Behaviour-based Wood Connection as a Base for New Tectonics

Marcin Wójcik
Technological University Dublin, marcin.wojcik@dit.ie

Jan Strumillo
Oslo School of Architecture

Follow this and additional works at: https://arrow.dit.ie/bescharcon

Part of the Architecture Commons

Recommended Citation
ABSTRACT
This paper joins into the debate on sustainable architecture and construction and the resilience of the architectural practice. It takes up the case of solid wood construction where heterogeneity of timber is considered a disadvantage in construction. Wood industry utilises expensive processes in order to overcome rather than exploit natural wood properties. We suggest a different approach that could lead to the reduction of environmental pollution and more economic use of resources, that is discussed with a proposed wood connection method based on harnessing material behaviour induced by a change of moisture relationships -- i.e. shrinkage. Two design paths are presented: (i) involving clinging of green component on dry insert and (ii) utilising anisotropy in green wood shrinkage. The main contribution of this paper is a new view on tectonics -- understood as proper use of materials -- that bridges the gap between wood material science and design disciplines. Both theoretical and methodological frameworks are presented and, supported by the demonstrated concept, showcase the potential of inducing far-reaching changes in the timber industry. By reducing waste and by reducing the need for chemistry and supplementary materials in wood joining and improving economic performance we can get closer to a sustainable practice.

Keywords: wood tectonics, material-oriented design, wood properties, digital manufacturing

1 INTRODUCTION
The project presented in this paper belongs to the intersection of the fields of (i) architectural tectonics, (ii) sustainable construction and (iii) construction technologies. Its main goal is the resilience of architectural practice. It is framed by the problem of solid wood construction, where it is argued for an alternative joining technique, based on material behaviour. The central research question being asked is how the inherent material properties can be used in the design and construction processes, with a working hypothesis that applying these may lead to a more sustainable and more feasible construction. Outlines of both theoretical and methodological frameworks together with designed and manufactured prototypes are presented in order to induce discussion.

1.1 The tectonic approach
The tectonic quality of architecture emerges from the interplay between material, construction technology, environmental and cultural factors, as evident in the development of splicing joints in the Japanese carpentry. In the seismic condition of Japan long timbers must be used for the necessary building rigidity, a fact that caused the depletion of tall trees as early as 11th-12th centuries. That environmental influence combined with the traditionally developed building forms, aesthetical canons -- such as the dislike for an exposed endgrain (koguchi) -- and the resistant yet easy to work with hinoki wood (Japanese cypress), had effectively led to the richness and sophistication of the tsugite joinery technique (Figure 1). At its peak, Japanese carpentry distinguished 200 different wood joints, both tsugite (splicing) and shiguchi (perpendicular), with more than 100 joints needed for construction of a single shrine or temple in the 17th-19th centuries [1].
The tools used affect the tectonic expression in a similar manner, as demonstrated by the example of the introduction of the old Germanic tool *klingeisen* – a curved drawknife, known as *medrag* in Norway (Figure 2) – and its influence on the appearance of log buildings in Scandinavia [2, 3].

In the same vein Christoph Schindler, architect, designer and researcher, sees wood construction as the interaction of matter, energy and information, on which he based his periodization model that integrates fabrication with manual, industrial and information technology. Through the production technology we can see the wood construction and acknowledge that the technology not only radically reshaped the production of buildings, but equally their construction and appearance [4].

In our project the term *tectonics* is understood as the *prescriptions regarding the proper use of materials* [5]. Its root -- the Ancient Greek term *tektōn* (téktōn) -- denotes a carpenter, a fact that signifies the important role of wood construction in the development of architecture. It is intended to take part in the historical discussion of the relation between form and matter in architecture, where it is proposed to see the form as emergent from the material and its capacities, as opposed to imposed onto the materials, like in the design based on proportioning systems and architectural orders. In the proposed tectonic approach two aspects are critical: (i) integration of material properties and behaviour with manufacturing and assembly logic and logistic and (ii) integration of the heritage of wood construction with state of the art technology.

### 1.2 The material

Wood is an extremely variable and stochastic material, involving a degree of randomness, where the physical properties are specie-specific while there exist approximately 30,000 species of trees. Its anisotropic behaviour, porosity and heterogeneity reflect the material’s complex internal structure [6]. The modelling of the mechanical behaviour of timber is further complicated by the fluctuations in material characteristics being dependent on environmental conditions: moisture, temperature and time. The very specific characteristics and behaviour of wood are a result of reciprocal hierarchies: heterogeneous structure of the cellular network dependant on the fibre arrangement and anisotropy dependant on the fibre direction, tree specie, piece shape and thickness.

Today we face a similar problem to the aforementioned depletion of large trees in old time Japan. Small dimensional sizes, variation and heterogeneity of timber are seen as a disadvantage: *In the past some of the difficulties could be overcome by selective utilization of certain species and reliance on*
the larger and older age classes of trees possessing more uniformity. It is now clear, however, that we are no longer able to enjoy such luxuries. More and more trees are characterised by small sizes and greater variability [6]. Thus remanufacture of timber is a way to meet the needs of modern economy. Remanufacture is a process not without impact on the environment. Approaching the problem from a different perspective our project utilises roundwood – a low-processed forest product.

2 THEORETICAL FRAMEWORK

The theoretical framework of the project is constituted by three concepts: (i) bio-cybernetics, (ii) biomimetic and (iii) material-oriented design. Sustainable solutions require transdisciplinary integration of multiple knowledge bases.

(i) Frederic Vester (1925-2003), a German biochemist, ecologist and the originator of networked thinking that is based on systemic and cybernetic approaches, opposes constructivist against evolutionary types of management. In the former the system is produced at great expense of material and energy, in the latter it emerges spontaneously at little expense. The 4th rule of his eight basic rules of bio-cybernetics outlines the strategy: exploiting existing forces in accordance with the ju-jitsu principle rather than fighting against them with the boxing method [7]. (ii) That in turn resonates with the comparison of biological and technological systems as presented by Julian Vincent (Figure 3), professor of biomimetics at the University of Bath. Vincent argues, that our technology kills the information of raw materials, by reducing, melting, dissolving, homogenising, thus achieving random material with no intrinsic information, further moulded, cast, turned, joint with a substantial expense of energy to make the material ordered with imposed shape and structure for the final product. Conversely to technological systems, biological systems use information, stored in the genetic code, rather than energy to solve technical problems. Information is used to self-assemble structures, that unlike the engineered solutions are hierarchical. Vincent points to our ability to tap abundant and cheap fossil fuels during the Industrial Revolution as a key turning point in our relationship with nature [8].

Figure 3. Comparison of biological effects and engineering TRIZ\(^1\) solutions arranged according to size / hierarchy. Technology uses energy as the primary driver for solving engineering problems across the nanometre to metre scales, with information playing a smaller role. In contrast, biological systems use energy sparingly (about 5% of the cases), relying instead on information and structure. The similarity in solving problems between those two systems is only 12% [9].

Applying these principles to wood construction means to find solutions based on material behaviour and self-organisational capacities rather than enforcing form over material. This approach would promote manufacturing and construction techniques that are non-wasteful, less energy consuming and toxic and provide vital alternatives to manufactured wood products in order to overcome the scarcity of good quality and large-dimensional timbers. By replacing energy-expensive industrial processes with the naturally occurring changes in the material and using its potential, such solutions, when scaled up, would constitute a significant move towards sustainability.

(iii) The problem of material agency of wood in construction can be tracked back to the 19th century and the rapid development of structural design induced by the introduction of homogeneous and isotropic materials – namely iron and later steel. Iron provided the physical basis for a mathematically

\(^1\) a theory of inventive problem solving developed in 1950s Soviet Union
oriented formulation of design, thoroughly justified by science what resulted in a shift of focus to a more rational, abstract and analytically driven understanding of construction in structural design [10]. The process of standardisation affected wood construction as well -- the balloon frame system based on the 2 x 4 inches module has been introduced in 1830s. Manuel de Landa, Mexican-American artist and philosopher, argues that with the invention of standardised and homogenised building materials design has been reduced to a routine and consequently the linguistically unarticulated knowledge of craftsmen about complex material behaviour has been disregarded [11]. Michael Hensel, architect and professor of architecture at the Oslo School of Architecture and Design (AHO), identifies architecture as a domain of active agency, where the spatial and material organisation complex is defined as a synthesis of the various scales and their interactions. While in the industrial tradition architects and engineers prefer materials that can be considered homogeneous and predictable -- as exemplified by the case of steel and iron -- Hensel postulates dynamic condition required by the spatial and material organisation characterised by active agency. Wood structure must be understood in relation to environmental conditions affecting its growth. Higher in the hierarchical organisation system, material behaviour is determined by the material properties and environmental conditions. This in turn has to be harnessed by architectural design, what is the basis of the instrumentalisation of material behaviour as performative capacity [12].

3 EXISTING EXAMPLES

Contemporary solid-wood building technology, primarily represented by cross-laminated timber (CLT) must still be considered a recent invention, although it has matured since its appearance on the market in the early 1990s. However when compared to the abovementioned balloon frame, post-and-beam or log constructions (pre-historic inventions) this must be considered young. CLT has become an industry-standard but its development is not over. CLT’s production started in European alpine countries and it involves laminating planks by means of polyurethane glue (Figure 4). Polyurethane is a synthetic polymer and as such it is non-biodegradable. This is problematic when the entire lifecycle of the composite element is considered. Solid-wood panel building systems rely on metal connectors for assembly e.g. self-tapping screws. CLT manufacture overcomes the anisotropic nature of wood. Dried wood is used to yield a product that is as homogenous and standardised as possible. CLT production and assembly leaves room for improvement and innovation, which has been recognised by researchers and entrepreneurs. The following examples challenge the established standard CLT solution. They have to be considered parallel tracks within the same line of development as this research. One objective of innovation is to achieve panels free from volatile organic compounds. A number of research projects and available products tackle this issue.

Starting in the 1970s Julius Natterer, German engineer and professor of wood construction at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, has worked with stacked-plank panels. Initially the softwood planks obtained from low-quality raw material were joined by steel nails, in later versions they were connected by means of dry beech dowels that swell by drawing moisture from the elements that they connect. This system, called Brettstapel, avoids using toxic adhesives in construction and allows all-wood element production. It employs the natural swelling phenomenon for the creation of a durable joint between the panel layers. Natterer chose not to patent the system and to make it available to everyone. Subsequently many firms have taken up the production based on his
A similar principle is employed in the production of NUR-HOLZ (timber-only) elements (Figure 6), produced by the firm Rombach in Austria since 2009 [15]. They have the form of panels that can be used as walls and floors. Instead of glue (or dowels, as in the case of Holz100 system) the layers of timber slats are connected by means of hardwood screws. The system does not exploit the behavioural potential of the material (e.g. swelling) but it achieves an adhesive-free bond to yield a commercially viable product.

Interlocking Cross Laminated Timber (ICLT) system is being developed at the University of Utah (Figure 7). ICLT avoids the use of adhesives or mechanical (metal) connectors in the manufacture of panels by using dovetail-joint connection. The panels are designed to make use of wastewood – they use beetle-kill pine – a sub-standard timber material abundant in North America after a longhorn beetle infestation. Boards are CNC-milled to form interlocking elements that provide bonding action for the panel. Similarly to CLT, the ICLT panels can be manufactured in many variants with different number of layers and corresponding element thickness for different structural and physical parameters. As of 2013 two experimental buildings have been constructed in Utah using the technology [17, 18].

A different approach characterises the Swiss TopWall system invented by the engineer Hermann Blumer. It uses the natural properties of wood for constructing walls (Figure 8). The low shrinkage
and high compressive strength of timber along the grain is exploited by positioning the wall elements vertically. The system has been used with success to erect a six-storey apartment complex in Zurich (Pool Architekten, Badenerstrasse, completed 2010). The 10 x 20 cm softwood studs are positioned next to one another and held in place by means of dowels that fix them to horizontal elements forming the top and bottom of each storey-high wall. They are also connected by dowels between themselves. The vertical elements are put in individually, allowing for a construction without using a crane. The resulting wall has a compressive strength comparable to concrete and many times that of a masonry wall of similar thickness [19].

Composite timber-concrete floor slab system developed by Julius Natterer of the EPFL in Lausanne is an example of low-treated wood use (Figure 9). One of the tested versions of the timber-concrete composite makes use of halved logs. An example of the use of this system is a house constructed in Clarens, Switzerland (1992). The composite action between timber members and the poured slab is provided by means of notches and complimentary steel anchors. Use of halved logs allowed the achievement of favourable economic results [21].

The AV3 system developed in Norway [22] features a composite panel for the erection of walls in single-family houses (Figure 10). Panels are composed as a three-layer sandwich: between two layers of tongue-and-groove connected heartwood elements of sitka spruce an insulating core of pressed wood shavings is placed. The machined elements make use of the natural, conical shape of logs. Their long edges are tapered and only by alternating their directions an overall regularity of the panel is maintained.
Friction welding of wood, explored by the IBOIS team at the EPFL in Lausanne employs the material properties of wood at its molecular level to create a permanent adhesive-free joint (Figure 11). Described in a number of papers (see for instance [23]) the technology of friction welding is used to bond metals and thermoplastics. It was shown that the same process can be used for bonding flat elements of wood. At present stage of development the technology can be used for creating joints that can be used inside of buildings/elements i.e. to create furniture or composite structural elements (weldlam). The limiting factor for large-scale elements is the costly machinery needed to produce sufficient pressure and high-speed friction required to achieve the bond. It is however imaginable, that large-scale solid-wood panels could be produced in the future using friction-welding.

![Figure 11. Friction welding (image source: [24])](image)

## 4 DESIGN POTENTIAL IN MATERIAL DEFICIENCIES

In line with the established theoretical framework it is proposed to harness the anisotropic shrinkage in timber as it dries, use roundwood -- a low-processed raw material, and avoid additional fasteners and bonding agents. Various deficiencies – dimensional instability, anisotropic behaviour, round and irregular shape -- are worked with and used to minimise the energy expenditure in production.

### 4.1 Orthotropic shrinkage and movement in timber

**Anisotropy may be utilised as a design strategy leading away from digital form-finding to trait-finding [25].**

Anisotropy present in timber is a result of the alignment in the vertical axis of a tree of 90 to 95% of the cells as well as the orientation of the microfibrils in the middle layer of the secondary cell wall. Longitudinal and transverse degree of anisotropy of timber shrinkage due to water relationships amounts to approximately 40:1, in regard to thermal movement to 10:1 and for thermal conductivity to 2.5:1 [26].

Dimensional instability of timber is often seen as a serious problem to overcome. As far as water relationships in wood are concerned it can be divided into two separate phenomena: (1) shrinkage -- activated on drying and (2) movement -- present in service throughout the component life-span due to seasonal or daily changes in relative humidity or a fluctuating environment. The dimensional instability in timber is anisotropic, dependant on the fibre direction, the degrees of anisotropy are further dependant on the tree specie and the way the log was converted.

1. On drying wood begins to shrink as its moisture content drops below 30%. For green wood it is equal to 60-200% and below ca. 30% the moisture is no more in the cell cavity but in the cell wall. That stage, called fibre saturation point (FSP), marks dramatic change in wood properties, for instance compression strength increases three-fold between there and an oven-dry state. As timber is orthotropic in its water relationships shrinkage is different on the three principal axes, dependent on the tree specie: longitudinal 0.1-0.3%, radial 2-6% and tangential 5-10%, however -- as wood is not used in the oven-dry state but in-service moisture content amounts to 8-15% -- we should consider 50-75% of the aforementioned values [26], [27].

2. The anisotropy of movement can be accounted for by the same set of values as for shrinkage, yet its magnitude amounts to approximately one third [26], [27].
4.2 Green wood in construction
Strength and stiffness of timber decreases with the increase of moisture content, and above 20% of moisture content timber is susceptible to attack by fungi. For these reasons moisture is removed from commercial timbers by air-seasoning or in the drying kilns [26]. Using green timber has a long history in vernacular architecture. European, Russian and Japanese carpenters developed various techniques in order to factor-in different rates of longitudinal, radial and tangential shrinkage in timber components. Some vernacular methods, like the fabrication of hay and crop forks or using dry dowels in green wood exploit the inherent properties and behaviour of the material. It is generally not known when the practice of drying wood prior to working it has been introduced, but up until late gothic times wood was worked green [2]. An interesting feature can be found in traditional Scandinavian log house construction: horizontal orientation of logs -- the most common building method for hundreds of years -- took advantage of the radial shrinkage of the logs when drying, making the building tight. Interestingly, changing the orientation of the logs to vertical in the 18th century in order to achieve more freedom in shaping the building plan, resulted in the lack of tightness varying with the moisture content in the air. This effectively led to the increased use of dried timber boards in construction from the 19th century [28].

4.3 Small diameter roundwood in construction
Small diameter roundwood has been widely used for centuries -- mostly for their convenience in size and where quality was of secondary importance -- in such structures as sheds, barns or fencing. Today it is not commonly used in the developed countries as a structural material due to the lack of design guidelines and readily available and reliable connectors, unavailability of the material through normal commercial channels, the difficulty when attaching cladding to irregular and round structure [29, 30]. Embodied energy of roundwood material is 40% lower than of sawn lumber [30]. Further, small diameter roundwood self-replenishes over a much shorter period of time than that needed for sawn timber. The cost of debarked round timber is roughly a half of sawn timber while the characteristic bending strength of unsorted material may be even double the value of sawn timber [29]. Furthermore, processing a material means energy expenditure and may have an impact on health risks posed by this material, and also on this material’s recycling: The higher the degree of processing, the lower the potential for quick and unproblematic decomposition [31].

4.4 All-wood connections
Today’s wood construction systems use metal fasteners -- brackets, plates, screws and bolts for connections, which is problematic for the three reasons mentioned below:
1. Metal fasteners impede recycling of wooden components due to the difficulty with partying-out in a demolition process. Only about 0.03% of industrial wood comes from recycling -- some 0.5 million cubic metres of wood is reclaimed yearly (242,000 tones in 2000 [32], while it is estimated that about a third of the 3,400 million of cubic metres of annual worldwide timber harvest [33] is used in construction [34]).
2. Metal fasteners penetrating wooden beams in unheated rooms rust where their galvanised coating has been damaged by abrasion upon entering the wood and the surrounding wood rots due to condensation on the cold metal. These processes are delayed by using toxic, chemical wood preservatives [1].
3. During a fire, metal fasteners become red hot after only 15 to 25 minutes causing structural failure of the joints and quick collapse of the building. The wood-to-wood joints guarantee burning buildings a longer resistance than do metal-to-wood joints [1]. A timber building system eliminating the need for metal connectors would substantially lower the environmental impact of structures erected using it by reducing the amount of energy used in the process and improving recyclability of timber components.

5 METHODOLOGICAL FRAMEWORK -- RESEARCH BY DESIGN
The chosen research by design method is based on experimental design projects. This method is not only best suited to address the research question but also the only possible to look at the topic of study from the chosen analytical perspective. There are three main reasons for carrying out research through physical experiments at full architectural scale:
1. Firstly, it provides for the interaction between construction, manufacturing and material
behaviour. It would not be possible to merely speculate about or simulate that interaction, as the number and character of involved parameters exceeds beyond computability. That interaction can only be captured by a physical process combining the digital and material domains. The sought solutions emerge from this synthesis of the digital and the material [35, 36].

2. Secondly, some phenomena are not scalable. It has been known since Galileo Galilei (1564 – 1642) that structural sizes cannot be increased by increasing all dimensions proportionally [37]. When scaled linearly by the same factor areas increase by a squared ratio while volumes increase by a cubed ratio. By the same token material behaviour is size-dependent too.

3. Thirdly, the mock-ups built at full scale allow for taking quantitative (using sensors and measuring equipment) measurements and qualitative (sensory) surveys that could be used in the evaluation and feedback thus enhancing the interactivity of the process.

This approach, contrary to speculative or simulation studies has a potential to shed some light onto the possible strategies of integration in architectural form of various criteria belonging to different domains.

Application of scientific working methodology, as formulated in natural science in the 17\textsuperscript{th} century due to its reductionist character considerably limits design potential [38]. That becomes evident in the working method of Antonio Gaudi (1883-1926) -- hanging chain models serving to establish catenaries, Heinz Isler (1926-2009) -- funicular and pneumatic models used to determine geometry of freeform shell structures or Frei Otto (b.1925) -- form-finding method using membrane models, suspended nets, soap films and bubbles, glue, paper, sand or the wool thread machines. This experimental working methodology and the resulting logical reasoning in the development and description of form does not (...) define any kind of design technique that can be generally applied in architecture [38].

Figure 12 depicts our proposed framework for the research by design process with integration of the intuitive and scientific working methods. Out of the synthesis of multiple input factors a problem is formulated, for which qualitative design questions are posed, addressed by a series of design solutions proposed and evaluated in a heuristic process. This approach builds upon the work of Herbert Simon (1916-2001), American scientist who defined design solutions as based on ill-structured problems, that cannot be solved by linear reasoning, and advised avoidance of optimised subsystems in favour of solutions satisficing (a portmanteau of satisfy and suffice) each subsystem. The satisficing solution in Simon’s definition is not a singular solution but a multiplicity of solutions [39]. Further, for the satisficing solutions scientific problems and more specific, quantitative questions may be formalised and addressed by logical reasoning, as a basis for evaluation feedback and refinement, and finally a selection and development of a chosen path.

Figure 12. Research by design method framework
6 BACK-TO-BACK – A TEST BED

As a test bed for the proposed theoretical and methodological frameworks a design and production of a solid timber wood panel has been selected. The chosen design solution – in line with the minimum energy expenditure and minimum intervention principles -- is the BackToBack method, based on (i) harnessing the material behaviour – i.e. shrinkage, for a connecting mechanism, and (ii) using halved wood logs with the cut faces as the finish, while the raw round backs directed to the inside are used for connection.

Two Norway spruce trees aged ca. 15-20 years had been felled in a forest east of Oslo. The acquired 100-140 mm roundwood was converted to two panels within 10 days while still green. Two design paths were followed (Figure 13):

1. Dry-in-wet. The connecting mechanism based on green wood tightening on dry wood while shrinking. Dry wood inserts were fitted into the receiving incisions in green wood.
2. Wet-in-wet. The connecting mechanism based on green wood anisotropic shrinkage. Special incisions were CNC-cut to harness the tangential shrinkage on the active side of the panel and tighten on the passive side.

Figure 13. Two BackToBack design paths

6.1 Dry-in-wet

This project demonstrates and tests how material behaviour, i.e. green wood shrinkage activated on drying could be used for tightening on dry wood elements.

A series of incisions -- 20 mm wide and 150 mm apart -- was cut at 45° angle to the halved-log axis on the bark side. As the inserts dry pine boards 20 x 120 mm were used (Figure 14). The resulting empty space inside of the panel could be used for thermal insulation, e.g. by means of injecting cellulose fibre insulation.

It has been assumed that the oblique orientation of these incisions would harness the natural shrinkage in green components and make them cling on the dry inserts. The further research questions involve the distribution, geometry and dimensions of these incisions and inserts.
6.2 Wet-in-wet
This project demonstrates and tests how material behaviour, i.e. anisotropic shrinkage activated on drying could be used for producing all-wood connections in solid wood panels. In Norway spruce, depending on author, tangential shrinkage amounts to between 4% [26] - 7.8% [40], radial to 2% [26] – 3.6% [40] and longitudinal to <0.1% [26] – 0.3% [40] (Figure 15). Our test pieces indicated 5% tangential shrinkage after 2 weeks of keeping the wood at room temperature.

A series of waving incisions -- 20 mm wide and 20 mm apart -- were CNC-cut perpendicular to the halved-log axis on the bark side, in order to produce the active elements of the panel. According to the abovementioned figures their width after drying should shrink to 18.5-19 mm and cling on the receiving ribs resulting from the identical incisions cut parallel to the log axis on the corresponding passive elements of the panel (Figure 16).
The waving pattern of the incisions and resulting ribs has been proposed in order to harness the tangential shrinkage, however its precise geometry, size and proportions remain subject to further research and development.

7 DISCUSSION
The main task of the presented prototypes is to illustrate the approach that makes use of material properties and behaviour instead of attempting to overcome them at the same time using material that is otherwise wasted. The minimisation of processing is achieved by halving (and/or debarking) only instead of full sawing on four sides prior to cutting the incisions. The connecting mechanism utilises only the phenomena already present in the material, without any external bonding agents at zero-energy expense. In this perspective the tests performed demonstrate that it is indeed possible to construct a behaviour-based connection and open way for further study.

If this path of development succeeded one could foresee large savings in chemicals, energy and time. The prototyped joint proposals exploit just two out of the many possible implementations of wood behaviour. Both proposed prototypes make use of wood shrinkage. The phenomenon of warp could potentially serve as a basis for the development of different types of joint. The presented prototypes must be further tested. More detailed and precise larger versions should be produced to allow accurate testing. Market viability of new products based on these principles requires further inquiry. And so does the exact environmental impact improvement and the resulting contribution of this technology to the sustainability of building practice.

7.1 The incisions pattern
The waving pattern of the incisions and resulting ribs in the wet-in-wet scenario has been proposed in order to harness the tangential shrinkage, however it remains subject to further research and development. The pattern: its geometry, sizes and proportions must factor in the structural behaviour of the panel as a building component, that is except of not being easily pulled apart it should transfer shear stress. Providing a shear force resistant connection between the pieces would dramatically increase the stiffness and hence the panel load-bearing capacity. The heterogeneous wood grain structure must be taken into account during sizing of the incisions regarding the shear force, a manifested reference to the material-oriented design. The material-informed design should include other variables affecting the shrinkage such as moisture content, tree specie and wood structural features.

A software model that would take into account the complex interplay of the abovementioned factors could help find a solution for the geometry of the incisions.

7.2 The tools
In the process both hand tools and a CNC milling machine were used.
The use of hand tools in the process was a potentially limiting factor due to two main reasons:
1. It did not permit to achieve sufficient precision to be able to accurately assess the results.
2. Additional work time was required to readjust the machines to the varying thickness through which they cut -- result of the conical, half-round cross-section and irregularity of the individual boles.

Both of the abovementioned problems applied to the CNC machining process as well, though these could be more easily overcome by different software and hardware setup. It has been noted during the experiment that CNC machining of green timber requires higher spindle speeds that offered by the milling machine available to us. At 6000 rpm the quality of the cut required a great deal of post-processing. In case of straight incisions a much quicker and producing better cut quality option would be to use a CNC machine with a circular saw rather than milling bits for cutting. Also, another CAM software, not based on STL solids as input but simply accepting CAD lines would highly speed up the process.

To this end -- besides the aforementioned development of software – an important line of progress of the project includes the development of hardware setup allowing for spending less energy and time on production.
7.3 The material
The aforementioned is highly affected by the wood material properties. This in turn, besides the moisture content, geometrical and structural traits heavily depends on the wood specie. Finding wood species making the most of the desired features is of paramount importance to the development of our project.

This approach draws inspiration from the Spruce Goose or Hughes-Kaiser HK-1 aircraft story: Teams were dispatched into the woods of the United States and Canada to find specific trees for specific parts of the plane. The HK-1 was designed not with the invariant code of aluminium but with the variant performance of specific and unique traits in actual material [41]. Originally, birch was chosen as a building material, but due to shortage in supplies fir, cottonwood, maple and balsa were used in different parts of the airplane accordingly to the specie-specific properties. In building construction, before the introduction of structural steel, builders often applied hardwood dowels in softwood structural elements, for their greater strength, connecting elements with more ease and saving time [42].

One recent example that illustrates that approach in architecture includes sports hall in Sargans, Switzerland where spruce and ash wood were used accordingly to their specific characteristics and role in the building (Blue Architects, completed in 2008).

As explained earlier, shrinkage for various popular woods may vary by as much as 200% (see 4.1). Further -- following the line of minimum intervention – as some species are more resistant to fungi, insect and rot attack than others, they could be used without any additional treatment. This feature is often combined with toxicity of the wood: yew (*taxus baccata*) and black locust (*robinia pseudoacacia*) are well known examples. There are rare cases of architectural application of yew for its properties (as the wood is scarce and currently under protection). Some 16*-18* century churches in Slovakia: in Hervartov (Figure 17), mainly, and in Tročany and Kežmarok, partly, were made from yew [2]. More recently the Albisgüetli forestry operations centre in Zurich (Fahrländer Scherrer Architekten, completed 2013) features cladding with three layers of yew shingles [43] (Figure 17).

![Figure 17. 16th century church in Hervartov (Slovakia) made from yew (photo M. Wójcik) and 2013 Albisgüetli forestry operations centre in Zurich clad with yew shingles (photo H.Henz, source [43])](image)

7.4 The supply chains
Another question concerns forestry and wood supply: as roundwood and green wood are not available through normal commercial channels, working with this kind of material is not possible in standard practice. Implementing this solution would require a general remodelling of the current supply chains. On the other hand finding use for the product of forest thinning can have long-reaching advantages. In silviculture the initial narrow spacing and later thinning strategy – necessary for improving the growth rate and wood quality -- makes the remaining trees twice as expensive as planting to a wider spacing, unless there was a commercial market for the thinned material [44].

The product of forest thinning contains juvenile wood affecting the longitudinal shrinkage that, from green to oven dry, amounts to 2%, result of shorter cells and high microfibril angle [44]. That feature, providing for an interesting synergy, could also potentially be investigated in the development of the shrinkage-based connection.
7.5 Implications for architecture

The presented panels are designed to be used as structural elements and double as exposed surface. This biologically inspired approach -- in nature often single material serves multiple functions -- saves energy, production time and money potentially spent on additional finishes. As discussed above (see 7.3) some species may even offer high resistance of untreated exposed surface. While it would be difficult to meet the present day thermal requirements with wood only without increasing the wall thickness to 40-50 cm, the dry-in-wet panel is more suitable for external walls as it provides internal space that, as mentioned earlier, could be used for additional insulation. The wet-in-wet scenario would be suitable for internal partitions or as a load-bearing leaf of an insulated wall. Both presented examples result in flat panels of even external surface. It remains to be answered how the wood-behaviour based connections could be further exploited architecturally by application of geometry, e.g. for their formal and aesthetical appeal, self-support, sound or light-wave reflection or attenuation.

8 ACKNOWLEDGEMENTS

We would like to thank: Trond Solberg for his help, Per Arne Dystland and Odd Roar Stenby for providing raw material for the experiments.

REFERENCES


[34] Lyons A. Materials for Architects and Builders, 2010 (Butterworth-Heinemann, Amsterdam; London)


