Brettstapel

Brettstapel production in other parts of the world; adapting techniques for utilisation of homegrown timbers in Britain

Our thanks to Dainis Dauksta who researched and wrote this
report on behalf of Woodknowledge Wales

Front cover image: The e3 Brettstapel apartment building in Berlin (image courtesy of Kaden + Klingbeil)

Contents

1. Executive summary

Although the term Brettstapel was created in the 1970s there are many historical precedents to this method of creating solid timber structural panels by joining parallel lamellae together using wooden or metal dowels.

Brettstapel panels are one of the most structurally efficient methods for creating solid shear walls and floor diaphragms in timber.

By substituting timber for concrete or masonry in solid panels, Brettstapel walls and floors effectively lock up carbon sequestrated by forests within durable structures.

Nailed Brettstapel panels have been used for over a century in American and Canadian mid-rise warehouse and industrial structures where they are called 'fire-resisting' floors; American insurance companies offer lower insurance rates for this type of heavy timber construction.

Brettstapel panels are not a non-glued equivalent to cross-laminated timber panels; they have distinct, different performance characteristics because the wood fibres are all aligned in one direction.

Manufacture can be scaled to suit funding availability. Both lamellae and dowels can be profiled on the same planer/moulder machine using different cutters; Brettstapel construction is ideal for smaller SMEs.

Varying grades and species of homegrown softwood can be utilised to create a wide range of Brettstapel panel types with varying characteristics to suit many applications.

North American historical heavy timber buildings and modern Central European Brettstapel buildings demonstrate the potential for this type of construction.

2. Introduction

The German term Brettstapel (Eng. stacked planks) is claimed to have been invented in the 1970s by Swiss engineer Julius Natterer to describe solid wood structural panels comprised of parallel softwood lamellae laminated together with either timber dowels or metal fixings and used as floor diaphragms or wall panels (Henderson, 2009).

The names Lamellenholz (lamellaewood) and Bohlenstapel (stacked boards) are also used to describe the system. Dübelholz (dowelwood) is often specifically used to describe panels fixed together with timber dowels. Typically wall elements are made in thicknesses of 80 to 120mm ± 2mm in panels up to 2.5 metres ± 5mm wide and 17 metres ± 2mm long. Ceiling and roof elements can be from 100 to 240mm ± 2mm deep and up to 2.5 metres ± 5mm wide in lengths up to 17 metres ± 2mm (Cheret, et al., 2000). The system has recently been named 'Dowellam' here in Britain in order to resonate with the well-known term 'glulam'.

Brettstapel panels can be considered as low carbon-embodied, high strength substitutes for conventional masonry or concrete floor diaphragms and shearwalls, capable of integration within modern methods of construction (MMC) regimes using prefabrication and just in time delivery instead of on-site construction. Several European manufacturers describe the process of carbon sequestration by trees as a unique selling point for these solid wood panel systems.

Amongst others German firm Zwick quotes figures for carbon storage within panels to enhance their 'ecological' credentials (Zwick-Holzbau, 2014). Solid wood panels of this type used in durable architecture transform the built environment into a carbon sink and create demand for the kind of softwoods grown in high yield plantation forests.

This report focusses more particularly on timber-dowelled Brettstapel panel manufacture where 'super' dry hardwood dowels are used to fix parallel softwood lamellae together. The higher moisture content of the lamellae causes dowels to expand and lock into place. fig. 1 shows a 2.5 metre long prototype Brettstapel panel manufactured for Woodknowledge Wales (WKW) using homegrown Japanese larch lamellae locked together with beech dowels.

There is a separate case study describing the Coed y Brenin visitor centre extension which was the first building in the UK to use homegrown timber in Brettstapel construction.
It is available here: http://bit.ly/1raHwty

Figure 1: Prototype larch Brettstapel panel made for WKW

The parallel alignment of lamellae and fibres makes for high stiffness along the grain of Brettstapel structural elements; however complete Brettstapel panels display the anisotropic behaviour characteristics of solid wood. Therefore each axis of a Brettstapel panel has different mechanical characteristics and considerable dimensional change related to moisture content may occur across the grain or, in other words, at right angles to the axial alignment of the wood fibres.

It is essential that Brettstapel panels be kept as dry as possible during construction in order to avoid expansion of panels which may cause consequent structural damage. Building design and specification of panels should allow for dimensional changes during the construction phase and afterwards in service.

3. Brettstapel precursors and similar techniques

3.1 Fire resisting floors

Actually the concept of fixing lamellae together with dowels in order to create large laminated panels or components has been extensively utilised historically but described using different terms e.g. ‘solid floor’ or ‘fire resistant floor’, shown in fig. 2 below (Ellis, 1914).

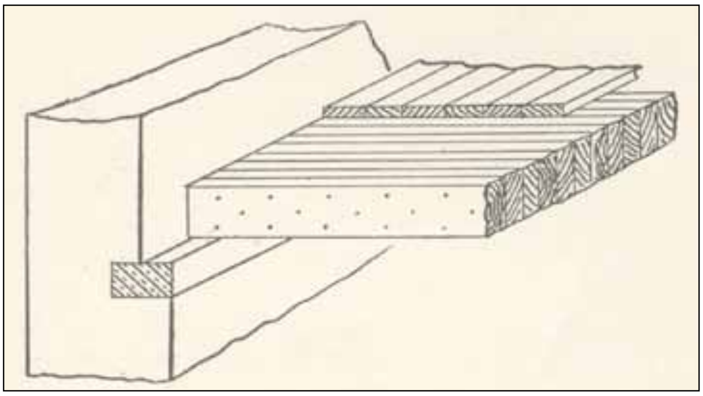


Figure 2: A ‘solid’ or ‘fire resisting’ floor (Ellis, 1914)

The fire resisting type of solid floor was used extensively in multi-storey warehouses in North America and Canada, often combined with heavy post and beam construction. An example from Toronto is shown in image 3; the ceiling is identical in appearance to that of a modern Brettstapel panel.

There are still at least 125 historical post and beam buildings in the Toronto area, some of which are eight storeys high and the oldest of which dates back to 1872 (Chui, 2013).

The longevity of these buildings suggests that there is potential for contemporary tall building construction using similar techniques incorporating Brettstapel floor diaphragms. The durability of the fire resisting Toronto buildings demonstrates the potential to use heavy timber structures as carbon sinks within the built environment, substituting for the concrete and steel structures more normally specified presently in Britain.

Figure 3: Fire resisting floor with post and beam construction at a former warehouse in Toronto (courtesy of FPInnovations)

A closer image of another fire resisting floor in a former Toronto warehouse is shown in fig. 4, the floor diaphragm is identical in appearance and function to modern European Brettstapel.

The American Wood Council (AWC) extolls the fire resistance of heavy timber framing. AWC points out that with a history going back 150 years and thousands of buildings of this construction type completed, insurance companies recognise their superior fire performance by offering lower rates in fire insurance schedules (American Wood Council, 2003).

A pdf is available from the
American Wood Council here: http://bit.ly/1rzu7yT

Figure 4: A closer image of a fire resisting floor in a former Toronto warehouse (courtesy of FPInnovations)

Figure 5: Hybrid steel frame with nail laminated Brettstapel floor diaphragms (courtesy of Kenneth Koo)

Recently in Canada, nail laminated floor diaphragms have been utilised with steel frames in hybrid industrial buildings. This compromise option uses timber as a high performance, low carbon substitute for concrete whilst allowing developers and engineers the advantage of using easily specified conventional steel structural frames.

Fig. 5 shows an example of one such hybrid structure in Vancouver. Using nailed lodgepole pine lamellae set on edge for the floor plates, it is the new headquarters of a major corporation (Koo, 2014); North America and Canada have massive volumes of pine beetle affected timber to utilise and this type of Brettstapel massive wood panel construction is an ideal application. Some of the steel structure is covered with a glulam envelope.

3.2 American grain elevators

Americans use the term 'grain elevators' for the tall grain storage structures which have become iconic images of the North American and Canadian prairies. These massive silos were usually all-timber structures until steel and concrete became the materials of choice for large industrial applications.

The Globe Elevators of Duluth, Minnesota were completed in 1887 and were at the time the largest in the world at just over 45 metres high, with the storage silos at around 142 metres long. Oak, Douglas fir, Eastern white pine and Southern yellow pine were all used in their construction. Elevator 1 used post and beam construction for the ground floor and horizontally stacked solid timber walls with several further storeys of post and beam timber framing sitting on top of the solid walls.

The Globe Elevators were in use until 1988 and only in recent years has demolition commenced with the intention to reclaim and recycle the timber used in their construction (Old Globe Reclaimed Wood Company, 2014).

A short 'YouTube' video is available here:
http://bit.ly/YXaSCw

The Globe grain storage silos were constructed by laying sawn timber lamellae horizontally and nailing them together. At corners and intersections, the planks were overlapped alternately in a similar manner to that used for the type of 'sleeping log' construction utilised across Scandinavia, Eastern Europe and Russia. Fig. 6 below clearly shows the lapped corner construction details. The solid wood silos could be described as horizontal, nailed Brettstapel construction.

These tall timber structures demonstrate the potential for tall massive wood constructions of the types that are now being rediscovered as architects and engineers seek low carbon solutions for the contemporary built environment.

Figure 6: Horizontal lamellae and lapped corners visible in the Globe Elevator silos

3.3 American heavy decking

The Americans and Canadians use the terms 'heavy roof decking' and 'plank decking' where double tongue and groove profiled softwood elements (available up to 100mm thick) are joined together using long metal fixings to create roof and floor diaphragms (Canadian Wood Council, 2000).

However European Brettstapel panels are generally manufactured off site whereas the American heavy decking is fixed on site.

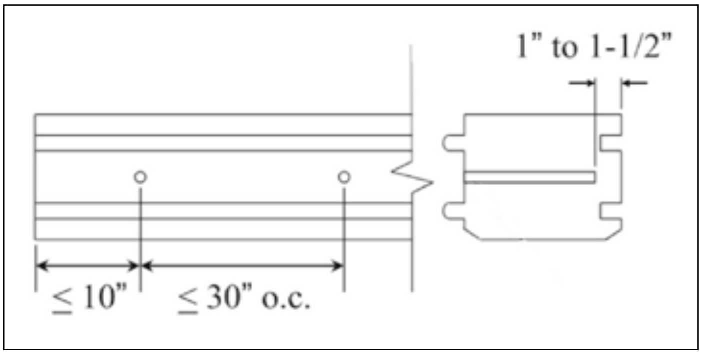


Figure 7: American heavy decking showing double T & G profile and holes for fixings

3.4 Stresslam

Several bridges have been constructed in America using a technique where plain lamellae are fixed together with orthogonal, post stressed steel bars which increase friction and load distribution between lamellae causing them to act as a diaphragm; the term 'Stresslam' has been applied to this type of structural panel. Fig. 8 below shows a Stresslam prototype structure being assembled as a large table in the author's workshop.

This used simple orthogonal tongue and groove lamellae later used for the first Welsh Brettstapel prototype panels; it is now in the Welsh School of Architecture.

Figure 8: Stresslam prototype structure being assembled in Mid Wales

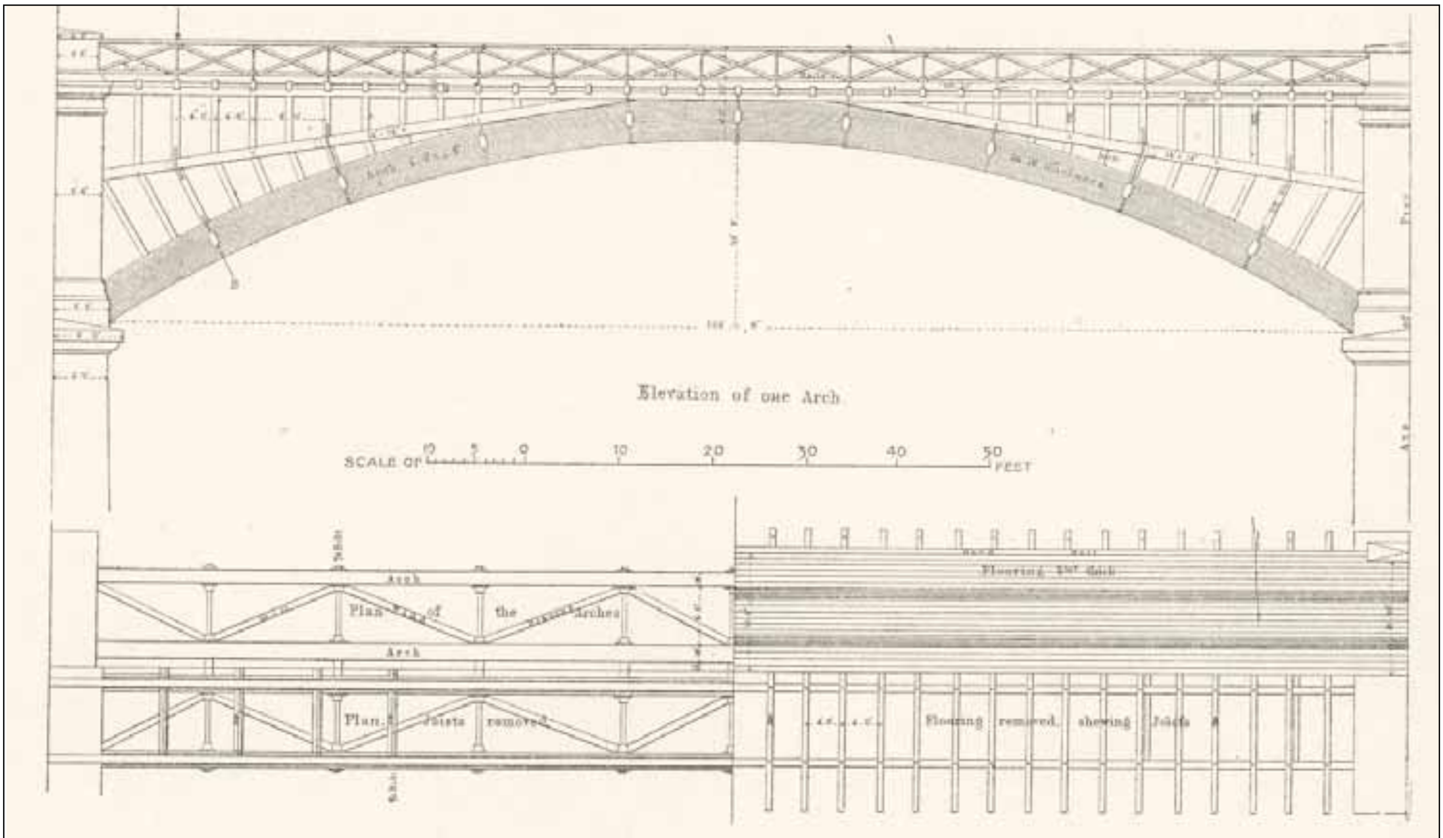
Solid timber walls are often associated with the horizontal 'sleeping log' type of construction common in Russia, Scandinavia and Eastern Europe but solid timber walls using vertically aligned interlocking elements were also commonly used in coffer dams and sheet piling (Ellis, 1914) before the introduction of steel. The stave churches of northern Europe were constructed with walls using rows of vertical planks fixed between grooved sill and floor plates, a technique often utilised in modern Brettstapel construction.

3.5 The Rouen and Le Havre railway bridge

The Rouen and Le Havre railway bridge shown below in fig. 9 was built across the Seine in the 19th century using prefabricated arched ribs 40 metres long with a cross section of 1.2 metres by 0.6 metres.

The ribs were made up by fixing 100mm thick pine lamellae together with 25mm diameter oak 'trenails' or dowels which were driven through two lamellae into the third and so on through the 1.2 metres deep section (Ellis, 1914). It is this method of joining parallel softwood lamellae into laminated structural panels using hardwood dowels which is now normally associated with the terms Brettstapel, Dübelholz or Dowellam.

Figure 9: The Rouen and Le Havre railway bridge, a massive dowelled timber arch (Ellis, 1914)



4. British examples of Brettstapel structures

In Britain few Brettstapel structures have been built so far. Perhaps the best known example is Acharacle primary school in Scotland, designed by the architects Gaia Group based in Edinburgh. This was the UK's first Brettstapel project and Austrian manufacturers Sohm were sub-contracted to manufacture, deliver and erect the structure.

Only one Brettstapel structure using homegrown timber has been built in Britain to date; the Coed y Brenin visitor centre extension near Dolgellau was designed by architects Architype, based in Herefordshire and London.

A Brettstapel wall at Coed y Brenin manufactured with homegrown Sitka spruce and Douglas fir is shown in fig. 10. Sub-contractors Williams Homes Ltd of Bala manufactured, delivered and erected the building during winter 2012-2013, the main contract having been awarded to Pochin Construction Ltd by Forestry Commission Wales.

The Coed y Brenin building is the subject of a WKW case study available here: http://bit.ly/1raHwty

Information about Brettstapel projects in the UK is compiled by architects James Henderson, Sam Foster and Matt Bridgestock on their website here: www.brettstapel.org

Figure 10: A Brettstapel wall at Coed y Brenin

5. Brettstapel characteristics

Laminating parallel lamellae together to form a panel may cause the stiffness of the panel to be higher than the stiffness of individual lamellae providing load can be effectively transferred laterally between adjacent lamellae via dowels and/or interlocking profiles such as tongue and groove.

This is known as the laminating effect, which is thought to arise through randomisation of defects (such as knots) throughout the panel allowing neighbouring lamellae to lap defects, in effect acting as fishplates (Thelandersson & Larsen, 2003). According to engineer Deb Turnbull of Edinburgh Napier University the increase in bending strength of Brettstapel floor diaphragms could be 10% (Turnbull, 2013).

Brettstapel panels are potentially the most efficient solid timber floor diaphragms because all the fibres are aligned axially along panels and each lamella can be dimensioned and profiled to form an optimal beam.

These panels can span further than the same thickness of cross-laminated timber (CLT) panel. When used as shearwalls, Brettstapel panels may carry up to twice the loadings allowed with the same thickness CLT panels (Smith, 2013).

The current fashion for specifying CLT presents the possibility of under-utilising its two-way capacity; when unused, up to 40% capacity of the material is wasted and hence, the panel becomes over-priced. CLT must be designed to its full capacity as a structural plate (Koo, 2014). Otherwise Brettstapel is the more rational choice because it uses less material to achieve the same loadings as CLT.

Interlocking profiles between lamellae may allow easy alignment of lamellae during panel fabrication as well as load distribution across panels. Figures set out in table 1 show potential spans (Spannweite) correlated with loadings in kiloNewtons per square metre (Belastung) using lamellae depths varying from 80mm to 220mm. This German table indicates that Brettstapel panels using 180mm deep lamellae of 11,000N/mm^2 stiffness or MOE (= C24 strength grade) may span 7.5 metres (Cheret, et al., 2000).

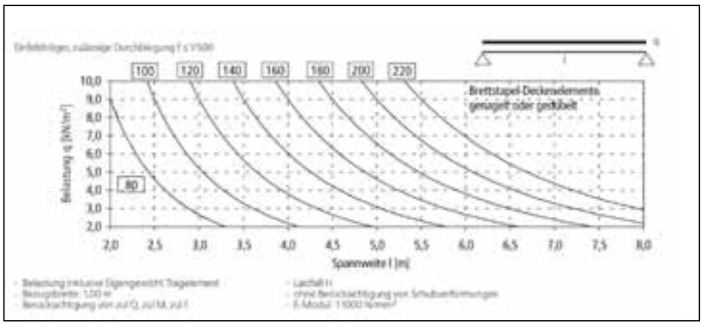


Table 1: German span tables for Brettstapel floor diaphragms

5.1 Utilising larch

Large volumes of British grown larch will be available over the next few years as the pathogen Phytophthora ramorum progresses through Britain. A large proportion of the available sawlog material is likely to pass or exceed the C24 strength grading criteria (Ridley-Ellis, 2013) and there could potentially be over two million m^3 of suitable sawlogs available in Wales alone (Dauksta, 2014).

There is huge potential to utilise diseased British larch to make high performance Brettstapel panels; heavy post and beam structures could also use larch and the techniques combined to create tall wooden buildings similar to those seen in Toronto and mentioned earlier in section 2.

5.2 Describing suitable timbers for production

It is often stated that Brettstapel can be manufactured from ‘low *quality*’ softwood. However this is a misunderstanding of the process which creates structurally efficient panels and the adage ‘garbage in garbage out’ applies.

In Southern Germany, Switzerland and Austria where most of the European manufacturers are clustered, many grades and types of Brettstapel panels are produced ranging from ‘industrial’ (which are normally covered or plastered) to precisely profiled and revealed ‘architectural’ grades. Industrial panels can use low *value* falling boards down to around 24mm thick but these are high stiffness material from outer parts of logs so the description ‘low quality’ is not appropriate.

However, the most expensive architectural or visual grade panels use thicker (generally up to 60mm, occasionally 100mm) lamellae which have been dried to as low as 12% moisture content and then accurately profiled through a high speed planer-moulder, a process where only more stable, selected grades of softwood may be utilised.

‘Low quality’ implies timber degraded by defects such as large knots or reaction wood, both of which cause distortion in drying leading to problems in machining profiles resulting in poor conversion rates and lower feed speeds.

Fig. 11 shows the simple tongue and groove profile used to make the prototype softwood lamellae for WKW trials carried out ahead of the Coed y Brenin project, Douglas fir lamellae are shown with the smooth profiled beech dowels originally trialled in Wales.

Figure 11: Simple tongue and groove Douglas fir lamellae with smooth beech dowels

5.3 Design of lamellae

Production of orthogonal tongue and groove lamellae profiles from rough sawn homegrown softwood can be somewhat inefficient i.e. 5mm or more thickness of lamella is lost in order to raise a 5mm tongue on one side and several millimetres can be lost on the opposite face in straightening and smoothing either side of the groove. WKW have designed a more efficient 100mm wide lamella profile which is shown in fig. 12 below.

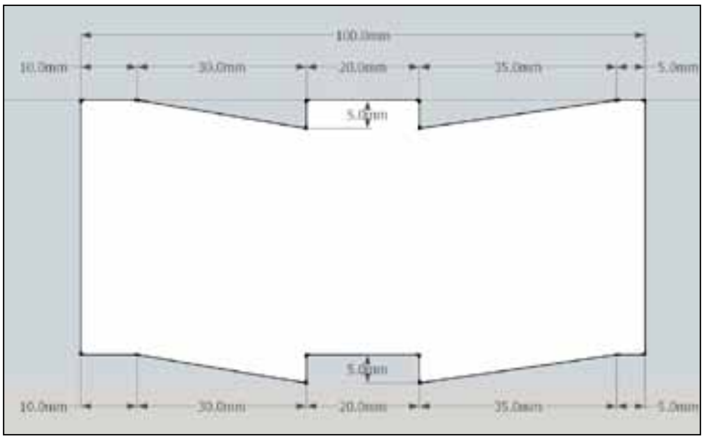


Figure 12: Lamella profile designed for WKW

Austrian manufacturers 'Sohm Holzbautechnik Gesmbh' have developed their own wave form profile which also optimises machined lamellae output volumes, complete panels by this manufacturer are shown below in fig. 13.

Figure 13: Complete panels using wave-form lamellae profiles at Sohm's factory in Austria

5.4 Production of lamellae

Softwood lamellae can be machined at very high rates of production using planer/moulders such as those manufactured by 'Weinig' (Michael Weinig AG, 2014). These machines can produce timber profiles in one pass using 'serrated back' cutters which may be readily drawn using free software such as 'Google Sketchup'. Completed profile drawings can be sent to tool grinding firms such as 'Whitehill Tools' in Luton who then grind blank cutters to the required profile (Whitehill Tools, 2014).

Actual serrated back cutters ground by Whitehill Tools to the WKW lamella profile are shown in fig. 14 below. Each profile face needs at least two matching cutters mounted in cylindrical 'blocks' which are then fitted onto the appropriate shaft on the planer/moulder. Blocks normally have four cutter mounting positions, enabling different cutter profiles to be mounted together with the principal cutters. This enables some limited profile modification without regrinding of principal cutters.

Thus different shadow grooves or acoustic rebates may be machined using the same principal cutters; shadow grooves can be machined using small simple orthogonal cutters.

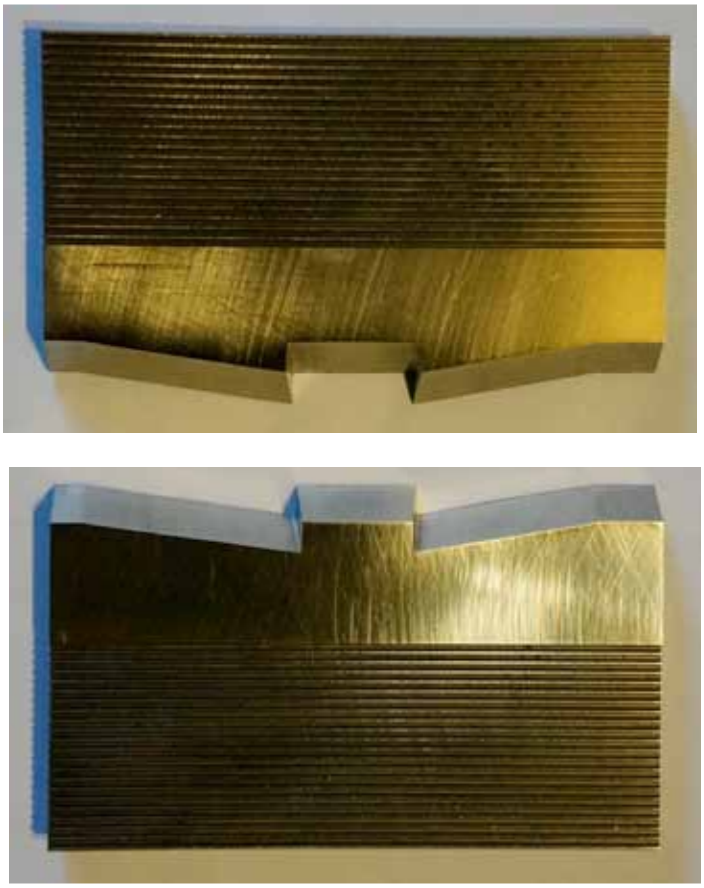


Figure 14: Opposing serrated back cutters ground to the WKW lamella profile

A typical planer/moulder is shown below in fig.15. Second hand machines may be obtained for less than £10,000 making this part of the production process easily accessible to SMEs. The Brettstapel manufacturing process machinery is not necessarily expensive; rather it is scaleable, allowing firms to expand their production by upgrading plant as demand grows.

Figure 15: A typical Weinig planer/moulder; capable of machining lamellae and dowels

Lamellae may be profiled in order to create specific characteristics. Visual grade Brettstapel panels sometimes have small rebates known as ‘shadow gaps’ machined on the revealed faces of their lamellae, these gaps help disguise shrinkage in service. When required, larger voids can be machined behind the shadow gap to increase acoustic performance within interior spaces.

Fig. 16 below shows completed Brettstapel panels with acoustic profiles machined into lamellae edges. The lamellae on the side faces of panels have large slots morticed ready for receiving loose tenons/tongues or large wooden ‘biscuits’ to assist alignment and location of adjacent panels.

5.5 Assembling panels

Many modern producers manufacture panels around 600mm wide and then join them together to form larger panels. Kaufmann GmbH of Oberstadion, Germany manufacture complete wall panels using simple industrial grade Brettstapel panels fixed between Douglas fir soleplates and header plates, shown in fig. 20. Panels can be composed for special applications e.g. by staggering lamellae, some variants are shown in figs. 17 and 18. Joints may be formed in several ways:

- Simple butt joints with dovetailed screws
- Half lap joints formed by fixing battens down side of panels
- Tongue and groove formed by fixing battens down side of panels
- Tongue and groove formed by machining profiles into lamellae sides
- Use of large ‘biscuits’ between panels fitting into machined recesses
- Loose tongue fitted into groove machined down side lamellae
- Steel dowel inserted into holes drilled into panel sides

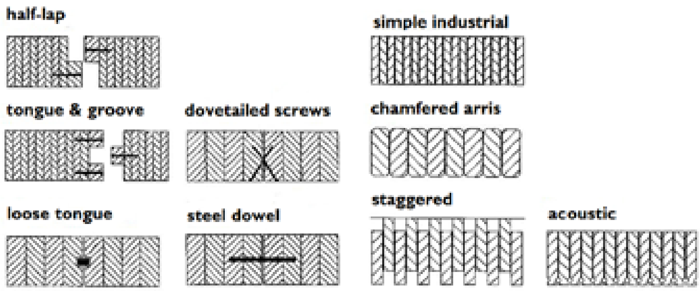


Figure 17: Brettstapel panel fixing options also showing some panel variants (Cheret, et al., 2000)

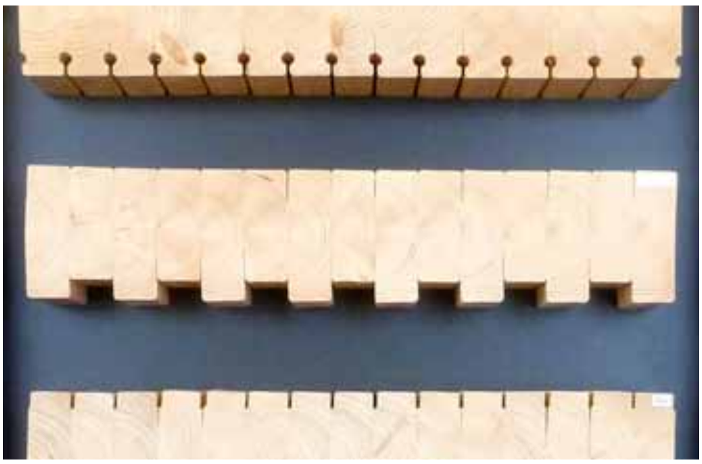


Figure 18: Cross sections of some Brettstapel panel variants

Figure 19: Industrial grade Brettstapel panels being assembled into prefabricated wall panels

Simple industrial grade Brettstapel panels can also be assembled and fixed with dovetailed screws through sole plates and header plates to create full length wall panels. In Germany, Douglas fir soleplates are sometimes used to increase durability or to resist moisture penetration into end grain.

Figure 20: Complete wall panels ready for delivery, showing Douglas fir sole plates and OSB racking and air-tightness boards

6. Timber properties

The subjective term ‘quality’ when applied to timber does not help to define the precise details of the material properties necessary to produce engineered timber elements. Furthermore commonly misconceived terms in regard to UK grown conifer plantation timber are often generalisations or the result of normative or subjective thinking and as such may not necessarily be useful in practice.

In attempting to understand how British grown softwoods may be utilised in engineered components, the science sometimes appears to be counterintuitive. This is certainly the case with timber density, (sometimes called specific gravity) an important property which in some species correlates with stiffness (MOE) but more importantly in Brettstapel production, it correlates closely with shrinkage and swelling.

The higher the density of timber the more shrinkage or swelling occurs with desorption/moisture loss or adsorption/moisture gain (Schulgasser & Witzum, 2011). This mechanism was documented as long ago as 1919 based on 200,000 tests carried out in America at Madison forest products laboratory (Newlin & Wilson, 1919). Fig. 21 below is a graph from the original document showing correlation between volumetric shrinkage and specific gravity.

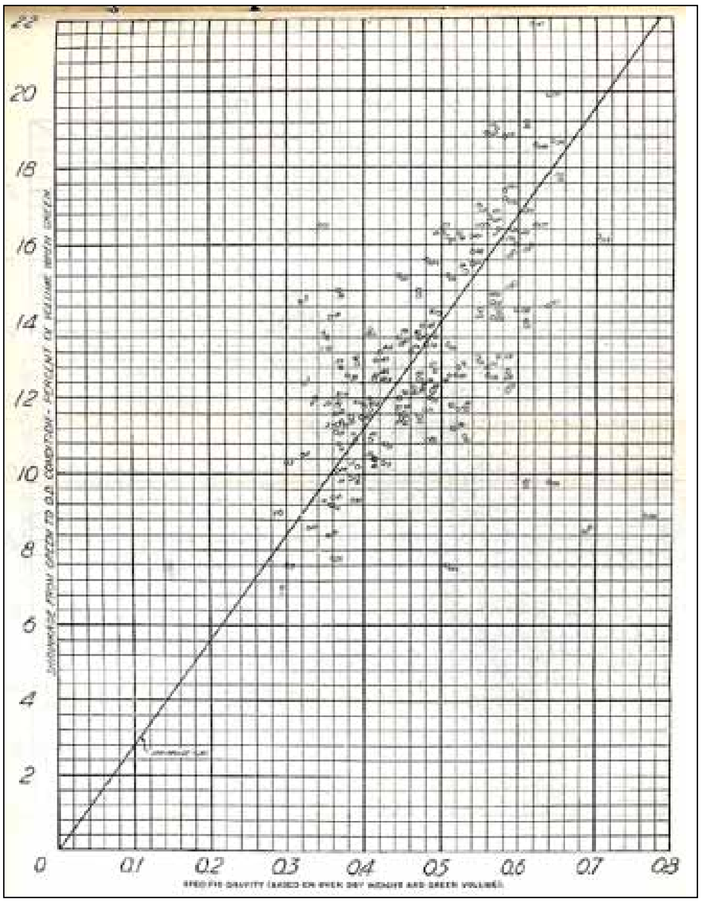


Figure 21: Newlin and Wilson’s graph showing correlation between shrinkage and specific gravity

6.1 Utilising British timbers

If lower density timbers exhibit less shrinkage and swelling then this places some species of fast growing conifers in Britain at a distinct advantage in regard to utilisation in Brettstapel. Those softwood species such as Sitka spruce which may decrease in density with increase in growth rate or other factors (Moore, 2011) could be particularly useful as Brettstapel lamellae.

Actually Sitka spruce timber with very wide growth rings (they can be up to 20mm in some favourable British conditions) may be rejected for many applications but with potential for higher dimensional stability than denser timbers it could be very well suited for Brettstapel. This is particularly important in Brettstapel panels where the parallel lamellae are relatively unconstrained laterally (unlike cross-laminated timber panels) and so dimensional stability is highly desirable. Conversely for dowels high rates of swelling on adsorption are desirable.

Brettstapel dowels are purposely 'super' dried down as low as 6% in order to allow moisture adsorption from lamellae with concomitant swelling thus mechanically locking lamellae together. There may be potential to exploit and optimise use of several UK-grown softwood and hardwood species (especially some of the underutilised minority species) for their particular material properties in order to make best use of them in Brettstapel; for instance, Grand fir lamellae and silver birch dowels.

One particular feature found in many UK-grown softwoods is pit aspiration, where microscopic openings (called pits) in the side walls of cells close off as the timber dries and significantly reduce moisture penetration through timber cross sections. Considered to be a problem for processors needing to penetrate non-durable softwoods with chemical treatments, pit aspiration is desirable in untreated Brettstapel panels where moisture penetration and subsequent lateral dimensional change may have disastrous consequences for a structure. Timbers exhibiting pit aspiration are called refractory and species including Sitka spruce, larch and Douglas fir all display this characteristic.

6.2 Drying British timbers

Homegrown softwoods have great potential for utilisation in Brettstapel panels. However, high yield plantation-grown softwoods offer a range of challenges firstly in drying and then later in utilisation. Despite 150 years of study our understanding of typical radial patterns in the cross sections of conifer stems has been described as minimal. Even the terms used to describe the varying types of wood found within the stem of conifers are debated (Meinzer, et al., 2011) although the generalisations 'juvenile' and 'mature' heartwood are commonly used by foresters and wood processors without necessarily understanding the complexities of typical radial patterns from pith to bark.

Juvenile wood generally refers to the first 5-25 years' growth of secondary xylem which has several undesirable features such as short cells with thin walls, low stiffness, more spiral grain, high microfibril angle and higher incidence of reaction wood. Furthermore these different features can change at different rates across a transition zone between juvenile and mature zones. Reaction wood formation is triggered by traumatic changes and along with juvenile heartwood exhibits high microfibril angle which can cause longitudinal shrinkage during drying (Haygreen & Bowyer, 1996).

Mature heartwood suffers little longitudinal shrinkage during drying (unless reaction wood is present) therefore when both juvenile and mature heartwood occur in the same board, the juvenile wood will shrink more than the mature wood with consequent dimensional change causing problems such as bowing. Spiral grain in juvenile wood can cause boards to twist during drying; boards cut from the centre of a sawlog (and containing a juvenile core) are particularly prone to twisting.

Juvenile stems may take on helical or sinusoidal conformations which are hidden beneath layers of mature heartwood until revealed during sawing; then the changing properties caused by the juvenile heart 'wriggling' along a board's length may cause various complex dimensional changes leading to problems in machining and/or significant loss in yield.

In attempting to dry sawn softwoods to make them usable in construction the changes in wood anatomy across tree stems are only part of the range of challenges facing processors; moisture content also changes from pith to bark. For example in Sitka spruce heartwood moisture content may vary from 40% to 80%. However in the sapwood (the outer zone of wood closest to the bark), moisture content in excess of 120% is encountered and values close to 300% have even been found (Moore, 2011).

Thus material properties can vary widely in one board. Modern sawmills convert material at such high rates there is little scope to change sawing patterns in order to separate juvenile heartwood from mature heartwood although the outer 'falling' boards with relatively high stiffness and high moisture content are normally separated but sold into low value markets.

There may be potential for new scanning and selection procedures capable of classifying boards according to density, end grain imaging, distortion types (e.g. cupping or bow), stiffness and moisture content (MiCROTEK, 2011). However, at present sawmill timber selection and binning infrastructures may work too slowly for such complex grading routines (Brownlie, 2013). Researchers have suggested that boards be selected and grouped according to moisture content before kilning but in practice this does not happen generally.

Therefore kiln charges may be composed of boards with many different material properties and a wide range of moisture contents. Risk aversion significantly influences kiln management as kilns grow in volume to accommodate the huge increases in sawmill production rates and so final mean moisture content has to be kept fairly high (around 18-20%) in order to take account of the varying timber types and distribution of final moisture contents found across a whole kiln charge.

Across much of Europe from France to the Baltic region, sawmills have traditionally relied on sawing hardwoods *en boule* or 'through and through' whereby logs are broken down by making parallel cuts across the transverse end face and down the length of logs. For drying, stickers are then placed between the resulting full width double waney-edged boards to give the appearance of a 'reassembled' log. This method of drying is still standard practice for hardwoods and fig. 22 shows oak logs which have been sawn and stacked *en boule*. However, even relatively large sawmills in southern Germany sometimes air-dry softwoods in this way and it may be one practical solution to the problem of drying conifer timbers with their widely varying radial properties.

Although double waney-edge boards contain both juvenile and mature zones, the juvenile core is bound within mature zones along both edges thus balancing drying stresses and reducing distortion. Double waney-edged boards can be processed through double band resaws or multirip saws for final dimensioning by taking off both waney edges simultaneously. This retains the juvenile material within mature heartwood zones and optimises the width of each board.

This technique is unlikely to be taken up by high volume softwood sawmills in Britain but may appeal to smaller processors who wish to sell into the niche market that Brettstapel manufacture offers. In creating drying stacks there may be scope to select out centre boards which include pith and much of the juvenile heartwood; these are the boards that are most likely to twist and induce distortion within stacks.

Large drying stacks of softwood do not necessarily need to be assembled *en boule*; actually randomly distributed double waney-edged boards may dry more successfully within a stack which is randomly distributing drying stresses. The most important factor is that boards are not cut in a manner which encourages distortion. This is one advantage of bespoke sawmilling, often carried out nowadays using horizontal bandsaws which by their design allow through and through cutting.

This topic is worthy of more study especially as softwood sawmilling becomes more polarised between high volume and bespoke processors; this method of drying may offer value adding opportunities for small sawmills seeking specialist markets.

Figure 22: through and through sawn oak stems stacked 'en boule'

6.3 Specifying moisture content

The somewhat high mean moisture content of kiln dried softwoods from major UK sawmillers is likely to be one of the most important factors influencing manufacture of engineered timber elements with British softwoods. 12% or lower moisture content is routinely specified for high quality architectural applications where heated environments may affect internal timber. Austrian Brettstapel manufacturer Sohm Holzbautechnik specify 12% ± 3% for well heated spaces, 14% ± 3% for rooms with low heating requirement and 16% ± 3% for agricultural use (Henderson, 2009).

When asked about typical moisture content for Brettstapel lamellae, a representative from German manufacturer Kaufmann Gmbh suggested that 15% moisture content was a useful guide (Kaufmann, 2012). Moisture contents at installation of between 15%-19% are also specified for American heavy T & G roof decking (American Wood Council, 2003). The British maritime climate brings rapid changes in weather and a generally high relative humidity that rarely dips below 80% throughout the year (Jenkins, et al., 2009).

Therefore specifying moisture content of Brettstapel panels is an important factor when planning Brettstapel structures; initial moisture content needs to be specified not only according to the intended characteristics of the internal spaces of structures but also how much moisture adsorption is possible during the construction phase.

Wetting of unprotected Brettstapel panels during construction may cause lamellae to expand across their width. Although consequent swelling of individual lamellae may not be significant, the expansion across panels containing many lamellae can be enough to damage structures. Exposed ends of lamellae are particularly vulnerable to moisture adsorption.

Even when expansion in lamellae thickness only occurs locally around lamellae ends nonetheless considerable thrust can be exerted by wide Brettstapel panels when positioned across or between floor diaphragms and connected shearwalls. When wall panels are fixed onto swelling lamellae ends structural damage may ensue. Moisture can be transferred by 'wicking' along lamellae and also between lamellae via dowels. Therefore localised wetting can quickly spread across panels; correct design detailing and strict weatherproofing protocols during construction are essential.

Difficulty in controlling the building environment during erection may mean that compromise moisture content levels may have to be agreed for every project, taking into account possible dimensional changes in Brettstapel panels caused by moisture uptake, whether because of relative humidity or direct water ingress during erection. Certainly several European authors allow up to 18% moisture content in lamellae presumably making allowance for local factors (Cheret, et al., 2000).

Some European manufacturers of solid wood building panels extoll this hygroscopic aspect of timber, claiming that mass timber elements are capable of buffering internal climates through moisture adsorption and desorption. Moisture exchange between Brettstapel panels and internal environments may moderate air temperature variations through phase change by up to ± 2% according to VTT, The Technical Research Centre of Finland (Simonson, et al., 2001).

The final appearance of revealed panels is not necessarily compromised by shrinkage as lamellae tend to shrink back individually so that only small gaps appear between each lamella. Shadow gaps are sometimes machined into revealed faces of lamellae to help disguise shrinkage lines. Gaps between lamellae due to shrinkage can be clearly seen below in this close up, fig. 23. But at normal viewing distances the gaps are not noticeable.

Figure 23: Lamellae shrinkage disguised by shadow gaps

6.4 Species for lamellae

Many conifer species grown in Britain could be utilised to manufacture Brettstapel lamellae. Sitka spruce has already been discussed above and providing that kiln schedules can be adjusted to account for the challenges in drying Sitka spruce boards to the moisture content necessary for modern timber engineering then this species may have great potential.

Some of the minor conifer species have excellent drying characteristics which may make them more dimensionally stable than spruce when kiln drying below 15% moisture content. Douglas fir is a good proposition in this respect as it generally appears to suffer less from reaction wood formation. Sawmillers' empirical observations in drying home-grown Douglas fir for use in well heated spaces (around 12%) reinforces the view that this species is amongst the more stable of UK grown softwoods for drying (Bullough, 2013).

The Douglas fir Association of New Zealand also states that this species has a reputation for dimensional stability (Douglas fir Association, 2009). A good example of the stability of Douglas fir boards is shown below in fig. 24; these boards are up to 450mm wide and 5.5 metres long and were kiln dried by the author to around 12%, they suffered little distortion despite being tangentially cut whereby cupping can be considerable in other species

Figure 24: Wide tangentially cut, kiln dried Douglas fir boards show little distortion in this instance

Japanese larch also displays low volumetric shrinkage but tends to suffer more with reaction wood and poor stem form therefore requires special care and kiln drying regimes. Grand fir and Western Hemlock are low value, underutilised timbers displaying low volumetric shrinkage values giving them great potential in Brettstapel production.

Low density species such as Western red cedar or Coastal redwood have very low shrinkage values making them ideal for lamellae. Coastal redwood has few commercial applications in Britain and growers struggle to find processors willing to pay the premium prices normally expected for durable timbers. Data from other species suggests that the non-durable sapwood zones could be of higher stiffness than the durable heartwood. Specialist processors could potentially market Coastal redwood falling boards for Brettstapel and heartwood for high value added cladding.

Western red cedar and Coastal redwood may be useful for Brettstapel panels in applications where high strength is not a priority, or high stiffness lamellae could be interspersed to add structural performance.

Table 2: Guide to stiffness (MOE) of suitable softwoods for lamellae production

Species	Volumetric shrinkage	Stiffness (Modulus of Elasticity)
Sitka spruce	low	medium
Douglas fir	low	medium-high
Japanese larch	low	medium-high
Western hemlock	low	medium
Grand fir	low	low-medium
Western red cedar	very low	low
Coastal redwood	very low	low

6.5 Panel production and length availability

Finger jointing to create long lamellae is common in Germany, Austria and Switzerland but is likely to be limited to a few manufacturers in Britain at the moment. Inwood Developments Ltd of East Sussex are one of few British timber engineering firms with their own finger jointing line (Inwood Developments, 2014) and have shown interest in Brettstapel manufacture using UK-grown softwoods.

However, it is possible to obtain sawn softwood up to 9.5m long from some Mid Wales sawmills e.g. Esgair Timber Company Ltd near Machynlleth (Esgair Timber Company Ltd, 2014); therefore Brettstapel panels up to this length are technically feasible in Wales but not in production at the time of writing this report. Peter Bottoms of Esgair Timber has stated his interest in manufacturing Brettstapel panels at the Machynlleth facility utilising softwoods grown in the firm's forest at Esgair.

There may be scope for building-up long Brettstapel panels by interspersing shorter lamellae between full length lamellae but no trials or research have been carried out here in Britain on this topic. The first image of a nailed fire-resisting floor (fig. 3, page 3) appears to show some butt-jointed lamellae in the top left of the picture (indicated). Too many unreinforced butt joints could reduce overall stiffness too much for panels made up in this way to be used as floor diaphragms but they could nevertheless work as structural wall panels.

This might be a method of utilising some short lamellae without finger jointing. At least one German construction site visited by the Limesnet study tour group (Spark, 2011) used structural walls made up of industrial grade Brettstapel where full height lamellae were alternated with shorter butt-jointed lamellae.

In order to raise the overall stiffness of panels, lamellae processed from low stiffness species could be interspersed at regular intervals with high stiffness species such as larch. This technique would optimise use of lower value, lower grade species in Brettstapel floor diaphragms.

7. Dowels

In Germany, Austria and Switzerland dowels for Brettstapel are normally produced from beech which is a common upland species in those countries and in plentiful supply. Stems grow straight and clear up to several metres long. European beech is a reasonably dense hardwood displaying large volumetric shrinkage and this property makes it ideal for Brettstapel dowels where swelling by moisture adsorption locks dowels into lamellae.

Beech is available in Britain but may suffer from one or more of several defects such as fluting, spiral grain, ring shake and colouring of the heart all of which reduce its commercial value. The value of Brettstapel dowels has been quoted as being well over £1000m^3 (Napier University, 2014) which may justify selection of better material from poorer grades of sawlogs and would certainly justify use of planking grade logs. Beech is challenged by the growing conditions of northern and western Britain where silver birch thrives.

However, birch, if not too fluted or convoluted could be a viable alternative to beech for production of dowels. It is also reasonably dense and displays high volumetric shrinkage, almost as high as beech. Broadleaved forests across England are largely unmanaged (Suttie, 2014) and there is great potential for sourcing high grade beech roundwood from favourable sites in southern England.

Value adding processes such as dowel making may offer opportunities to small specialist English firms wishing to utilise local hardwoods such as beech. Although it is appropriate to source softwood Brettstapel lamellae in Scotland or Wales, it may be a sensible option for UK Brettstapel producers to collaborate and source beech dowels from England. Other dense hardwood species such as hornbeam and even some red oaks such as willow oak could offer potential for dowel production.

Softwood species tend to have lower volumetric shrinkage values than hardwoods. However there may be potential to use species such as Scots pine if higher density material could be selected from crowded, suppressed trees which have grown with small, dense growth rings. Furthermore pines grow clear material with high moisture adsorption properties between knot whorls which may make the species useful for Brettstapel dowel making.

Trade or Common Name	Botanical Name	Density kg/m³	Bending strength $f_{m,mean}$	MOE E_{mean} N/mm²	Tensile strength $f_{t,o,mean}$ N/mm²	Movement Class
Ash	Fraxinus excelsior	689	116	11900	136	Medium
Beech	Fagus Sylvaticus	689	118	12600	180	Large
Silver birch	Betula pendula	673	123	13300	N/A	Large
Oak	Quercus robur Quercus petraea	689	97	10100	90	Medium
Sycamore	Acer pseudoplantanus	561	99	9400	155	Medium
Scots pine	Pinus Sylvestris	520	89	10000	92	Medium

Movement classes:
Change in cross grain dimension for moisture content range of 5-30%
Small -1% for every 5% change in mc
Medium -1% for every 4% change in mc
Large -1% for every 3% chnge in mc

Table 3: Mechanical characteristics of possible dowel species (courtesy of COCIS, Napier University)

Conventional planer/moulders such as those made by Weinig, Wadkin, SCM and Griggio are capable of dowel production. Good, used 4, 5 or 6 head machines may be purchased for a few thousand pounds on auction websites such as 'eBay' or 'Apex Auctions', allowing SMEs to start Brettstapel manufacture with little investment. Both smooth and longitudinally ribbed dowels may be machined. German Brettstapel manufacturers tend to use either 16mm or 20mm diameter beech dowels produced by other specialist timber profile machinist firms.

This could also be a possible scenario in the UK because beech does not grow well in the areas of softwood production where Brettstapel is most likely to be manufactured. It is therefore logical to ship the higher value low volume dowel components to the Brettstapel manufacturers. Serrated-back cutter blocks, with knives ground to produce a half round profile used in the final top and bottom heads of a planer/moulder, are capable of producing several metres of dowel per minute. In order to enable machining of dowels for production of prototype panels for WKW and Edinburgh Napier University, CAD drawings were produced of cutter profiles.

These could then be emailed to specialist toolmaking firms such as Whitehill Tools in Luton (Whitehill Tools, 2014) for them to grind cutters for mounting in standard serrated-back cutter blocks. Cutters were ground to produce dowels with diameters oversized by 0.5mm in order to create a friction fit between dowels and lamellae which could hold panels together whilst dowel expansion through moisture adsorption occurred to finally lock dowels in place. 20.5mm diameter dowels inserted into a 20mm hole gave best results in tests carried out by Deb Turnbull at Edinburgh Napier University (Turnbull, 2013).

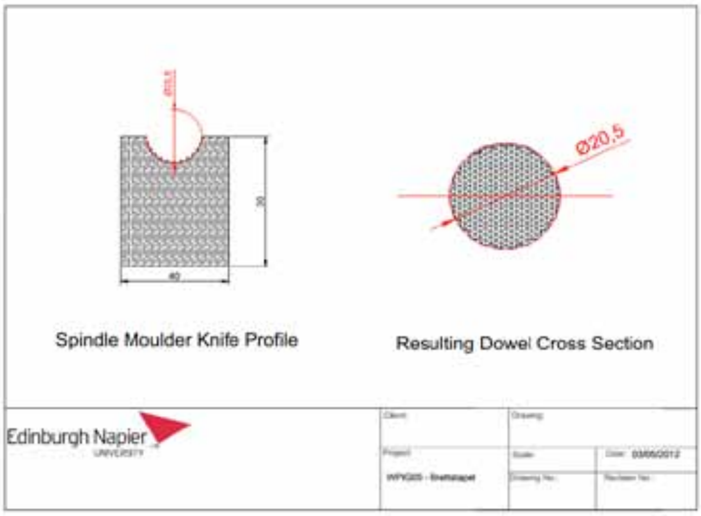


Figure 25: CAD drawing of 20.5mm diameter cutter profile for ribbed dowels (drawn by J. Hawker)

Using a square cross section batten a few millimetres larger than finished diameter, two serrated back cutter blocks mounted on the last top and bottom shafts of a planer/moulder can produce smooth or ribbed dowels. For clarity, fig. 26 shows cutter blocks taken out of the machine demonstrating their positioning in relation to the dowel; knives point in the direction of rotation. Cutters can be ground with multiple dowel profiles to increase production, for instance, in order to machine four separate dowels in parallel in one pass through a planer/moulder.

Figure 26: Serrated cutter blocks showing how rotating knives can produce ribbed dowels

7.1 Racking strength of panels

OSB racking boards can be nailed to the back (non-revealed) face of Brettstapel wall panels to impart racking strength as structural engineers assume that wooden dowels alone do not create enough racking capacity for shear walls. Because air tightness is an important factor in modern high thermal performance construction, 18mm OSB can be used both to increase racking strength and create an air-tightness layer (Dauksta, 2013). Designers need to check exactly which type, grade and thickness of OSB should be specified in order to optimise performance. Other types of racking boards may be used, for instance plywood.

However OSB tends to be the cheapest option and at the time of the 'Limesnet' (Spark, 2011) Brettstapel study tour in 2012 most of the German, Austrian and Swiss Brettstapel firms visited were using OSB. There is some debate about formaldehyde off-gassing from OSB panels but tests at Bangor University have shown that this is normally within safe levels and that food such as tomatoes can off-gas higher levels of formaldehyde than OSB (Ormondroyd, 2014). Soft fibreboards may also be used, for instance 15mm 'Hunton Bitroc' achieves sufficient racking strength when used on open panel timber frames (Braathen, 2010) but of course this is a more expensive option than OSB.

At the time of writing some limited research is being carried out at Bath University in order to quantify the contribution dowels may make to racking performance of Brettstapel panels. Thomas Sohm's patent application in regard to angled dowels is now considered to be withdrawn (see section 10 below). This will allow researchers to study and quantify the possible increase in racking strength resulting from utilisation of dovetailed dowels.

There is considerable scope to use other methods to increase racking strength; for instance fixing of softwood boards or planks diagonal to lamellae. This method is often utilised in North America where design codes for this method are available for conventional open panel timber framed buildings (Thelandersson & Larsen, 2003). Diagonally fixed softwood boards as sheathing/racking layer using low grade, high stiffness falling boards could have potential for firms that prefer to market Brettstapel panels as 'ecological' or 'natural' alternatives to conventional forms of construction.

8. Bench production and drilling rigs

Williams Homes of Bala, the contractors responsible for building the Coed y Brenin visitor centre extension, produced the Brettstapel panels for the centre as a simple bench joinery exercise. Sash cramps were used for clamping lamellae together, long augers in hand-held drills were used for boring holes through lamellae and dowels inserted by hammering. This method can be refined by mounting hand-drills in a jig or onto a flat plate so that the assembly can slide easily on the bench top whilst keeping the auger positioned parallel to bench surface and at the right height for boring the holes at the appropriate position on the panel edge to be bored.

Short dowels, e.g. 300-400mm length can be used for creating wider panels by building panels up a few lamellae at a time, and overlapping dowels for each section. This was described in Ellis in regard to the Rouen and Le Havre railway bridge; *dowels were driven through two lamellae into the third and so on through the 1.2 metres deep section* (Ellis, 1914).

Some firms in the cluster of Brettstapel production in southern Germany, Austria and Switzerland use long dowels that penetrate right through their standard width (600mm) panels. Swiss firm Holmag Holzbearbeitungsmaschinen AG fabricate specialist timber processing machinery and have developed a Brettstapel production line which is capable of fabricating panels from 2.5 to 12 metres long, 200mm to 650mm wide and 50mm to 220mm deep.

Kaufmann Gmbh of Oberstadion use a Holmag machine which can be seen here: http://bit.ly/1rzvttw

Swiss Brettstapel manufacturer Kaufmann Oberholzer who use the brand 'Optiholz' have fabricated their own Brettstapel production line; their clamping, boring and dowel inserting line is shown in fig. 27 below. They use smooth dowels inserted at right angles to the lamellae. Kaufmann Oberholzer's Optiholz can be seen here: http://bit.ly/1ooP8EL

Figure 27: The Brettstapel production line at Kaufmann Oberholzer in Switzerland

Kaufmann Oberholzer have developed their own method for optimising stiffness of floor diaphragms by making composite panels with a cast concrete upper face which works in compression whilst the timber lamellae work in tension on the panel underside. This is an optimal arrangement for the two materials; load is transferred between layers via screwed steel fixings and trenches cut into the top face of the lamellae. fig. 28 below shows a batch of Brettstapel/concrete floor panels delivered 'just in time' to a construction site in Switzerland. Panels are ready for craning into position direct from the trailer; simple overlapping rebates are formed by nailing timber rails along panel edges and then casting the concrete over the rail.

The technique for creating composite floor diaphragms using timber and concrete or other types of masonry has been used extensively in Europe, especially to increase stiffness of floors in old buildings. The topic deserves more study here in Britain; there may also be scope to include wood chips within the concrete.

Figure 28: Composite Brettstapel/concrete panels delivered just in time to a site in Switzerland

A simple Sketchup schema in fig. 29 shows the arrangement of a Brettstapel clamping and drilling line which could be manufactured competitively in Britain. The fixed fence and rail for carrying the moving drill carriage are used as a chassis to which are fixed identical modules for clamping.

A moving fence is fixed to the ends of rams which are able to push lamellae together. The drill head is mounted on a moving carriage and could be arranged on a turntable onto which are mounted rails to allow angled drilling. This simple design does not include a magazine for holding dowels or a ram system for insertion. However, dowels could be inserted reasonably quickly using an air hammer.

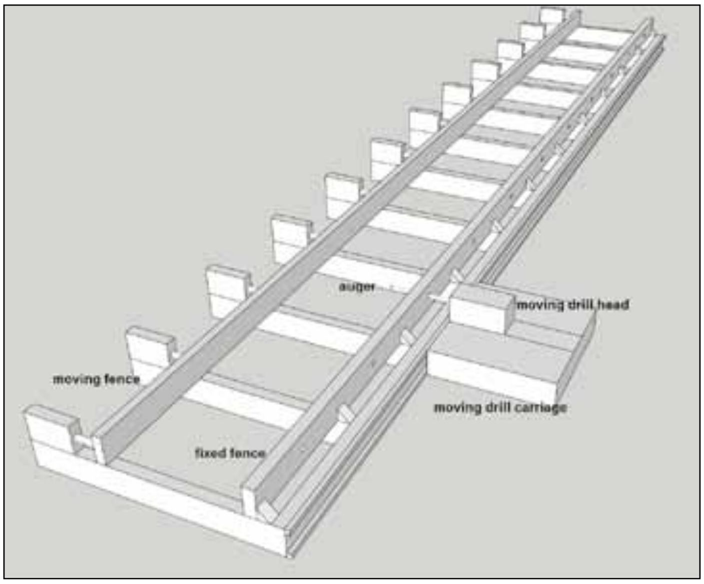


Figure 29: A simple schema for a modular Brettstapel clamping and boring line

Assembly and dowelling of lamellae for Brettstapel can be carried out using basic, cheap techniques and equipment although of course less mechanisation incurs higher manual labour input. Nevertheless this scalability of production process will allow SMEs to start manufacture without large investment and may suit firms who are already making complete timber frame buildings - Brettstapel floors and shear walls could widen their design options.

9. Gun drills and augers

Deep hole drilling in any material is a highly specialised operation which is well understood by very few and opinions vary as to how best results might be achieved when drilling through clamped Brettstapel lamellae in order to insert dowels. The German, Austrian and Swiss SMEs visited by the Limesnet group in 2011 all appeared to be using single flute 'gun barrel' drills of the type shown in fig. 30 below.

This type of tool was designed originally to bore metals such as steel to create precisely machined components such as gun barrels; there is a detailed thesis on the topic of gundrilling here:
www.a_viktor.tripod.com/PeterThesisWriter.pdf

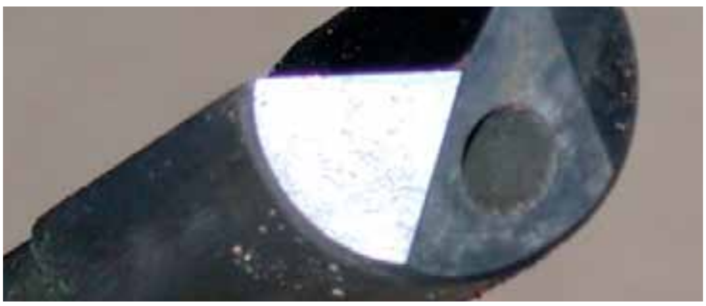


Figure 30: The cutting end of a gun drill showing air hole and single flute

The gun drill is a hollow spindle tool with a flute machined down one side. Compressed air or a lubricating fluid such as cutting oil (for metals) can be pumped down the hollow centre which drives chips created at the cutting edge down the flute on the outside of the drill to exit at the entry point of the drill. The Limesnet group were able to observe this type of drill in action at Kaufmann Oberholzer in Switzerland and the sound of the compressed air being used for clearing wood chips was quite obvious.

Some breakout was evident on the exit holes of lamellae at the Holmag production line of Kaufmann GmbH in Oberstadion, although this did not appear to be common on panels situated in other areas of the production line. Even where gun drills had been used to bore panels as wide as 600mm, there appeared to be little or no deviation and exit holes were generally precisely positioned.

The use of gun drills for boring Brettstapel panels may initially be challenging for British firms starting out with the technique. The gun drill is almost certainly not appropriate for mounting in a hand-held drill but could be well suited for use on a clamping and boring line where the drilling unit is mounted on rails.

Figure 31: Break-out occurring at gun drill exit holes at Kaufmann GmbH on a Brettstapel insulated 'twin wall' element.

Technical details of proprietary gun drills may be found here: http://bit.ly/1zDYZwB

Triple fluted, tri-flute or tri-cut augers are considered by some artisans to be useful when attempting deep hole drilling in timber. John Lloyd of T.J Crump Oakwrights Ltd reports better results with these tools than with traditional single flute ship augers when deep boring massive green oak components.

One of the best known manufacturers of wood drilling augers, Irwin Tools, claims better results and less break-out with the 'Speedbor' tri-flute auger (Irwin Tools, 2014) but these augers are only 150mm long and would need shank extensions for use in deep boring. The Irwin guide to their drilling products is here: http://bit.ly/VNhFNh

Specialist timber frame power tool firm 'Timberwolf Tools' supply tri-cut augers up to 457mm long, these may have some potential for firms starting out in Brettstapel production using hand held power tools. Their website is here: http://bit.ly/1nC6oqz

Japanese toolmakers 'Star-M' make single flute ship augers up to 600mm long and 30mm diameter; however they are significantly more expensive than the Irwin single flute equivalents. There may be significantly increased risk of single flute augers wandering in the wood as they encounter knots or reaction wood but they need more testing in Brettstapel in order to better judge their performance. Star-M products can be seen here: http://bit.ly/1tUpVqc

Williams Homes of Bala, the contractors who built the Coed y Brenin visitor centre extension reported a high wastage of single flute augers whilst making the Brettstapel panels for the visitor centre (Williams, 2014). Deb Turnbull of Napier University reported some wandering of augers and oversizing of entry and exit holes when using single flute augers for drilling through 24mm thickness lamellae. This caused the outer lamellae to be somewhat loose-fitting on their dowels (Turnbull, 2013). However, when drilling through thicker, 45mm lamellae the author found this not to be a problem. More practical experience in deep drilling Brettstapel lamellae is needed in order to find optimal production techniques that suit British conditions; no doubt more information on the topic will emerge as SMEs experiment with Brettstapel manufacture.

10. Thomas Sohm's patent application

There has been considerable discussion at the Brettstapel Network organised by Edinburgh Napier University (Napier University, 2014) and at the Woodknowledge Wales steering group about IPR in regard to Brettstapel manufacture. A particular point of debate was the utilisation of dovetailed or angled hardwood dowels in Brettstapel panels over which Thomas Sohm of Sohm Holzbautechnik GesmbH attempted to gain a patent. A search using keyword 'Sohm' on the European Patent Office register brings up the file EP2409821- *Method for manufacturing panel elements.*

The documents cited in this application include AT410335B, the bibliographic data and abstract which describe the angled dowel configuration over which Thomas Sohm attempted to claim IPR:

Plate element comprises a number of adjacent boards (1) or beams arranged edgewise to the surface of the plate element and connected by wooden dowels (3). The angle (5) between the wooden dowels and the surface normal (4) on the broad sides of the boards or beams is at least 15, preferably at least 25 deg. Wooden dowels are provided in both directions to the surface normal. Preferred Features: The wooden dowels are made of hardwood. The angle between the wooden dowels and the surface normal is a maximum of 45, preferably 30-35 deg.

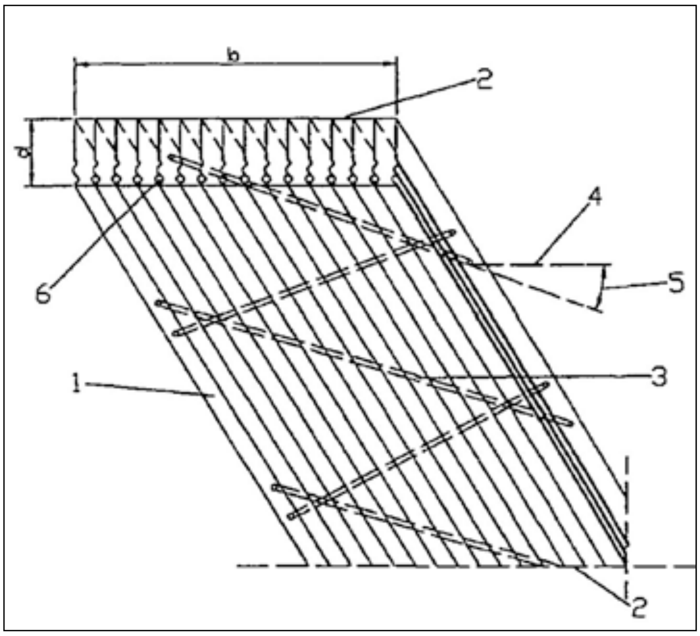


Figure 32: Drawing of dovetailed dowels in the abstract of Sohm's application (EPO, 2014)

Access to the documents submitted by Thomas Sohm and his representatives may be gained here: http://bit.ly/1pgGNJ5

At the time of writing, Thomas Sohm's patent application appears to be no longer pending. When accessing the documents the status of the application was described thus: The application is deemed to be withdrawn *Database last updated on 12.04.2014.*

The dovetailed dowels shown in Sohm's drawing appear to be full length. The process of inserting such long dowels is somewhat challenging without recourse to specialised machinery.

Thomas Sohm also made a patent application for the drilling and dowel insertion machinery used in Sohm's own production line. However, by overlapping shorter dowels in the manner described above in section 7, the process of dowel insertion is made easier and dovetailing dowels increases load carrying between lamellae (Thelandersson & Larsen, 2003). Air hammers with custom tools able to cup dowel ends to prevent mushrooming, spreading or splitting could potentially speed up dowel insertion.

11. Conclusion

It is demonstrably possible to produce Brettstapel panels using UK grown timbers. The variability of Welsh grown softwoods allows production of shear wall panels and floor diaphragms with a wide range of properties. Low density or low stiffness softwoods from high yield conifer plantations could be ideal for lamellae, their low moisture movement imparting stability to panels. High stiffness species such as larch can be utilised to create high performance panels and large volumes of this species will become available as Phytophthora ramorum progresses through British forests.

Douglas fir could be an ideal species for Brettstapel production, its stiffness combined with dimensional stability make it ideal for high grade Brettstapel. Furthermore, the readily saleable heartwood could be sold into high value sawnwood markets whilst the higher stiffness sapwood outer boards could make excellent lamellae. Brettstapel may be optimised in several ways; species may be varied to alter structural properties or high stiffness lamellae interspersed between lower stiffness lamellae to increase overall structural performance of a panel.

Both lamellae and dowels can be produced at high volumes using conventional planer moulders. Used machines are readily available for a few thousand pounds. Whilst lamellae might be more likely to be produced near to areas of the UK where suitable softwood supplies are readily available such as Wales, Scotland and Northeast England, dowel production might be better suited to the parts of England where high grade beech is available. Since the demise of the English homegrown beech furniture industry, dowel production could be a small scale opportunity to revive utilisation of English beech in a high value adding process.

Although Brettstapel appears to be a more old-fashioned panel material when compared to CLT, it gives optimal performance in shear walls and floor diaphragms because of parallel alignment of fibres. CLT in comparison, if not designed properly to optimise its two way properties, does not necessarily offer best value in all solid wood panel applications. Furthermore Brettstapel production is scalable and is therefore available as a viable, low investment option for small firms.

A production line could readily be set up in steel shipping containers to create a 'flying factory' capable of being transported from site to site. The technique can be used in a wide range of panel products; priced according to scale and varying from cheap, mass, industrial grade panels to expensive, bespoke panels using attractive high value timbers. The variety of applications is limited only by the imaginations of designers.

The success of SMEs such as Kaufmann Gmbh of Oberstadion in southern Germany attests to the potential of Brettstapel as a solid wood panel product. In following the footsteps of German, Austrian and Swiss Brettstapel manufacturers, British timber growers and processors could learn many important lessons about better utilisation of local timbers. Perhaps the most important lesson is to understand their materials properly through scientific study and use them optimally rather than using subjective or normative judgements and then miss value adding opportunities.

Although Brettstapel alone can be used to create structures, it also works well with other forms of construction. An obvious compromise for British developers at present might be conventional steel frame structures which use Brettstapel floors like the Canadian example cited in section 2. Kaden and Klingbeil's e3 apartment building in Berlin, shown in fig. 33 uses a glulam post and beam frame with Brettstapel walls and floors. At seven storeys high it predated the CLT Stadthaus built later in London and like the latter was for a short period the world's tallest residential timber structure (Jaeger, 2008). The e3 project offered apartments varying in cost from 1900 to 2400 Euros and demonstrated the cost efficiencies achievable with heavy timber construction.

Figure 33: the e3 Brettstapel apartment building Berlin (courtesy of Kaden + Klingbeil)

The Toronto warehouses and Duluth grain elevator described in Section 2 clearly show the viability and durability of this type of structure; they also show how innovations in timber construction have developed over centuries and are rediscovered sometimes after long interludes. Fig. 34 shows the nine storey Butler Brothers' building in Minneapolis.

This former warehouse used Douglas fir post and beam construction, the timber structure was optimised by diminishing the solid post size from bottom to top of the building. It is now possible to grade structural timber components individually using acoustic tools such as the Brookhuis MTG; this offers the possibility of strength grading in order to position components optimally within a structure.

Connections in the Butler Brothers' building are reinforced with iron saddles. Along one horizontal axis, some bridging joists are made by bolting two lamellae together and others are solid Douglas fir; the timber was sourced from the contractor's own forest. There are no technical barriers to building structures such as these in Britain and combined with Brettstapel they offer a method for building inspirational tall wooden buildings which need only modest investment in production facilities.

Using large volumes of solid wood in structures such as these can lock up carbon within durable, attractive architecture whilst increasing demand from well designed and managed conifer plantation forests which suit the growing environments of Wales and Scotland.

Figure 34: The interior of the nine storey Butler Brothers' building in Minneapolis

By utilising this joined up thinking, the construction industry can benefit the environment and create jobs along the supply chain from rural hinterlands all the way through to urban industrial and residential zones. Best of all the underlying philosophy, tried and tested in Germany, Austria and Switzerland, offers a low carbon future by creating viable, sophisticated built environments using local renewable resources.

By embracing this philosophy Wales and Scotland could transform their economies from that of post-industrial revolution based on fossil fuels to neo-industrial revolution based on sustainable forestry.

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