IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Butt-joint bonding of timber as a key technology for point-supported, biaxial load bearing flat slabs made of cross-laminated timber

To cite this article: S Zoellig *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **323** 012144

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012144 doi:10.1088/1755-1315/323/1/012144

Butt-joint bonding of timber as a key technology for point-supported, biaxial load bearing flat slabs made of cross-laminated timber

Zoellig S[1], Muster M[2], Themessl A[3]
[1] Timber Structures 3.0 AG, Thun, CH
[2] ETH Zurich, Chair of Structural Engineering - Timber Structures, Zurich, CH
[3] Bern University of Applied Sciences for Architecture, Wood and Civil Engineering (BFH), Biel, CH

stefan.zoellig@ts3.biz

Abstract. An efficient butt-joint bonding technology allows to build new types of timber structures. Under the name Timber Structures 3.0 a connection has been developed which connects timber elements with an end-grain to end-grain butt joint bonding. Therefore, it is now possible to build continuous, point supported flat slabs in cross laminated timber (CLT). Multiple CLT slabs are connected rigidly together and are only supported by columns. Some major challenges had to be solved in terms of bending strength of the glued connection and shear resistance of the part of the slab above the column. The research in both topics is successful and more projects were built in the last two years using this technology. Starting point was a real scale structure at ETH Zurich, followed by a working platform for a timber construction company and finally four three storey residential buildings. The research team is continuing to optimize the different elements of this innovative technology and will soon provide engineers with guidelines to design their own biaxial, point supported timber flat slabs.

1. Introduction

The research project “Wooden slabs in commercial and industrial buildings” has made huge progress since it was started in 2016 [1]. The goal of the research project is to build skeleton structures with flat slabs in timber. Therefore, a biaxial, point supported cross-laminated timber flat slab was developed. As CLT slabs are limited to approximately 20 m length and 3.4 m width a rigid connection is necessary. This key technology, the butt joint bonding of timber, has proven it’s applicability in the last two years. The research team from BFH Biel, ETH Zurich, Timber Structures 3.0, Timbatec, Henkel & Cie., and Schilliger Holz have increased the knowledge about all parts of a biaxial, point supported CLT flat slab. With microscopic analysis the important parameters of the bonded butt joint were revealed and therefore the reliability could be increased. At the same time the implementation of the bonding process into the construction process was improved. Besides the rigid connection of the CLT slabs, transmitting the forces from the slab into the columns is the second crucial part. In 2012 tests at ETH Zurich showed that beech plywood plates can resist high bending moments and shear forces. To lower the cost of construction the same investigations were made with CLT and reinforced CLT plates. This investigation showed that CLT slabs can also withstand high forces. The combination of the

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012144 doi:10.1088/1755-1315/323/1/012144

gained knowledge led to interesting projects which were accomplished in the last two years.

2. Evolution of timber structures

To explain the actual innovation of this project and the created possibilities in timber construction, we must take a step back. For centuries trunks and beams have been used to build houses. Trees were cut down, branches removed, debarked and sawn to beams and planks to construct buildings. In the 20th century, trees were sawn into boards, dried, planed and glued to glulam or more recently to CLT. With these products a structural beam can be larger, longer and more homogenous than a tree. This development is illustrated in Figures 1 and 2.

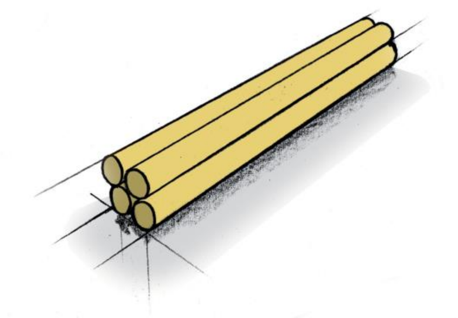

Figure 1. Timber Structures 1.0: Trunks and beams

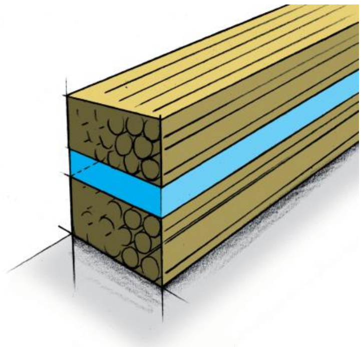

Figure 2. Timber Structures 2.0: Glulam and CLT

The current development illustrated in Figure 3 allows the butt joint bonding of fibres and therefore leads to the 3rd generation in timber construction called Timber Structures 3.0. The rigid connection of several CLT slabs allows new types of timber constructions. Figure 4 shows a multi storey skeleton structure as it is possible to build when several CLT slabs are connected rigidly to a single flat slab.

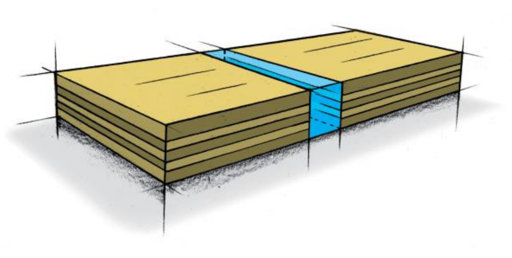

Figure 3. Timber Structures 3.0: Butt joint bonding technology

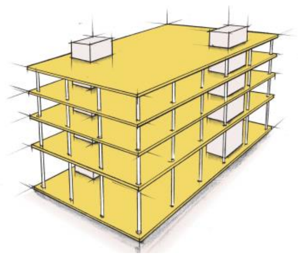

Figure 4. Typical skeleton structure

3. Environmental impact

Replacing building materials with high energy demands for production is a major challenge to achieve a sustainable built environment. Timber constructions have made remarkable progress in the last ten years. In Switzerland, 7.5% of the new built structures were made in timber in 2017. This share almost doubled since 2015. Not only an increased share of buildings is being built in timber, but also the volume of this buildings has increased by 25% over the last 15 years [2]. In the field of residential buildings, timber construction has established itself. In office and business buildings timber construction struggles to provide adequate solutions so far. The here presented technology could increase the current share of only 0.7% of newly built timber office and business buildings per year in Switzerland [2] and replace energy-intensive materials like steel and concrete.

4. Recent research

4.1. Structural system

The structural system shown in Figure 4 is divided into four structural elements. The first element is the rigid connection between the CLT slabs. This connection has to resist bending moments and shear forces. The current status of research is presented in chapter 4.3. The second element is the part of the slab around the column. This element has to lead high shear forces into the column, transfer vertical loads from upper storeys to the next column and at the same time resist high bending moments. The conducted research of this element is presented in the following chapter. The third element is the CLT slab band spanning from column to column. The fourth element is the part of the slab lying between the CLT bands. This element mainly has to resist small biaxial bending moments and therefore does not necessarily have to be a massive timber element such as CLT. Elements three and four are not part of this paper, as they are of lower interest than elements one and two.

4.2. Slab to column connection

Point supported slabs are mostly used for office or industry buildings. For such structures a column grid of 6 - 8 m is required and live loads of 300 - 500 kg/m^2 have to be considered. From this background several scenarios arise with punching loads varying from 380 kN up to 1050 kN. In 2012, Lorenzo Boccadoro tested the punching behaviour of six real scale plates at ETH Zurich [3]. The tested plates had dimensions of 2.5 m by 2.5 m and were 24 cm, 32 cm and 40 cm thick. The plates had a central opening with a diameter of 30 cm. Three of these plates were made of beech plywood and three were made of a combination of beech plywood and spruce boards. The load carrying capacity of all the plates was higher than the required resistance.

To improve the cost efficiency of the flat slab, CLT plates were tested by Marcel Muster in 2017 [4]. CLT plates with dimensions of 2.1 m by 2.1 m, as illustrated in Figure 5, were chosen to be tested. From the elements shown, six specimens were assembled. The basic element was always a six-layered 18 cm thick CLT plate. Two plates consisted of CLT only with opening diameters of 20 cm and 30 cm respectively. On one plate an additional load distribution ring made of beech plywood was placed (Figure 3 bottom left side). Another plate was tested with glued on beech plywood plates on both sides (Figure 3 top right) and finally two plates consisted of both a placed-on load distribution ring and glued on beech plywood plates.

A special feature in the CLT slab is an opening on top of the column as it can be seen in Figure 5. This opening is necessary to lead vertical loads from upper storeys through the slab without subjecting the CLT slab to stresses perpendicular to grain. This necessity on the other hand leads to a great challenge within this research process: at the point where the highest bending moments occur, a part of the slab is missing.

In Figure 6, the load-displacement behaviour of the tested plates is shown. Specimens 1 to 3 did not have any reinforcement plates. Specimen 3 had an additional set on load distribution ring made of beech plywood placed on the hydraulic jack and therefore a higher ultimate load. Specimen 1 with the black dotted line showed early deformations due to the narrow support area which led to a crushing of the timber perpendicular to grain.

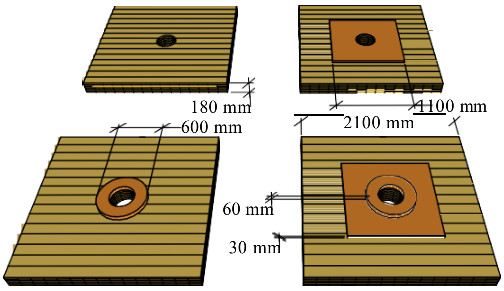

Figure 5. Tested plates

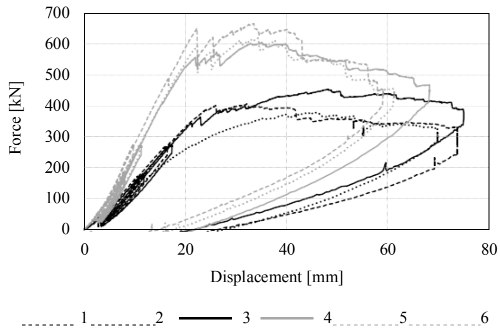

Figure 6. Load-displacement punching tests

The punching tests showed that the chosen slabs are able to transfer high shear forces into the column and can resist high bending moments. With an increase of the thickness of the slab it is also possible to fulfil the requirements defined earlier. In the following table the characteristics of the tested slab, the thickness and the ultimate loads are listed. Specimens F240, F320, F400 were tested by Lorenzo Boccadoro in 2012 [3]. These compositions could be used in situations with higher live loads than 5 kN/m^2.

Table 1. Performed punching tests

Specimen	Ultimate Load	Composition	Opening	Support
1	380 kN	18 cm CLT	D = 30 cm	D = 38 cm
2	408 kN	18 cm CLT	D = 20 cm	D = 40 cm
3	455 kN	18 cm CLT	D = 30 cm	D = 52 cm
4	605 kN	18 cm CLT + 2x3 cm beech plywood	D = 20 cm	D = 40 cm
5	620 kN	18 cm CLT + 2x3 cm beech plywood	D = 30 cm	D = 52 cm
6	666 kN	18 cm CLT + 2x3 cm beech plywood	D = 20 cm	D = 52 cm
F240	1350 kN	24 cm beech plywood	D = 30 cm	D = 55 cm
F320	2257 kN	32 cm beech plywood	D = 30 cm	D = 55 cm
F400	3138 kN	40 cm beech plywood	D = 30 cm	D = 55 cm

4.3. Butt joint bonding

To connect the slab elements rigidly together, various methods were evaluated between 2009 and 2012. Only a bonded butt joint technology can fulfil the broad requirements. So far, no certified adhesive exists on the market for directly bonded butt joints. Purbond AG, part of the Henkel Group, has developed a 2-component polyurethane adhesive which can be used for the required purpose. In the first development stage, various geometries of bonded joints were examined. The simplest geometry to be produced was the butt joint, but also different profiles as v-rabbets and finger joints were examined [5]. In various experimental tests it was studied which thickness of joints could be filled considering different conditions such as different temperatures or joint widths. More than 1’000 tensile tests on lamellas in 24 series have been carried out [[5],[6],[7],[8],[9],[10],[11]]. From these tests, important conditions and requirements for quality assurance were established. Füllemann [6] further examined different influences on building site: minimum joint thickness, temperature, moisture content, soiling with oil or dust, movement and vibrations and different types of pre-treatment of the connecting end-grain faces. Lehmann [11] finally determined by seven series of tests with totally over 250 test specimens statistically reliable strength values for the tensile and bending strength of a bonded butt joint in CLT plates. The tests allowed further a better understanding of the influence of moisture changes and the effects of long-term stresses on the bending strength of the bonded butt joint. The bending strength was determined in four-point bending tests illustrated in Figure 7 with variations of the thickness of CLT, wood moisture and load duration applied with springs as shown in Figure 8.

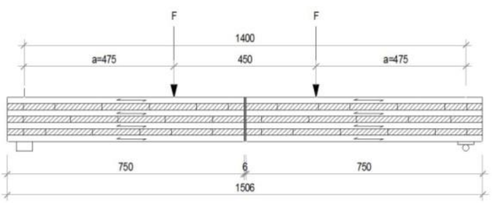

Figure 7. Four-point bending tests on butt joint bonded CLT-beams.

Figure 8. Long-term bending tests on butt joint bonded CLT-beams.

The results of this study showed a consistent good quality of the bonded butt joint. Through this progress, characteristic bending strengths from 15.6 N/mm^2 to 20.7 N/mm^2 were achieved depending on the wood moisture content and the load duration. These values were higher than all strength values reached before.

To reduce the appearance of bubbles in the glue line different techniques were tested most recently [12]. On the one hand, the roughness of the surface seemed to have an influence which was controlled by sanding the surface. On the other hand, different methods to seal the grains were developed and tested. Tensile strength test results showed that there was a considerable increase of mean tensile strength when combining sanding with roughness P 100 and applying a pre-treatment to the of end-grain surface. By sanding the end-grain surface, the intensity of bubbles occurred was reduced to a maximum of 10% of the complete fracture surface area. Latest results of tensile strength tests on butt joint bonded boards with improved adhesive formulation show a characteristic tensile strength higher than 15 N/mm^2. As tensile tests always show lower values than bending tests, an increase in bending strength can be expected. Specimens of this series show partly ripped out wood fibres. To examine that, broken specimens were rejoined with fluorescent PVAC adhesive and examined under the UV-light microscope. This is shown in Figure 9 [12]. The actual rupture line is visible through the fluorescent PVAC adhesive and the numbers indicate ripped out fibres (1), adhesive (2) and wood (3).

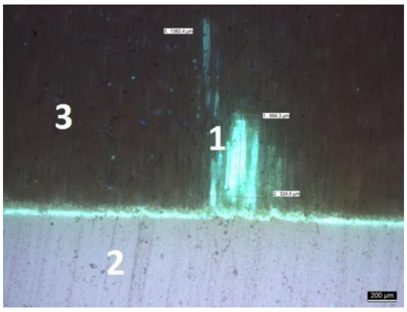

Figure 9. UV-light microscopy picture of broken and rejoined tensile specimen

As research is continuing, even higher strengths of the butt joint bonding are expected. Further research is also done in the process of how to implement the TS3 system the most economical way, meaning e.g. the conservation of the pre-treated surface and on-site construction processes. As in timber structures often serviceability or in other words deformation and vibration are governing a design, the achieved bending strength of the bonded butt joint are already sufficient to build biaxial, point supported flat slabs with a column grid up to 8 m by 8 m.

5. Proof of concept

In the last two years several projects were built with the bonded butt joint technology. In the following, three selected projects are presented.

5.1. Real scale, long term test ETH Zurich

The first real scale structure with a bonded butt joint was built at ETH Zurich in April 2017. Four 26 cm thick and 3 m by 3 m large CLT plates were glued together creating a corner supported 6 m by 6 m slab. The slab was subjected to a distributed load of total 96 kN representing a permanent load in an office building. A roof protected the slab from heavy rain. Since 2017 the slab has been exposed to moisture and temperature changes and also rain, as the roof was leaking several times. Nevertheless the slab showed no signs of weakness. Deformation measurements showed a creep factor of 1.3 after one and a half years. The slab was disassembled in April 2019 and will be reassembled at another place to continue the long-term experiment.

Figure 10. Real scale, long term test at ETH Zurich

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012144 doi:10.1088/1755-1315/323/1/012144

5.2. Working platform Wangen b. Duebendorf

In spring 2017 the timber construction company Flueck Holzbau decided to build a new working platform in their factory. The platform was assembled out of three 13 m by 2.5 m large and 36 cm thick CLT slabs glued together along the long side. The slab is line supported on both sides over the 13 m. The slab is designed to withstand distributed loads up to 500 kg/m^2. To reinforce the slab and to avoid large deflections 14 steel bars were inserted into the slab and later post-tensioned. Three load cells were installed to monitor the behaviour of the post-tensioning.

Figure 11. Working plattform in use

Figure 12. Post-tensioned working plat- tform

5.3. Residential buildings Grossaffoltern

Four three storey residential buildings were built close to Biel in the second half of 2018. The floor plans are 12 m by 7 m rectangles with surrounding line supports and three, respectively four (in the left apartment of Figure 14) columns aligned in the centre of the slab. The flat slabs were built out of three and four 16 cm thick and 12 m by 2.5 m large CLT slabs glued together at the long sides.

Figure 13. Residential building

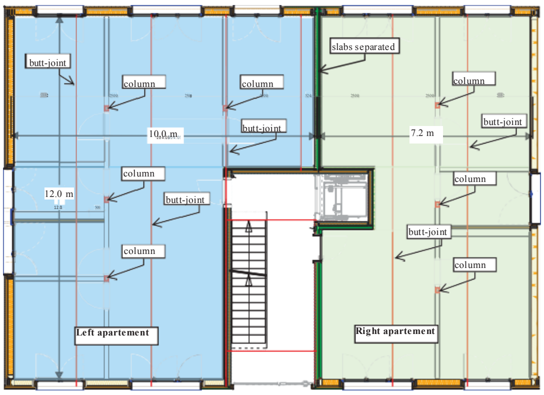

Figure 14. Layout of the CLT slabs

To validate the structural design of the biaxial, point supported slab ETH Zurich performed vibration measurements at different stages of construction. This measurements will help to op- timize future projects.

6. Outlook

The research about the slab to column connection is mostly finished. The next step will be the combination of the design guidelines to provide engineers a reliable and user-friendly design approach. To this design approach a guidance on improving the robustness of the CLT flat slab will be added as soon as the research about this topic is completed. The research about the bonded butt joint is continuing as there is still potential to increase both bending and tensile strength. Besides that, the research team is working on a European Technical Assessment (ETA) for the butt joint bonding.

7. Acknowledgement

The project is a collaboration of Timbatec AG, Timber Structures 3.0 AG, Schilliger Holz AG, Henkel & Cie. AG, ETH Zurich and BFH Biel. Gratefully acknowledged by the authors is the intense cooperation among the partners of this project, as well as Innosuisse, which is funding the ongoing project in large part.

Article I. References

[1] S. Zöllig, A. Frangi, S. Franke, and M. Muster. Timber Structures 3 . 0 – New Technology for Multi-Axial , Slim , High Performance Timber Structures. In *World Conference on Timber Engineering (WCTE2016)*, Vienna, Austria, 2016.

[2] J.Selberherr. StadtausHolz–aktuelleMarktentwicklungen. *SonderpublikationvonTEC21–Schweizerische Bauzeitung, der Fachzeitschrift für Architektur, Ingenieurwesen und Umwelt*, pages 8–11, 2018.

[3] L. Boccadoro. *Experimentelle Untersuchungen zum Durchstanzen von Holzdecken (Flachdecke)*. Master's thesis, ETH Zurich, 2012.

[4] M. Muster and A. Frangi. Punching behaviour of continuous two-way CLT flat slabs at interior connections to columns. In *World Conference on Timber Engineering (WCTE 2018)*, Soeul, Korea, 2018.

[5] A. Schawalder. *Untersuchungen zu baustellentauglichen Verbindungen mittels Hirnholzverklebungen im Holzbau*. Master's thesis, Berner Fachhochschule, 2013.

[6] U. Fuellemann. *Untersuchungen ausgewählter Parameter von stirnseitigen Holzverklebungen.* Master's thesis, Berner Fachhochschule, 2014.

[7] M. Geck and S. Passerini. *Erarbeitung eines Delaminierungsprüfverfahrens für stumpfe, stirnseitige Kebstoffverbindungen*. Master's thesis, Berner Fachhochschule, 2014.

[8] T. Koelmann. *Untersuchungen zu stirnseitig verklebten Bauteilen mit Biegebeanspruchung im Holzbau*. Master's thesis, Berner Fachhochschule, 2014.

[9] F. Kunz. *Untersuchungen zur stirnseitigen Verklebung von Holzbauteilen.* Master's thesis, Berner Fachhochschule, 2015.

[10] D. Angehrn. *Tragverhalten von stirnseitig verklebten Brettsperrholzplatten*. Master's thesis, ETH Zurich, 2015.

[11] T. Lehmann. *Ermitteln von Bemessungswerten für tragende stirnseitige Verklebung mit Biegebeanspruchung im Holzbau*. Master's thesis, Berner Fachhochschule, 2015.

[12] A. Themessl, M. Lehmann, D. Salzgeber, and S. Franke. Butt joint gluing of cross laminated timber. In *World Conference on Timber Engineering (WCTE 2018)*, Seoul, Korea, 2018.