

TIMBER STRUCTURES 3.0 - NEW TECHNOLOGY FOR MULTI-AXIAL, SLIM, HIGH PERFORMANCE TIMBER STRUCTURES

S. Zöllig¹, A. Frangi², S. Franke³, M. Muster⁴

¹Timbatec, Stefan.Zöllig@timbatec.ch

²ETH Zurich, frangi@ibk.baug.ethz.ch

³BFH Biel, steffen.franke@bfh.ch

⁴ETH Zurich, marcel.muster@ibk.baug.ethz.ch

This paper was originally published for WCTE 2016 in Austria.

KEYWORDS

Butt-joint bonding, Biaxial load bearing, Timber flat slab, CLT

ABSTRACT

Until today, all known timber building systems allow only slabs with a uniaxial load bearing action. Thereby, in comparison to normal reinforced concrete slabs, timber slabs are often thick, expensive and complicated to build. The reason for this is that there is no efficient connection technology to rigidly connect timber slab elements to each other. Alternative solutions are hybrid structural systems with concrete or steel, however, this combination of materials results in some disadvantages especially in terms of weight, ecology, construction time and costs.

In the framework of a large research project a new timber slab system has been developed and already tested in first real applications. The developed slab system is designed for housing, commercial and industrial buildings. The slab system works as a flat slab carrying vertical loads biaxial and consists of timber slab elements like CLT glued together on site with a high performance butt-joint bonding technology. Research about the central slab element, the butt-joint bonding and fire tests have already been performed. The research showed the feasibility of this innovation. In 2015 a first prototype was built in Thun, Switzerland. A large three year research project started 2016 with the goal to reach market maturity.

1 INTRODUCTION

Since 2009 the Swiss Engineering Company Timbatec, ETH Zurich, BFH Biel, Purbond (Henkel Group) and Schilliger Holz are working together in a project called "Wooden slabs in commercial and industrial buildings". The objective of the project is the development and implementation of a biaxial load carrying timber flat slab based on elements like CLT glued together on site with a high performance butt-joint bonding technology. In the meantime several bachelor and master theses were performed. The results from the research projects are promising: On one hand, it was proved that it is possible to produce timber flat slabs

with a column grid up to 8.00 x 8.00 m and a live load of 5 kN/m² [3, 4]. This at a comparable cost to normal reinforced concrete flat slabs, but only with one-fifth of the weight and with barely no CO₂ emissions. On the contrary, a large amount of CO₂ is being stored within the structure. The research project has led to a first prototype ready to be built. Further, the newly developed bonding connection technology opens new fields of application for timber constructions. Timber beams by almost any length or plates of almost any dimension can be produced. For example, rigid walls, floors or shells of any shape can be made. This development is so ground breaking, that one can speak of a new generation in timber construction.

2 EVOLUTION OF TIMBER STRUCTURES

2.1 Timber Structures Generation 1.0: Trunk and beams

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.

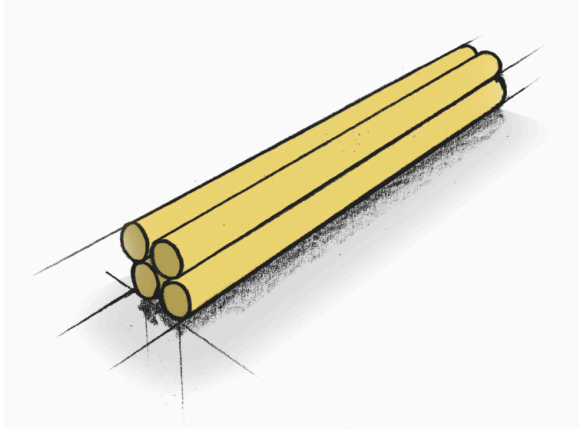


Figure 1: Timber Structures 1.0: Trunks and beams.

2.2 Timber Structures Generation 2.0: Glulam and CLT

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 and longer than a tree. Also curved structural beams are possible. Massive CLT panels of a size up to around 3.40 m width and 20 m length can be industrially produced today.

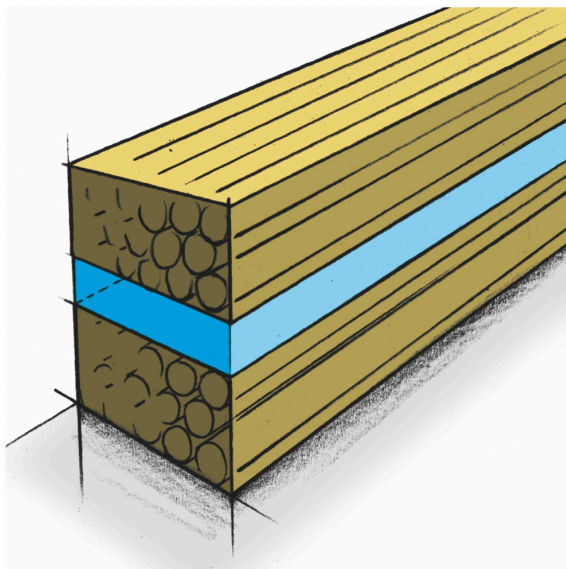


Figure 2: Timber Structures 2.0: Glulam and CLT.

2.3 Timber Structures Generation 3.0: Butt-joint bonding technology

The current development now allows the butt-joint bonding of fibres and therefore can lead to the 3rd generation in timber, called and patented as Timber Structures 3.0. However, for a wide application of this innovative technique further research is necessary.

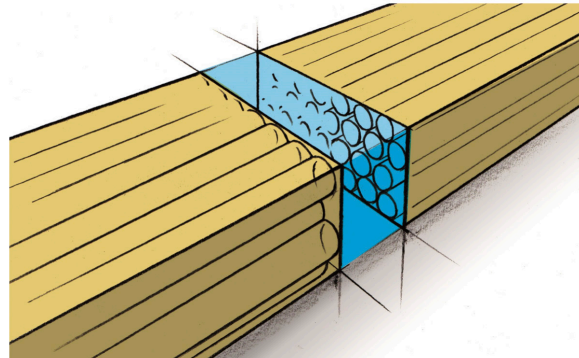


Figure 3: Timber Structures 3.0: Butt-joint bonding technology.

3 RECENT RESEARCH

3.1 Structural System

The aim of the newly developed technology is to be able to realise typical skeleton buildings with timber as shown in Figure 4, consisting of only glued timber elements, without using fasteners like screws, nails or metal plates. The main building parts are walls for the lateral structural system and columns and flat slabs for the vertical structural system. The main challenge is the development of a biaxial high performance load bearing timber slab.

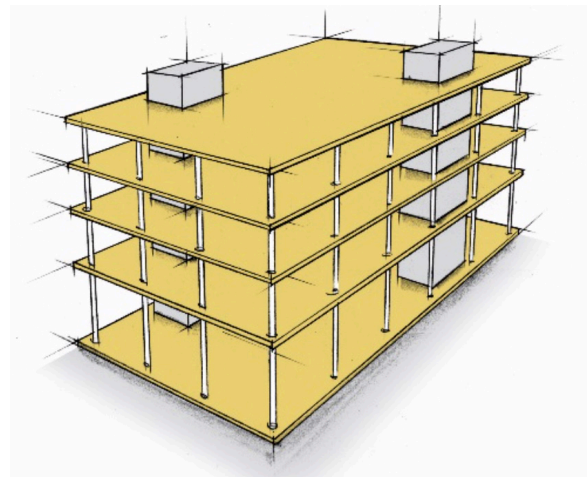


Figure 4: Typical skeleton structure.

Due to constraints of prefabrication, transportation and assembly processes, it is essential to divide any type of floor plans into slab elements in an efficient way. In a parametric study the typical floor plan shown below has been found to be most suitable. The green elements should transfer the load biaxial to

the uniaxial load bearing red elements which transfer the load to the central elements marked in blue around the columns. The blue elements are similar to the reinforced concrete flat slabs subjected to high bending moments and shear forces.

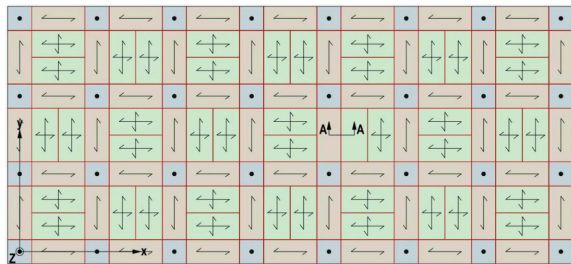


Figure 5: Floor plan.

3.2 Central column slab elements

A fundamental static issue is the highly stressed area around the column and how a reinforcement of the central slab elements against punching of the column is possible. Boccadoro made a theoretical analysis and tested 6 different layer constructions in 1:1 scale for verification [1]. Main material for the central slab elements was LVL made of beech, which has very good mechanical properties compared to common softwood. Six specimens were tested for punching at ETH Zurich: Three homogeneous massive plates made of beech plywood and three hybrid plates made of beech plywood and common spruce boards. The plate thickness was 240 mm, 320 mm and 400 mm. A basic study showed the benefit of the beech plywood based material in terms of bending and shear strengths. With simple static models at first hand and later on using a FE-program the expected load carrying capacity of the central slab elements was estimated. Then, six central slab elements of 2.5 x 2.5 x 0.24, 0.32 and 0.40 m were tested on the strong floor at the ETH Zurich. The slab elements were loaded by a centrally located cylinder to simulate the effect of the introduction of force into the slab. The specimens failed at forces between 1'150-3'100 kN. These values are very high and show the great potential of the mechanical properties of the slab elements made of beech LVL.

The crucial part of the evaluation was the analysis of the observed very ductile behaviour of the beech plywood slab elements, which is rather exceptional in timber construction as timber usually behaves in a brittle manner. This ductile behaviour can be explained with the hypothesis of stress redistribution in the width and partially in the height of the cross-

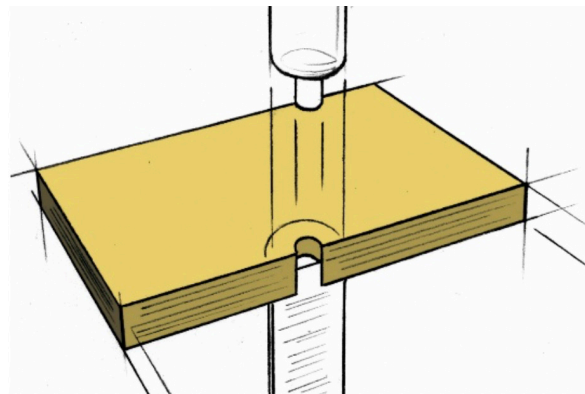


Figure 6: Central slab element on top of a column.

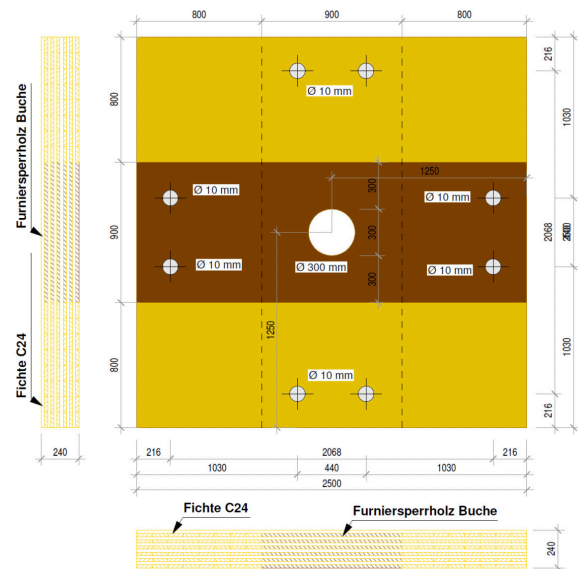


Figure 7: Central column slab element tested at ETH Zurich for punching (hybrid specimen).

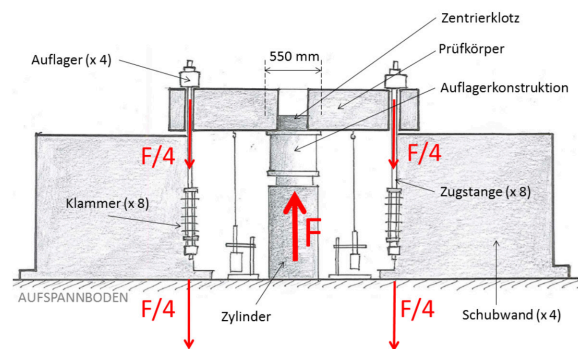


Figure 8: Test set-up of a central column slab element.

section. While the cracks grow outward, the central area of the board is relieved progressively and the bending stresses are transferred to the outer area of the element. At the homogeneous specimens, the plateau of maximum force is more distinct compared to the one in the hybrid specimens [1,5].

3.3 Butt-joint bonding

To connect the slab elements to each other, various methods were evaluated. Geometric form-fitting such



Figure 9: Testing a central slab element at ETH Zurich.

Table 1: Results from punching shear tests on central slab elements

Slab	Load carrying capacity			Effective Force	Load bearing safety
	Test results	Characteristic value	Design value SIA 265		
	$F_R = F_{cr}$	F_{Rk}	$F_{Rd} (\gamma_M / \eta_M = 1.5, \eta_w = \eta_c = 1)$	F_{Ed}	$F_{Rd} \geq F_{Ed}$
Name	kN	kN	kN	kN	
K240	1'362	800	533	690	Not ok
F240	1'155	1'026	684	690	Not ok
K320	1'700	1'515	1'010	700	Ok
F320	2'100	1'951	1'300	700	Ok
K400	2'500	2'328	1'552	710	Ok
F400	3'099	2'878	2'066	710	Ok

K = beech plywood and spruce boards combined
F = beech plywood

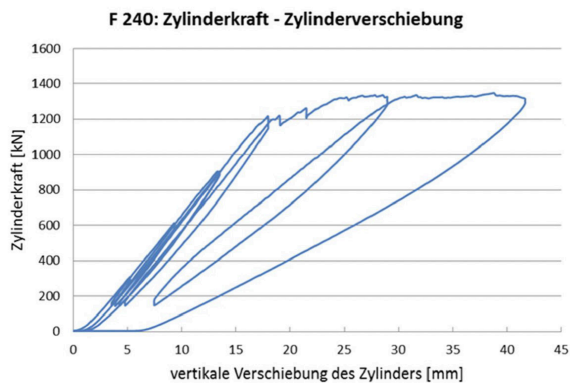


Figure 10: Ductile behaviour of central slab element F240.

as a terracing or tongue and groove would lead to expensive machining time and massive consumption of material through the double plate surface in the connecting area. Due to the transverse tensile stresses at the terracing, the plates would have to be provided with additional reinforcements. Finger joints are susceptible to damage and carry low tensile stresses perpendicular to grain if they are arranged careless. Therefore a bonded butt joint technology

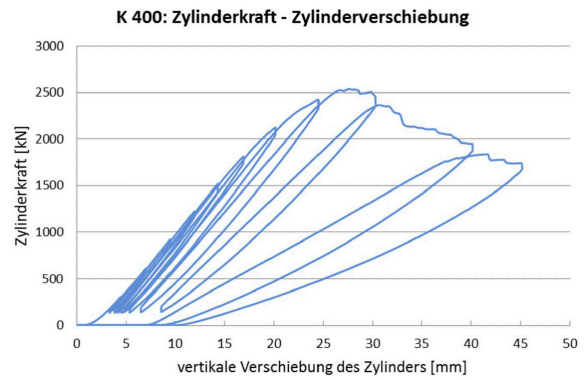


Figure 11: Ductile behaviour of central slab element K400.

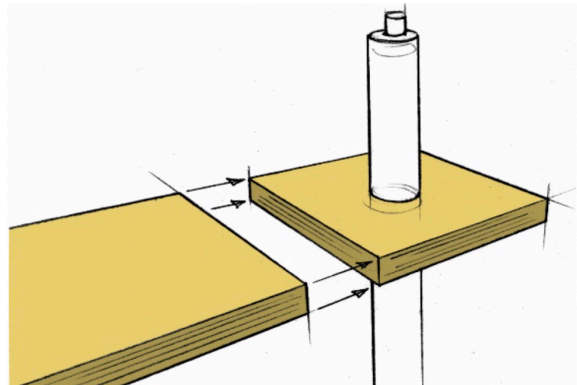


Figure 12: How to connect slab elements?

was envisaged. So far, no certified adhesives 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 purposes.

In the first development, 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 [6].

In various experimental tests it was studied which thickness of joints could be filled taking into account for different circumstances such as different



Figure 13: Butt-joint bonding of lamellas [6].



Figure 14: Butt-joint bonding of lamellas while testing [6].

temperatures or joint widths. Over 1'000 tensile tests on lamellas in 17 series have been carried out [6,7,8,9,10,11,12]. The filling procedure from below is very important, so that any air bubble moves to the top and no air pockets are created. From these tests, important conditions and requirements for quality assurance were established. Füllemann [7] 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.

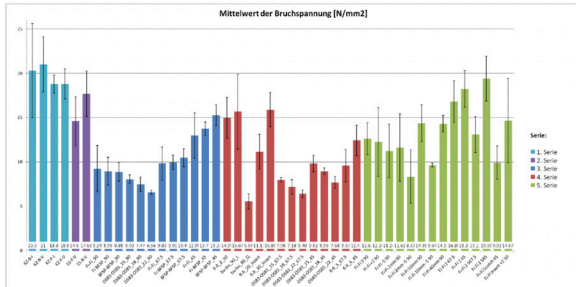


Figure 15: Results of tensile tests.

Lehmann [12] 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 of 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, with different variations of geometry, wood moisture and load duration.

The results of studies showed a consistent good quality of the bonded butt joint. Through this progress, characteristic bending strengths from 15.6 N/mm² to 20.7 N/mm² were achieved. These values are higher

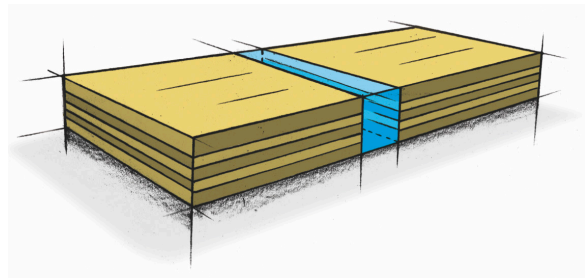
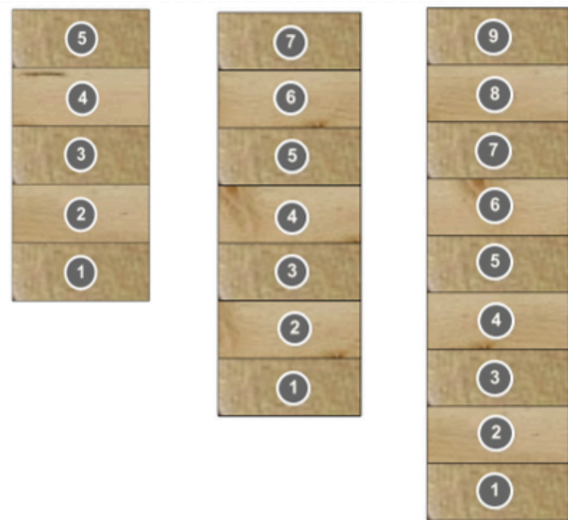


Figure 16: End-grain bonding of CLT-plates.

than all strength values reached before.

The studies on the influence of moisture showed that an increased moisture content of the wood lead as expected to a reduction of the bending strength. In addition, it was recognised that the moisture content depends on the cutting direction and the positioning of the boards in the test specimen and the flow of moisture into the wood is mainly problematic in the lateral zones. In the studies about the effects of a long-term loading no significant change in strength was observed.



Querschnitt 1 Querschnitt 2 Querschnitt 3
Figure 17: CLT cross-sections 50 x 100 / 140 / 180 mm for bending tests.

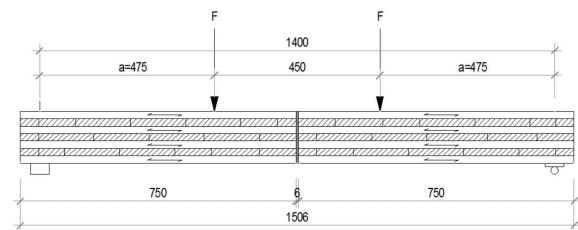


Figure 18: Four point bending tests on CLT-beams with bonded butt joint in the middle span of the specimen.

3.4 Fire tests

In the master thesis of Bühlmann [2] small-scale and large-scale fire tests on butt bonded plywood and CLT-



Figure 19: Long-term load bending tests on CLT-beams with bonded butt joint in the middle span of the specimen.

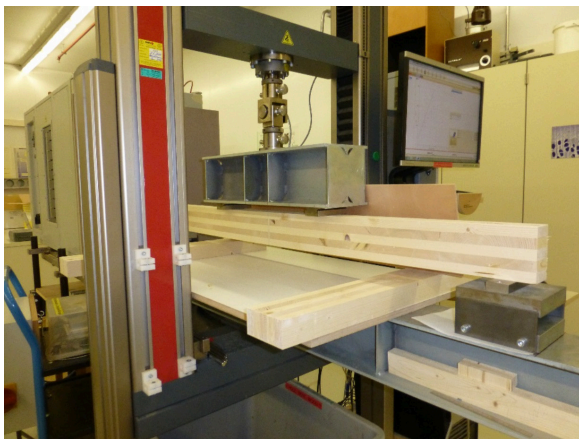


Figure 20: Test set-up for bending tests on CLT-beams.

plates were performed (see also [13]).

Six small-scale fire tests were carried out with four different bonded butt joints each. The specimens made out of beech plywood and spruce CLT had the dimensions of 1.2m x 0.9m and had each two 6mm and 12mm wide joints. The test specimens were exposed to ISO standard fire curve for 30, 60 and 90 minutes on one side. With thermocouples temperatures were recorded in the joints. After the fire test the char layer was removed and the charring depth was determined.

Table 2: Results of the bending tests on CLT-beams

Übersicht Ergebnisse	Serie 1	Serie 2	Serie 3	Serie 4	Serie 5	Serie 6	Serie 7	Referenzserie
Schaumbildung [1-3]	0.7	0.56	0.7	0.9	0.5	0.63	0.94	1
Anteil Fügeteilbruch [%]	2.34	2.13	2.27	4.13	0.53	0.53	2.77	0.20
Anteil Kohäsionsbruch [%]	16.48	19.02	18.80	18.59	17.86	15.97	17.10	4.60
Anteil Adhäsionsbruch [%]	81.17	78.86	78.93	77.28	81.55	84.53	80.10	95.20
Mittelwert Bruchspannung [N/mm ²]	25.69	22.2	24.69	21.10	20.22	19.92	21.26	16.60
Standardabweichung [N/mm ²]	3.67	3.09	3.43	2.5	2.0	2.57	2.92	5.20
Variationskoeffizient: [N/mm ²]	14.3	13.9	13.89	11.89	16.68	12.89	13.75	31.25
Charakteristischer Wert m_k [N/mm ²]	20.77	17.00	18.52	16.62	16.68	15.65	16.35	12.16
Designwert m_d [N/mm ²]:	9.10	7.94	8.64	7.74	7.79	7.31	7.63	5.67

Thus the following main conclusions on the fire behaviour of the bonded butt joints can be made:

- The fire behaviour of the joints is similar to the fire behaviour of timber.
- The depth of charring in the joints is equal or less than for the residual cross-section of the specimens made of spruce CLT or beech plywood. The influence of the joint increases with the duration of the fire and the joint thickness.
- For the different joint thicknesses and specimens charring rates could be determined as followed:

Table 3: Results of the small-scale fire tests on specimens made of spruce CLT and beech plywood

Fichte BSP	6mm Fuge	$\beta_0 = 0.59\text{mm/min}$
		$\beta_{\text{schicht2}} = 0.77\text{mm/min}$
Fichte BSP	12mm Fuge	$\beta_0 = 0.52\text{mm/min}$
		$\beta_{\text{schicht2}} = 0.53\text{mm/min}$
Buche FU	6mm Fuge	$\beta_0 = 0.66\text{mm/min}$
		$\beta_{\text{schicht2}} = 1.07\text{mm/min}$
Buche FU	12mm Fuge	$\beta_0 = 0.66\text{mm/min}$
		$\beta_{\text{schicht2}} = 0.78\text{mm/min}$



Figure 21: Small-scale fire test on spruce CLT-plate after removing the char layer.

In order to verify the overall global structural behaviour of the slab system, a large-scale fire test with a loaded CLT asymmetric plate was carried out on the horizontal furnace at EMPA in Dubendorf. The CLT plate had the dimensions of 5.35 x 2.85 x 0.2m and was manufactured of four CLT elements with three bonded butt joints.



Figure 22: Bonding of CLT elements for the large-scale fire test.

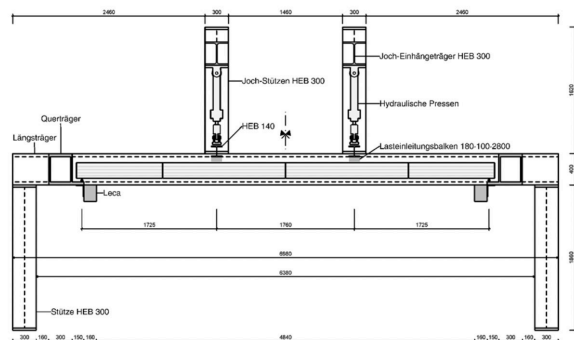


Figure 23: Test set-up for the fire test (longitudinal section).

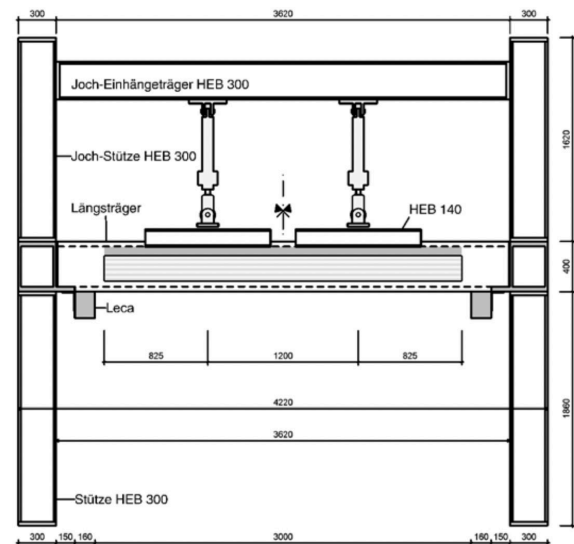


Figure 24: Test set-up for the fire test (cross-section).

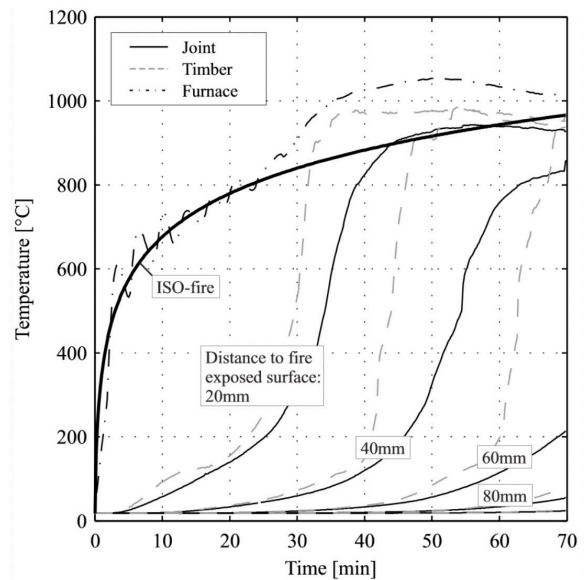


Figure 25: Temperature development in the CLT plate at different locations during the large-scale fire test.

The specimen was supported as a simple beam and loaded during the fire test with a constant load of 4 x 8 kN in the third points. The load level for the fire design was calculated according to Swiss Standards SIA 260 and SIA 261 for an office building taking into account a span of 8m and a biaxial action of the CLT plate. The temperature was recorded with thermocouples on the surface, between the layers of the CLT plates and in the joint. In addition, the vertical deformation and the load were measured.

The main results of the large-scale fire tests can be summarized as followed:

- The CLT-plate with bonded butt joints reached a fire resistance of 69 minutes.
- The CLT-plate failed due to brittle failure of the bonded butt joint.

4 PROOF OF CONCEPT

A multi-storey apartment house was built with the Timber Structures 3.0 technology in Thun, Switzerland in 2015.

5 FUTURE RESEARCH

For the further development of the innovative technology a 1.3 Million CHF research project has recently been approved. It will be carried out from 2016 to 2019.



Figure 26: Building site of a multi-storey building Thun, Switzerland.

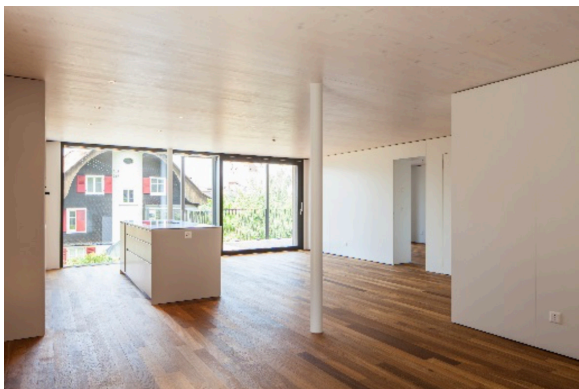


Figure 27: Timber Structures 3.0 flat slab.

6 CONCLUSIONS

The Timber Structures 3.0 technology marks the start into a completely new way of thinking and designing timber structures. The novel technology opens a wide field of new applications in research, technologies and markets.

RESEARCH PARTNERS

Research Partners: Timbatec Holzbauingenieure Schweiz AG and Timber Structures 3.0 AG (Stefan Zöllig), Berner Fachhochschule BFH Biel (Steffen Franke, Andreas Müller), ETH Zurich (Andrea Frangi), Purbond AG of the Henkel Group (Christian Lehringer), Schilliger Holz AG (Ernest Schilliger and Werner Leibundgut).

REFERENCES

- [1] Boccadoro L.: Experimentelle Untersuchungen zum Durchstanzen von Holzdecken. Master Thesis, ETH Zürich, Institut für Baustatik und Konstruktion, 2012.
- [2] Bühlmann A.: Brandverhalten von stirnseitig

verklebten Brettsper Holzplatten. Master Thesis, ETH Zürich, Institut für Baustatik und Konstruktion, 2014.

- [3] Zöllig S.: Geschossdecken für Gewerbe und Industrie, Machbarkeitsstudie - Schlussbericht BAFU Aktionsplan Holz 2009. Timbatec AG, Thun, 2009.
- [4] Zöllig S.: Geschossdecken für Gewerbe und Industrie - Schlussbericht BAFU Aktionsplan Holz 2012. Timbatec AG, Thun, 2012.
- [5] Grüter B.: Untersuchungen zum Tragverhalten von Holzplatten aus Buche. Master Thesis, ETH Zürich, Institut für Baustatik und Konstruktion, 2013.
- [6] Schawalder A.: Untersuchungen zu baustellentauglichen Verbindungen mittels Hirnholzverklebungen im Holzbau. Berner Fachhochschule, Architektur Holz und Bau, Biel, 2013.
- [7] Füllemann, U.: Untersuchungen ausgewählter Parameter von stirnseitigen Holzverklebungen. Berner Fachhochschule, Architektur Holz und Bau, Biel, 2014.
- [8] Geck, M., & Passerini, S.: Erarbeitung eines Delaminierungsprüfverfahrens für stumpfe, stirnseitige Keibstoffverbindungen. Berner Fachhochschule, Architektur Holz und Bau, Biel, 2014.
- [9] Koelman, T.: Untersuchungen zu stirnseitig verklebten Bauteilen mit Biegebeanspruchung im Holzbau. Berner Fachhochschule, Architektur Holz und Bau, Biel, 2014.
- [10] Kunz, F.: Untersuchungen zur stirnseitigen Verklebung von Holzbauteilen. Berner Fachhochschule, Architektur Holz und Bau, Biel, 2015.
- [11] Angehrn, D.: Tragverhalten von stirnseitig verklebten Brettsper Holzplatten. Master Thesis, ETH Zürich, Institut für Baustatik und Konstruktion, 2015.
- [12] Lehmann, T.: Ermitteln von Bemessungswerten für tragende stirnseitige Verklebung mit Biegebeanspruchung im Holzbau. Berner Fachhochschule, Architektur Holz und Bau, Biel, 2015.
- [13] Klingsch E., Klippel M., Boccadoro L., Frangi A.,

Fire tests on cross-laminated timber slabs and concrete-timber composite slabs, Test report, Institute of Structural Engineering, ETH Zurich, 2016.
