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SOLUTIONS FOR EDGE CONNECTIONS TO BUILD TWO-WAY SPANNING CROSS LAMINATED TIMBER SLABS

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ABSTRACT: Two-way spanning slabs made of cross laminated timber (CLT) require a rigid connection of the single elements. In particular for point-supported flat slabs this connection is necessary to enable spans that exceed the transport-related width of the single CLT-elements. The paper shows solutions how this connection could be designed and realized. In addition to the load-bearing capacity, especially the rotational stiffness is a crucial factor for the edge connection. A certain stiffness is needed to meet the requirements of a floor in terms of serviceability. To determine the load-bearing capacity and stiffness, four-point bending tests were performed on different types of possible edge connection solutions. The investigations revealed two connection types that meet the specified criteria without on-site gluing. One approach consists of a timber-concrete-composite system. Here, reinforcing bars are glued into the narrow surface of the CLT-element and the gap between the adjacent CLT-elements is then casted on-site. A second, completely dry application is to use a system connector with serrated steel plates. This serration ensures the force transmission between the CLT-elements by the connector. In addition to the results of these two types, also further options for the edge connection are presented.

KEYWORDS: Cross laminated timber, two-way spanning slab, flat slab, joints, edge connection, rotational stiffness

1 INTRODUCTION

The Unit of Timber Engineering at the University of Innsbruck has been intensively investigating point-supported flat slabs within the last few years [1-3]. This construction method has its architectonical charm, because it avoids walls and joists, enabling a much more flexible floor plan and increasing the effective living space. An essential structural characteristic of this construction method is the biaxial load carrying capacity of the flat slab. Cross laminated timber (CLT) could be a very suitable material for point supported flat slabs due to its bonded, crosswise layers. However, if the column grid of the floor exceeds the transport and production related maximum width and length of the CLT panels (width: 2.5 – 3.5 m, length ≤ 22 m), a supporting system with joists is still used by the designers most of the time, see Figure 1. The CLT is thereby only loaded in one direction. Nevertheless, the aim is to build flat slabs with a column grid of 5.0 to 7.0 m without any joists to compete with conventional concrete construction. This poses two major challenges from a structural point of view. One of them is the high load concentration in the area of the point support. This topic is treated very comprehensively in the works of [4-6], for example. Secondly, due to the limited width and length, the panels need to be connected on the construction site, so that a flat slab made of CLT can perform a biaxial load-bearing behaviour at all. This joint has to transfer mainly bending moments and shear forces. It should be easy to assemble, as rigid as possible and show ductile failure for reasons of robustness. This paper focuses on the edge connection of such CLT panels. Beginning with an overview of existing solutions for the joint, alternative approaches are shown and new systems are presented. For point supported flat slabs, requirements for the edge connection are defined and the experimental results for selected solutions are analysed in this respect. The findings about structural behaviour of CLT edge connections is not restricted to the use in a flat slab. The connection can also be applied for line supported CLT slabs in order to improve the system's stiffness (e.g. for a better dynamic behaviour), also rigid edge connections can increase the advantageous load-bearing behaviour of CLT near openings, see Figure 2.

Figure 1: *Types of point supported slab constructions with spans of 5 – 7 m*

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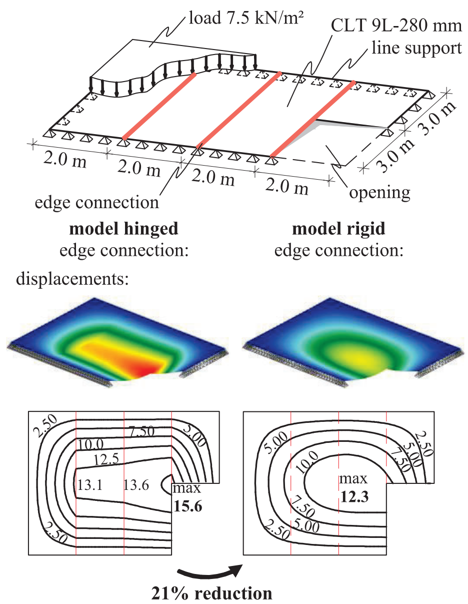

Figure 2: Benefit of rigid edge connection for a CLT slab with opening (exemplary)

2 SOLUTIONS FOR THE DESIGN OF THE CLT EDGE CONNECTION

2.1 OVERVIEW OF STATE OF KNOWLEDGE

For the construction of edge connections which enable the transmission of bending moments in addition to shear forces, approaches with splice plates are frequently found in the literature. The plates are usually made of wood-based panels. These are connected to the CLT either by means of screw press gluing [7] or by inclined screws [8]. The force transmission between the two elements takes place via the loading of either the screws or the adhesive joint and the plates. Tests on these types of connections have also been carried out at the University of Innsbruck [9]. A similar approach to enable a rigid connection in the secondary load-bearing direction of the CLT is presented in [10]. Here, the screw press gluing plates made of laminated veneer lumber (LVL) are additionally milled in with finger-joint like profiles.

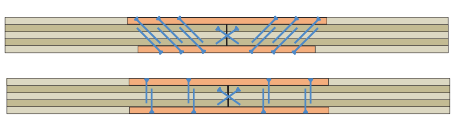

Figure 3: Solutions with wood-based panels and inclined screws or screw press gluing

In [11] a special two-component polyurethane adhesive is used for butt gluing of the full narrow surface of the CLT. The approach of glued-in perforated steel plates presented in [12] may also be used for the edge connection. A similar solution is also presented in [5], where sandblasted steel plates are applied. Apart from connections based mainly on adhesives, [2] presented a concept of a dovetail joint combined with a synthetic reaction resin. This solution adds a form closure to the chemical bonding.

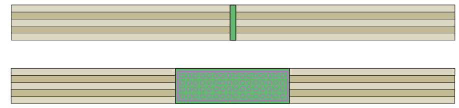

Figure 4: Solutions with adhesives (butt gluing and glued-in-perforated steel plates)

These investigations in the literature show a wide variety of solutions with different quality in terms of rigidity and load-carrying capacity. A comparison between different studies is difficult, because the authors didn´t use the same raw material or test setups.

2.2 CONCEPTS WITH CONVENTIONAL MATERIALS

In the work of [13], several solutions for the edge connection were investigated with tests in the laboratory using the same general conditions in each series (CLT dimensions and quality as well as the test setup). Therefore, four-point bending tests were carried out in order to determine the rotational stiffness and load carrying capacity of the edge connection. One solution was similar to the method presented in [8]. However, steel plates are used and fully threaded screws with angled washers were arranged inclined in the tension and compression zone of the edge connection. [13] used for another series self-tapping screws within a planar scarf joint. They should enable the transmission of bending moments and reinforce the CLT panel at once.
A further concept involves a butt joint where a post-tensioning system is installed to compress the joint and therefore enable the application of bending moments before a gap on the tension side of the element occurs.

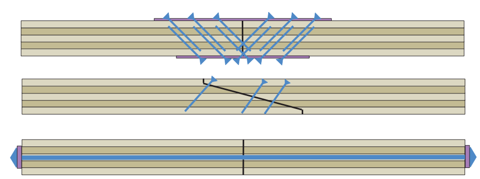

Figure 5: "Dry" solutions with conventional construction materials

Another approach in [13] was the use of glued-in reinforcing bars for realising the joint by a timber concrete composite (TCC) system. Here, a lap splice of the reinforcement was created between the two narrow surfaces. The resulting gap is further reinforced acc. to EN 1992-1-1 and then casted with standard concrete. A comparable method was suggested in [14] for the construction of two-way spanning TCC slabs.

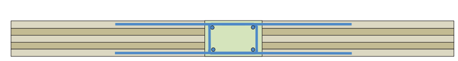

Figure 6: Timber concrete composite solution [13]

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The results from [13] give the opportunity to compare several construction types in terms of the rotational stiffness of the joint solutions and also the load-carrying capacities. Hence, the next chapters will refer to this work more often.

2.3 CONCEPT WITH SERRATED STEEL PLATES

The Unit of Timber Engineering at the University of Innsbruck is currently developing a new connector for edge connections, which is based on steel plates with micro-teeth [15]. The principle function of this system is illustrated in Figure 7. With the help of pre-tensioned threaded rods, wedges are used to press micro teeth of steel plates into the milled slot surfaces of the CLT. The force is transmitted via the connectors steel plates and the interlocking between the CLT panel and the numerous small teeth.

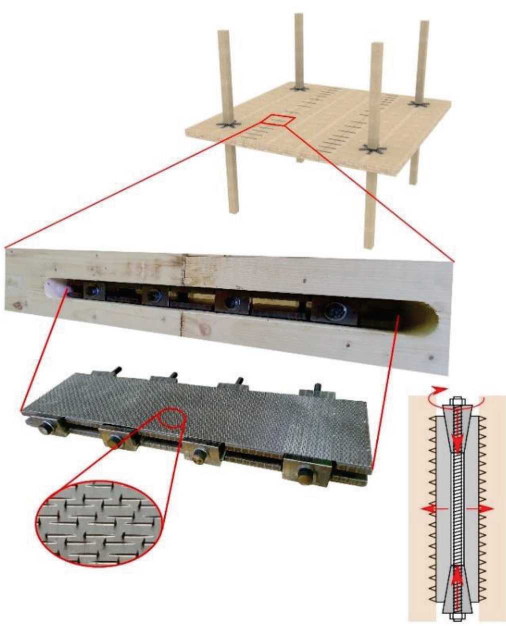

Figure 7: *System connector with serrated steel plates – operating principle [16]*

The major advantage using this type of connection is the mechanical interlocking between the serrations and the timber. As shown later, high stiffnesses with ductile failure can be achieved with this method. Due to the small teeth, the insertion resistance can be reduced compared to punched metal plate fasteners. The pre-tensioning of the threaded rods is intended to ensure the permanent insertion of the teeth over time.

3 INFLUENCE ON VIBRATIONS AND BENDING MOMENTS

Connections are often simplified as rigid or hinged. This section will show how important it is to take the real stiffness into account when designing point supported flat slabs. The focus is on the impact of the stiffness of the edge connections on the vibrational behaviour and the bending moments, even though the impact on deflections, the fire safety, the load carrying capacity or the robustness of the total structure are important aspects, too.
The edge connection between two CLT elements can be simplified to a rotational spring stiffness k_φ (see Figure 8). It´s actually obvious, that this spring has to be rigid and strong enough to prevent the formation of a kinematic chain in point supported flat slabs.

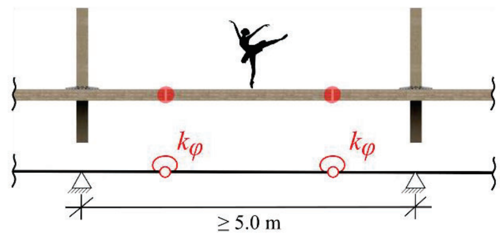

Figure 8: *Panel joints in point supported flat slab*

Within a parameter study of a simple floor system, the effect of the rotational stiffness of the edge connection is shown. The spans of a slab system with 3 x 3 fields are varied between spans of 5.0 and 7.0 m for different CLT element thicknesses (see Table 1). Figure 9 illustrates the model which was used for the parameter study. In general, this construction method requires the use of CLT with a layer structure that generates a balanced bending stiffness ratio ($EI_{ef,x}$ / $EI_{ef,y}$) between the main and secondary load-bearing direction, as shown in Table 1.

Table 1: *CLT used for the parameter study*

CLT depth	Layer	$EI_{ef,y}$ / $EI_{ef,x}$	Layup
200 mm	7	0.838	20-40-20-40-20-40-20
240 mm	9	0.946	20-40-20-20-40-20-20-40-20
280 mm	9	1.079	20-40-20-40-40-40-20-40-20
320 mm	9	0.910	20-40-40-40-40-40-40-40-20

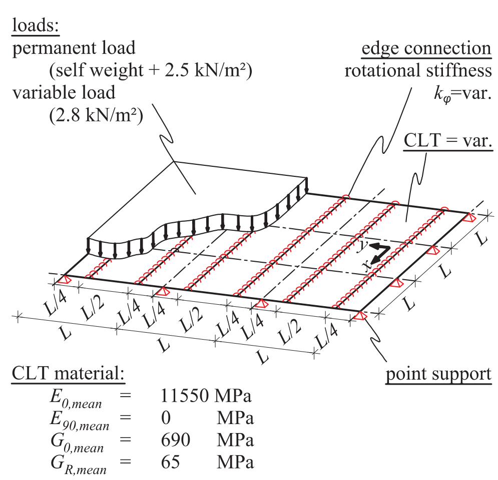

Figure 9: *Parameter study of a point supported flat slab*

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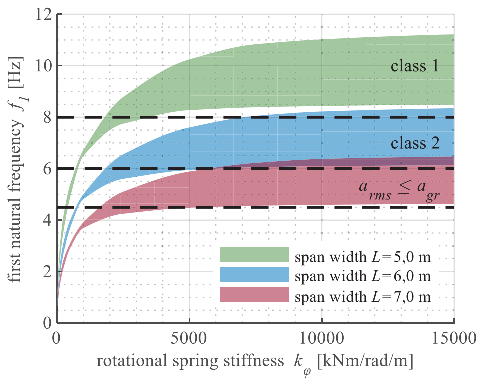

Figure 10: *Influence of rotational spring stiffness on first natural frequency (classification acc. frequency criterion in Eurocode 5)*

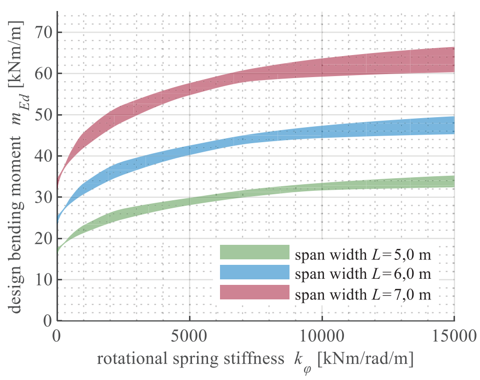

Figure 11: *Influence of rotational spring stiffness on maximum design moment*

The rotational stiffness of the edge connection significantly influences the floor's vibration behaviour. This is shown in Figure 10 by the relation of the first natural frequency of the slab and the rotational stiffness considered. However, it can also be seen that this influence is decreasing as the rigidity is increasing. This influence can also be observed for the maximum bending moment occurring in the edge connection. In the slab considered, this maximum moment occurs in the outmost connection of the end spans.
An important finding of this study is that completely rigid connections are not necessary for the application of the edge connection in point-supported flat slabs. Since connections with stiffness above 5000 kNm/rad/m only improve the investigated system to a minor extent.

4 DETERMINATION OF STIFFNESS AND LOAD CARRYING CAPACITY

The parameter study underlined the relevance of the bending load bearing capacity of the connection as well as the corresponding rotational spring stiffness.

4.1 EXPERIMENTAL APPROACH

Four-point bending tests can be carried out according to the specifications given in [17] in order to gather findings about stiffness and load-carrying capacity of different types of edge connections. By comparing the stiffness of the joined panel with a continuous one, the rotational spring stiffness of the connection can be determined from this test. This was already shown by [5] and described with Equation (1). Where a is the distance from the load to the bearing, l the static length of the specimen, F the full load of the hydraulic cylinder. The displacements w_{ref} and w_{con} are described in Figure 5. At best, the stiffness of a continuous panel is first determined non-destructively. Then the panel is cut, reconnected and finally tested again. However, the stiffness of the continuous CLT panel can be determined analytically too. An advantage of this approach is in general, that the rotation don´t have to be measured.

$$K_\varphi = \frac{a\,l}{8 \cdot \left(\frac{w_{con}}{F_{con}} - \frac{w_{ref}}{F_{ref}}\right)} \qquad (1)$$

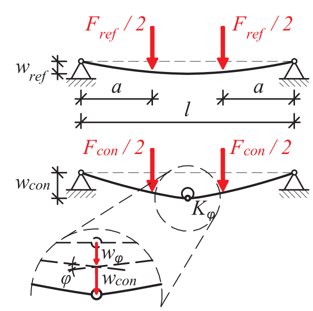

Figure 12: *determination of rotational stiffness of the edge connection*

4.2 INVESTIGATED SOLUTIONS

Seven different solutions of the edge connection were investigated by four-point bending tests. The detailed description can be found in Table 2 and in Figures 13 to 19. Series A, B, C, D, F and G were taken from [13].

Table 2: *Investigated solutions (n – number of tests, l & a acc. to Figure 12)*

Series	Solution	*n* [-]	*l* [m]	*a* [m]
A	butt joint	2	4.80	1.60
B	glued-in steel plates	3	4.80	1.60
C	inclined screws	3	4.80	1.60
D	scarf joint	3	4.50	1.50
E	post-tension system	3	4.75	1.58
F	TCC-system	3	4.80	1.60
G	system connector	3	4.20	1.40

For the tests, 240 mm thick, CLT elements with 7 layers were chosen with a layup of 30-40-30-40-30-40-30. Series A was also used as a reference test to determine the stiffness of a continuous panel. A two-component epoxy resin was used as adhesive. The same resin was used in Series B to glue in the perforated steel plates. The screws

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applied in the test complied with the European Technical Approval (ETA) [18]. For Series F, the used concrete quality was C30/37 with reinforcement steel B550. The post-tension system applied in Series E may be taken from ETA [19].

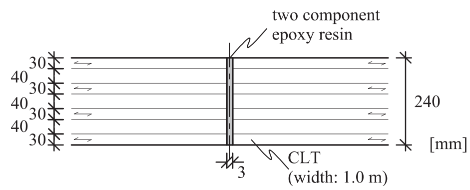


Figure 13: *Series A - butt joint - connection detail*

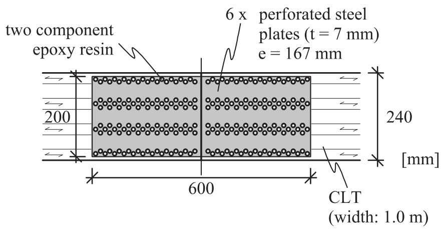


Figure 14: *Series B - glued-in steel plates - connection detail*

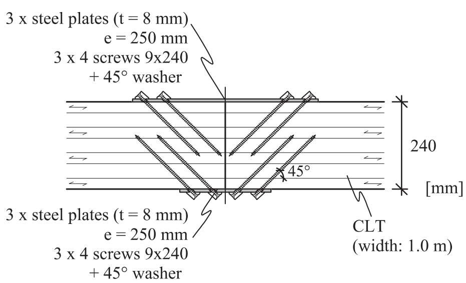


Figure 15: *Series C - inclined screws - connection detail*

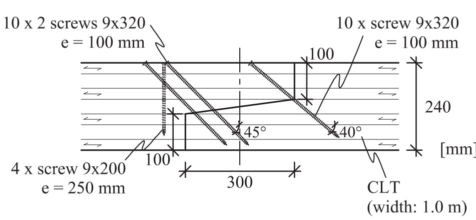


Figure 16: *Series D - scarf joint - connection detail*

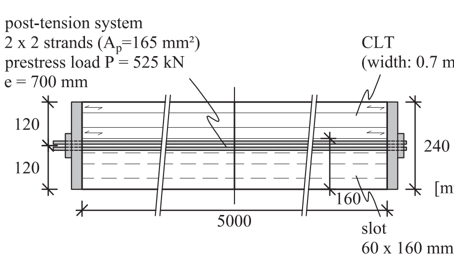


Figure 17: *Series E - post-tension system - connection detail*

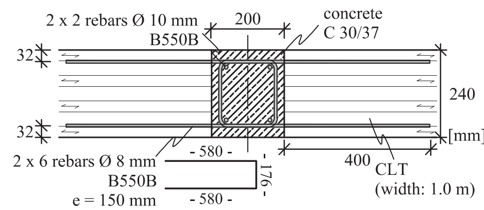


Figure 18: *Series F - TCC-system - connection detail*

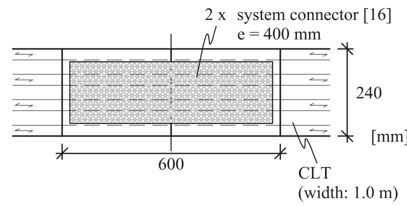


Figure 19: *Series G - system connector - connection detail*

5 RESULTS AND DISCUSSION

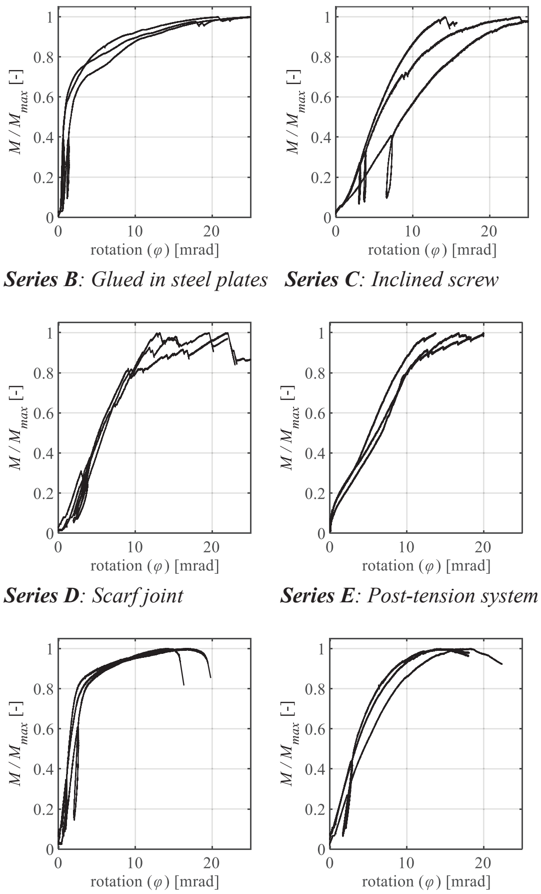
The main results of the investigations can be found in Table 3. In addition to the load bearing capacity, an overview of the rotational spring stiffnesses for each series is given. Due to the small number of tests, characteristic values are not stated.

Table 3: *Main results of the experimental study*

Series	F_{max} [kN]	m_{mean} [kNm/m]	$k_{\varphi,mean}$ [kNm/rad/m]
A	44.4 83.4	51.1	∞
B	169.3 167.3 164.4	133.6	∞
C	88.4 79.5 99.1	71.2	2170
D	64.9 73.6 64.3	50.7	2760
E	51.3 50.2 49.1	56.7	3840
F	39.8 46.9 47.5	35.8	14120
G	66.0 75.0 46.1	42.4	6170[1)]

[1)] Only tests 2 and 3 were considered. No global displacement transducers were used in test 1. For all 3 tests the same two system connectors were used.

Series A using the butt joint provided a reference stiffness of a continuous panel to determine the rotational stiffness of the remaining series. The specimens failed in a brittle manner on very different load levels.



***Series B**: Glued in steel plates* ***Series C**: Inclined screw*

***Series D**: Scarf joint* ***Series E**: Post-tension system*

***Series F**: TCC-system* ***Series G**: System connector*

***Figure 20:** Moment-rotation diagrams of experimental study*

The series with the glued-in perforated steel plates (Series B) failed in a much more ductile way. Here, very high load-bearing capacities were observed. The load-bearing capacity of the joint may be aligned to the load of the edge connection via the spacing of the glued-in plates. The failure of the test specimens was announced by an opening of the gap between the panels. This is due to yielding of the steel plates in this area. However, there was no difference in the initial stiffness between the reference tests (Series A) and the glued-in perforated steel plates. Therefore, both solutions may be classified as rotationally stiff connections. As presented in Figure 10 an absolutely rotationally stiff connection is not necessary for the use of an edge connection in a point supported flat slab.

The Series C using inclined fully threaded screws resulted in a clearly lower rotational spring stiffness. The initial spring stiffness is only about 2200 kNm/rad/m, although there is a clear increase in stiffness while unloading and reloading the specimens. The tests revealed tensile failure as well as withdrawal failure of the screws. The equivalent rotational spring stiffness of the planar scarf joint (Series D) is only insignificantly higher at around 2800 kNm/rad/m. The specimens failed in a more brittle manner than the series with inclined screws (Series C). Although screws perpendicular to grain were installed to avoid this failure, when reaching the load-bearing capacity, a failure combination of rolling shear and tension perpendicular to grain occurred. A corresponding image of the resulting cracks is presented in Figure 21.

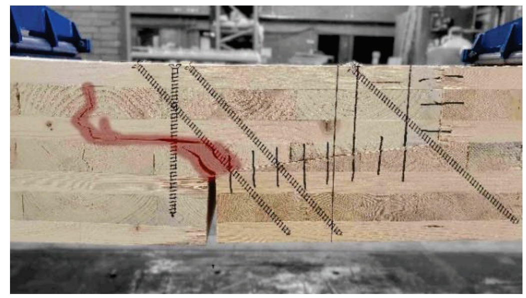


***Figure 21:** Failure of Series D - scarf joint (cracks coloured)*

The results of the rotational stiffness for the Series E using the post-tensioning system are also within this range. A stiffness of approx. 3800 kNm/rad/m is obtained here. The load was stopped when a clear decrease of the system stiffness occurred.

For the application in point supported flat slabs, the solutions for the edge connection of Series C, D and E do not meet the requirements stated in section 3. This is mainly caused by the insufficient rotational spring stiffness. However, Figure 22 shows the application of such a stiffness for a flat slab supported on all four sides. The numerical solution for the first natural frequency of a continuous slab corresponds well to the analytical solution according to [20].

Considering the individual CLT elements with a hinged connection reduces the eigenfrequency of the system significantly. Here, even the use of small spring stiffnesses can contribute to a system improvement.

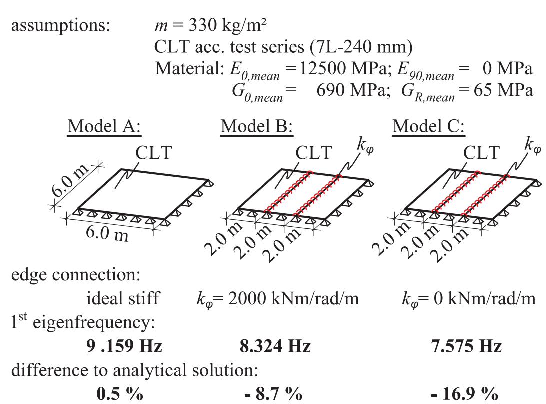


***Figure 22:** Influence of rotational spring stiffness on the first natural frequency for a flat slab supported on all four sides*

A much higher rotational spring stiffness was reached in Series F, using the TCC system. On average, a value of about 14100 kNm/rad/m could be achieved. In these tests the glued-in rebars started yielding before failure. This failure was announced by an opening of the gap between the concrete and the CLT panel.

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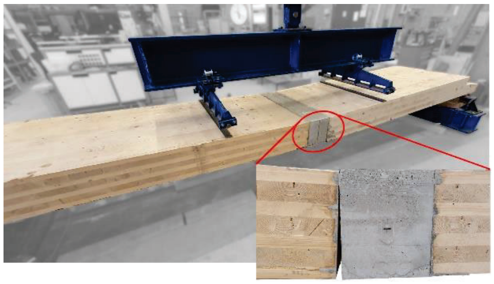

Figure 23: *Failed specimen of Series F - TCC system - opened gap between CLT and concrete*

The force occurring in the rebar may be determined with a similar analytical model as for concrete constructions. However, for CLT the compressed zone should be only assumed at the stiffer longitudinal layers. The stress in the reinforcement may then be calculated over the height of the compressed zone (x) and the inner lever arm (z).

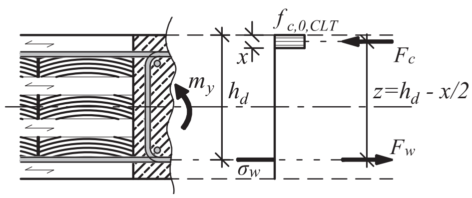

Figure 24: *Analytical model for Series F – TCC system*

$$x = h_d - \sqrt{\frac{f_{c,0,CLT} \cdot h_d^2 - 2 \cdot m_y}{f_{c,0,CLT}}} \qquad (2)$$

$$F_w = \frac{m_y}{z}$$

This analytical model already represents the tests quite well. The results of this model are shown in Figure 25 by comparison with the experimental results once for reaching the yield stress (f_y = 550 MPa) in the rebar as well as the tensile strength (F_{tens} = 33.3 kN acc. to tensile tests).

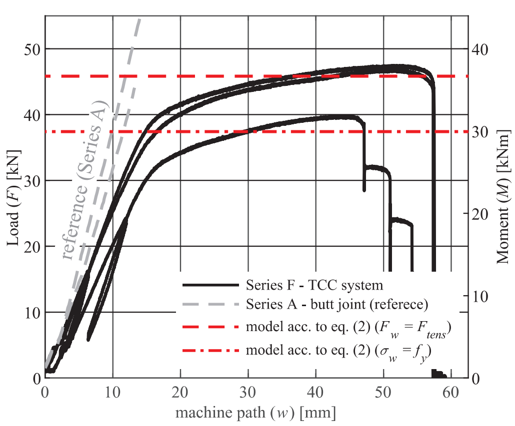

Figure 25: *Results Series F - TCC-system comparison with analytical model acc. to Equation (2)*

Notably, one of the tests showed a significantly lower load-bearing capacity. A possible explanation is that the gluing of one rebar was inaccurate there. To avoid the risks of non-properly fabricated gluing, in the next step the rebars were replaced by fully threaded screws. The force is again transmitted via a lap splice of the screws in the concrete. For this system, comprehensive investigations have been carried out which led to the ETA [21] and will be published in more detail in the future [22].

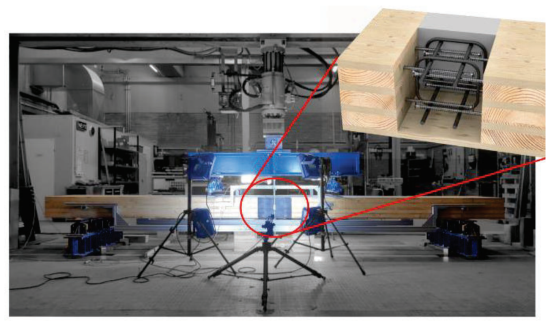

Figure 26: *Ongoing investigations on a TCC-system with self-tapping fully threaded screws [22]*

A completely "dry" solution for the edge connection was carried out using the system connector shown in Figure 7. This connector enables a significant reduction in construction time, for instance by eliminating curing times. With an average of approximately 6200 kNm/rad/m, this system also achieves a rather high rotational spring stiffness.

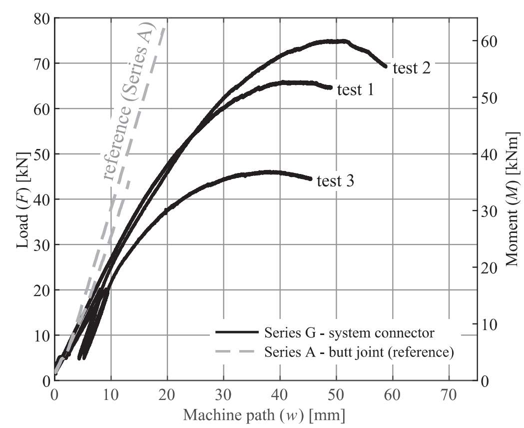

Figure 27: *Result Series G - system connector in four-point bending tests*

These were tests with first prototypes of the connector. There was only one set of two connectors available. So, these two connectors were used three times in a row. While the initial stiffness remained relatively constant, the load bearing capacity decreased significantly in the third test. This may be due to the reuse of the connectors. However, ductile failure behaviour was always observed.

6 CONCLUSIONS AND OUTLOOK

The edge connection between two elements in cross laminated timber slabs has a major influence on the behaviour of the entire system. In an experimental study, solutions for this joint were investigated with regard to the application in point-supported flat slabs. Based on a parameter study, the rotational spring stiffness of the connection is determined as an essential parameter for the suitability. Four-point bending tests are an appropriate test for determining the load-carrying capacity as well as the rotational spring stiffness. It showed that some of the solutions may be more appropriate to improve other slab systems than point supported flat slabs.

Two connection types were identified that meet the mechanical requirements for edge connections used in point supported flat slabs without any on-site gluing. One is the TCC system with glued-in rebars and the other the use of a system connector with micro-teeth. Both connection types are characterised by a distinct ductile failure behaviour and can easily be adapted to the load by variation of the spacing between the fasteners. However, questions regarding the long-term behaviour and the performance of the connection under biaxial loading still remain for both connection types.

The results presented for the TCC system were the initial impulse for further studies. A system where self-tapping, fully threaded screws are used instead of glued-in rebars is the subject of ongoing research.

A major benefit of the system connector compared to the remaining connection types is the quick assembly and the lack of any curing time. The possibilities of using micro-teeth as a new type of joining technique in timber constructions reach far beyond the application at the panel joint. Hence, the University of Innsbruck is currently carrying out extensive research on this topic.

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