Chapter 4

Plywood and other veneer-based products

Mark Hughes, Aalto University, Finland

4.1 Introduction

The history of plywood can be traced back centuries, but it really came to prominence as a structural engineered wood product through two significant innovations: the invention of rotary peeling for producing thin wood veneer in the late nineteenth century and the advent of synthetic waterproof adhesives in the early twentieth. Waterproof adhesives such as phenol formaldehyde led to the manufacture of strong and durable wood composites that could be used in demanding exterior applications, whilst the development of rotary peeling enabled veneer to be produced at an industrially viable scale. Later, adaptations of the lay-up led to the introduction of laminated veneer lumber (LVL) and subsequently to parallel strand lumber (PSL), which created new application areas for veneer-based, engineered wood products, which continue to expand to this day.

There are, and have always been, a number of highly specialised uses for plywood and veneer. One of the key advantages of veneer as opposed to sawn wood is that it maximises the yield of material from the log. This means that for decorative purposes such as furniture overlays, expensive or rare woods, such as burr birch or walnut can be economically utilised. Plywood itself has also been used in many exotic applications such as in aerospace and for boat building, but it is as a construction material, as components in furniture and in transport applications, that plywood and other veneer-based materials are mainly to be found.

This chapter provides an overview of the history and applications for veneer-based products as well as giving an outline of the manufacturing process and the applications for, and the performance of, these materials. There is focus on the relationships between raw materials, manufacturing processes and the properties of the final end
product. Changes in raw material resources as well as developments in the manufacturing process and online monitoring will lead to veneer-based products of superior quality and performance. So, far from being a group of products that have reached the end of their development cycle, there are many new and exciting innovations taking place that are likely to see plywood, LVL and its cousins continue to be important wood-based products well in to the future.

4.2 History and market

Plywood truly has a long history. A type of plywood, forming part of a coffin dating from the Egyptian third dynasty over 3500 years ago has been found. It consisted of six 4 mm thick layers of sawn wood, arranged in cross-wise fashions that were held together using wooden dowels (Lucas 1926; Taylor 2001). Later developments saw the wooden pegs being replaced by animal-based glues and the thickness of the layers of wood reduced to around 3 mm (Patrick and Minford 1991). Modern plywood is generally manufactured in much the same way, but from veneers – thin (generally less than 3mm) slices of wood that are produced by ‘peeling’ logs on a special lathe – that are dried and coated with glue and are pressed together with alternate veneers placed orthogonally to form a flat plate or curved structure. The production of peeled veneers for plywood manufacture only became really viable with the invention of the rotary lathe by Immanuel Nobel in the late nineteenth century. However decorative veneer produced by ‘slicing’ a block or ‘flitch’ of wood was introduced earlier and is still produced today. The advent of waterproof synthetic wood glues in the 1930s and their subsequent development during WWII led to a post war boom in plywood manufacture.

Veneer then is the basis of plywood, but it is also to be found in other wood-based composites, laminated veneer lumber, perhaps being the most important recent addition to the family of veneer-based wood composites. LVL differs from plywood in that the veneers are glued together and pressed with the grain of all veneers generally oriented in the same direction, forming a beam-like product. Bonded with structural adhesives, LVL is mainly used in load-bearing structures or as a component in structural wood products like I-beams (Fig. 1). One of the key advantages of veneer over sawn wood is that the yield of material is far greater since the wood is literally sliced, so there is no loss of material through the saw cut or ‘kerf’ or in converting an essentially cylindrical form into a rectangular prismatic one. This is particularly advantageous
where high value species are being utilized. However, in the peeling of a cylindrical log into a flat sheet of veneer, the stresses induced in the material, together with the anatomical features of the wood itself, lead to artefacts such as peeling ‘checks’ – cracks in the wood on the tension, or ‘loose’, side of the veneer. This has certain implications that will be discussed more fully in a later section.

Figure 1: Composite I beam consisting of an oriented strand board web and LVL flanges

Despite the introduction of several new structural wood-based composites such as oriented strand board (OSB) and oriented strand lumber (OSL), structural veneer-based products like plywood, LVL and parallel strand lumber – a product similar in concept to LVL but using long, narrow, strands of veneer – continue to thrive, whilst veneer produced for decorative purposes enjoys steady demand.
As can be seen from Figure 2, despite the worldwide economic downturn that took hold in 2008, there is little evidence of any slowdown in the global production of either plywood or veneer up to 2012. The situation in the European Union (Figure 3) is slightly different, reflecting the rather steep economic slowdown experienced during the same period. It is interesting to note however, that before the slowdown in economic activity, there had been a steady rise in plywood production in the EU. So, despite having a history of perhaps 4000 years, plywood is still a product very much in vogue. As we shall see later in this chapter, plywood has been used in many applications in the past, not just as a construction material, but in aerospace, transportation and in furniture as well. Plywood continues to be used extensively in these traditional areas and some of
the developments that are currently taking place and new innovations that have been introduced in recent years may perhaps yet see veneer-based products enjoy a new lease of life.

4.3 The manufacturing process

An overview of the plywood manufacturing process in the Nordic countries is shown in Figure 4. With some variations, the same basic steps are employed elsewhere in the world and have remained largely unchanged since the advent of industrial plywood manufacture at the beginning of the 20th Century (Baldwin 1994). LVL is produced in much the same way as plywood, with the main differences occurring during the lay-up, hot-pressing and further processing stages.

![Schematic overview of the plywood manufacturing process in the Nordic countries (Suomen Metsäyhdistys ry)](image)

Figure 4: Schematic overview of the plywood manufacturing process in the Nordic countries (Suomen Metsäyhdistys ry)
4.3.1 Raw material selection

The process begins with selection of the raw material. Both hardwoods and softwoods are used in the manufacture of plywood with the selection depending upon the intended application and availability of logs of suitable form and dimensions. In general only softwoods are used to produce LVL, though this is changing and, for example, the German company Pollmeier now produces its “BauBuche” LVL product using beech wood (Pollmeier 2013). This is indicative of the changing raw material resource that has affected the production of veneer and plywood throughout its history and seems likely to influence the manufacture of veneer-based products into the future. In the early days of plywood production in the USA it was possible to peel giant old-growth Douglas fir, having diameters perhaps exceeding 2 m (Baldwin 1994). Nowadays, it is not uncommon for Finnish plywood mills to peel spruce or birch logs of no more than 30 cm in diameter. In addition to the smaller diameter raw material, the quality and availability of logs is changing too as competition for the raw material from other sectors, such as the pulp and paper industry and the nascent biorefinery industry increase.

In Europe there is an increasing hardwood resource, mainly beech in central Europe, which is likely to influence the production of veneer-based products into the future. In addition to having a minimum diameter of around 25 cm, the key requirements for logs used in the production of veneer and veneer-based products are that they are straight with minimal taper and contain as little sloping grain, knots or rot as possible. After harvesting, which in the Nordic countries is usually in the winter, the logs are transported to the mill. There is some evidence, at least in birch wood, that the felling season can have a rather profound effect on the physiochemical properties of the veneer surface as well as the adhesive bond strength developed with certain resins (Rohumaa et al 2014), which could be used to advantage industrially to minimize the amount of glue required or improve performance.

4.3.2 Log conditioning

Once the logs have been delivered to the mill, the first step is to condition them prior to debarking and veneer peeling or slicing. Conditioning the log generally involves heating it either by steam or hot water in order to raise the temperature sufficiently to
facilitate debarking and soften the wood material to ease the peeling or slicing process, thus producing a smoother and better quality veneer (Lutz 1960 1977; Corder and Atherton 1963; Salmén 1982; Placet et al. 2007). In industrial peeled veneer production in the Nordic countries, this conditioning step generally involves soaking the logs at temperatures of between 30 and 40 °C for around 24 hours. Sliced birch veneer produced for decorative purposes is generally soaked at around 70 °C for the same period of time. Depending upon the ambient temperature (which in winter can be below -30 °C and in summer above +30 °C), as well as the diameter of the log, the temperature at the core of the log can vary considerably. For instance it has been shown that for a log of some 30 cm in diameter, it takes between 18 and 24 hours for the core temperature to reach that of the water in which it is being soaked. Another method of heating the logs is to steam them, which is commonly used to heat beech logs for example. More recently, infrared radiation has been considered as a means of directly heating the log during the peeling process and has shown some promise in this respect (Dupleix 2013). The principal drawback to this approach is that the heating rate using IR is insufficient to match the high peeling speeds currently used in industry (Dupleix et al. 2013).

Perhaps the main advantage of heating the log prior to veneer production is to soften the wood material sufficiently to ensure that during peeling lathe checking is minimized (Lutz 1960 1977; Corder and Atherton 1963; Salmén 1982; Placet et al. 2007) since the depth and frequency of checking can significantly affect the properties of plywood (Rohumaa et al. 2013) and LVL (Pot et al. 2014), particularly the bonding between adjacent veneers (Rohumaa et al. 2014). As wood is heated, the various cell wall polymers reach their respective glass transition temperatures, $T_g$ (Fig 5). In green logs the moisture content is generally high and above the fibre saturation point (f.s.p.) thus depressing the $T_g$. As may be seen from the figure, the $T_g$ of lignin and hemicellulose, which function as ‘matrix’ materials in the wood cell wall, can be below 100 °C even when the moisture content is as low as 20 %. This implies that heating green wood to temperatures around 70 or 80 °C can soften the material sufficiently to ensure good peeling (see Section 4.2.3)
With certain species, hardwoods in particular, heating can lead to other changes that can affect not only the technical performance of veneer-based products but also the visual characteristics of the veneer. For instance, it is well known that beech wood acquires a reddish hue upon heating and steaming is used to homogenize the colour difference between heartwood and sapwood (Tolvaj et al. 2009). Birch species on the other hand become lighter in colour as the soaking temperature is increased. Although this behaviour is exploited industrially – for instance it is common practice to soak birch logs at around 70 °C, prior to slicing into decorative veneer (rather than the more usual 40 °C used in peeled veneer production) to make them lighter in colour – the underlying mechanisms are not well understood. This is, however, changing since it is known that not only does the conditioning temperature affect the colour of the veneer but it also affects the wettability of the surface and indeed the bond strength with certain resins such as phenol formaldehyde (Rohumaa et al. 2014). Recent research in this area has, for example, focused on trying to identify the chemical pathways leading to these changes (Yamamoto et al. 2013).

Even though soaking is one of the first steps in the production of veneer and veneer-based products, its impact can potentially be profound. It has even been observed, for example, that the effect of different soaking temperatures can still be discerned after the veneer has been dried at a temperature of 180 °C (Rohumaa et al. 2014), implying that there are benefits to be gained either in terms of better product
performance or lower consumption of (still mainly fossil-derived) glues, by carefully controlling the conditioning process. Of course soaking and steaming are both energy intensive, even if the energy is produced from residues; soaking ponds occupy a relatively large footprint, whilst the effluents from the soaking process can pose disposal problems. For these reasons, alternative methods of heating the logs have been investigated in recent years and alternatives such as the aforementioned heating by infra-red radiation may help alleviate some of the problems associated with the soaking process.

4.3.3 Veneer peeling

Veneer peeling is one of the most important operations in the production of veneer for plywood and LVL manufacture. Though slicing or, occasionally, sawing is used to produce decorative veneer, the majority of veneer (>90%) is produced by rotary peeling. Essentially the process involves cutting a thin ribbon of veneer from the surface of a rotating log, known as a block or bolt, with a sharp knife in much the same way as the skin of an apple is peeled off. During the process a more-or-less cylindrical form is converted into a flat plate and because of the stresses created by the cutting action, cracks or checks form on the side of the veneer closest to the centre of the log. The checked side of the veneer is known as the ‘loose’ side whilst the outer surface, which remains free of checking, is known as the ‘tight’ side. The checks form in a direction perpendicular to the surface and propagate though the veneer thickness at an oblique angle as illustrated in figure 6. The depth of the checks can vary and in some cases can be up to 70-80% of the veneer thickness. Hardwood veneer, such as birch is typically peeled to 1.5 mm thickness whilst softwood is more usually cut to around 3 mm for plywood and LVL manufacture.

Figure 6: Peeling checks in birch veneer

Before peeling, the conditioned logs are first debarked, scanned for metallic objects that would otherwise damage the delicate knife edges, and cut to length so that they
will fit into the peeling lathe. Optical systems employing lasers are generally used in industry to centre the logs on to the lathe spindles. The lathe first ‘rounds-up’ the block, converting it into true cylindrical form by removing the surface layers of sapwood, known as ‘fish tails’, before the peeling process begins. Modern peeling lathes are very sophisticated and much of the process is automated (Figure 7).

Figure 7: Block loaded onto a laboratory rotary lathe ready for peeling

The cutting knife is held against the surface of the rotating bolt whilst either a fixed or rolling ‘nose bar’ applies a compressive pressure slightly ahead of the knife edge to help prevent fracture of the wood and control the fracture path. Rollers on the opposite side of the block compensate for the pressure applied by the nose bar and knife. The sharpness of the knife edge, the knife angle (i.e. the angle of the knife edge relative to the log), the nose bar pressure, temperature of the log and the speed of rotation will all have an effect on the quality of the resulting veneer, including the occurrence of checks (Sellers 1985).

Before drying, the veneers may be scanned and defects or other irregular features such as discolouration may be removed by clipping, after which the veneers are sorted by moisture content to ensure that drying proceeds as optimally as possible.
4.3.5 Drying

Generally drying is accomplished by passing the veneer sheets through a convective type hot air drier in which the internal temperature and relative humidity, as well as the residence time of the veneer is controlled to ensure that the veneers are dried to a low moisture content suitable for gluing and hot pressing, but not ‘over dried’, which can lead to surface inactivation resulting in poor bond quality (Christiansen 1992). Typically the veneers pass through several zones in the drier that first heat the veneers, then remove free water and finally drive off the bound water. Heterogeneous moisture content in the veneer can lead to localised wetter or drier regions that can subsequently affect the bonding process during hot pressing. Regions of higher final moisture content can lead to the build-up of steam pressure that can result in blows and blisters that affect the integrity of the panel. For this reason, the development of techniques that enable the moisture content of veneers to be measured online and with good spatial accuracy are needed (Antikainen 2014). Typical drier temperatures are of the order of 160 °C, which result in veneers being dried in a matter of a few minutes.

The drying process is energy intensive, accounting for around 70% of the thermal energy used by the mill and up to 60% of the total energy consumed (FAO 1990). As such, any improvements in drying process efficiency could result in significant overall energy savings. Alternative drying methods have been investigated, such as a contact drying method that dries veneer by contact with a hot platen on one surface and by the application of a partial vacuum to the other surface (Paajanen 2012). This method is claimed to reduce drying time significantly and may result in overall energy savings, however, at the time of writing this system is not available commercially.

Before the application of glue, the veneers are cooled and are generally non-destructively tested to grade them according their specific gravity and moisture content. Since the strength properties of veneer are closely related to specific gravity, and moisture content impacts upon the bonding process, assessing these parameters is very important in plywood and LVL production. The non-destructive testing of veneer for moisture content and specific gravity is generally carried out using microwave technology. Subsequently, the occurrence of knots and other defects may be detected using machine vision that scans the surfaces of the veneers.
4.3.5 Jointing, composing, patching

An extremely important aim in plywood and LVL production is to maximise the yield of useful veneer that becomes part of the product. The need to clip out defected parts of veneer and the possible requirement to peel shorter logs can result in the necessity to join several smaller pieces together to produce veneer sheets that are of a suitable size for plywood or LVL production. Veneers can be joined in the direction of the grain by creating scarf joints that allow a sufficient overlap to ensure that good bonding takes place. In this way veneers can be joined together (which is limited by the length of the log) to an almost unlimited length. Scarfing is impractical for joining veneers across the grain and so to join veneers in this direction, smaller veneers are composed using hot melt glue to butt joint the veneers to form a continuous mat. Hot melt strings are then used to reinforce the joint to give it added integrity. The larger veneer sheets created by jointing and/or composing can then be cut to the desired dimensions for plywood manufacture. Generally jointed or composed veneers are used in the core of plywood. Any remaining defects, such as loose knots, open holes or pitch pockets, are detected using machine vision and the veneers are repaired by replacing the defected portion of veneer with a patch of defect free veneer.

4.3.6 Gluing and lay-up

Although there have been attempts made to bond veneer sheet together without using adhesives (Ruponen et al 2014), the extreme water sensitivity of the resulting product has meant that to date commercial plywood and LVL is still bonded with an adhesive. The first synthetic glue used to bond wood veneer was phenol formaldehyde (PF), which was invented in the early 1900s. PF is a thermosetting resin, requiring heat and pressure for good bonding, which is characterised by exceptionally good strength, water and thermal resistance, making it the resin of choice for the manufacture of structural engineered wood products, especially those destined for exterior, and even marine, applications. So-called WBP (“weather and boil proof”) plywood uses PF resin to bind the veneers. For interior applications, other formaldehyde-based resins, such as urea formaldehyde (UF) and melamine urea formaldehyde (MUF), which is more water tolerant than UF, are frequently used. UF and MUF differ from PF in that they are white in colour and so produce an almost invisible glue line, unlike PF which is dark reddish-brown in colour, producing a distinctive visible glue line. UF is thus preferred for applications such as furniture or other interior uses. It is also less expensive than PF, though it has poorer strength properties and is easily hydrolysable.
UF, MUF and PF contain formaldehyde, which is coming under increasing pressure because of it classification as a human carcinogen and alternatives are being actively sought. Formaldehyde-free resins systems, such as Ashland’s Soyad™ adhesive technology (Ashland 2014) which is based on soy protein, have been introduced commercially in the past decade or so. These systems are suitable mainly for products destined for interior applications, and as yet there is little to rival PF resin for exterior plywood and LVL, which still dominates in the manufacture of these products (Baldwin 1995). Polyurethane/isocyanate resins have the potential for use in structural engineered-wood composites, though their use in plywood and LVL is currently more limited. Over the years there has been much interest in the use of various bio-based resources such as lignin, tannins and vegetable oils to create thermosetting resins to replace PF resins suitable for use in wood panels manufacture though to date there has been little commercialisation of these technologies.

In general only thermosetting resins are used to bond the veneers in plywood and LVL, however, the utility of plywood in particular can be improved by bonding the individual veneers with a thermoplastic polymer, enabling the manufactured panels to be subsequently thermoformed. The Finnish company UPM Kymmene recently launched their UPM Grada® product which is produced as a flat sheet but which can subsequently be thermoformed by heating to 130 °C before moulding (UPM 2014)

Liquid thermosetting resins can be applied to the surface of the veneer sheets in a number of ways: spray and curtain coaters as well as roller glue spreaders and by the extrusion of foamed resins. Spray and curtain coaters provide high capacity glue spreading, whilst roller spreaders are more versatile. The extrusion of foamed resin is also used to ensure good coverage and properly filled glue lines. The carrier solvent for UF and PF resin is water and the solids content (i.e. dry matter content) is usually between 45 and 55% for PF and 65% for UF (Stokke et al. 2014). The resin spread rate for PF is generally between 100 and 244 g/m², which is the mass of the resin including the solvent (Stokke et al. 2014).

4.3.7 Pre-pressing and hot pressing

Following the application of glue onto the surface of the veneer, the required numbers of sheets are laid-up to form the desired eventual thickness of plywood or LVL. In the
case of plywood, alternate veneers are laid up orthogonally and, with an uneven number of veneer sheets (3, 5, 7 etc.), the grain direction of the two surface veneers will be in the same direction and a ‘balanced’ structure is created, i.e. the structure is symmetrical about the mid-plane of the plywood panel. This is important to ensure that there is no distortion or warping in the final panel. In LVL the situation is slightly different in that most, but not necessarily all, the veneers are laid-up with the grain in the same direction. Generally there is some time – the ‘open time’ – in between glue application and prepressing, which allows the glue to penetrate the structure of the wood surface which can improve the eventual bond strength. Following lay-up, which can be either manual or automated, the billet of glued and laid-up veneers is pre-pressed to begin the consolidation process. Following pre-pressing, the billet is hot-pressed, generally in a multi-daylight press, to consolidate the panel, forming an intimate glue line and curing the resin. In the case of PF resin, the plates of the hot press are heated to a temperature of around 130 °C, and higher than this for UF resin. The press pressure and thickness are carefully controlled to ensure an even thickness in the final panel and the duration of pressing will depend on the panel thickness: thicker panels requiring longer press times to ensure that the core veneers reach a temperature sufficient to fully cure the resin.

4.3.8 Finishing

Following hot-pressing, the consolidated plywood or LVL panels are trimmed by saw and cut to the desired dimensions and any further defects may be identified and repaired by automatically patching or manually filling with epoxy putty. Finally the panels are sanded and graded.

4.4 Properties and performance

Plywood can be regarded as the original engineered wood product. Its cross-banded construction utilises the inherent differences in the dimensional stability of wood ‘along’ and ‘across’ the grain (the swelling and shrinkage of wood along the grain is << swelling and shrinkage across the grain) to minimise movement (small changes in dimensions due to changes in the wood’s moisture content), thus making plywood a very dimensionally stable material. Furthermore, the anisotropy in wood’s mechanical properties is significantly reduced in the cross-ply construction of plywood. Natural
features such as knots and sloping grain are generally considered to be defects when wood is used as a structural material. Producing thin veneers, gluing them together and laying them up with the grain oriented in the same direction helps homogenise the resulting material properties of LVL by randomly distributing these defects, thereby making the material more reliable structurally. Introducing veneers oriented perpendicular to the majority of veneers in LVL construction helps improve the dimensional stability and compressive properties of the material. The structure of plywood and veneer-based products is then the basis for the excellent engineering properties of these materials.

4.4.1 Structure

Plywood is composed of layers of veneer laid-up crosswise to form the desired thickness of material (Figure 8). The minimum number of plies is 3 but up to 35 veneers may be used to produce 50 mm thick birch plywood (Handbook of Finnish Plywood). In Finnish plywood manufacture the main species used are birch, spruce and occasionally pine – coniferous species. Thin birch and coniferous veneers are nominally 1.4 mm in thickness, whilst coniferous veneers are between 2.0 and 3.2 mm thick. In Finland, plywood may be composed entirely of one species or a combination of both birch and coniferous species. The standard constructions are:

- Birch: where only birch veneers are used in the construction
- Combi: where there are two birch veneers on each face and the inner veneers alternate between coniferous and birch
- Combi mirror: where there is one birch veneer on each face, with alternate coniferous and birch inner veneers
- Conifer: where the construction is entirely of coniferous veneers throughout the construction. The face veneers are of spruce or sometimes pine.

Plywood panel sizes range from 1200 mm x 1200 mm up to 1525 mm x 3660 mm.
Laminated veneer lumber is constructed of rotary peeled coniferous veneers, 3 mm in thickness, that are laid-up such that the grain in all veneers runs in the same direction. Typically the veneers are laid-up to form billets between 21 and 90 mm in thickness and between 1.8 and 2.5 m wide. After hot-pressing, the billets are machined into a range of standard sizes or are cut to bespoke dimensions. Typical heights of beams range from 200 to 400 mm. A certain number of veneers – up to 20% – may be oriented perpendicular to the majority of veneers in LVL, providing added dimensional stability to wide LVL panels and improved compression and shear properties.

4.4.2 Quality and physical properties

Plywood is classified according to the grades of the surface veneers, which are set out in European standard EN 635 (parts 1-3) and its counterpart elsewhere in the world. Essentially surface veneers are classified according to the presence of knots and other visible defects such as holes, splits and discolouration. The surface grades do not, in general, have any significant effect upon the structural performance of a plywood panel. The density of plywood panels is a reflection of their construction. For example, the air-dry densities of birch (Betula pendula) and spruce (Picea abies) are in the ranges 630-670 kg m$^{-3}$ (birch) and 400-450 kg m$^{-3}$ (spruce) and the densities of birch plywood, combi plywood, coniferous (thin) plywood and coniferous (thick) plywood are 680, 620, 520 and 460 kg m$^{-3}$ respectively (Handbook of Finnish Plywood). The density of coniferous LVL made from spruce is given as 480 kg m$^{-3}$ (Kerto® 2014).

Being primarily composed of wood, plywood and LVL have good insulation properties, akin to that of solid wood of comparable density and moisture content. Plywood can be
can be used at temperatures ranging from as low as -200 °C up to 120 °C. This has led to plywood being used, for example, in the lining of containers for transporting LNG (liquefied natural gas), which must be cooled to a temperature of -163 °C to become liquid.

4.4.3 Mechanical properties

The mechanical properties of plywood and LVL are also closely linked to their structures and to the raw materials that comprise them. Wood itself is highly anisotropic; for example the longitudinal Young’s modulus of birch $E_L$ is around 16.3 GPa, whilst the radial ($E_R$) and tangential ($E_T$) moduli are 1.11 and 0.623 GPa respectively (Dinwoodie 2000). Since peeled veneer is cut more-or-less tangentially, the degree of stiffness anisotropy ($E_L: E_T$) is of the order of 25:1 in this species. Other species, such as spruce and pine exhibit similar degrees of anisotropy (Dinwoodie 2000). The same is true of wood’s strength properties; however, here the difference between longitudinal and transverse strength properties can be even greater. For example the difference between the longitudinal and transverse strength of Douglas fir is almost 50:1!

Arranging the veneers in a crosswise manner and gluing them will clearly help reduce the degree of anisotropy as the grain direction in one veneer will be at right angles to the grain angle in adjacent veneers. Thus the high longitudinal strength and stiffness of a veneer will help reinforce the lower strength and lower stiffness of neighbouring veneers oriented perpendicularly. An important point is that a “balanced” structure is retained, ensuring that there are no unwanted distortions when the plywood is loaded or when the moisture content changes (since moisture movement is also highly anisotropic). For this reason, plywood is composed of an odd number of veneers, with three up to thirty five plies being commonly produced. In plywood, the degree of anisotropy is significantly lower than in native wood; however the degree of anisotropy in the plywood itself will again depend upon its construction. Assuming that the veneers are all of the same thickness then the degree of anisotropy will decrease as the number of veneers in the lay-up increases (Dinwoodie 2000). This concept is easy to grasp: in a 3-ply construction there will be two face veneers and one core veneer arranged at a right angle to the surface veneers, so the ratio of the number of veneers placed orthogonally to each other will be 2:1. In a 9-ply construction this ratio will be 1.25:1, since there will be 5 veneers (including both surface veneers) oriented in one direction and 4 orthogonally, whilst in a 35-ply construction, the ratio will be only
around 1.06:1. Some typical values for the mechanical properties of Nordic plywood are presented in Table 1.

Table 1: Selected mechanical properties of plywood
(Handbook of Finnish Plywood 2002)

<table>
<thead>
<tr>
<th>Nominal thickness (mm)</th>
<th>No. of plies</th>
<th>Characteristic strength (N/mm²)</th>
<th>Mean modulus of elasticity (N/mm²)</th>
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<td>Compression</td>
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</tbody>
</table>

With LVL there are rather different requirements since this material is generally used either as beams or as columns. In this case the structure is eminently suitable to the application: generally all veneers are oriented in the same direction, so the degree of anisotropy is similar to that of solid wood. Introducing a proportion of veneers at right angles to the majority running along the length – up to 20% of the total – can improve the shear properties of LVL when use as a beam. One of the key advantages of LVL over solid wood is that during the manufacturing process, strength reducing defects, such as knots and sloping grain, are randomised throughout the structure of LVL, or even entirely eliminated. In addition, stronger veneers can be placed judiciously within the structure so as to maximise the strength potential. Typical values of LVL mechanical properties are given in Table 2.
Table 2: Selected mechanical properties of Kerto® LVL (Kerto® 2014)

<table>
<thead>
<tr>
<th>Property</th>
<th>Kerto-S¹</th>
<th>Kerto-Q²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(21-90 mm)</td>
<td>(27-69 mm)</td>
</tr>
<tr>
<td><strong>Bending strength</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edgewise (depth 300mm)</td>
<td>44.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Flatwise, parallel to grain</td>
<td>50.0</td>
<td>36.0</td>
</tr>
<tr>
<td><strong>Tensile strength</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel to grain (length 3000 mm)</td>
<td>35.0</td>
<td>26.0</td>
</tr>
<tr>
<td>Parallel to grain, edgewise</td>
<td>0.8</td>
<td>6.0</td>
</tr>
<tr>
<td><strong>Compressive strength</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel to grain</td>
<td>35.0</td>
<td>26.0</td>
</tr>
<tr>
<td>Parallel, edgewise</td>
<td>6.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Parallel, flatwise</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Shear strength</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edgewise</td>
<td>4.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Flatwise, parallel to grain</td>
<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Modulus of elasticity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel to grain, along</td>
<td>13800</td>
<td>10500</td>
</tr>
<tr>
<td>Parallel to grain, edgewise</td>
<td>430</td>
<td>2400</td>
</tr>
<tr>
<td>Parallel to grain, flatwise</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td><strong>Shear modulus</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edgewise</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Flatwise, parallel to grain</td>
<td>600</td>
<td>120</td>
</tr>
</tbody>
</table>

¹Kerto-S: standard construction with the veneers in all plies oriented in the same direction.

²In Kerto-Q approximately 20% of the veneers are oriented perpendicular to the main direction of the veneers, providing added stability to the product.

4.4.4 Durability

One of the key attributes of phenol formaldehyde (PF) resin is its excellent stability when exposed to moisture and elevated temperature. Nevertheless, the wood remains susceptible to biological attack by fungi and other microorganisms if the moisture content is high enough such as when plywood or LVL is exposed to conditions corresponding to use classes 3-5 (exposed to weathering, in ground contact or permanently submerged in sea or brackish water). Unlike solid wood, but like other
wood-based composite products, plywood and LVL can undergo physical degradation resulting from a breakdown of the adhesive bond holding the veneers together, resulting in delamination (Trinh et al. 2012a). Although the bond created with a PF resin is more durable than with UF resin, the possibility of delamination cannot be ruled out and so, in practice, protection of the end grain and surfaces is important to retard this physical degradation mechanism. Delamination is the result of uneven stresses caused by the swelling and shrinkage of the plies relative to each other, so one way to reduce this is to modify the veneers to reduce dimensional instability. Many techniques have been developed to improve the dimensional stability of wood and to reduce its susceptibility to bio-deterioration, including thermal, impregnation and chemical modification (Hill 2006) and several of these have been investigated in plywood. Trinh et al (2012a,b) for example evaluated the effect of modifying beech veneers with N-methylol-melamine compounds for the production of plywood, whilst Dieste et al. (2008), investigated the properties of plywood made from birch and beech wood modified with DMDHEU (1.3-dimethylol-4.5-dihydroxyethyleneurea), finding that dimensional stability was improved without significant change to the other mechanical properties of the plywood, other than a certain loss in work of fracture. Thermal modification is nowadays the most commercially advanced wood modification method and it therefore unsurprising that it has been explored as a means of improving the durability of plywood (Aro et al. 2014).

4.5 Applications and future trends

This chapter started out by stating that plywood is one of the oldest, if not the oldest wood-based composite material known to humankind and, despite its maturity as a product, it is still very much in vogue. With the advent of LVL and PSL – the “new kids on the block” – veneer-based products have enjoyed a renaissance in recent years and global demand remains strong. Arguably, it is the excellent specific properties of these materials that have ensured that they are to be found in wide ranging applications.

Plywood and laminated veneer products have been, and are, used in many demanding structural applications requiring the good durability offered by PF resins. These have ranged from airscrew blades – the origin of LVL – to high performance sailing boats. The principal applications for structural plywood are nowadays in construction, furniture, transportation and packaging (FEIC, 2014). In the construction sector, plywood is used in technically demanding formwork, which requires it to be coated
with a phenolic film. Other applications in this sector include scaffolding working platforms, the lining and panelling of houses, roof elements, in wood-based construction, facades and flooring. Generally plywood is produced in flat panels, but the ability to form veneers into three-dimensional shapes makes it attractive to the furniture industry for chairs (Fig. 9), tables and other products.

![Figure 9: Plywood chair](image)

The good strength- and stiffness-to-weight ratios of plywood makes it a good choice in a range of transportation related applications, such as the flooring for trailers and in the side walls and the flooring of railway wagons, vans, horseboxes, lorries and buses. In addition plywood is used in shipbuilding, for the flooring and lining of cargo holds and the flooring of car decks and, as discussed in Section 4.4.2, its properties make it suitable for LNG tankers. The other main application area for plywood is packaging, where again its good specific properties make it invaluable, particularly when shipping valuable items such as precision engineered components. Since LVL was introduced around 40 years ago, it has rapidly gained acceptance as an engineered wood product, particularly in the United States. LVL is principally used in construction applications, either in its own right in roofing or flooring, or as a component in a system such as “I”
joists.

What about the future of plywood and LVL? With a rapidly growing global population coupled with diminishing (finite) resources, it is clear that we must become significantly more resource efficient not just in the future, but now. We must reduce our dependence on non-renewable resources and begin to “live within our means”, which in practice means the greater utilisation of renewable resources, of which wood is the most important. Wood-based composites and engineered wood products offer excellent opportunities to use wood effectively and efficiently and veneer-based products are particularly suitable in view of their excellent structural qualities.

As hinted at in Section 4.3.1, it seems likely that the raw material resource will continue to change, especially if competition for the raw material, for energy production or for chemicals, increases substantially. However plywood and potentially LVL too can respond to this. Plywood has traditionally been produced from very many wood species and indeed many non-wood species such as bamboo too, so there is no reason to believe that the production of plywood and other veneer-based products will stop because of changes in the raw material. Indeed, it seems that veneer-based products are able to adapt to new raw materials rather well, as the new “BauBuche” LVL product described in Section 4.3.1 illustrates. Though there are already alternatives to UF resins for interior grade plywood production, at the present time there are few commercially available alternatives to PF. This may of course change in time as many research groups are trying to develop new, formaldehyde free, resins from renewable resources, or even entirely eliminate the adhesive binder altogether. These developments could potentially help reduce the environmental impact of veneer-based products further by eliminating the fossil-based component and reducing the emission of volatile organic compounds.

Increasing the functionality and quality of veneer-based products is the aim of many companies and researchers alike. Products such as the thermoformable Grada® plywood described in Section 4.3.6 is a good example of a material with enhanced functionality. Additional functionality and hence value can be introduced by, for example, modifying the wood material to render it more durable or dimensionally stable. Though perhaps not providing a step change in functionality, the quality, consistency, performance and resource efficiency of existing veneer-based products could be improved through, for example, the greater control offered by
computer-based, non-destructive measurement techniques coupled with real-time feedback to the production process.

So, rather than being a group of wood-based materials that have reached the end of their development cycle, plywood, LVL and other veneer-based products seem set to have a bright future. Partly this can be attributed to their exemplary properties and partly to the new innovations that continue to be made.

### 4.6 Resources

There are several textbooks that provide good coverage of plywood and its manufacture. Though written a quarter of a century ago, Terry Sellers Jr’s “Plywood and adhesive technology” gives in-depth treatment of the technological aspects of plywood manufacture in the USA and is still relevant today. “Plywood and veneer-based products” by Richard F. Baldwin published in 1995, again with a focus on North America, provides a broader coverage of the plywood and veneer-based products industry, from the history of the industry, through the manufacture of veneer-based products to business aspects. Though not specifically covering plywood and veneer-based products, the recently published “Introduction to wood and natural fiber composites” by Douglas D. Stokke, Qinglin Wu and Guangping Han provides a good general introduction to wood-based composites. More specific information about the properties, performance and applications of plywood, LVL and other veneer-based products can be found in publications such as the “Handbook of Finnish plywood” published by the Finnish Forest Industries Federation and the online resources of APA – The Engineered Wood Association, provides a lot of information, not just about plywood and veneer-based products, but also about all forms of engineered wood products. For more specific aspects of the science and technology of plywood and veneer-based materials, the scientific literature covers most aspects.

The characteristics, properties and performance of plywood are covered by several EN, ASTM and other standards. EN 635 (parts 1-3) for example is concerned with classification of softwood and hardwood plywood by surface appearance. This group of standards is concerned with the classification plywood from the surface appearance, taking account of the natural features of the wood as well as defects arising from the production process. EN 636 (again in 3 parts) is concerned with the specification of plywood under different environmental conditions, taking into account the bond...
quality (EN 314) as well as the biological durability of the veneer used in the plywood construction. EN 314 is concerned with the quality of the bond between veneers and is determined by the adhesive type and core veneer quality.

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