The Smile: The first large scale use of hardwood CLT

Lächelnde Skulpttur aus Tulipwood (CLT) – the Smile

Sculpture souriante en tulipier de Virginie (CLT) – the Smile

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1. Introduction

The Smile, constructed for the 2016 London Design Festival represents the first large scale use of hardwood CLT. In terms of the forces between the panels, to create a torsion tube, it is also arguably the most ambitious structure ever built in CLT. This paper looks at the development of the structural use of the American hardwoods, discusses why tulipwood was chosen for The Smile and explains the structural design.

2. Development of structural use of the American hardwoods

For the courtyard roof of Portcullis House (Figure 1, London, completed 2001), Hopkins Architects were keen to achieve very thin members and Arup suggested the use of American white oak. The timber had never been used before structurally in Europe and detailed testing at BRE showed that it could achieve D50 strengths, enabling incredibly thin members.

The American hardwoods had traditionally been used for joinery, but Portcullis demonstrated the structural potential and encouraged the American Hardwood Export Council to test three further species at BRE (Structural Design in American Hardwoods, Arup, 2005) – red oak, ash and tulipwood. It was this testing which enabled Arup and AL_A to design the tightly bent micro-laminated members of the Timber Wave for the 2011 London Design Festival (Figure 2). However, of the three timbers tested, by far the most interesting was tulipwood.

Fast growing and capable of being harvested after only 40 years, tulipwood has a similar density to softwood but the strength of hardwood. The low density makes it is easy to dry, machine and connect (such as with standard self-tapping screws); this ease of making connections was vital, since it is the connections which dominate the cost of any timber structure. There are about one billion cubic metres of standing tulipwood trees in the south eastern United States. The clear material is popular for painted joinery work, but the lower grade material with knots has little value. This abundant lower grade waste material appreared to be the perfect raw material for CLT.

It was for this reason that tulipwood was chosen for the CLT panels for the Endless Stair (Figure 3, Arup and dRMM, London and Milan, 2013). The CLT strengths were determined from the original tulipwood strength testing at BRE, combined with new rolling shear tests which were carried out at Trento University. The latter showed excitingly that the tuliwood had nearly 3x the strength and stiffness of spruce in rolling shear. However, the Endless Stair was still very much an experimental project, limited to small panels of hardwood CLT. The next step was to build a structure using full size commercial panels.

3. Architectural concept

Alison Brooks Architects were commissioned to design a tulipwood CLT structure for the 2016 London Design Festival using large CLT panels that would visibly demonstrate the strength of the hardwood. Alison Brooks' concept was to create a double cantilever, curved into the shape of a smile. The double cantilever was to be inhabitable, to create an interactive sculpture.

The CLT was to be visually exposed both inside and outside. While CLT should not be used in Service Class 3, the installation was only to be in place for 4 weeks, such that decent roof waterproofing, end grain sealant and a surface sealer on the vertical outer faces would ensure that the timber remained in Service Class 2, in spite of the London climate.

4. Structural design

4.1. Overall size and geometry

The overall size and geometry was ultimately dictated by the need to minimise transport costs and wastage. The maximum panel (or lorry) width which can be transported within the UK without an escort is 4.5m, as long as it is off the road by 6am. This dictated both the 4.5m width of the Smile and the width (and therefore length) of the curved central wall panels (Figure 4). It was eventually agreed to slope the boards of the outer wall panels (rather than the architectural preference for perfectly horizontal outer boards); this minimised the wastage in cutting a curved panel from a straight piece and also maximised the strength by limiting the slope of grain.

Tulipwood is generally available as 1‟ or 25.4mm thick planks. This implied 20mm laminates after planning and thus a minimum viable CLT thickness of 100mm as a 5 layer board. Thicker 7, 9 and 11 layer panels were used for the central wall, roof and floor panels to resist the higher stresses in these locations.

The structure is entirely constructed out of tulipwood, apart from the softwood foundation beams and also the roof panels, which are fairly lowly stressed and therefore able to use softwood (with tulipwood on the lower surface for appearance). The total length of 34m was ultimately dictated by the volume of donated tulipwood available.

The entire structure is constructed from just 12 large CLT panels, straight panels for the walls and curved panels for the roof and floor.

4.2. Design load

Eurocode 1 would suggest a design load of 4kPa, implying about 600 people. However, with only a single exit fire regulations dictated a maximum of 60 people and managed access. In view of the steep slope towards the ends of the cantilever, it was decided that the 60 people would not crowd tighter than 3kPa and thus the two critical loadcases were taken as 3kPa at one end to create a rocking load and 3kPa in one corner to create a twisting load. The site is relatively exposed and near the river; wind loads were therefore taken as 0.7 kPa.

4.3. Overall structural behaviour

The overall structure is fixed down to a wooden box, concealed under the ground and filled with 20 tonnes of steel counterweights (Figure 5). In view of the variable ground below (hard spots representing the remains of the 19th Century Millbank prison, and soft spots representing the 3m of fill around the prison foundations), a relatively large 10x4m foundation was chosen. The central floor of the Smile was then thickened to 220mm to enable it to cantilever 250mm beyond the foundation to support the walls of the Smile.

It was decided to use the walls alone to support the cantilevers without help from the roof or floor as flanges. This was mainly because flange action would have demanded diagonal screws on plan to form the wall to floor/roof shear connections, whereas the screws in these locations really needed to be perpendicular to the walls on plan both to form the stiff wall to roof connection, and also to support the weight of the floor.

The outer sections of wall are connected with a steel tension plate to carry the cantilever end moment (Figure 6), combined with a vertical line of screws to carry the vertical shear.

The central section of wall was thickened to accommodate the stress concentrations around the door opening, to resist the distortion of the torsion tube, and to provide space for the screwed fixing down to the floor. Separate vertical screws were provided to resist overall rocking and diagonal screws to carry the wall cantilever horizontal compression under the door and into the foundation beams (Figure 7).

It was important to keep the inside of the Smile free of structure to enable uninterrupted internal views. In order to resist lateral wind loads, the eventual solution was to rigidly fix the walls to the roof via a glulam beam to create a portal frame (Figure 8); because of the grain direction of the wall panels, the thickness of the walls contributing to portal action was only 60mm; this in turn limited the potential for architectural openings in the walls. In order to resist the distortion of the torsion tube over the foundation, the horizontal screw centres in this location were closed up to 50mm (Figure 9).

Steel splice plates were also used to connect the roof and floor panels for diaphragm action.

4.4. Modelling

The CLT panels are connected with axially loaded screws made from high strength steel. Since these are very brittle, with only about 0.25mm of necking and extension to failure, it was important to make the structure as determinate as possible. For example, the screws forming the vertical wall to wall shear connection were inserted perpendicular to the wall panels to ensure they would be an order of magnitude less stiff than the diagonal screws used to carry the tension through the steel splice plate. Similarly, and as noted above separate groups of vertical and diagonal screws were used to resist the vertical push/pull either side of the door and the horizontal thrust under the door.

In terms of calculating the forces around the door opening, two bounds were considered – a rectangular stress block above the door opening to conservatively calculate the compression under the door, and a triangular stress block above the door opening to conservatively calculate the maximum tensile stress in the wood above the door. This was one of the more highly stressed areas of the structure and dictated the overall 3.5m height of the wall panels.

Similarly, a triangular stress block on the compression side was assumed at the wall to wall connection.

In view of the isotropic nature of the CLT it was found quicker and easier to undertake all the calculations by hand rather than by FE analysis.

Panel shear was checked following the latest research[1] from Graz University also in accordance with the methods in the European Technical Approvals.

4.5. Strength of the tulipwood CLT

The tulipwood was graded to BS 5756 and the strength of the CLT was then calculated from first principles based on the previous strength testing which had been undertaken.

4.6. Connections

Approximately 6000 Rothoblass screws were used to connect the panels, varying from 100 – 500 mm long. The strength of the screws was based on the ETA, enhanced to allow for the slightly greater density of the tulipwood.

Long diagonal screws were used to carry the weight of the floor (Figure 10) and additional horizontal screws were added to prevent bending of these screws due to flexure of the thin 100mm floor panels.

5. Construction

5.1. Fabrication of the tulipwood CLT

The tulipwood CLT was fabricated by Zueblin Merk. Tulipwood is nearly as easy to work with as spruce, just needing a slightly different PU glue formulation. The main challenges are the random widths of the available boards which can lead to more wastage; to reduce the wastage boards were cut to 100mm widths, but this in turn led to a tendency for the narrow boards to twist when the panels were being assembled before pressing. In the future it is hoped to find saw-millers willing to supply pallets of constant width 140mm boards.

5.2. Construction

Despite the large number of screws, construction was completed in just 5 days, demonstrating the ease of fixing into the tulipwood. Figure 11 shows the completed structure.

6. Conclusions

Tulipwood appears to offer an ideal alternative to spruce for internally exposed CLT for high end applications. It has a superior appearance (Figure 12) and the higher strengths will enable thinner panels and help to offset the slightly higher costs of the raw material. Further testing and approvals will be required before the product can be commercialised, but the response from the architectural profession to date has been very positive.

References

1. Verification of CLT-plates under loads in plane (Thomas Bogensperger, Thomas Moosbrugger, Gregor Silly, World conference on timber engineering 2010)

Figure 1: The courtyard roof of Portcullis House, London 2001

Figure 2: The Timber Wave, London 2011

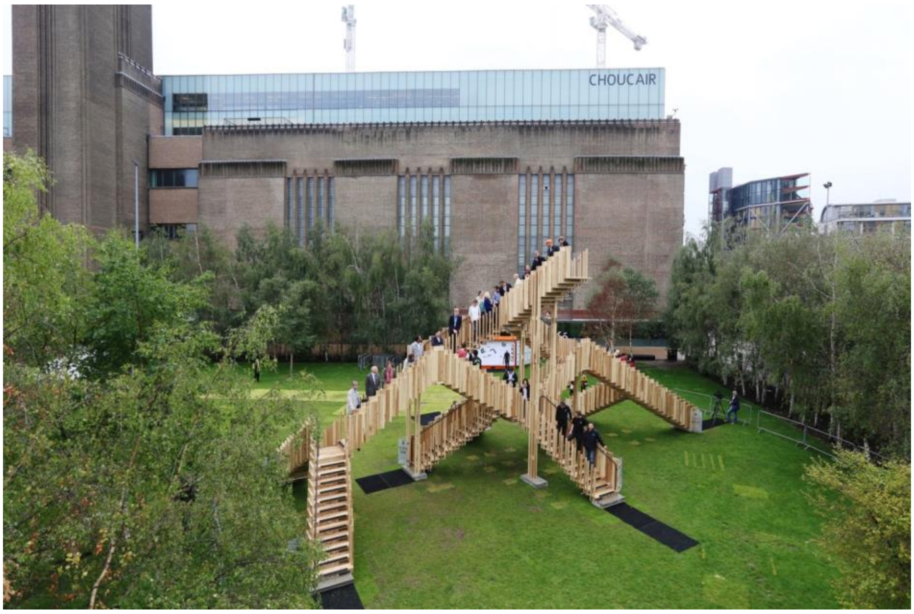

Figure 3: The Endless Stair, London 2013

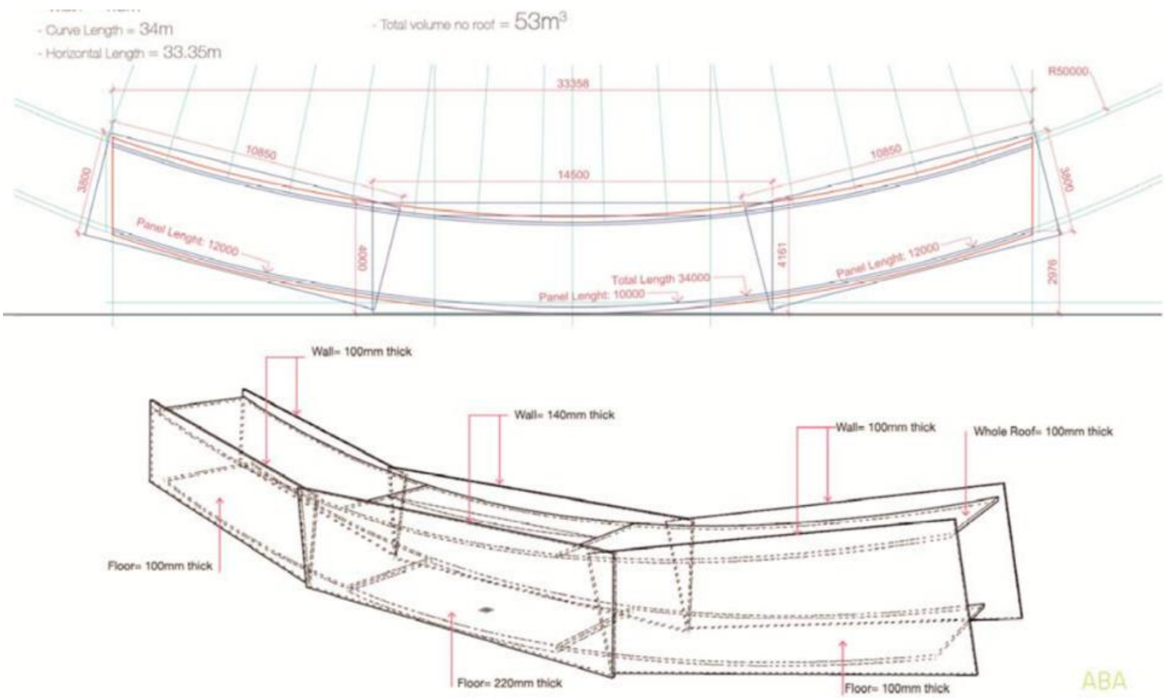

Figure 4: The Smile – Panelization

Figure 5: The Smile – Foundation counterweights

Figure 6: The Smile – Wall to wall connection

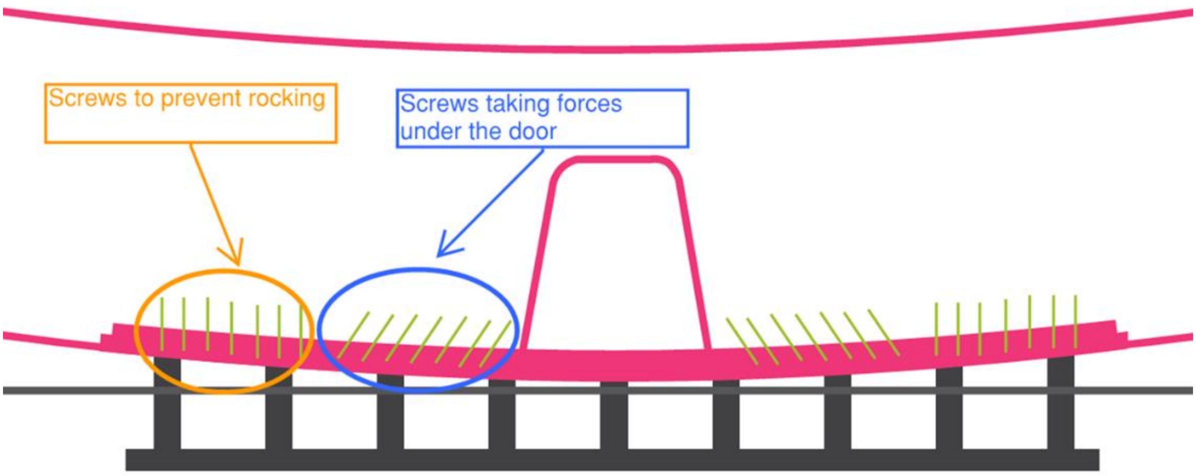

Figure 7: The Smile – Connection to foundation

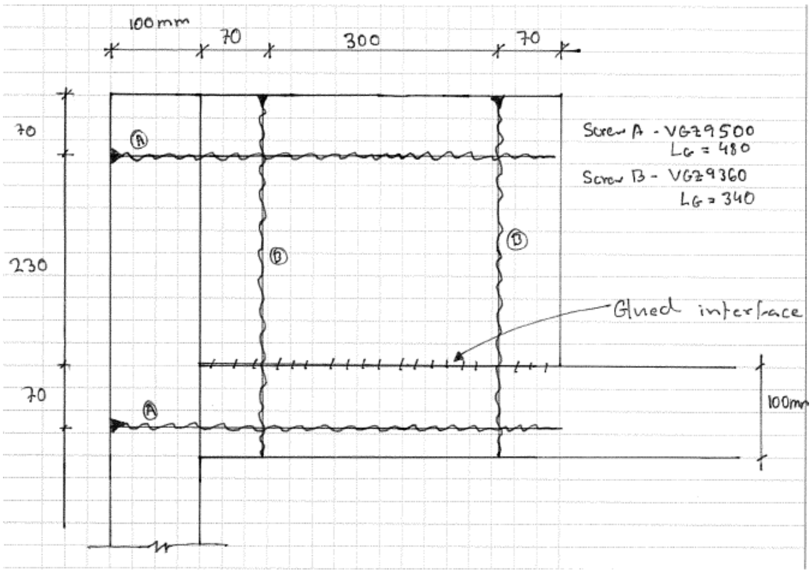

Figure 8: The Smile – Roof to wall connection (detail)

Figure 9: The Smile – Roof to wall connection

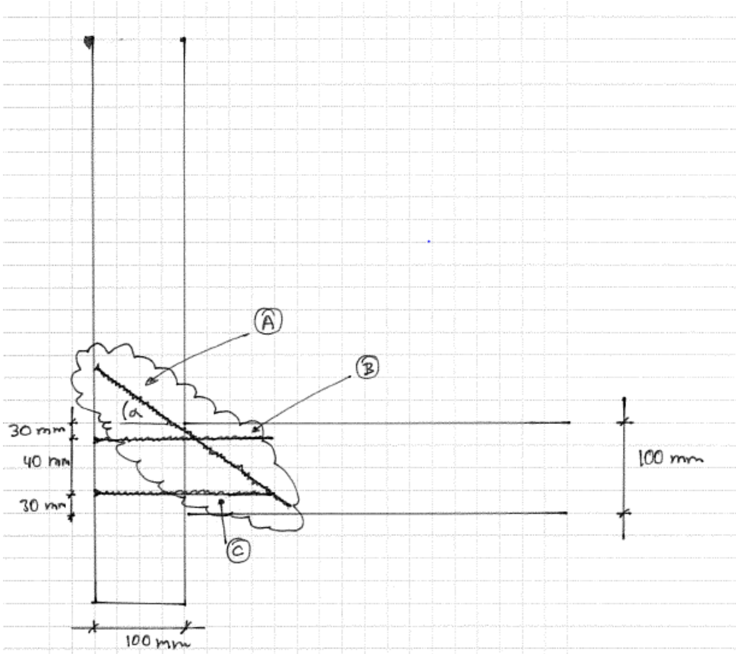

Figure 10: The Smile – Floor connection

Figure 11: The Smile - Completed structure

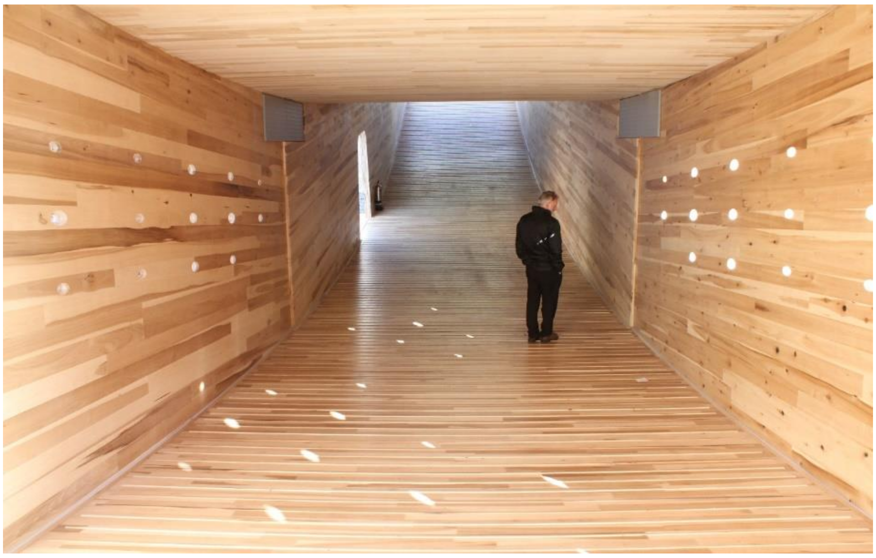

Figure 12: The Smile – Completed structure