TULIPWOOD CLT PROPERTIES AND MANUFACTURING REQUIREMENTS

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EXECUTIVE SUMMARY

The information contained in this document is designed to offer the architect, designer, structural engineer and CLT manufacturer an introduction to the working properties of American tulipwood as a hardwood timber species that has the potential to be used in niche CLT projects where its mechanical properties and aesthetic appeal can be used to their full advantage.

INTRODUCTION & BACKGROUND

Cross laminated timber (CLT) is an emerging construction material that, in the last 20 years, has seen an exceptional rise in use. Reasons for this are related to its outstanding capability for prefabrication and its remarkable structural and environmental benefits. CLT is almost exclusively made with softwood timber species. However, the possibility of using hardwoods for CLT production is beginning to be of increasing interest. Beside the benefits related to the use of CLT, hardwood CLT shows enhanced mechanical properties and aesthetic appeal.

This technical brief focuses on and presents the research and manufacturing activity undertaken for the delivery of a demonstration project, *MultiPly*, which utilised CLT produced with American tulipwood. This engineered timber structure is the result of the fruitful collaboration of a number of partners involved in the various stages of the project's development, from design to the final assembly. After an overview of state-of-the-art research on hardwood CLT, this work presents a detailed description of the various stages of the delivery of the project.

> Beside the benefits related to the use of CLT, hardwood CLT shows enhanced mechanical properties and aesthetic appeal

Despite the increasing attention towards hardwood CLT, research on this material is still scarce. Moreover, European CLT standard *EN 16351:2015* timber structures, cross laminated timber requirements, addresses mainly softwoods as lamination material, but also includes poplar. The demonstration project presented in this document aims to further expand the current knowledge on the topic and to demonstrate that hardwood CLT is a viable option capable of satisfying the requirements set out in current regulations, including end product quality and mechanical performance.

AHEC has undertaken a number of landmark projects utilising tulipwood CLT, each underpinned by research and development activity to further expand their portfolio of knowledge and information on this material. The most notable of which are *Endless Stair*, *The Smile* and, most recently, *MultiPly*.

MultiPly was a collaboration between AHEC, Waugh Thistleton Architects and Arup, as part of London Design Festival 2018, that challenges how we build our towns and cities. Combining sustainable U.S. tulipwood with innovative methods of modular construction, *MultiPly* confronts two of the current age's biggest challenges – the pressing need for housing and the urgency to fight climate change. A unique partnership of business, academia and applied research came together to manufacture the tulipwood cross laminated timber panels (CLT) for *MultiPly*. Timber Design Initiatives Ltd, Glenalmond Timber Company Ltd, Construction Scotland Innovation Centre (CSIC) and Edinburgh Napier University's Centre for Offsite Construction + Innovative Structures (COCIS) all made key contributions.

These innovative timber structures have been fostered by AHEC in order to demonstrate the potentiality of the use of tulipwood CLT in construction and the delivery of *MultiPly* constitutes a further corroboration of this intent.

Tulipwood is one of the most prolific hardwood timber species in the U.S. and is unique to North America. Tulipwood has a very high strength to weight ratio, ideal for the manufacture of laminated structures; its good working properties and dimensional stability make it an excellent material for hardwood CLT production. In addition, tulipwood's aesthetic characteristics, such as its natural colour variation, from creamy white to pale yellow to olive green, make it particularly attractive for use as a building material.

PIONEERING TULIPWOOD CLT

ENDLESS STAIR, 2013

Some five years passed before another opportunity arose – again for London Design Festival – to take the investigation of U.S. tulipwood to the next stage, this time in the *Endless Stair*, a structurally challenging installation designed by dRMM Architects and Arup engineers. Based on the mathematically impossible images conceived by the Dutch graphic artist, M.C. Escher, the three-storey network of stairs is now widely recognised as the pioneer use of hardwood in CLT manufacture.

Imolalegno in Italy fabricated the 187 CLT steps and balustrade elements and Nüssli in Switzerland put them all together, forming the final structure which was erected on site in front of the Tate Modern on the South Bank of the Thames, structural testing having previously been carried out by Trento University. The resulting sculptural installation was as visually challenging as it was technically and, importantly, was the first significant public demonstration of the cross lamination potential of U.S. tulipwood.

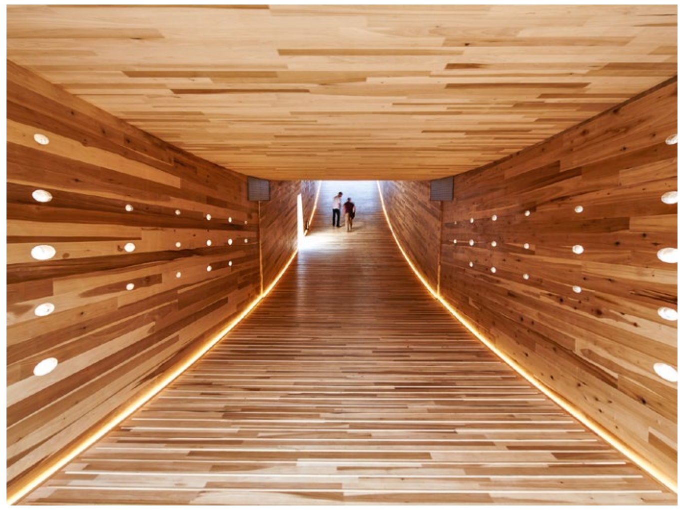
Visitors exploring Endless Stair at London Design Festival 2013

Endless Stair, by dRMM Architects and Arup for London Design Festival 2013

THE SMILE, 2016

The knowledge gained from the *Endless Stair* project was taken further with *The Smile*, another AHEC collaboration with Alison Brooks Architects and Arup Engineers for London Design Festival 2016. The team developed a temporary installation to stand in the courtyard of the Chelsea College of Art that showcased the structural and spatial potential of CLT, manufactured from U.S. tulipwood, and to showcase the material's lightweight characteristic that significantly reduces the amount of fibre (mass) required to achieve the same strength performance as the equivalent softwood product.

The Smile's spectacular 3m high, 4.5m wide and 34m long, curved box was formed from a series of panels 4.5m wide, 12m long using long self-tapping screws and stainless steel plates to make the connections. *The Smile* represents the first-ever use of industrial-size hardwood CLT panels, manufactured specifically for the project by Züblin in Germany.



Interior of The Smile

The Smile, by Alison Brooks Architects, for London Design Festival 2016

MAGGIE'S CENTRE, 2017

The following year saw the completion of the first permanent building made from hardwood CLT: *Maggie's Oldham* in the grounds of the Royal Oldham Hospital, a specialist cancer centre in the north of England. In this case, U.S. tulipwood was selected by dRMM architects (who had cut their design teeth with this material on the *Endless Stair*) not only for its potential to deliver large format glue laminated panels but, given the function of the building, for its visual beauty and warmth.

As with *The Smile*, the 20 five-ply panels – ranging in size from 0.5m to 12m long – were produced in Germany by Züblin. For AHEC, *Maggie's Centre* represented a milestone in almost a decade of innovative research and development into the structural potential of hardwood: the demonstration that U.S. tulipwood CLT was capable of being manufactured on a commercial scale for a project with a very tight budget. The use of U.S. tulipwood CLT by the construction industry was now apparent for all to see.

Maggie's Centre, by dRMM Architects, Oldham, 2017

Maggie's Centre, Oldham, interior

MULTIPLY, 2018

In 2018, AHEC demonstrated a project even more ambitious than before: a three-storey, three-dimensional maze, named *MultiPly*, designed by Waugh Thistleton Architects and engineered by Arup for London Design Festival 2018. The challenges were threefold: first to develop a system of load-bearing hardwood CLT panels and connections which are sufficiently strong and stable to support the large numbers of people traversing the installation at any one time; second, to deliver a structure that can be dismantled and re-used after the festival; and third, to fabricate the entire installation in the UK. This last issue was perhaps the most problematic to resolve within the timescale available, given that – at the point of the project's initial conception by Waugh Thistleton Architects and Arup engineers – no capacity existed in this country to actually manufacture the innovative panels required. Fortunately, the Construction Scotland Innovation

MultiPly, by Waugh Thistleton and Arup for London Design Festival 2018

Close-up of MultiPly with architect Andrew Waugh, co-founder of Waugh Thistleton Architects

Centre's (CSIC) Innovation Factory opened its doors towards the end of 2017 and was able to fill this void, its huge prototyping factory facility housing the first large-scale vacuum press for CLT production to be found anywhere in the UK.
The complete structure comprises 17 interconnecting modules, made from a total of 102 60mm and 100mm thick x 2.6m long visual grade CLT panels, using lamellae processed at the Glenalmond Timber Company Ltd and the panels themselves fabricated at the Construction Scotland Innovation Centre. Working with CSIC, rather than an established continental CLT, producer enabled Waugh Thistleton and ARUP to have more control through each stage of the manufacturing process and to refine the intricate design. Highlighting the potential for the speed of construction of the modules was paramount. All of the joints were digitally manufactured by Stage One with great precision and, to make the design even more streamlined, there are only two steel construction details. These clever design details meant the structure could be assembled in under a week.

Its first location, at the remodelled Sackler Courtyard of the Victoria and Albert Museum in London, is the roof to the subterranean gallery below, with no foundations, a unique demand that was added to the project. The lightweight property of tulipwood CLT lended itself perfectly to the space and meant Waugh Thistleton could scale the structure up to 9 metres tall.

Its flexible design meant that, following London Design Festival, six of the original modules were relocated to a temporary home in South Crescent on London's Store Street as part of a collaboration with New London Architecture. A set of benches and tables, manufactured with thermally modified American tulipwood, were also placed around the pavilion for external applications.

It's third location saw the pavilion travelling across the Channel to Milan for Interni magazine's *Human Spaces* exhibition, as part of Milan Design Week. Its new inception in Italy showed how easily it could be reconfigured to meet the users' needs.

MultiPly at Milan Design Week, 2019

AMERICAN TULIPWOOD

Commercially, American tulipwood, *Liriodendron Tulipifera*, is one of the most prolific hardwood species from the U.S. hardwood forests, comprising around 8% of the U.S. temperate hardwood forest and is unique to North America, having been eliminated in Europe by the last ice age.

FOREST DISTRIBUTION AND AVAILABILITY

Tulipwood trees grow exclusively in North America and are widely distributed throughout most of the eastern United States in mixed hardwood forests. It is a single species and is not a poplar (Populus) being a Magnoliacae producing wood that is superior to the many poplar species. The trees are identified by the tulip-like flowers which give rise to the name. Given optimum growing conditions, a mature tree can be harvested in around 45 years, similar to commercially grown Sitka spruce in the UK and Europe.

FOREST GROWTH

At the time of writing, Forest Service Inventory and Analysis (FIA) data shows U.S. tulipwood growing stock is 1.02 billion m^3, 7.7% of the total U.S. hardwood growing stock. American tulipwood is growing 32.5million m^3 per year while the harvest is 12.8million m^3 per year. The net volume (after harvest) is increasing by 19.7million m^3 each year. U.S. tulipwood growth exceeds harvest in all states.

> It takes 0.97 seconds to grow 1m^3 of American tulipwood

The replacement rate is calculated from total U.S. annual increment of the specified hardwood species derived from the U.S. FIA program and assumes that 2 m^3 of logs is harvested to produce 1 m^3 of lumber (i.e. 50% conversion efficiency). The rapid rate of replacement is due to the very large volume of hardwood trees in U.S. forest.

MATERIAL AVAILABILITY

Tulipwood from the USA is readily available as sawn lumber in a wide range of grades and thicknesses – 4/4" (25mm) through to 16/4" (75mm) – due to its ease of drying. A relative knot free timber, average lumber widths and lengths can be higher than other commercial species. Tulipwood is used in plywood production but with more limited availability as decorative veneer. The sapwood produces the often-preferred whiter wood, as the heartwood usually exhibits strong colour variation. However, the use of unsorted tulipwood, displaying all its natural colour variation, is on the rise, particularly in Europe. Tulipwood is sold in the U.S., and sometimes referred to in export, as 'yellow poplar' but should not be confused with European or Chinese poplar.

DESCRIPTION

Tulipwood has less strong grain characteristic than species such as ash and oak and is more like maple in character, but darker in colour and much softer. However, there is a marked difference between the sapwood and heartwood of tulipwood. The sapwood is creamy white, whereas the heartwood can vary from pale yellow or brown and even green to purple in extreme cases. The wood darkens with time on exposure to UV light and the green colour will turn brown. The wood of tulipwood is straight-grained with a medium to fine texture. The size of the sapwood and some physical characteristics will vary according to growing regions. The timber has many desirable characteristics and is suitable for a wide variety of important uses.

This very available, cost effective and versatile American hardwood is exported around the world and many designers and architects are exploring its exciting natural colour variation. A heavy purplish-blue mineral colour is limited in the upper lumber grades and unlimited in the Common lumber grades. Because the Common grades are generally stained or painted in finishing, a grey colour is allowed in the wood after surfacing.

GRADING

All the hardwood exported from America to Europe is graded by reference to the rules of the National Hardwood Lumber Association (NHLA). The two grades of relevance are 'First and Seconds' (FAS) and 'Number 1 Common' (No.1C). The higher of the two, FAS, will provide boards, each with between 84% and 100% 'clear' faces, that is, free of all defects. The lower grade, No.1C, will provide boards with faces between 66% and 84% clear of defects. While these are high specifications, no limits are placed on the size of the knots when they occur, or the slope of grain, the principal two parameters of any structural grading system. To use American hardwoods with confidence in structural applications, it is necessary to have design data which applies to material graded in accordance with a structural grading standard complying with *EN 518*. Currently, no single standard is accepted throughout Europe.

One such grading standard that does comply with *EN 518* is *BS 5756*. It provides straightforward rules for grading hardwood into two grades, TH1 and TH2. The upper grade, TH1, is more appropriate to the American hardwood stock, maximising the quality of the individual pieces without producing unduly low yield rates.

> Tulipwood is becoming more readily available in fixed widths

PHYSICAL AND MECHANICAL PROPERTIES

The timber has relative low density, with high bending, shock resistance, and stiffness values, but is lower in compression and hardness.
The wood has medium steam-bending capability and is extremely stable when fully dry and not installed in humid conditions. It is easy to finish and stain, so is highly suitable for furniture and joinery.

> Tulipwood has extraordinary overall strength properties relative to weight, making it highly suitable for structural applications, such as glue-laminated beams and cross laminated timber (CLT)

In 2001, American Hardwood Export Council (AHEC) teamed up with Arup and commissioned the Building Research Establishment (BRE) in the UK to undertake testing of four American hardwood species, including tulipwood, in order to determine their characteristic values for structural design.

Tulipwood (Liriodendron tulipifera)			**Durability rating: 5 (not durable; approx – Handbook of Hardwoods, BRE) Approx yield on re-grading to TH1: FAS-90%**	
Material graded to BS 5756: Grade TH1				
For design in accordance with Eurocode 5			For design in accordance with BS 5268	
characteristic values for tulipwood		Footnote*	permissible stresses and moduli for tulipwood	
Bending – parallel to grain $f_{m,k}$ N/mm^2	41.7		Bending – parallel to grain $f_{m,k}$ N/mm^2	14.6
Tension – parallel to grain $f_{t,0,k}$ N/mm^2	25.0		Tension – parallel to grain $f_{t,0,k}$ N/mm^2	8.8
Tension – perpendicular to grain $f_{t,90,k}$ N/mm^2	0.5		Tension – perpendicular to grain $f_{t,90,k}$ N/mm^2	0.7
Compression – parallel to grain $f_{v,k}$ N/mm^2	26.8		Compression – parallel to grain $f_{v,k}$ N/mm^2	11.3
Compression – perpendicular to grain $f_{c,90,k}$ N/mm^2	6.8		Compression – perpendicular to grain fc,90,k N/mm^2	3.9
Shear – parallel to grain $f_{v,k}$ N/mm^2	4.0		Shear – parallel to grain $f_{v,k}$ N/mm^2	2.0
Mean modulus of elasticity – parallel to grain E0,mean N/mm^2	11,900		Mean modulus of elasticity – parallel to grain E0,mean N/mm^2	11,300
5% modulus of elasticity – parallel to grain E0,05 N/mm^2	10,000		Min modulus of elasticity – parallel to grain E0,05 N/mm^2	7,800
5% modulus of elasticity – perpendicular to grain E90, mean N/mm^2	800		Mean modulus of elasticity – perpendicular to grain E90, mean N/mm^2	570
Mean shear modulus Gmean N/mm^2	750		Mean shear modulus Gmean N/mm^2	700
Characteristic of density Pk kg/m^3	456		Characteristic of density Pk kg/m^3	470
Average density Pmean kg/m^3	552		Average density Pmean kg/m^3	568

Table 1 – Summary of tulipwood's properties from BRE research

**Tulipwood, while having D40 strength and stiffness, is not dense enough to qualify for the lowest strength class D30.*

Table 1 shows the characteristic values for strength and stiffness for tulipwood derived from the BRE study.

PERFORMANCE AND WORKING PROPERTIES

Tulipwood lumber is easy to machine, plane, turn and glue with good performance screwing. Because tulipwood's density is similar to softwood, standard self-tapping screws can be used without pre-drilling. Tulipwood can easily be stained and polished to a very good finish. The wood can be susceptible to movement in performance in humid conditions.

BONDING

Tulipwood bonds well with a fairly wide range of adhesives under a moderately wide range of bonding conditions.

MAIN USES

Currently, the main uses for tulipwood are typically construction, furniture, interior joinery, kitchen cabinets, doors, panelling, architectural interior joinery and mouldings, edged-glued panels, plywood (USA), turning and carving. It is ideally suited for engineered wood.

> Tulipwood is harvested from natural, sustainably managed forests of North America, with excellent environmental credentials, and is a key species in many export markets

THERMALLY MODIFIED TIMBER

Thermally modified timber is timber which has been heated in a controlled setting to between 180°C and 210°C. This baking process effectively removes sugars and starches and hemicelluloses which in turn provides enhanced stability and durability and reduces shrinking and swelling over time. Thermal wood modification changes the appearance of the wood, giving it deeper brown tones throughout. Thermo treating significantly increases timber's water resistance and is already proven in hardwood cladding.

Thermally modified U.S. tulipwood cladding at Maggie's Centre

> The *MultiPly* project was the first time that thermally modified timber had been incorporated as a protective layer for cross laminated timber, which was designed to be located outdoors for 4 weeks

MANUFACTURING

The realisation of the project has involved every step of CLT production, from the timber procurement to the panels' final assembly. Different institutions worked together to deliver *MultiPly*.

Among the key partners were; Glenalmond Timber Company Ltd in Perth where the boards were defect cut, finger jointed, planed and cut to length, the Construction Scotland Innovation Centre (CSIC) near Glasgow, where all the tulipwood CLT panels were manufactured; the Centre for Offsite Construction and Innovative Structures (COCIS) at Edinburgh Napier University, Edinburgh, which undertook the structural testing and analysis and Stage One in York, where the CLT panels were cut to size, profiled and assembled.

A total of 111 CLT panels, comprising three – and five-ply 20mm tulipwood lamellas of various widths were produced in accordance with *EN 16351* using a Woodtec Fankhauser vacuum press. All glued faces of the lamellae were primed prior to assembly and the panels prepared and lacquered once fabricated and cured.

The panels were manufactured to visual grade quality and designed to be located outdoors. As such, all panels were sanded and lacquered on both faces once curing of the adhesive was complete.

The manufacture of tulipwood CLT was undertaken in accordance with *BS EN 16351 Timber structures – Cross laminated timber – Requirements*.

The manufacturing process can be divided into four distinct phases:

- **Procurement**
  - o Resource categorisation
  - o Drying
  - o Grading
- **Pre-processing of lamellae**
  - o Defect cutting
  - o Finger jointing to create endless lamellae
  - o Cutting of the boards to length
  - o Planing
- **Assembly**
  - o Sorting
  - o Timber preparation
  - o Laying up
  - o Adhesive application
  - o Pressing
  - o Curing
- **Post-processing**
  - o Cutting and profiling
  - o Surface and edge finishing (if applicable)

For the *MultiPly* demonstration project three types of panels were produced: two types of structural panels, made of three and five-layer 20mm lamellae; and one type of non-structural panels, made of three layers of lower grade lamellae.

SUPPLY CHAIN

There is currently no commercial volume producer of CLT in the UK. However, via collaboration between AHEC and project partners it was successfully demonstrated that tulipwood CLT could be manufactured in the UK via the instigation of a supply chain arrangement with necessary quality assurance conducted by an academic research partner.

> AHEC and its project partners have successfully demonstrated that tulipwood CLT could be manufactured in the UK

AHEC's project partners for *MultiPly* were:

- **Waugh Thistleton Architects**
- **ARUP**
- **London Design Festival**
- **Construction Scotland Innovation Centre**
- **The Glenalmond Timber Company Ltd.**
- **Edinburgh Napier University**
- **Timber Design Initiatives Ltd.**
- **Stage One**

PROCUREMENT

The first stage in the CLT manufacturing process is the procurement of certified timber from sustainably managed forests.

The tulipwood for the *MultiPly* project was supplied to AHEC from a number of timber donators in the east of the USA and shipped to Scotland.

Tulipwood prior to processing

Timber was donated by U.S. sawmills:

- **Allegheny Wood Products**
- **Baillie Lumber Company**
- **Bingaman Lumber Inc.**
- **Boss Lumber Corporation**
- **Classic American Hardwoods**
- **Collins Hardwood**
- **Northland Forest Products**
- **Northwest Hardwoods**
- **Parton Lumber**
- **Thompson Hardwoods Inc.**
- **with additional material supplied by James Latham Timber in Hertfordshire, UK.**

MATERIAL COMPATIBILITY

EN 16351 stipulates specific criteria for the performance and production requirements of cross laminated timber. The compliance of CLT with the requirements of the standard required to be demonstrated by declaration of appropriate mechanical properties, bonding strength, resistance and reaction to fire, dimensional stability, release of dangerous substances and durability.

EN 16351 states:
"Each timber layer shall be made of laminations of one strength class or manufacturer specific strength class. Each timber layer may be produced from laminations made of mixed species, if these species have similar technical properties, especially regarding swelling and shrinking. The properties of the timber layers shall be taken as the properties of the laminations from which they are made of."
and:
"The corrected thickness of the cross section shall not deviate from the nominal thickness by more than ± 2mm or 2 % of the nominal thickness, whichever is greater. The corrected thickness of the single layers shall not deviate from the nominal thickness by more than ± 1mm."

As such, all lamellae used in the manufacture of CLT must be appropriately graded.

> All lamellae used in the manufacture of CLT must be appropriately graded

The moisture content of all lamellae must be between 6% and 15% (inclusive); unless the adhesive manufacturer requires different moisture content within the given range (see later section for moisture content requirements specific to PUR adhesive).

The range of moisture content between adjacent laminations bonded together parallel to the fibre shall be not greater than 5 %.

Tulipwood after fingerjointing and planing

> The range of moisture content of all lamellae bonded together must not exceed 5%

PRE-PROCESSING

> Tulipwood can be machined using identical tooling and methods to that of softwood. There are no special requirements

TIMBER GRADING

The raw material for the *MultiPly* project included timber of varying quality. The Glenalmond Timber Company Ltd visually graded all lamellae to a General Structural Temperate Hardwood (TH1) grade. Because of the high element of structural integrity required by the complex *MultiPly* design all of the timber was graded to the highest TH1 grade. Where structural requirements are less complex such as a vertical load bearing wall (as in the *Maggie's Centre*'s wall panels) a less stringent grade may be applied.

To support the grading process and bolster all of the information gathered at this stage, Edinburgh Napier University acoustically characterised the resource using a Brookhuis MTG acoustic timber grader. A sub-set of boards was also structurally tested to verify these results.

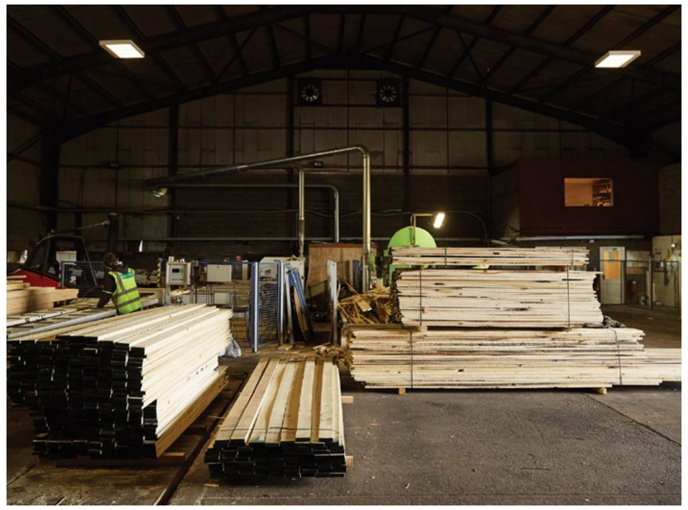
CUTTING AND FINGER JOINTING

The boards were sawn in to two standard widths (95 and 145mm) to maximise yield and ensure a consistent arrangement of the material when laid up in to panels.

Non-conforming characteristics were cut out of the boards and the conforming sections finger jointed into endless boards, which were then cut to lengths compatible with the panel dimensions.

In accordance with the the Glenalmond Timber Company Ltd's factory production control process, structural testing of the finger joints was undertaken on a sample range to verify structural robustness.

At this stage, Edinburgh Napier University also undertook a range of structural testing on a sample range of fabricated panels, in accordance with *EN 16351*, comprising bending strength and stiffness, rolling shear, tension and bonding strength to verify the structural properties of tulipwood CLT.



Tulipwood being processed at Glenalmond Timber, Perth

PLANING

The Glenalmond Timber Company Ltd planed all the lamellae on all four sides to a constant thickness and width such that all lamellae were square edged, of a consistent section size and with smooth, even surfaces on all sides.

EN 16351 states that:
"The planing shall be carried out not more than 24 h before bonding, unless the species and the storage environment are such that unacceptable surface changes will not take place."

It is highly unlikely in a modern-day CLT factory environment that any significant change in environment would occur.

CHECKS UPON ARRIVAL

Upon arrival at Construction Scotland Innovation Centre the moisture content and timber temperature of a sample range of timber was checked and recorded.

Tulipwood upon arrival at CSIC

PRIMING

PRIMER

Henkel Loctite HB S Purbond adhesives are commonly used for timber bonding. When bonding hardwood species, Henkel recommend that surfaces are conditioned with a primer solution, Loctite PR3105 Purbond, prior to application of adhesive.

The primer concentrate contains neither solvents nor formaldehyde. The primer solution is uniformly applied to the timber surface to achieve homogeneous conditioning and an enhanced glue line quality.

APPLICATION

The primer concentrate was mixed at a ratio of nine parts tap water to one part primer concentrate (9:1) in accordance with the manufacturer's instructions.

The primer is applied in a uniform manner to all surfaces that are to be glued, within 6 hours of them having been planed.

For tulipwood, Henkel recommend that primer is applied at a rate of 10g/m^2 on each surface. Once the primer has been applied all lamellae should be separated by timber stickers and left for a minimum of 10 minutes prior to gluing to allow air to circulate and the primer to activate.

Primed lamellae must be glued within 360 minutes of being primed. If this time is exceeded, primer must be re-applied and the process repeated.

BONDING

ADHESIVE

Henkel Loctite Purbond PUR HB S609 was used to bond the lamellae.

Purbond PUR HB S609 is a liquid single-component polyurethane adhesive. The adhesive cures under the action of air humidity and moisture in the wood to yield a strong non-brittle film.

Other adhesives in the Loctite HB S Purbond range may be used but the open time and corresponding press times vary accordingly.

The maximum open (assembly) time – the time after the adhesive is applied during which an effective bond can be made – for Purbond PUR HB S 609 is 60 minutes.

The minimum press time – the duration for which the bonded lamellae must remain under pressure in the press – for Purbond PUR HB S 609 when used to bond softwood is 150 mins at a temperature of 20°C, relative humidity of 65% and timber moisture content of 12%. The pressing time for softwood is typically 2.5 times the open time of the adhesive; Henkel recommend that in the case of hardwoods the pressing time is 5 times the open time. As such the press time for tulipwood is increased to 300 minutes under the same conditions.

Adhesive with a 60 minute assembly time was selected to allow an adequate amount of time for this process

As the lamellae were loaded in to the press manually, rather than by automated means as would be typical for commercial manufacture, adhesive with a 60 minute assembly time was selected to allow an adequate amount of time for this process. Where the loading process is automated e.g. using a vacuum lift and lateral lamella conveyor, time to load the press is greatly reduced, and as such adhesive with a reduced assembly time and corresponding press time may be used.

TIMBER MOISTURE CONTENT FOR BONDING – ADHESIVE MANUFACTURER REQUIREMENTS

Henkel stipulate that the timber moisture content at the joint surfaces that are to be glued together must be no less than 8%. The permissible upper limit of the wood moisture content is governed by the respective national product standards but must be below 18%.

The timber moisture content must be no less than 8% and no greater than 15% to bond effectively

Application of adhesive during panel manufacture at CSIC

EN 16351 stipulates that all lamellae must have a moisture content no greater than 15%.

ADHESIVE APPLICATION

At the time of adhesive application, the bonding surfaces must be clean.

The adhesive must be used in accordance with the instructions of the adhesive manufacturer. Application of the adhesive takes place via a suitable application system.

Depending on the application system, the adhesive is applied to one or both sides at the rate of approximately 120 – 160 g/m^2, typical for softwood. Henkel recommended that the adhesive spread rate for tulipwood is 170 g/m^2. The components are pressed together immediately afterwards.

GLUE LINE THICKNESS

For moisture curing one-component polyurethane adhesives the maximum glue line thickness shall be less than or equal to 0.3 mm.

> The maximum glue line thickness when bonding tulipwood with PUR adhesive shall be less than or equal to 0.3mm

PRESSING

The first two lamellae are placed longitudinally in the press and laid as close as possible to one another, effort being made to ensure that any gaps between the edge faces of the lamellae are kept to a minimum. Adhesive is then applied in a uniform manner in accordance with the manufacturer's guidance.

Each subsequent lamella is laid up perpendicular to the previous layer and adhesive applied in the same manner.

Load is applied vertically to the lamellae and a constant load maintained for the prescribed press time.

The CLT shall be moved or processed in a way that the post-curing process is not affected by deformation or vibration.

CLT panels under load in the vacuum press

FURTHER PROCESSING

The components can undergo further processing after the curing time of the adhesive has elapsed.

STORAGE TIME AFTER PRESSING

The bonded components must be stored at a temperature of approximately 20°C for at least 10 hours after the press time has elapsed.

> After pressing, panels must be stored at a temperature of approximately 20°C for at least 10 hours

CLT panels in press after assembly time has elapsed

CLT panels in storage after removal from press

FACTORY PRODUCTION CONTROL

To satisfy the requirements of EN 16351, factory production control (FPC) samples of nominal dimensions must be pressed alongside, and be representative of, the parent panels.

> Factory production control samples must be pressed alongside the parent panels

Each FPC sample shall represent the specification of the parent panels i.e. if the parent panels are five-ply then the FPC sample must also be five-ply such that it has the same quantity of layers and glue lines.

All FPC samples must be primed in the same manner as the parent panels. The process for pressing the FPC sample is identical to that of pressing the parent panels.

Once cured the FPC sample shall be subject to the standard delamination test in accordance with *EN 16351*.

POST-PROCESSING

Because all of the panels for the *MultiPly* project were visual grade and for temporary external use they were rough sanded to remove adhesive residue on the surface, then fine sanded to flatten in preparation for application of lacquer.

Two layers of Sayerlack AZ3430/00 lacquer concentrate with no crosslinker was uniformly applied by spray, with no sanding between layers in accordance with the manufacturer's instructions. Treatment was applied to both front and rear faces.

Tulipwood can be readily sanded and prepared. The lacquer applied required no additional curing time or special surface preparation specific to tulipwood. There were no additional special conditions or requirements where this was concerned.

CLT panel sanded and lacquered

All post processing of the tulipwood CLT panels was undertaken by Stage One using a Computer Numerical Controlled (CNC) cutting machine.

Tulipwood CLT can be machined using the same tooling and methods as softwood. There are no additional special conditions or requirements where this is concerned.

> Tulipwood CLT can be machined using the same tooling and methods as that of softwood

CNC machining at Stage One, York

ENVIRONMENTAL CONDITIONS

Air temperature and relative humidity must be controlled and maintained during production. As per softwood, air temperature should be approximately 20°C and must be no less than 15°C (18°C during curing of the glue lines) and relative humidity approximately 65% and must be no less than 40% and no greater than 70%.

> The manufacturing environment should be approximately 20°C and 65% relative humidity during curing

COMPARISON WITH SOFTWOOD BONDING – SUMMARY

In summary, based upon their research on hardwood bonding, Henkel specify that the following requirements are adhered to when bonding hardwood species using single part polyurethane adhesives:

- **Application of primer to all glued surfaces**
- **Double press time**
- **Increased adhesive spread rate**

Henkel have undertaken research into bonding hardwood using single part polyurethane adhesives, though not using tulipwood specifically, and have agreed to provide the project partners with all relevant information for review prior to devising a further research programme specific to tulipwood and based upon the findings of AHEC's own research to date.

STRUCTURAL TESTING

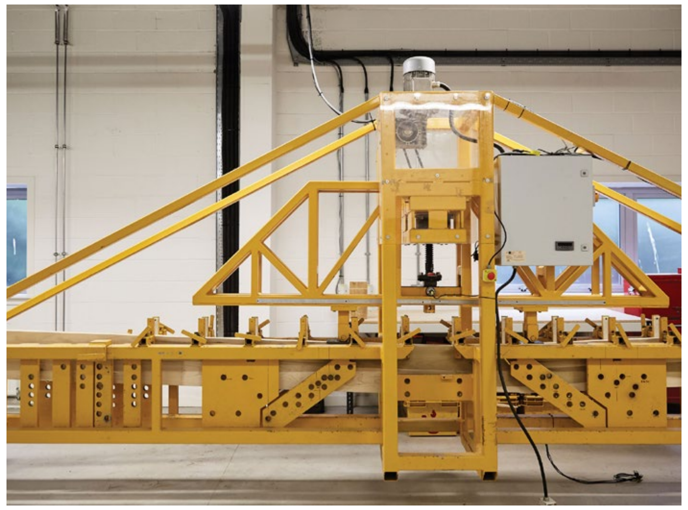
EDINBURGH NAPIER UNIVERSITY

The Centre for Offsite Construction and Innovative Structures (COCIS) at Edinburgh Napier University (ENU) has undertaken a comprehensive study in accordance with EN 16351 to investigate the structural performance and some physical properties of tulipwood and tulipwood CLT.

This study comprised test programmes for:

- **Resource categorisation**
- **Tensile strength of Finger Joints**
- **Bending strength and stiffness in and out of plane**
- **Rolling shear**
- **Glue line shear**

The properties of tulipwood CLT derived in this study provide benchmark information for CLT fabricated from tulipwood and will be influenced by the material characteristics of the base material. The test programme is given below in Table 2.



Edgewise bending testing at Edinburgh Napier University

Test type	Test standard	Property		No. of specimens
1. Preliminary tests (Base Material Properties)				
1.1 Acoustic grading of timber layers	BS EN 384:2016 & BS EN 14358:2016	Modulus of elasticity	$E_{0,mean}$	200
		Density	ρ_k	
1.2 Bending test	BS EN 408:2010	Bending strength	ρ $f_{m,k}$	20
		Modulus of elasticity	$E_{0,mean}$	
		Density	ρ_k	
1.3 Tension test	BS EN 408:2010	Tensile strength	$f_{t,0}$	20
		Modulus of elasticity in tension	$E_{t,0}$	
		Density	ρ_k	
2. CLT Testing				
2.1 Bending out-of-plane	BS EN 16351:2015 & BS EN 408:2010	Modulus of Elasticity	$E_{0,mean}$	7
		Bending Strength	$f_{m,k}$	
2.2 Bending in-plane	BS EN 16351:2015 &/ or EN 789:2004	Modulus of Elasticity	$E_{0,mean}$	8
		Bending Strength	$f_{m,k}$	
2.3 (Rolling) Shear test	BS EN 16351:2015 &/ or EN 789:2004	(Rolling) Shear stiffness	$G_{9090,lay}$	8
		(Rolling) Shear strength	$f_{v,9090}$	
2.4 Bonding Strength (Shear test)	BS EN 16351:2015	Bonding strength of glue lines between layers	Pass Shear	8

Table 2 – Proposed test programme for tulipwood CLT

TULIPWOOD LAMELLAE CHARACTERISATION – ACOUSTIC CATEGORISATION

Further reading: ENU Test Report R1437_FO067_001 MTG (tulipwood) & R1437_FO067_002 MTG2 (tulipwood)

Overview

The tulipwood resource was acoustically characterised using a Brookhuis MTG acoustic timber grader. Tests were performed on 200 boards, prior to defect cutting and finger-jointing.

The purpose of this phase of research was to undertake preliminary structural assessment of U.S. tulipwood CLT and to evaluate the effect of thermal modification on the mechanical properties of U.S. tulipwood.

Assessment was undertaken by means of laboratory tests carried out to recognised standards. The main objective of this research was to assess and compare the properties of a number of pre-selected tulipwood timber lamellae by means of acoustic grading using MTG Timber grader.

Tests were performed on unmodified timber lamellae prior to defect cutting and finger-jointing.

Results, comparisons and findings

The results were calculated in accordance with *EN 14358:2016* and are expressed as characteristic values; Table 1 (p.12) shows the result obtained in comparison with the characteristic values of reference given by the *British Standard BS 5756* for grade TH1 tulipwood.

In addition to the above tests, 20 bending tests of a sample range of individual lamella previously assessed by means of acoustic characterisation were undertaken. This allows for direct comparison of the results and to establish an adjustment factor.

Based on the results from acoustic characterisation of 200 samples, the stiffness of U.S. tulipwood boards (static MOE) is 11.91 kN/mm^2, which corresponds with the TH1 properties obtained by the BRE in 2001. Furthermore, the study has demonstrated that the stiffness of tulipwood lamellae sampled for this study is 8% higher than the stiffness of C24 and comparable with a D35 timber strength class, as per *BS EN 338:2016*

Tulipwood CLT panels of MultiPly at its third iteration in Milan 2019

The study has demonstrated that the stiffness of U.S. tulipwood lamellae sampled for this study is 8% higher than that of C24 and comparable with a D35 timber strength class

The characteristic density of U.S. tulipwood sample boards measured equal are to 410 kg/m^3, which is 10% lower than the value stated in the BRE study. The value is also significantly lower than what could be expected from a hardwood species, the characteristic density of tulipwood obtained in this study is 14% lower than characteristic density of D18 (lowest hardwood strength class listed in *EN 338*).

The characteristic density of U.S. tulipwood sample boards measured equal are to 410 kg/m^3

Conclusion

According to the results from this study, U.S. tulipwood exhibits enhanced properties when compared to softwood, which is normally used for the European manufacture of CLT (C24 grade). On the basis of test results, the stiffness of tulipwood material acoustically characterised was higher than C24 strength class, the expectation would be that the CLT panels themselves would achieve a higher modulus of elasticity (MoE) than the equivalent European manufactured product.
A summary and comparison of the acoustic categorisation results are given here in Table 3.

Property		Tulipwood BRE	Tulipwood Napier	C24	D35
Stiffness properties in kN/mm²					
Modulus of Elasticity	E0,mean	11.90	11.91*	11.00	12.00
Density in kg/m³					
Characteristic density	ρk	456	410	350	530
Mean density	ρmean	552	486	420	640

Table 3 – Acoustic categorisation results
**Static MOE – value modified with the adjustment factor of 1.1*

TULIPWOOD LAMELLAE CHARACTERISATION – TENSILE STRENGTH

Further reading: ENU Test Report R1437_FO060_001 Tension (tulipwood)

Overview

A test programme was devised to assess the tensile strength of finger-jointed tulipwood and to investigate the influence of this configuration upon the structural performance of timber when subjected to tensile forces.
20 samples of identical specification were tested.

Tension strength values for each specimen were derived in accordance with EN 408:2010:+A1:2012 cl. 16.3.2.

Results, comparison and findings

The results and findings from tests carried out according to the test programme are summarised and compared in tables 4a and 4b below.

Tensile strength *f*t,0,k (N/mm²)			
Min	**Max**	**Mean**	**Characteristic***
25.36	49.32	40.73	29.48
*Characteristic values in accordance with BS *EN 14358:2006*			

Table 4a – Tensile strength test results summary for finger-jointed tulipwood

Property		Tulipwood BRE	Tulipwood Napier	C24	D50
Characteristic tensile strength (N/mm²)	*f*t,0,k	25.0	29.5	14.5	30.0

Table 4b – Tensile strength comparison

Conclusion

Based on the results obtained from this initial laboratory work, it appears that finger-jointing has little effect on the structural performance of tulipwood. The characteristic tensile strength of finger jointed tulipwood lamellae in this study was approximately 15% higher than the value derived by BRE. Moreover, this study has shown that the characteristic tensile strength of finger-jointed tulipwood lamellae is 51% higher than C24 and comparable with a D35 timber strength class, as per BS EN 338:2016. Tests were performed on un-primed finger-joints using Henkel Purbond PUR adhesive.

> This study has demonstrated that the characteristic tensile strength of finger-jointed tulipwood lamellae is 51% higher than that of C24 and comparable with a D35 timber strength class

Tests results have shown that the inclusion of a finger joint has no negative effect upon the structural performance of tulipwood. The characteristic tensile strength of finger jointed tulipwood lamellae was, in fact, higher than the tensile strength of TH1 timber grade.

Table 4c gives a summary of the results for the tulipwood lamellae categorisation study.

Mechanical property	Verification method	Value
1. Base Material (lamella) properties		
Modulus of elasticity		
parallel to the grain of the boards, E0,mean	BS EN 384:2016 & BS EN 14358:2016	11.91 kN/mm²
Characteristic density, ρk	BS EN 384:2016 & BS EN 14358:2016	410.18 kg/m³
Mean density, ρmean	BS EN 384:2016 & BS EN 14358:2016	485.79 kg/m³
2. Other mechanical actions		
Tensile strength of finger-joint, ρmean		
parallel to the grain of the boards, ft,0,k	BS EN 408:2010 13.3	29.48 N/mm²

Table 4c – tulipwood lamellae characterisation – results summary

> The inclusion of a finger joint has no negative effect upon the structural performance of tulipwood

FLATWISE BENDING

Further reading: ENU Test Report R1437_FO032B_002 Flatwise Bending (CLT)

Overview

A test programme was devised to assess the bending properties (strength and stiffness) of CLT panels fabricated from tulipwood with load applied perpendicular to the plane of CLT (out-of-plane). This load configuration allows the investigation of the slab-like behaviour of CLT.

7 samples of identical specification were tested.

Results, comparison and findings

According to the test results contained in Figure 6, the mean MoE is 11,010 N/mm², whilst the characteristic bending strength is 45.06 N/mm². These two values should be used in most cases for structural engineering calculations when designing a CLT floor slab element.

The results and findings from bending tests undertaken in accordance with the test programme are summarised on the next page and allow for the direct comparison of the out-of-plane bending properties obtained in this study with the values declared by two major European CLT manufacturers, both of whom utilise nearly 100% of C24 graded softwood (with an allowable % utilisation of C16) for the manufacture of CLT.

> This study has demonstrated that the characteristic bending strength of tulipwood is 47% higher than that of European softwood CLT products

Sample reference	Ultimate load, Fmax [kN]	Modulus Of Elasticity, E0 [N/mm²]	Bending strength, fm [N/mm²]
FB_1	51.78	9,122	69.53
FB_2	42.69	9,961	57.33
FB_3	49.81	9,868	66.88
FB_4	40.78	11,623	54.76
FB_5	39.38	11,120	52.88
FB_6	52.32	13,174	70.26
FB_7	41.81	12,204	56.14
Minimum	39.38	9,122	52.88
Maximum	52.32	13,174	70.26
Mean	45.51	11,010	61.11
Characteristic	33.56	7,920	45.06
Standard deviation	5.56	1442	7.5
COV (%)	12.23	13.09	12.23

Table 5 – Bending out-of-plane results summary

Conclusion

Based on the results from 7 samples presented in Table 5, the out-of-plane stiffness performance of tulipwood CLT is sufficient to be used for structural use.

According to the results in Table 5, the highest MOE obtained in this study is 13,174 N/mm² whilst the lowest to 9,122 N/mm². The variation between the results from a relatively low sample set of 7 tests, suggests that the base material used for the CLT fabrication is influencing the performance of the panels. Better results would be expected if the sample set was larger.

Furthermore, considering the fact that the stiffness of acoustically characterised tulipwood exceeds the stiffness of C24 strength class then the expectation would be that the CLT panels themselves would achieve higher MoE values than the products currently manufactured in Europe.

In terms of bending strength, all tulipwood test samples outperformed their European softwood CLT counterparts. The characteristic bending strength is equal to 45.06 N/mm² and is 47% higher than the characteristic bending strength of existing European CLT products.

EDGEWISE BENDING

Further reading: ENU Test Report R1437_FO032A_001 Edgewise Bending (CLT)

Overview

A test programme was devised to assess the bending properties (strength and stiffness) of CLT panels fabricated from tulipwood with load applied parallel to the plane of CLT (out-of-plane). This load configuration allows the investigation of the beam-like behaviour of CLT.

8 samples of identical specification were tested.

Results, comparison and findings

According to the test results contained in Table 6, the mean Modulus of Elasticity is 12,433 N/mm², whilst the characteristic bending strength is 34.49 N/mm². These two values should be utilised in most cases for structural engineering calculations when designing a beam element made out of CLT.

Both, bending stiffness and strength values obtained in this study were directly compared with the values declared by two major European CLT manufacturers, both of whom utilise nearly 100% of C24 graded softwood (with an allowable % utilisation of C16) for the manufacture of CLT.

Sample reference	Ultimate load, Fmax [kN]	Modulus Of Elasticity, E0 [N/mm²]	Bending strength, fm [N/mm²]
EB_1	29.77	11,934	46.20
EB_2	28.39	11,950	44.05
EB_3	28.35	13,000	43.99
EB_4	28.32	12,481	43.94
EB_5	25.93	12,790	40.24
EB_6	31.73	12,501	49.24
EB_7	24.08	12,075	37.36
EB_8	26.61	12,735	41.29
Minimum	24.08	11,934	37.36
Maximum	31.73	13,000	49.24
Mean	27.90	12,433	43.29
Characteristic	22.23	11,053	34.49
Standard deviation	2.36	407	3.66
COV (%)	8.46	3.27	8.46

Table 6 – Bending in-plane results summary

Conclusion

Based on the results from 8 samples tested the mean in-plane bending stiffness of tulipwood CLT is comparable with the declared MOE of softwood CLT manufactured by two major European CLT manufacturers. Unlike CLT samples tested with loads perpendicular to plane of the panels (described in the previous section), the stiffness results from in-plane bending tests show less variation, which increases the certainty of the results from this small sample group.

With further optimisation of categorisation/selection of the base material used for the manufacture, as well as enhancement of level of knowledge via test work of varying lamellae sizes and lay-ups, the expectation would be that the tulipwood CLT panels would achieve an even higher MoE value, enhancing their competitiveness against the products currently manufactured in Europe.

> In terms of bending strength, all tulipwood test samples outperformed their European softwood counterparts

The characteristic bending strength is 30% higher than characteristic bending strength values declared for other European CLT products.

ROLLING SHEAR

Further reading: ENU Test Report R1437_FO072_001 Rolling Shear (CLT)

Overview and test programme

A test programme was derived to evaluate rolling shear properties (strength and stiffness) of CLT panels fabricated from tulipwood.

8 samples of identical specification were tested.

Results, comparison and findings

According to the test results contained in Table 7, the mean rolling shear modulus equal to 197 N/mm^2, whilst the characteristic rolling shear strength equal to 2.00 N/mm^2. These two values are most likely to be utilised for structural engineering calculations when designing a floor slab element made out of CLT.

The results and findings from rolling shear tests carried out according to the test programme are summarised in Table 7. This allows for the direct comparison of the rolling shear strength and stiffness properties obtained in this study with the values declared by two major European CLT manufacturers, both of whom utilise nearly 100% of C24 graded softwood (with an allowable % utilisation of C16) for the manufacture of CLT.

Sample reference	Ultimate load, Fmax [kN]	Rolling Shear Modulus G9090 [N/mm²]	Rolling Shear Strength fv,9090 [N/mm²]
RS_1	57.45	158	3.19
RS_2	57.04	208	3.17
RS_3	66.06	267	3.67
RS_4	63.22	205	3.46
RS_5	58.89	267	3.28
RS_6	48.66	133	2.68
RS_7	42.23	126	2.33
RS_8	54.51	208	3.04
Minimum	42.23	126	2.33
Maximum	66.06	267	3.67
Mean	56.01	197	3.10
Characteristic	36.28	86	2.00
Standard deviation	7.66	55	0.43
COV (%)	13.68	27.74	13.72

Table 7 – Rolling shear results summary

Conclusion

Based on the results from 8 samples presented in Table 8, the mean rolling shear stiffness of tulipwood CLT is significantly higher than the declared shear modulus of softwood CLT manufactured by two major European CLT manufacturers. Despite relatively large variation of the results (values range from 126 N/mm^2 to 267 N/mm^2), each tested sample outperformed their European softwood counterparts by an average of approximately 72%. These results potentially put tulipwood in an advantageous position with regards to other CLT products (softwood) currently manufactured in Europe.

> Each tested sample outperformed their European softwood counterparts in rolling shear stiffness by an average of approximately 72%

In terms of rolling shear strength, all tulipwood test samples outperformed their European softwood counterparts. According to the results obtained in this study characteristic rolling shear strength equal to 2.0 N/mm^2 which is up to 50% higher than characteristic rolling shear strength values declared by two major European CLT manufacturers.

> In terms of rolling shear strength, all tulipwood test samples outperformed their European softwood counterparts

BOND STRENGTH

Further reading: ENU Test Report R1437_FO069_001 Bond Strength (CLT primed) & R1437_FO069_002 Bond Strength (CLT not primed)

Overview and test programme

A test programme was devised to assess the bond integrity of CLT panels fabricated from tulipwood. Overall 8 samples were tested in shear, 4 with and 4 without primer in order to also investigate the influence of primer used during the manufacture on shear capacity of the glue lines of tulipwood CLT.

8 samples in total were tested.

Results, comparison and findings

Based on the test results outlined above the characteristic shear capacity of primed samples equal to 3.05 N/mm^2 whilst the shear capacity of not primed samples equals to 1.90 N/mm^2. The 38% drop in characteristic performance of specimens without a primer was governed by relatively high variation between the results, with the highest shear capacity of 4.00 N/mm^2 and lowest of 2.63 N/mm^2. The reduction in performance of samples without primer by 7% can also by observed when analysing the mean result values.

The results and findings from bonding shear tests for primed and non-primed specimens, undertaken in accordance with the test programme are summarised in tables 8a and 8b. This allows for the direct comparison of bond integrity of tulipwood CLT manufactured with and without a primer.

Sample reference	Ultimate Load, Fmax (kN)	Shear capacity*, Fv (N/mm²)	Verification**
B_3D_1	6.01	3.71	Pass Shear
B_3D_5	6.29	3.73	Pass Shear
B_3D_6	5.82	3.41	Pass Shear
B_3D_7	5.85	3.44	Pass Shear
Minimum	5.82	3.41	
Maximum	6.29	3.73	
Mean	5.99	3.57	
Characteristic	5.12	3.05	
Standard deviation	0.21	0.17	
COV (%)	3.56	4.80	

Table 8a – Bond strength results summary (primed)

** Calculated in accordance with BS EN 16351:2015 Annex D cl. D5*

*** In accordance with BS EN 16351:2015 cl. 5.2.5.4.3*

Sample reference	Ultimate Load, Fmax (kN)	Shear capacity*, Fv (N/mm²)	Verification**
B_2D_2	5.43	3.24	Pass Shear
B_2D_3	6.70	4.00	Pass Shear
B_2D_4	5.70	3.39	Pass Shear
B_2D_5	4.34	2.63	Pass Shear
Minimum	4.34	2.63	
Maximum	6.70	4.00	
Mean	5.54	3.31	
Characteristic	3.11	1.90	
Standard deviation	0.97	0.57	
COV (%)	17.50	17.05	

Table 8b – Bond strength results summary (not primed)

** Calculated in accordance with BS EN 16351:2015 Annex D cl. D5*

*** In accordance with BS EN 16351:2015 cl. 5.2.5.4.3*

Conclusion

Based on the results from 8 tests presented in tables 9a and 9b, all samples have met the minimum required shear capacity for CLT set out in *BS EN 16351*. However, this study suggests that there is a 38% (characteristic) and 7% (mean) drop in bond performance of a non-primed tulipwood CLT in comparison to primed CLT.

However, the sample set was small and it is recommended that further investigation on the influence of primer upon the bond integrity of tulipwood CLT be undertaken since its performance will have an effect on overall properties of an end product, including the out-of-plane stiffness.

In addition, the press time should also be considered for further research given the influence it may have. Limiting the press time and application of primer would improve overall fabrication productivity.

SUMMARY OF RESULTS

Tables 9a and 9b summarise and compare the properties of tulipwood CLT based upon the laboratory test results undertaken in this study.

Mechanical property	Verification method	Value
1. Mechanical actions perpendicular to cross laminated timber		
Modulus of elasticity • parallel to the grain of the boards, E0,mean	EAD 130005-00-0304, 2.2.1.1, Ieff	11010 N/mm^2
Shear modulus • perpendicular to the grain of the boards, G9090,mean	BS EN 16351:2015, F.3.3	196.57 N/mm^2
Bending strength • parallel to the grain of the boards, *f*m,k	EAD 130005-00-0304, 2.2.1.1, Weff	45.06 N/mm^2
Shear strength • perpendicular to the grain of the boards (rolling shear), *f*v,9090,k	BS EN 16351:2015, F.3.3	2.00 N/mm^2
2. Mechanical actions perpendicular to cross laminated timber		
Modulus of elasticity • parallel to the grain of the boards, E0,mean	EAD 130005-00-0304, 2.2.1.1, Inet, Anet	12430 N/mm^2
Bending strength • parallel to the grain of the boards, *f*m,k	EAD 130005-00-0304, 2.2.1.1, Weff	34.49 N/mm^2
3. Other mechanical actions		
Bond integrity	BS EN 16351:2015, 5.2.5.4.3	Pass

Table 9a – tulipwood CLT – mechanical properties

MANUFACTURER	1	2	Tulipwood CLT
1. Bending out of Plane (flatwise i.e. floor slab)			
Modulus of elasticity • parallel to the grain of the boards, E0,mean • perpendicular to the grain of the boards, E90,mean	12500 N/mm^2 370 N/mm^2	12000 N/mm^2 370 N/mm^2	11010 N/mm^2 * 800 N/mm^2**
Shear modulus • parallel to the grain of the boards, G090,mean • perpendicular to the grain of the boards (rolling shear), G90,mean	690 N/mm^2 60 N/mm^2	690 N/mm^2 50 N/mm^2	750 N/mm^2** 197 N/mm^2*
Bending strength • parallel to the grain of the boards, *f*m,k	24 N/mm^2	24 N/mm^2	45.06 N/mm^2*
Tensile strength • perpendicular to the grain of the boards, *f*t,90,k	0.4 N/mm^2	0.4 N/mm^2	0.5 N/mm^2 **
Compressive strength • perpendicular to the grain of the boards, fc,90,k	2.5 N/mm^2	2.5 N/mm^2	6.8 N/mm^2 **
Shear strength • parallel to the grain of the boards, *f*v,090,k • perpendicular to the grain of the boards (rolling shear), *f*v,9090,k	4 N/mm^2 1.5 N/mm^2	4 N/mm^2 1 N/mm^2	4 N/mm^2 ** 2 N/mm^2 *
2. Bending in plane (edgewise i.e beam)			
Modulus of elasticity • parallel to the grain of the boards, E0,mean	12500 N/mm^2	12000 N/mm^2	12433 N/mm^2 *
Shear modulus • parallel to the grain of the boards, G90,mean	460 N/mm^2	N/A	N/A
Bending strength • parallel to the grain of the boards, *f*m,k	24 N/mm^2	24 N/mm^2	45.06 N/mm^2 *
Tensile strength • parallel to the grain of the boards, *f*t,0,k	14.5 N/mm^2	14.5 N/mm^2	25 N/mm^2 **
Compressive strength • parallel to the grain of the boards, *f*c,0,k	21 N/mm^2	21 N/mm^2	26.8 N/mm^2 **
Shear strength • parallel to the grain of the boards, *f*v,090,k	2.5 N/mm^2	2.5 N/mm^2	N/A

Table 9b – CLT properties comparison

**In accordance with test results outlined in this report*

***In accordance with BS 5756: Grade TH1*

HENKEL

DELAMINATION

In support of the *MultiPly* project Henkel & Cie. AG agreed to undertake delamination testing of factory production control samples in their structures test laboratory in Sempach Station, Switzerland

A total of 32 factory production control samples of varying specification, including samples comprised wholly of thermally modified tulipwood (TMT), were subjected to delamination testing in accordance with EN 16351.

The test reports concluded that the test specimens fulfilled the requirements of EN 16351 and, based upon these results, that the bonding system used is well suited to produce tulipwood CLT according to European quality requirements.

CONCLUSIONS

CSIC CONCLUSIONS – MANUFACTURING

Henkel specified a number of conditions specific to the manufacture of tulipwood CLT which differ to that of the typical manufacturing process and parameters for that of the softwood species cited in EN 16351. To reiterate, these are as follows:

- **Application of primer solution to all glued faces**
- **Minimum press time doubled from 150 minutes to 300 minutes**
- **Application/spread rate of the adhesive increased to 170g/m^2, compared to 120 to 160g/m^2 typical of softwood CLT**

When compared with the manufacture of softwood CLT, the process of applying primer and stacking lamellae appropriately to allow the primer to activate introduces an extra step in the manufacturing process and perhaps the most challenging of the three parameters stated above. As well as additional investment to implement and maintain the priming process and increased production time, this could potentially create a bottleneck in the manufacturing process.

Increased press time would naturally result in increased overall production time and have an impact upon production schedules.

Increased adhesive spread rate would naturally result in an increased overall volume of adhesive required, which would have to be replenished more frequently. This might also result in an increased quantity of adhesive leeching to the outer surfaces.

The results produced from structural testing of tulipwood CLT samples by Edinburgh Napier University and the delamination testing of the factory production control samples by Henkel have indicated that tulipwood can be effectively bonded using PUR adhesive and demonstrate that it has robust structural properties, at least equivalent to those of CLT manufactured with C24 softwood lamellae – the majority of it's properties tested in fact being superior.

A limited comparative study of glue-line bond strength was conducted at Edinburgh Napier University to investigate the effect of the primer solution upon the bond strength of PUR between layers of tulipwood CLT. Samples both with and without primer were tested. This study, though not conclusive, would indicate that although the primer enhances the bond strength between layers, that the bond strength of the non-primed samples was satisfactory. The results of delamination testing undertaken on factory production control samples without primer also reflects these findings.

Results of delamination testing of a limited number of samples using a lower adhesive spread rate of 150g/m^2 and reduced press time of 150 minutes, though not conclusive, give some indication that the bond strength is satisfactory within these parameters.

EDINBURGH NAPIER UNIVERSITY CONCLUSIONS – STRUCTURAL PERFORMANCE

The use of hardwood timber species for the production of CLT represents an opportunity to add value to the resource.

The formation of a CLT plate serves to enhance the properties of a structural element via re-engineering the baseline performance of available material and create larger structural components primarily for wall, floor and roof applications.

The use of hardwood timber species for the production of CLT represents a great opportunity for the implementation of Solid Laminate Timber Systems and for the development of under-utilised and lower grade timber species. Several research projects have confirmed the feasibility of this product and underlined the benefits that the use of hardwood species can bring to CLT performance.

Boards of U.S. tulipwood

The realisation of the demonstration project, *MultiPly*, further demonstrates the opportunity for the application of hardwood CLT, in particular tulipwood, and proves once again its excellent performance and enhanced qualities.

The current standards for CLT production are geared towards softwood species and there is a scarcity of available and applicable information on the use of hardwood species for CLT manufacture.

This research has demonstrated that an enhancement of baseline material performance (strength and stiffness) is achieved for most properties of tulipwood CLT with the exception of bending stiffness in the flatwise orientation (out-of-plane i.e. floor slab). The modulus of elasticity obtained from tests flatwise on the available sample range equated to 11,010 N/mm^2, which is the equivalent of C24 strength class MoE. This value is considered relative to the 11901 N/mm^2 MoE value for the sub-set of tulipwood material sampled for the acoustic characterisation QA process for the *MultiPly* project (note: the timber strength class most commonly employed for the manufacture of the CLT in Europe is C24 with an allowable % utilisation of C16). On the basis that acoustically characterised tulipwood from the *MultiPly* project was higher than C24 MoE, the expectation would be that the CLT panels themselves would achieve a higher MoE value via the re-engineering process.

All the tulipwood CLT material properties ascertained from this study, as well as the properties based on the baseline material (tulipwood) declared for TH1 strength grade were compared relative to values as declared by two major European manufacturers. Based on this comparison, the properties of tulipwood CLT are favourable to European softwood CLT, with the exception of out-of-plane stiffness. It should be noted that both these major CLT manufacturers in Europe prior to 2014 declared the values of 11000 N/mm^2 (ETA-08/0271) for the out-of-plane stiffness of the CLT manufactured in their factories – a value less than that ascertained from this tulipwood CLT sample range. The increase in stiffness from 4 years ago could be the result of optimised categorisation/selection of the base material used for the manufacture as well as enhanced level of information via test work of varying lamellae sizes and lay-ups. The samples utilised in this study were limited to a 3 x 20mm lamellae lay up for one load span test condition. Further, the base material utilised for the CLT fabrication is influencing the characteristic values ascertain as is shown by the variation in results across the panels tested.

In conclusion, it is therefore demonstrated that the fabrication of tulipwood CLT from the process put in place for the *MultiPly* project is viable and that this process could be replicated for further projects where tulipwood CLT is to be used for structural purposes.

Application of primer and press/assembly time are both important parameters when considering fabrication productivity. There is a reduction in bond strength performance when primer is not applied and, whilst above the threshold required for CLT fabrication, this could be a topic for further investigation. Reducing the press time in line with that of softwood CLT manufacture would also warrant further investigation.

The baseline material of tulipwood has enhanced properties as compared to softwood normally of C24 grade, which is used most typically for the European manufacture of CLT. This enhancement is reflected when comparing CLT to European manufactured softwood CLT, with the exception of flatwise bending. However, the performance of the CLT within this study will be influenced by the characteristics of the base material used for the actual panel fabrication. This is compounded further by the statistical analysis,

Close-up of tulipwood CLT panels

itself influenced by the size and variability of the sample ranges (both base material and CLT panels). In particular, the variability of the flatwise CLT tests and the tests taken on a single panel with a relatively thin lay-up over one load span condition is considered to be adversely affecting the final results, particularly the characteristic results on the basis by which these are derived. Therefore, to fully optimise performance, prior to the commercialisation and certification process, follow-on analysis and additional test work is recommended which could run concurrently with a follow on project working via the same process or in collaboration with a full scale CLT manufacturer.

It is worth noting that the information from this study would be sufficient with appropriate levels of QA to satisfy preliminary structural design and analysis work of a system with subsequent optimisation/value engineering taking place based on full knowledge of the base material to be used in production.

GLENALMOND TIMBER CO. CONCLUSIONS – PRE-PROCESSING

With a key aspect of the project being to explore the extent to which low or relatively-low grade tulipwood could be used successfully in the production of structural cross laminated timber, Glenalmond Timber Co. was selected to carry out the pre-processing work as it had all of the necessary facilities to carry out visual grading, sawing, finger-jointing and planing of the material shipped from the USA. The three containers of flat-sawn boards supplied to Glenalmond for the project had already been graded in the USA to NHLA Rules as Number 2 Common (No.2C) and Number 3 Common (No.3C). Two thirds of this material (i.e. two containers) was of No.2C grade whilst the other third (one container) was of No.3C grade.

GRADING

On arrival at Glenalmond Timber's premises at Methven in Perthshire, the previously flat-sawn tulipwood boards were visually graded by Glenn Sharples of CATG to the TH1 structural standard provided for in *BS 5756*, with boards extracted that did not meet the required criteria. This resulted in significant wastage: a result of the timber having been supplied in unfinished and variable widths. For future reference, were timber to be supplied from the USA already sawn to width, a standard container could accommodate a greater amount of usable timber, resulting in a considerable saving of time in the grading and sorting process in the UK and ensuring greater yield from the material.

U.S. tulipwood boards

SAWING AND FINGER JOINTING

The remaining boards (the bulk of the timber supplied) were then sawn to two widths to optimise yield and to ensure the material could be passed through the finger jointing and planing machines effectively. At this stage, further waste material (large knots, waney edges, splits, etc.) was cut out to enable a variety of board lengths suitable for finger-jointing to be produced from defect-free timber. The extent of waste material removed meant that some of these lengths were extremely short – again to maximise yield – resulting in excessive numbers of finger-joints, further adding to production time and cost.

PLANING

The finger-jointed process complete, the boards were then planed, with the resulting material showing excellent quality. These long finger-jointed boards were then cut to lengths to suit the required design dimensions and to maximise efficient panel fabrication in CSIC's vacuum press.

TRANSPORT

With all material, once planed, required to have adhesive applied to it within 24 hours, the finished timber needed to be transported from Glenalmond's

CNC-machined tulipwood panel

premises in Perthshire to those of the Construction Scotland Innovation Centre in Blantyre, a 78 mile (125.5 km) / 1.5 hour journey. The speed of panel production possible in CSIC's vacuum press, together with the time required for the adhesive used in the manufacture of the CLT panels to cure, meant that the total volume of timber had to delivered in batches on a daily basis, thus introducing an additional cost and time factor to the project.

CONCLUSION

The unusual circumstances of this prototypical project required a unique solution to the pre-processing and panel manufacturing process. The production of CLT in Europe typically sees close proximity between the forest resource, the sawmill and the panel manufacturing facility, and the CNC machining, all of which was not available in a similar relationship in the UK at this time. Manufacturing cross laminate timber from hardwood – an innovative concept in itself – was always going to introduce new challenges in the UK where no commercial CLT panel production facilities currently exists.

Nevertheless, it is entirely conceivable that tulipwood imported from the USA could be efficiently and economically manufactured into cross laminated timber in the UK and Europe if more of the pre-processing was carried out in the USA (i.e, finished board widths supplied to the UK and Europe ready to be finger-jointed and planed) and if the cross laminated timber press (whether vacuum or hydraulic) was located adjacent or close to the pre-processing facilities in order to reduce or remove the transportation costs highlighted above.

RECOMMENDATIONS FOR FOLLOW-ON RESEARCH

This project implemented the pilot production of tulipwood CLT for the *MultiPly* pavilion exhibited as part of London Design Festival 2018 and demonstrated the compatibility of tulipwood with the CLT production process. The process implemented could be successfully replicated for further projects where the pilot production of CLT is to be used for structural purposes. The results of the research to date would justify a more exhaustive study, necessary to further investigate the effects of the application of primer, reduced press time and reduced adhesive spread rate, in both isolation and combination, when bonding tulipwood with PUR to form CLT, in order to provide conclusive results.
In order to fully optimise the performance and production process, prior to the commercialisation and certification, follow-on analysis and additional test work is recommended, which could be undertaken concurrently with a follow-on project working via the same process or in collaboration with a full scale CLT manufacturer.

Having more knowledge about the influence of primer and pressing time on the structural integrity of hardwood CLT would potentially lead to further optimisation of the manufacturing process which would be of importance from a productivity and corresponding commercialisation perspective.

If the scope of follow-on research is limited to investigating only a single parameter, then investigation into eliminating the use of primer specifically for tulipwood CLT might form the

CLT panels of U.S. tulipwood being assembled for MultiPly primary focus, given the scale of potential impact this has upon the manufacturing process.

Future research topic recommendations:

- **Enhanced test programme to investigate bond strength for primed and non-primed samples**
- **Enhanced test programme to investigate bond strength for reduced press time**
- **Enhanced test programme to investigate bond strength for reduced adhesive spread rate**
- **Further lay-up analysis utilising analytical techniques including design considerations (wall, floor and roof elements) for standard design scenarios**
- **Enhanced test programme for additional lamellae sizes and lay-ups with a view to considering the most appropriate panel spec relative to the most appropriate market utilisation**
- **Follow on project applying effective QA process and any necessary concurrent test work**
- **Creation of full structural design guide as well as additional consideration on building performance specification**
- **Follow-on supply chain integration and full ETA.**
- **Identification, examination, questioning and testing of every stage of the process**

Logs of U.S. tulipwood

RESOURCES

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IMAGE CREDITS

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WAUGH THISTLETON

Waugh Thistleton is a research-oriented practice dedicated to designing buildings and places of the highest architectural quality that also acknowledge their impact on the environment. The studio practices sustainability in the widest sense of the word, focusing not solely on energy in use, but on embodied energy and longevity. The team believes passionately that sustainability and world-class design solutions should be one and the same thing.
@waughthistletonarchitects

ARUP

Arup is the creative force at the heart of many of the world's most prominent projects in the built environment and across industry. With over 80 offices in 35 countries Arup has more than 13,000 planners, designers, engineers and consultants delivering innovative projects across the world with creativity and passion.
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STAGE ONE

Stage One are a creative construction and manufacture company working within the architecture, theatre and events industries. Collaborating with some of the world's most creative minds, they have constructed each of the Serpentine pavilions since 2009; worked with RSH+P on a Prouvé House; manufactured complex façade panels for Zaha Hadid's Chanel pavilion; and built Thomas Heatherwick's iconic London 2012 Olympic cauldron. they combine innovative design, engineering and technology to deliver astonishing impact on a global platform.
@stageoneltd

AHEC

For over 25 years the American Hardwood Export Council (AHEC) has been at the forefront of international wood promotion, successfully building a distinctive and creative brand for U.S. hardwoods. AHEC's global programme of activities secure a future for American hardwoods by demonstrating the performance and aesthetic potential of these sustainable materials, while providing valuable creative inspiration and technical advice.

LONDON DESIGN FESTIVAL

London Design Festival is a key constituent of London's autumn creative season, alongside London Fashion Week, Frieze Art Fair and the London Film Festival. Established in 2003 its role is to celebrate and promote London as the world's design capital and gateway to the international design community and it has now established a reputation as one of the largest and most exciting design events in the world. This year the Festival will run from 15-23 September and over 400 events and installations will be on offer across the capital, from an exciting programme at the V&A to plus over 300 partners who will participate in the nine-day Festival.
@L_D_F_Official

CONSTRUCTION SCOTLAND INNOVATION CENTRE (CSIC)

CSIC supports Scotland's construction related businesses to innovate, collaborate and grow by matching innovation requirements with business support and academic specialists. Focusing on Business, Product, Process and Service forms of innovation, CSIC offers advice, funding, facilitation and access to the appropriate expertise, improving Scotland's global competitiveness and growing economic impact. CSIC facilitates collaboration with Scottish businesses, academia (through 13 partner universities) and public sector organisations, enabling businesses to benefit from Scotland's world-renowned skills, expertise and fair approach to business in areas such as Infrastructure Delivery, Offsite Construction, Low Carbon Solutions, Architecture and Retrofit.
@CSotIC

GLENALMOND TIMBER COMPANY

Glenalmond Timber Company is a third generation family run business with over 90 years of experience; employing a team of professionals, highly experienced across all disciplines within the timber industry. Their Methven factory houses the latest finger jointing technology, CNC detailing and moulding lines. They can engineer and detail large section glulam and CLT projects, modular building components, feature trusses and bespoke prototyping. They also operate a quay and distribution facility on Perth harbour with the largest low-pressure treatment facility in the UK where their in-house stevedoring team can accommodate vessels of over 4000m3.
@glenalmondtimber

CENTRE FOR OFFSITE CONSTRUCTION + INNOVATIVE STRUCTURES (COCIS), EDINBURGH NAPIER UNIVERSITY

COCIS undertakes leading fundamental and applied research for industry, government and public sector bodies in the thematic area of industrialised building systems. The COCIS team are recognised as the a-go-to team for innovation in construction practice with a particular emphasis on industrialised timber technology delivering on high impact work. COCIS provide an impartial knowledge base and as such facilitates communication between the supply chain and offsite enterprises through to the onsite construction phase. COCIS is also committed to ethical, impartial, and objective academic research and works as a team to deliver the highest level of quality through collaboration. Acting as a centralised knowledge base with respect to sustainable materials and offsite methods of design and construction COCIS has developed a strong international profile and has the strategic objective to work in partnership with external stakeholders and industry to "research, innovate and commercialise" construction technologies for tomorrow's communities.

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