an automated bonding evaluation system (ABES) machine, seen in Figure 9 (Adhesive Evaluation Systems, Inc.). Pressure, pressing time, temperature, duration, cooling time and force were controlled by the ABES for samples tested directly in a sequence. Other samples which were climate cycled were removed from the ABES after pressing and replaced in the ABES in time for the tensile-shear test.

Other samples were bonded together to study the bond-line zone without subjecting them to the tensile-shear-strength test. The micro-structure of the mentioned zone was studied in a scanning electron microscopy (SEM).

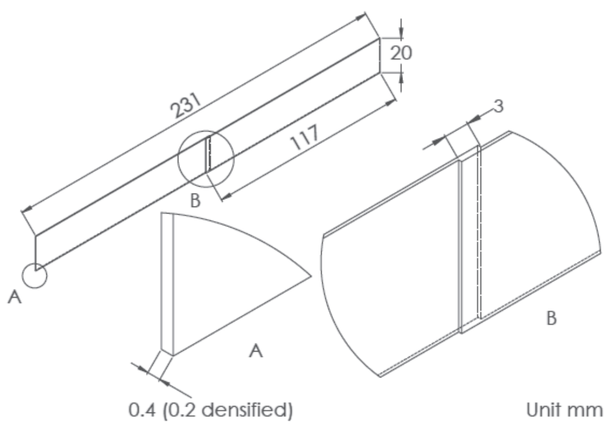


Figure 16 Sample with detailed views describing the thickness and the overlap.

Results

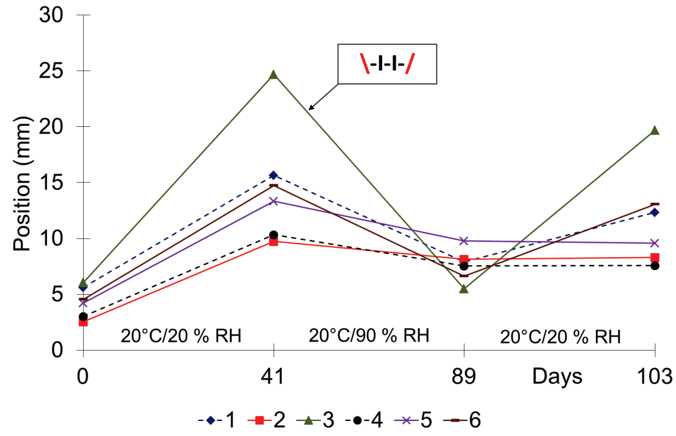
Shape stability

Of the parameters studied, it was clear that fibre orientation and moisture content variations were the main reasons for the distortion and poor shape stability of laminated veneer products (LVPs). The distortions directly after moulding were in general small, but the distortions increased after the products had been subjected to variations in relative humidity (Paper I).

The shells with a symmetrical structure showed a low twist after moulding and during climate cycling. Laminates with two veneers with the same fibre deviation symmetrically oriented in the laminate resulted in less twist than a single veneer with the same fibre deviation placed at the corresponding location, while two veneers with the same fibre deviation asymmetrically oriented in the laminate gave a twist that was more than double that of a single veneer. Divergent veneers inside the laminate led to less distortion than divergent outermost veneers (surface veneers) (Figure 17) (Paper II).

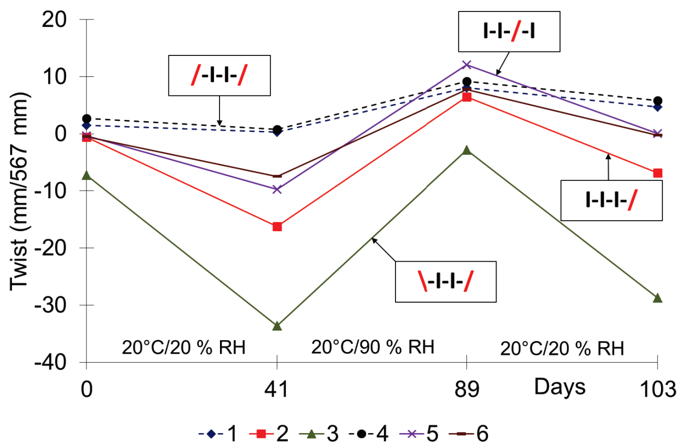
Another observation was that a fibre deviation in the longitudinally oriented veneer affects twist, while a deviation in the transversally oriented veneer led to cupping, to a greater extent. However, the effect of the transversally oriented veneer was only tested to a limited extent, as shown in Figure 17 (Paper II).

A variation in the climate in which the laminated products are stored can lead to large distortions, as shown in Figure 17, although the veneers were well-conditioned to the same MC before moulding. Variations in the MC of the products release internal tensions and distortion occurs. In general, the shape of an LVP is sensitive to changes in MC, but if the veneers are not well conditioned before moulding, distortion may occur even if the products are stored in a very stable climate, as shown in Figure 18 (Paper I).



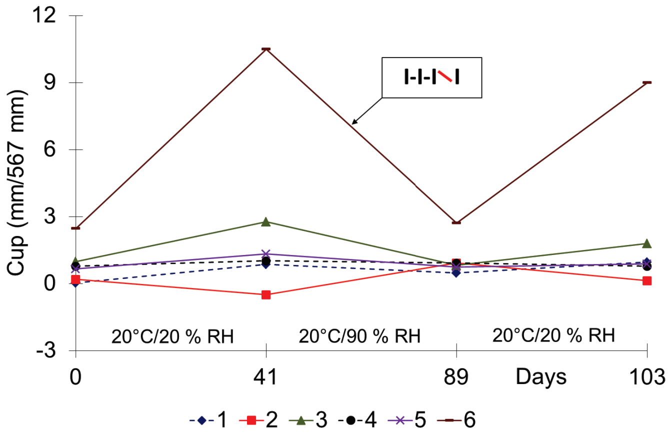
Position (mm)
\-I-I-/
20°C/20 % RH
20°C/90 % RH
20°C/20 % RH
Days
1
2
3
4
5
6

a)



Twist (mm/567 mm)
/-I-I-/
I-I-/-I
I-I-I-/
\-I-I-/
20°C/20 % RH
20°C/90 % RH
20°C/20 % RH
Days
1
2
3
4
5
6

b)



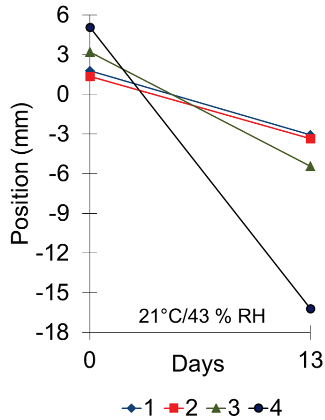
c)

Orientation of lengthwise (L) and transverse (T) veneers seen from "front to back" are L1−T2−L3−T4−L5−T6−L7.
Group number 1 have no deviation in fibre orientation.
Groups 2–6 have veneers with different fibre orientation. Group number:
2. L7=+7°, 3. L1=-7°, L7=+7°, 4. L1=+7°, L7=+7°, 5. L5=+7°, 6. T6=+7°

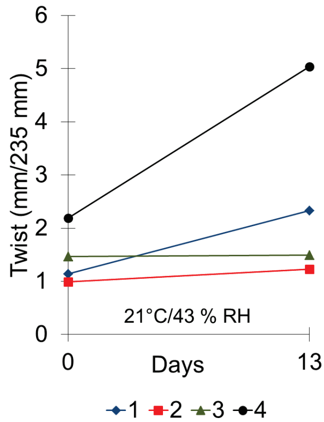
Figure 17 Changes in distortion parameters with time of a seven-ply veneer exposed to different climate conditions. a) Mean position, b) twist, and c) cup in shelves of birch manufactured with veneers with different fibre orientations. The rectangles in the figures indicate fibre directions in veneers. The results are from Paper II.

Figure 18 shows the position and twist for seat shells of birch with different MCs in some of the veneers in the assembly. Immediately after moulding, there were only small differences in position and twist in the different groups. After 13 days of conditioning at a constant climate, however, the seat shells with the most asymmetric MC profile exhibited a substantial change in position and an increase in twisting, *i.e.* poor shape stability. The shells with all the veneers at the same MC or with only one or both of the outermost veneers at a higher MC showed only a moderate change in shape during storage (Paper I).

The results indicate that, if the veneers are well-conditioned before moulding, the distortion of the moulded assembly in use is reduced, and that a high MC in several of the veneers in the assembly can lead to considerable distortion after moulding, especially when the moisture is asymmetrically distributed in the assembly. However, a high MC in surface veneers do not cause any significant distortion, see for example groups 2 and 3 in Figure 18.



a)



b)

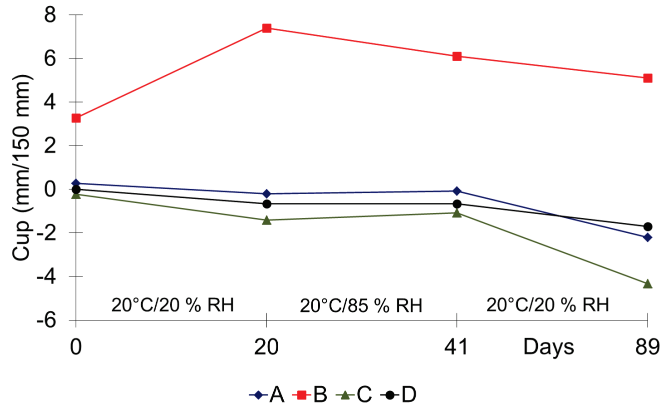
Group number:

1. all seven veneers with 5 % MC
2. 5 veneers with 4% MC and surface veneers with a slightly higher MC (7 %)
3. the veneer closest to the concave side of the seat shell with 19 % MC and the rest of the veneers with 5% MC
4. 3 veneers with 19 % MC closest to the seat shell on the concave side and 4 veneers with 5% MC

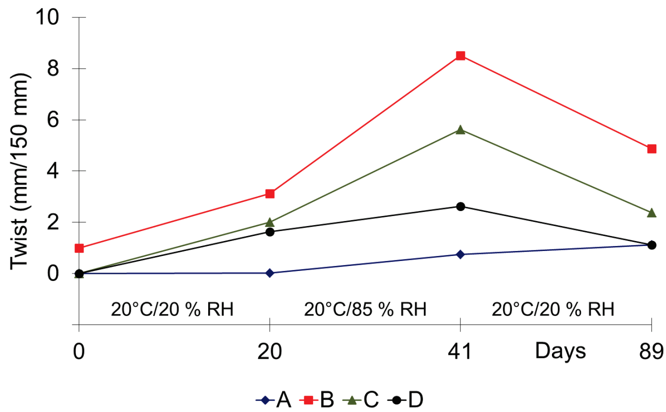
Figure 18 a) Mean position and b) twist as a function of time in seat shells of birch manufactured with veneers having different moisture contents and exposed to a constant climate. Results from Paper I.

Crosswise in-plane orientation of the veneers gives the best shape stability, as is a well-known fact both in the literature and in practice. This principle of veneer orientation is commonly used for example in plywood. In Paper III, it was shown that the orientation of the loose side of the veneer also affects the shape stability. The highest shape stability have LVPs in which the veneers are crosswise in-plane oriented with regard to fibre direction and with the loose side of the veneers oriented in the same way, upwards or downwards, with respect to the lathe checks on the loose side (group 1 in Figure 19). In contrast, the lowest shape stability has the LVP in which the veneers are parallel in-plane oriented with regard to fibre direction with the loose side of the veneers oriented in the same way (group 2 in Figure 19) (Paper III). The result of the tests presented in Paper III clearly shows that the orientation of the loose side has a considerable influence on shape stability.

In the comparison between the two investigated species, birch was more shape-stable than beech (Paper I). This is consistent with the values for shrinkage in the tangential direction reported by Thunell and Perem (1952).



a)



b)

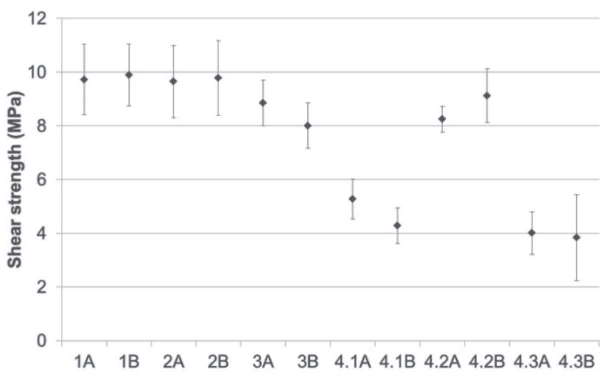
Group number:

1. loose side down for all veneers and the middle veneer with a perpendicular fibre orientation
2. loose side down and all veneers parallel
3. loose side down except for the bottom veneer and all veneers parallel
4. loose side down except for bottom veneer and middle veneer perpendicular

Figure 19 *a) Mean cupping and b) mean twist as a function of time in three-layer plane-press laminates with different orientations of veneer exposed to different climates. Results from Paper III.*

Bond-line strength

Shear strength tests were carried out to study the effects on the bond-line strength of different methods of enhancing the formability. The results showed that the bond-line strength was not influenced by densification, pre-bonding with paper without climate cycling, or pre-bonding with a non-woven (NW) polypropylene fabric using a mixture of UF and PVAc. The bond-line strength was however considerably lower than in the reference for a veneer strengthened with NW pre-bonded solely with UF or PVAc adhesive, as shown in Figure 20 (Paper V).

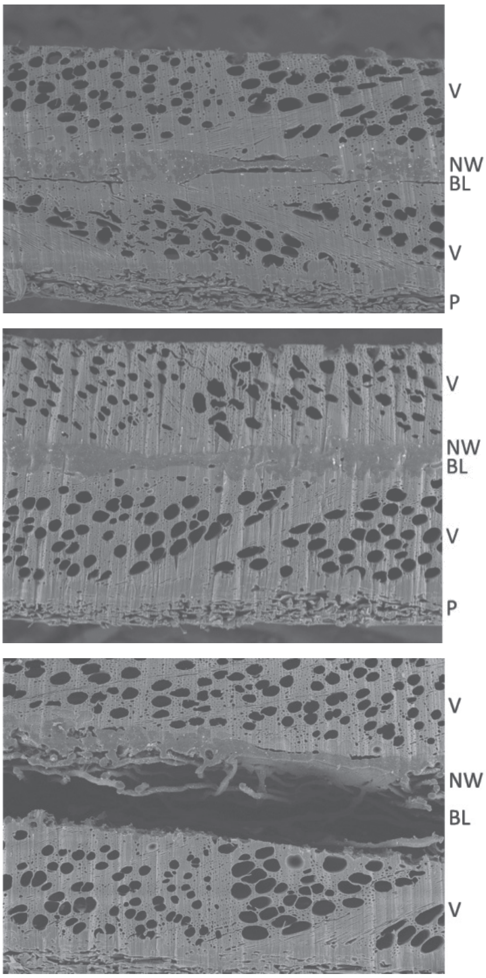


Group number:

1. unmodified veneer as reference
2. densified veneer
3. veneer pre-bonded with paper that included a HMA
4. veneer pre-bonded with non-woven polypropylene fabric (NW) glued to the veneer with a:
   - 4.1. UF
   - 4.2. 50/50 UF and PVAc
   - 4.3. PVAc

Figure20 Mean bond-line shear strength A) Samples not exposed to climate cycling, and B) samples exposed to climate cycling. Results from Paper V.

The climate cycling changed the type of failure especially for the group with densified veneer and the group with veneer pre-bonded with paper. One reason was that the densified veneer teased to swell to its former thickness and the paper swelled during the climate cycling. Veneer strengthened with NW pre-bonded with UF or PVAc adhesive had a weak bond-line, since the pre-bonding interferes with the bonding between the veneers, shown in Figure 21 (Paper V).



The NW filled with UF is a darker shade of grey in the SEM than the veneers. The cracks in the bond-line indicate low adhesion between adhesive and veneer.

The NW pre-bonded with a mixture of UF and PVAc. The penetration in the bond-line and the adhesion appear to be very good.

The NW pre-bonded with PVAc. The penetration and adhesion of the adhesive in the bond-line was low, as shown by the openings in the bond-line.

Figure 21 SEM micrographs showing cross sections of the bond-line zone for samples pre-bonded with NW. Results from Paper V.

Discussion

The work and the results presented in this thesis contribute to the understanding of what causes LVP rejects and thereby contributes to their reduction. The results make clear that it is possible to improve the shape stability of LVP and to predict whether the methods used to enhance the formability of the veneers will provide excellent bond-line strength. However, much remains to be done to gain a deeper understanding.

Regarding shape stability, the most important of the studied parameters is fibre orientation in combination with moisture content (MC) variations in the LVP. Distortion is generally small directly after moulding, but after the LVPs have been exposed to variations in RH, the distortion increases, depending on the RH of the air surrounding the product. Since the climate in most surrounding areas varies considerably over the year it is difficult to recommend a specific MC. In any case, it is however important that the core veneers in the laminate are conditioned to the same MC, as different MCs in the veneers in the laminate lead to asymmetry, as shown by the results of this work. It is important to condition the veneers to a MC, so that they, together with the water added with the adhesive, have a target MC representative of the end-user's environment.

The fibre orientation should always be straight grain and the veneers should always be assembled symmetrically to give the highest shape stability. However, it is difficult to have full control of the veneers since trees are not symmetrical cylinders. This makes it virtually impossible to produce a veneer that is parallel to the grain, both on its face and throughout its thickness; the orientation of peeling also plays a role. This means that it is important to have a knowledge of the final requirements and have a good working relationship with the veneer supplier.

Symmetry should always be sought in the production of LVPs. It is incorrect to try to compensate for one deviation fault with the opposite fault, as that may lead to asymmetry and lower the shape stability.

The methods used to measure shape stability were time-efficient but built on simplistic methods to obtain data relating to predetermined shape disorders. However, the methods yielded sufficient information for the aim of this thesis.

A more comprehensive measurement method than those used in Papers I–III was tested to digitize geometries with a combination of 3D-coordinate measurements and optical scanning (Blomqvist *et al.* 2011). The method would be useful for more detailed studies and for evaluating simulation models. More extensive experimental results are needed to ensure a good basis for simulations, especially in the area of material data concerning wood species. Blomqvist *et al.* (2015), for example, had problems finding mechano-sorption data for birch.

Several areas need to be further clarified in order to achieve shape-stable LVPs; for example, the influence of adhesive; the distribution of pressure, temperature, stresses, and strains during moulding; and the development of numerical methods to better predict the final shape (Paper IV). Some of the challenges lie in the design of the tests, the measurement parameters, and the control of materials and processes. The design of the tests requires control of several crucial components, and the perspective from which the tests are designed must be clarified. Wood is a poorly defined material, which means that it is difficult to control. In Paper V, formability has been used solely as a basis for studies on the effect of the bond-line strength. In the conference reports that present these studies, the stretching of the surface veneer and the penetration of adhesive into surface veneers has been examined (Blomqvist *et al.* 2014a–c). It would be of great interest to the industry and academia to study the conditions of formability and to further investigate methods to enhance formability in order to be able to produce more advanced shapes to compete with materials other than LVPs. This area opens up for studies on veneer properties and mould tools design.

An initial test to investigate whether uneven surface pressure while moulding affects the shape stability has been performed in the context of this thesis. The setup was similar to that described in Paper III. The study, which is unpublished, revealed no significant differences. A new study has been prepared, in which other aspects of pressure will be analysed to determine, for example, whether a reduction in the pressure before full curing has been reached affects the shape stability. Further, samples of another shape will be used, and the samples will be bent instead of plane-pressed.

Conclusions

The results of the work presented in this thesis show that it is possible to improve the shape stability of LVPs if an in-depth understanding of the materials and process parameters can be implemented in the manufacturing process. To achieve shape stability of LVP, it is desirable

- to set requirements and control the veneers with regard to the fibre angle and equilibrium moisture content (EMC),
- to plan warehousing, before and during production, of the veneers and ensure conditioning,
- to condition the veneers to an MC which together with the added moisture from the adhesive used in the process matches the climate in which the final product will be used,
- to consider the orientation of the veneers regarding fibre orientation, the side of the veneer (loose versus tight side) and the species, and
- to seek symmetry at all times.

When veneers are treated to enhance formability, it is important to check that the treatment does not prevent the adhesive from penetrating the wood surface or otherwise weaken the bond-line. Therefore, the bond-line strength in constructions which include the pre-treatment of the wood surface should always be controlled.

Future work

For the continuing improvement of LVPs, the following issues have a high priority:

- The development of material data to provide a better basis for simulation models (in the Beech versus birch chapter; in the Discussion chapter).
- The choice of the MC of the veneer and the added moisture from the adhesive affects the customer experience since it affects how the LVP will shrink and swell in the environment in which it is placed (Papers, I–IV). This is an example of how decisions made during the production of LVPs affect customer experience. The extent to which choices in the processes affect the customer experience of the product needs further study.
- The development of adhesives in relationship with the bonding ability of the wood surface to achieve good adhesion (Paper IV) in harmony with both the internal and external environments.
- How stress and strain affect the formability. This issue merits exploration in order to determine whether the design of moulding tools can be improved (Paper IV).
- The effect of uneven contact pressure. The literature indicates that the applied pressure influences the shape stability. This merits exploration in order to determine whether the design of the moulding tools can be improved (Papers I and IV).
- The development of prediction methods (Paper IV) useful for the industry.
- High shape stability is a prerequisite for more automated production (Eliasson 2014; in the Parameters chapter). With regard to improvements to facilitate a more automated production, there is a need to explore whether there are other ways of dealing with the determination of the material.

References

Anderson, E. A., Earle, G. F. (1972). Design and Aesthetics in Wood. Albany: State University of New York Press.

Bergman, R., Puettmann, M., Taylor, A., Skog, K. E. (2014) The Carbon Impacts of Wood Products, *Forest Products Journal*, 64, (7/8), 220–231.

Blomqvist, L., Johansson, J., Sandberg, D. (2011). Contact free measurement of complex shapes in the wood industry. In: *Cost Action FP0904, Mechano-chemical transformations of wood during THM processing*, Biel (Bienne), Switzerland, 143–144.

Blomqvist L. (2013). Shape stability of laminated veneer products. Licentiate Thesis, Linnaeus University, Växjö, Sweden.

Blomqvist, L., Johansson, J., Sandberg, D. (2014a). Modification of surface veneer to reduce damage in laminated veneer products during manufacturing. In: *Final Cost Action FP0904, Recent Advances in the Field of TH and THM Wood Treatment*, Skellefteå, Sweden, 50–51.

Blomqvist, L., Johansson, J., Sandberg, D. (2014b). Veneer modification for improved formability when moulding laminated veneer products. In: *Forest Products Society (FPS) 68th International Convention*, Quebec City, Canada.

Blomqvist, L., Sterley, M., Sandberg, D., Johansson, J. (2014c). The influence of veneer modification on adhesive bond strength. In: *Proceedings of the 10th meeting of the Northern European network for wood science and engineering (WSE),* Edinburgh, Scotland, 150–155.

Blomqvist, L., Berg, S., Sandberg, D. (2015). Chipless machining: Challenges in Manufacture of Laminated Veneer Products. In: *Proceedings of the 22nd International Wood Machining Seminar (IWMS 22)*, Quebec City, Canada, 1, 155–164.

Boutelje J., Rydell R. (1995). Träfakta: 44 träslag i ord och bild. (Facts on wood: 44 species in words and pictures). Stockholm: Swedish Institute of Wood Technology Research (in Swedish).

Dinwoodie, J. M. (2000). Timber, its nature and behaviour. London: Taylor & Francis.

Eliasson, L. (2014). Some aspects on quality requirements of wood for use in the industrial manufacture of single-family timber houses. Doctoral thesis, Linnaeus University, Växjö, Sweden.

EN 205 (2003). BS EN 205:2003. Adhesives – Wood adhesives for non-structural applications – Determination of tensile shear strength of lap joints.

Encyclopaedia Britannica (2015a).
http://global.britannica.com/biography/Charles-Eames-and-Ray-Eames/
downloaded 2015-10-12.

Encyclopaedia Britannica (2015b).
http://global.britannica.com/science/urea-formaldehyde-resin/
downloaded 2015-10-01.

Forest Products Laboratory (2010). Wood handbook wood as an engineering material, General technical report FPL GTR-190. Madison, Wis: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory.

Herman Miller, Inc. (2016).
http://www.hermanmiller.com/content/hermanmiller/northamerica/en_us/home/design-resources/images.html?text=Herman%20Miller:Products/Eames%20Lounge%20Chair%20and%20Ottoman#
downloaded 2016-03-03.

Hill, C. A. S. (2006). Wood Modification: chemical, thermal and other processes. Chichester, England: John Wiley & Sons, Ltd.

IKEA (2016). http://www.ikea.com/PIAimages/46190_PE142932_S5.JPG/
downloaded 2016-03-03.

Knight, E.V., Wulpi, M. (1927). Veneers and plywood, their craftsmanship and artistry, modern production methods and present-day utility. New York: The Ronald press company.

Koch, P. (1964). Wood machining processes. New York: The Ronald Press Company.

Kollmann, F. F. P., Côté Jr, W. A. (1968). Principles of wood science and technology. Berlin: Springer-Verlag.

Marra, A. A. (1992). Technology of wood bonding: principles and practise. New York: Van Nostrand Reinhold.

Meyer, L. H. (1947). Plywood: what it is – what it does. New York: McGraw-Hill Book Company, Inc.

Müller, A. (2006). Method for the production of a three-dimensional, flexibly deformable surface element. U.S. Patent No. 7131472B2.

Navi, P., Sandberg, D. (2012). Thermo-hydro-mechanical processing of wood. Lausanne: EPFL Press.

Ormarsson, S. (1999). Numerical analysis of moisture-related distortions in sawn timber. Doctoral Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Oxford Dictionaries (2016a).
http://www.oxforddictionaries.com/definition/english/biopolymer/
downloaded 2016-01-08.

Oxford Dictionaries (2016b).
http://www.oxforddictionaries.com/definition/english/polymer/
downloaded 2016-01-08.

Pfriem, A., Herold, N. (2015). Simultaneous moulding and fixation of veneer by furfuryl alcohol modification. In: *Thermosets 2015 – from Monomers to Components*, Berlin, Germany.

Republic of Fritz Hansen (2016).
http://www.fritzhansen.com/en/fritz-hansen/asset-bank/
downloaded 2016-03-03.

River, B. H., Vick, C. B., Gillespie, R. H. (1991). Wood as an adherend. Treatise on adhesion and adhesives. Volume 7. New York: Marcel Dekker, Inc.

Rowell, R. M. (2013). Handbook of wood chemistry and wood composites (2nd rev. ed.). Boca Raton: Taylor & Francis.

Rowell, R. M., Ellis, W. D. (1984). Reaction of epoxides with wood. Res. Pap. FPL 451. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Shaykett, J. (2012). A Bent for Design. *American Craft Magazine*, November 19, American Craft Council.

Stevens, W. C., Turner, N. (1970). Wood Bending Handbook. Woburn, MA: Woodcraft Supply Corp.

Suchsland, O. (2004). The swelling and shrinkage of wood. A practical technology primer. Madison, WI: Forest Products Society.

Thunell, B., Perem, E. (1952). Svenskt trä (Wood from Sweden). Stockholm: Strömbergs (in Swedish).

Van de Velde, K., Kiekens, P. (2002). Biopolymers: overview of several properties and consequences on their applications. *Polymer Testing*, 21 (4), 433–442.

Yorkshire air museum (2015). http://yorkshireairmuseum.org/exhibits/aircraft-exhibits/world-war-two-aircraft/de-havilland-mosquito-dh98-nfii/ downloaded 2015-10-27.

Yorkshire air museum (2016). http://yorkshireairmuseum.org/wp-content/uploads/2010/03/featured-image-1-4.jpg/ downloaded 2016-03-03.

Other relevant publications not included in the thesis

Peer-reviewed articles in international journals

Blomqvist, L., Johansson, J., Sandberg, D. (2013). Basic knowledge of wood properties for improved performance of laminated veneer products. *Pro Ligno*, 9(4), 549–556.

Peer-reviewed conference reports with international coverage

Blomqvist, L., Berg, S., Sandberg, D. (2015). Chipless Machining: Challenges in Manufacture of Laminated Veneer Products. In: *Proceedings of the 22nd International Wood Machining Seminar, IWMS 22*, Quebec City, Canada, 1, 155–164.

Blomqvist, L., Johansson, J., Sandberg, D. (2014). Modification of surface veneer to reduce damage in laminated veneer products during manufacturing. In: *Final Cost Action FP0904, Recent Advances in the Field of TH and THM Wood Treatment*, Skellefteå, Sweden, 50–51.

Blomqvist, L., Johansson, J., Sandberg, D. (2014). Moisture-induced distortion of laminated veneer products. In: *Forest Products Society (FPS) 68th International Convention*, Quebec City, Canada.

Blomqvist, L., Sterley, M., Sandberg, D., Johansson, J. (2014). The influence of veneer modification on adhesive bond strength. In: *Proceedings of the 10th meeting of the Northern European network for wood science and engineering (WSE),* Edinburgh, Scotland, 150–155.

Blomqvist, L., Johansson, J., Sandberg, D. (2014). Veneer modification for improved formability when moulding laminated veneer products. In: *Forest Products Society (FPS) 68th International Convention*, Quebec City, Canada.

Johansson, J., Blomqvist, L., Sandberg, D. (2013). Challenges using dielectric heating for THM processing of solid wood. In: *COST Action FP0904 Workshop, Evaluation, processing and predicting of THM treated wood behaviour by experimental and numerical methods*, Iași, Romania, 55–56.

Blomqvist, L., Johansson, J., Sandberg, D. (2013). Moisture-induced distortion of laminated veneer products. In: *Proceedings of the 9th meeting of the Northern European network for wood science and engineering (WSE),* Hannover, Germany, 178–183.

Blomqvist, L., Johansson, J., Sandberg, D. (2013). Shape stability of THM-processed laminated veneer products glued with bio-based adhesive systems. In: *COST Action FP0904 Workshop, Evaluation, processing and predicting of THM treated wood behaviour by experimental and numerical methods*, Iași, Romania, 99–100.

Blomqvist, L., Rowell, R. (2012). Bio-based adhesives at laminated veneers. In: *Proceedings of the 8th meeting of the Northern European Network for Wood Science and Engineering (WSE)*, Kaunas, Lithuania, 221–225.

Blomqvist, L., Johansson, J., Sandberg, D., Kifetew, G. (2012). The influence of individual veneer orientation on the shape stability of planar lamination. In: *COST FP0904 Workshop, Current and Future Trends of Thermo-Hydro-Mechanical Modification of Wood. Opportunities for new markets?*, Nancy, France, 160–162.

Blomqvist, L., Johansson, J., Sandberg, D. (2011). Contact free measurement of complex shapes in the wood industry. In: *Cost Action FP0904, Mechano-chemical transformations of wood during THM processing*, Biel (Bienne), Switzerland, 143–144.

Blomqvist, L., Johansson, J., Sandberg, D. (2011). Improving the performance of bended laminated veneer products. In: *Cost Action FP0904, Mechano-chemical transformations of wood during THM processing*, Biel (Bienne), Switzerland, 147–148.

Licentiate thesis

Blomqvist, L. (2013). Shape stability of laminated veneer products. Licentiate Thesis, Växjö, Linnaeus University Press.

Reports in Swedish

Sandberg, D., Blomqvist, L. (2007). Formstabilitet hos formpressade hyllplan (Shape stability of moulded shelves). Växjö, Växjö universitet, Teknik & design, 16 (in Swedish).

Sandberg, D., Blomqvist, L. (2007). Klimat i produktionslokaler vid Svensson & Linnér AB (Climate in production areas at Svensson & Linnér). Växjö, Växjö universitet, Teknik & design, 9 (in Swedish).

Sandberg, D., Blomqvist, L., Johansson, J. (2007). Material- och produktionsparametrars betydelse för formstabiliteten hos skiktlimmade fanerprodukter (The importance of material and production parameters to the shape stability of laminated veneer products). Växjö, Växjö universitet, Teknik & design, 94 (in Swedish).

Sandberg, D., Blomqvist, L. (2006). Formändringar hos formpressade fönsterkarmar vid ändrad fuktkvot (Changes in moulded window frame shape due to changes in moisture content). Växjö, Växjö universitet, Teknik & design, 7 (in Swedish).

Sandberg, D., Blomqvist, L. (2006). Fuktkvotsvariation i fanerbuntar vid ändrad relativ luftfuktighet (Moisture content variations in veneer bundles due to changes in relative humidity). Växjö, Växjö universitet, teknik & design, 13 (in Swedish).

Sandberg, D., Blomqvist, L. (2006). Inverkan av fanerens fuktkvot på formstabiliteten hos skiktlimmade skal (Impact of veneer moisture content on the shape stability of laminated shells). Växjö, Växjö universitet, Teknik & design, 8 (in Swedish).

Sandberg, D., Blomqvist, L. (2006). Inverkan av fiberorienteringen på formstabiliteten hos skiktlimmade skal (The impact of fibre orientation on the shape stability of laminated shells). Växjö, Växjö universitet, teknik & design, 12 (in Swedish).

Sandberg, D., Blomqvist, L. (2006). Inverkan av limmets torrhalt på formstabiliteten hos skiktlimmade fanerprodukter (Impact of adhesive dry content on the shape stability of laminated veneer products). Växjö, Växjö universitet, Teknik & design, 12 (in Swedish).

Sandberg, D., Blomqvist, L. (2006). Inverkan av limspridningen på formstabiliteten hos skiktlimmade skal (Impact of adhesive distribution on the shape stability of laminated shells). Växjö, Växjö universitet, 9 (in Swedish).

Sandberg, D., Blomqvist, L. (2006). Inverkan av ojämn limspridning på formstabiliteten hos skiktlimmade skal – Förstudie (Impact of uneven adhesive distribution on the shape stability of laminated shells: A feasibility study). Växjö, Växjö universitet, 12 (in Swedish).

Sandberg, D., Blomqvist, L., Svensson, N. (2006). Produktivitetsmätning vid skiktlimning - störningsanalys vid CNC-bearbetningen (Measuring the productivity of laminated bonding: Interference analysis at CNC machining). Växjö, Växjö universitet, Teknik & design, 19 (in Swedish).