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Advancing Timber for the Future Built Environment

A NEW APPROACH TO WOOD - WOOD CONNECTIONS THAT FULFIL STATIC, FIRE PROTECTION AND ACOUSTIC REQUIREMENTS

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ABSTRACT: Basic knowledge of timber-timber connections for bar-shaped components is available in timber construction. Can such connections also be used for flat elements such as cross laminated timber (CLT)? This scientific paper presents the "double dovetail tenon" system connector. It consists of two dovetail-shaped tenons that are 180 degrees opposite each other on their overlapping surface. The joint is characterised by the fact that both, the orientation of the veneers and the inclination of the flanks can be variably selected. No additional screws or other metallic parts are required for the connection. The CLT elements are joined by hooking them together. The system connector is made of softwood veneer layers (LVL). The basic shape of the system connector's tenons is based on the requirements of the European Technical Assessment (ETA) for dovetail tenons milled onto bars. The LVL can be orientated edgewise (HK) or flatwise (FK). For both veneer arrangements, geometry optimisations lead to load increases of 50%. In addition to the structural investigations, fire protection and sound insulation were analysed. The fire protection properties analyses consisted of three stages: the connector, the CLT and the combination in the two. The sound insulation was tested under real building conditions with the new hook-in system connector. The results of the tests fulfil the Austrian requirements of standards and guidelines.

KEYWORDS: solid wood, cross laminated timber, wood-wood connector, double dovetail tenon, hook-in system

1 – INTRODUCTION

Whereas 30 years ago, mainly rod-shaped elements were used for the construction of buildings, today CLT-elements are more common. CNC joinery technology is once again enabling the use of wood-wood connections in bar-shaped components. The research question that the timber construction department at the University of Innsbruck asked itself years ago was: Can wood-wood connections also be used for flat components such as CLT? How do they have to be designed and constructed in order to meet the requirements of modern timber building? These considerations led to the so-called "double dovetail tenon", a system connector that can be manufactured independently of the supporting structure. This pure wood-wood connection consists of LVL and fulfils not only the structural but also the physical building requirements, such as fire and sound insulation. The components are assembled using the same hook-in system as for milled dovetail connections.

2 – DESCRIPTION OF CONNECTOR

The coupling element made of LVL was developed on the findings of bar-shaped dovetail tenon joints. It consists of two dovetailed tenons that overlap by 180 degrees. Depending on the arrangement of the veneer layers, the connector can be produced in an edgewise (HK) or flatwise (FK) design. The connector variants can be made from one or two parts (as shown in Figures 1+2).

Figure 1. V1(left), V2 (mittle), V3 (right) connector variants

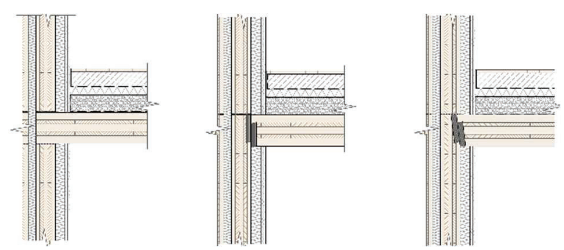

Figure 2. Comparison of conventional construction with the hook-in system, which can be mounted straight (centre) or inclined at 7° (right)

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2.1 STATIC PROPERTIES

Three-point bending tests, one connector on one support [2]

The standard shape of the system connector (variant 1) is based on the requirements of Z-9.1-649 [1] and only has flanks inclined up to 6° on both sides. There are two further variants that have been specifically designed for wall-ceiling connections. In variant 2, the load-bearing capacity in the ceiling area was increased by stepping the the tenon base. Variant 3 is made from two parts that are glued and dowelled together. The veneers are aligned flatedged (FK). This veneer arrangement improves the dimensional stability and also saves material for the two different tenon geometries, but it is more susceptible to rotations of the supports. Variants 2+3 increase the load-bearing capacity in the floor area by 50% compared to variant 1. The spanwidth influences the rotation of the supports, so the choice of the veneer arrangement of the connector variant is crucial. The illustrations below show the built-in differences, the three connector variants and a diagram comparing the load-deformation behaviour of the three variants (as shown in Figure 3 and Table 1).

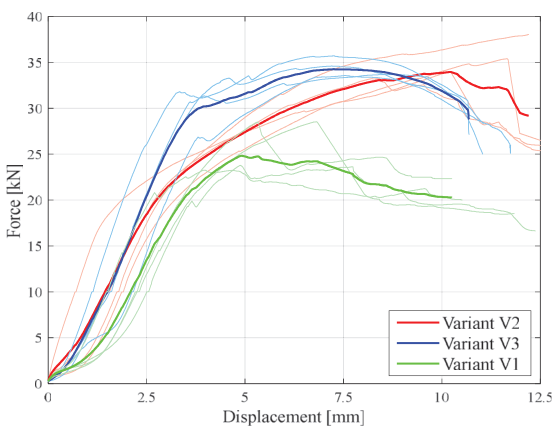

Figure 3. Results of 3-point bending tests (l = 1,0 m, 4 tests each), rotationless on supports, shown below

Table 1: Results of 3-point bending tests

Series	Tests	l	$F_{v,mean}$	$F_{v,k}$	COV
[-]	[-]	[m]	[kN]	[kN]	[%]
Variant V1	4	1.0	26.0	19.1	11.1
Variant V2	4	1.0	35.3	29.4	6.9
Variant V3	4	1.0	34.4	29.6	5.0
			+32%	+55%	

Four-point bending tests for the application of this connector [2]

To verify the results on large scale systems, 4-point bending tests of a 1.25 m wide CLT-element with 3 connectors on both sides were conducted (as shown in Figure 4).

Figure 4. 4-point bending tests of wall-ceiling system connection

The tests were carried out on a system connection consisting of the following components:

- 3 corresponding coupling elements with center distance a = 410 mm

- 1230 mm wide and 0.64 m high wall elements CLT 5s 100 mm positioned on both sides

- 1230 mm wide ceiling panel CLT 5s 160 mm suspended on both sides - the effective span is L = 4.14 m with variant 3 and L = 5.00 m with variant 1.

Ceiling overhangs in the transverse direction correspond to $a/2$ = 205 mm and are therefore balanced. In the longitudinal direction of the panel, a tolerance of 1 to 2 mm should be provided on both sides (as shown in Figures 5 and 6).

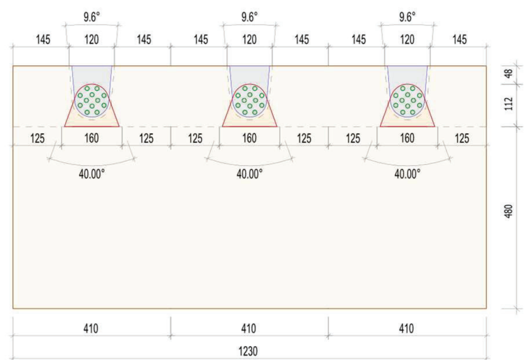

Figure 5. CLT-wall with connector arrangement

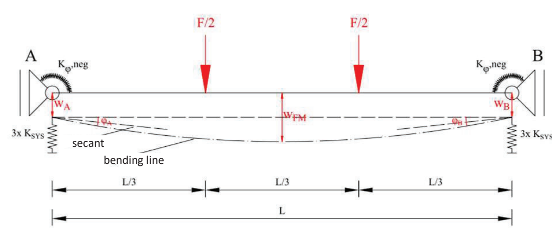

Figure 6. Static system of the testing setup

The symmetrical support conditions with the same stiffnesses $3 \cdot K_{SYS}$ result in bending deformations, which cause support rotations φ. According to the rotation spring stiffnesses $K_{\varphi,neg}$, negative clamping moments M_{neg} arise due to the occurring rotations, which are low and have no influence on the bending of the floor, but can cause damage in the connection. At the same time, an eccentric transverse force transmission takes place at the

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supports. Due to the symmetrical support, the support force corresponds to half the machine force $F/2$.

Failure of variant 1: notching of the CLT-ceiling

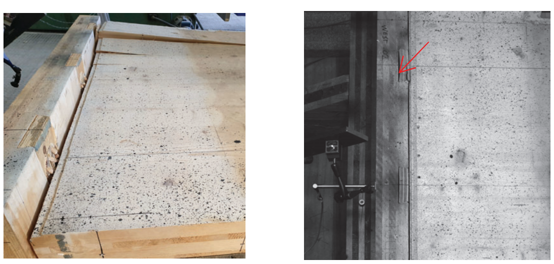
(a) notch failure (b) rotation damage

Figure 7. Failure of variant 1: (a) notching of the CLT-ceiling (b) rotation damage

Improving the stability to prevent notch failure of the floor (mode 3) by geometry optimization results in higher loads on the connector (mode 2), which increases the overall load-bearing capacity of the system connection (as shown in Figure 7).

Failure of variant 3: shear / rotation of the connector

The system connection with variant 3 now fails on the connector (mode 2) because of the optimised geometry. This happens with lower loading than in the low-rotation 3-point bending tests because of the occurring rotations at the support. Nevertheless, compared to variant 1, the higher connection performance is clearly visible.



(a) Connector Failure (b) Rotation damage

Figure 8. Failure of variant 3: shearing and rotation of the connector

The optical measuring system was also used in the laboratory tests (as shown in Figure 8). In variant 3, one edge connector fails in transverse tension before the overall failure. When the entire connection fails along the support line, the two other connectors shear off and the CLT floor collapses in the area of the decisive connector.

Results of 4-point bending tests with rotation on supports [2]

Table 2: Results of 4-point bending tests

Series	Tests	l	$F_{v,mean}$	$F_{v,k}$	COV
[-]	[-]	[m]	[kN]	[kN]	[%]
Variant V1	4	5.0	24.2	20.4	6.3
Variant V3	3	4.1	29.8	25.9	6.0
			+23%	+27%	

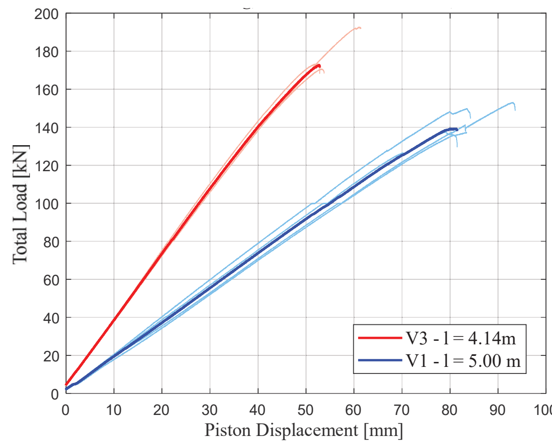


Figure 9. Results of 4-point bending combination tests V 1 and V3

Displacement transducers were removed before failure of the CLT-ceiling (as shown in Figure 9).

Table 3: Total area loads achieved with connection

Series	$\Sigma\, p_{mean}$	$\Sigma\, p_k$
[-]	[kN/m²]	[kN/m²]
Variant V1	23	20
Variant V3	35	30

As shown in Tables 2 and 3, variants 1 and 3 can transfer very high loads. This means that for the loads typically occurring in buildings, only two connectors would be sufficient for the static load of CLT floor elements with 125 cm. To increase overall safety, three connectors are recommended for the CLT floor element in question. This redundancy increases robustness. Due to the high load-bearing capacity of the connectors, the distance between the three connectors can be increased for wider CLT floor elements.

2.2 FIRE PROTECTION

Experimental investigations of dovetail connectors on bar-shaped components under fire exposure show that an unprotected connector does not meet the fire protection requirement R30 (30-minute fire resistance). In order to reproduce the experimental results in the numerical investigations, the gap in the connection, which is responsible for heat transport, must be taken into account [3]. This shows that the connection gap has a major influence on the behaviour of the connection under fire load. Studies on conventional metal connectors also show that in timber construction, the gap size has a significant influence on fire load in unprotected systems. Protective measures, such as the use of a fire-resistant laminate, can reduce the gap size to a purely aesthetic issue [4]. Research results on aluminium dovetail connectors show that with a gap ≤ 1 mm on all sides of the connector, a timber cover of at least 31 mm or 43 mm is required for a fire protection requirement of R30 or R60, respectively [5]. In Austria, the fire protection requirements are regulated in OIB Guideline 2 [6]. There are 5 Building

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Classes (BC). In this investigation the focus is on BC 5, which distinguishes between buildings with a maximum of six storeys and an escape level ≤ 22 m, and buildings with more than six storeys above ground. In both cases, apart from the top storey, a fire resistance of REI 90 (R= resistance, E = room closure, I = insulation)is required for all load-bearing and separating components. On the top floor, however, only a fire resistance of R60 is required for the components in question. Buildings with more than six storeys require A2 component fire behaviour (flame-retardant/noncombustible), which means that the use of wood is only possible with additional extensive protective measures. This paper provides solutions for R60 and R90.

Case study based on a BC 5 timber building

The case study is based on a building design developed as part of the Bigwood research project (as shown in Figure 10) [7] with six floors above ground and an escape level of 15.4 metres. For adequate fire protection, the requirements of BC 5 for up to six full storeys must therefore be met. The task here is to use the coupling element as often as possible and to meet the fire protection criteria.

Figure. 10. Six-storey timber building (BIGWOOD) [7]

The analysed ceiling system (as shown in Figure 11), with 350 m² per floor level, consists of 72 CLT elements with a width of 125 cm. In order to meet the acoustic requirements, the static system of single-span beams was chosen. The maximum ceiling span width is 4.70 metres. For each CLT element, three coupling elements with a 42 cm spacing are used on each side. In each storey 432 timber connectors are used. The ceiling element used corresponds to type CLT 5s 160 mm (40/20/40/20/40) and the wall element to type CLT 5s 100 mm (20/20/20/20/20), respectively.

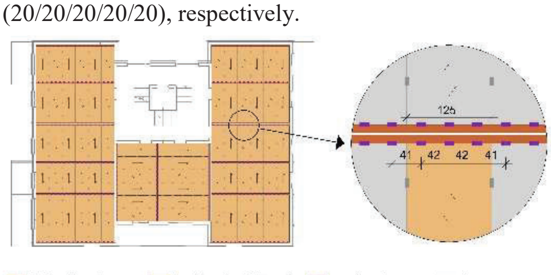

Figure. 11. Analysed ceiling system

In contrast to bar-shape components (beams), in solid timber construction with CLT, only a one-sided fire attack is possible. Before the complete ceiling system can be analysed under fire load, the fire resistance period of the connector must be known. It is determined using the burning rate β_n = 0.7 mm for laminated veneer lumber according to EN 1995-1-2 [8]. The effects of corner fillets and cracks are also taken into account. Since the burn-off of the wall lamella is decisive for the complete ceiling system, it is assumed in this investigation that the connector is additionally protected on the wall side with non-combustible materials. The layer bonding of the laminated veneer lumber used for the connector is bonded with phenolic resin adhesive. It has a temperature resistance of up to 250°C. A two-component epoxy adhesive with a temperature resistance of 200°C is used for dowelling and bonding the shear surface of the assembled connector (variant 3). Due to the low thermal conductivity λ_R = 0.13 W/mK of the laminated veneer lumber, it is assumed that the temperature in the connector will drop sharply after the burn-off point. This ensures the temperature resistance of the bonded joints. Tests on the burn-off behaviour of CLT panels show that there is a significantly increased burn-off rate after the first lamella has burnt off. Therefore, the connector burn-off rates, which are carried out in this investigation using results from scientific literature, can only be defined with precision in the area of the ceiling lamella of the CLT panel. As the connector itself fails after a 25 mm burn-off, and most ceiling lamellas have a thickness of 30-40 mm, the values determined in this test can be applied to most building projects. The effect of heat transport via the connector gap cannot be considered in the specified test method.

Table 4: Burn-off LVL of connector according to EN 1995-1-2[8]

Fire exposure duration	Burning rate β_0	Burn-off
[mm]	[mm/min]	[mm]
10	0.7	7.0
15	0.7	10.5
20	0.7	14.0
25	0.7	17.5
30	0.7	21.5
35	0.7	24.5

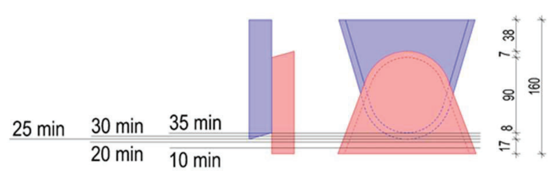

Figure. 12. Fire behaviour of the double dovetail tenon system connector

Research results from loaded fire tests on dovetail joints on bar-shaped components show that the joint fails when the base of the tenon burns off (as shown in Figure 12 and Table 4) [3]. It corresponds to the wall-side tenon base of the coupling element. It first burns off after 25 minutes of fire attack. After 35 minutes, the bevels in the area of the mortise and tenon base are completely burnt off, which means that the connector will no longer be

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securely in place. The results show that a fire resistance period of at least 25 minutes can be attributed to the connector and that connection failure is expected after 25 to 35 minutes.

EN 1995-1-2 [8] specifies a burn-off rate $\beta_n = 0.7$ mm for cross laminated timber, taking into account the effects of corner fillets and cracks, if the negative effects due to heat transport via the joint are not taken into account. For a fire exposure of 30 min, this results in a burn-off depth of 21 mm. In the case of the ceiling-side tenon, it can be assumed that the burn-off only has a minimal effect on the load-bearing capacity, as only the face of the tenon is exposed to direct fire load and therefore only the flanks experience burn-off. Although the wall-side tenon itself does not experience any burn-off, it is nevertheless decisive for the failure of the connection under fire load. After a 30-minute fire exposure, only 6 mm of the connector's 27 mm wall-side bearing pocket is left in the tenon base.

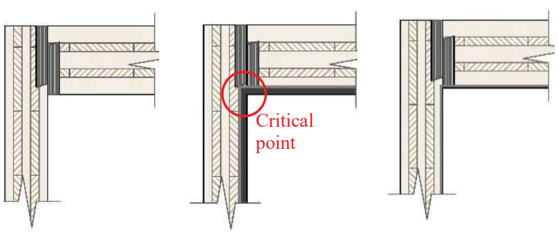

Figure 13. Comparison of fire behaviour of the installed system connector without fire load (left), 30-minute fire load 21 mm (centre) and 10-minute fire load 7 mm (right).

As the load bearing capacity of a dovetail joint is based solely on the tenon base [1], an R30 fire rating cannot be achieved. The unprotected system has a fire resistance of only 10 minutes, which corresponds to 7 mm of burn-off. This leaves 20 mm of the wall-side pocket and a distance of 15 mm between the wall-side tenon and the burn-off. In order to achieve the required R60 or R90 fire protection requirements of BC 5, fire protection measures must be taken to protect the joint (as shown in Figure 13).

Solutions and connector samples that achieved the required fire resistance of REI 60 or REI 90 are presented below.

Mounting variants and fire protection measures for R60 and R90

R60 fire resistance can be applied to the top storey of BC 5. The coupling element can be protected from fire attack by attaching a facing shell to the load bearing wall components. The facing shells are made of 12.5 mm GFB (gypsum fiber board), t_{ch} = time until the components to be protected start to burn = 21 min according to EN1995-1-2 [8] and 50 mm mineral wool, tch = 29 min according to EN1995-1-2 [8]. The connection area to the ceiling element must be sealed with a non-combustible insulating material (melting point > 1000°C) or a fire protection foam. With this measure, the fire resistance of the facing lasts 50 minutes. The fire resistance of the system itself is 10 minutes. For this system the R60 fire resistance requirement is therefore guaranteed. The CLT ceiling element can be left visible with a fire resistance requirement of R60, if this is taken into account in the design.

If there are no additional sound insulation requirements and a suspended acoustic ceiling is installed, the non-combustible cladding can be applied directly to the CLT wall element. For example, with two 12.5 mm GFB, $t_{ch} = 56$ min according to EN1995-1-2 [8], the R60 fire protection requirement can be achieved. In this variant, the ceiling connector must also be fire protected by two 12.5 mm GIFA strips protruding at least 70 mm in all directions. The GFB strips can be applied locally to each individual connector or as a continuous strip. A 60-minute fire attack with a burn rate of $\beta_n = 0.7$ mm [8] results in a burn-off rate of 42 mm for the cross laminated timber. The selected 70 mm provides therefore effective fire protection for the connector with a fire resistance requirement of R60.

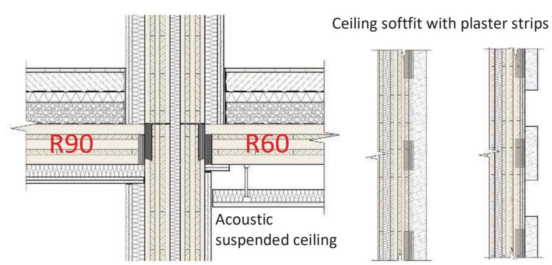

Figure 14. Fire protection measure R90 (left) - Fire protection measure R60 (right) - wall-side and ceiling-side facing shells, min 70 mm wide

Fire resistance R90 is achieved for the coupling element by means of a facing shell on the wall and ceiling sides. The facing shells consist of two 12.5 mm GFB, $t_{ch} = 56$ min according to EN1995-1-2 [8] and 50 mm mineral wool, $t_{ch} = 29$ min according to EN1995-1-2 [8]. The fire resistance duration of the facing layer is 85 minutes. The fire resistance duration of the system itself of 10 minutes guarantees the R90 fire resistance requirement for the system (as shown in Figure 14 and Table 5).

Table 5: Duration of fire protection measures according to EN1995-1-2 [8]

Structure element	Thickness of material	Fire resistance time	
	[mm]	[min]	
GF-board	12.5	--	21
GF-board	2 x 12.5	56	--
Mineral wool	50	29	29
Coupling element	--	10	10
		∑ 95	**∑ 60**

The connection of the wall facing shell to the ceiling element and the connection of the ceiling facing shell to the wall facing shell is sealed with a non-combustible insulating material with a melting point > 1000°C or a fire-resistant foam. In terms of fire protection, it is possible to directly clad the cross laminated timber elements with gypsum plaster fire protection boards. To achieve the necessary fire protection requirements, GFB with a thickness of 18 mm, t_{ch} = 86 min according to EN1995-1-2 [8], must be used. However, a facing layer is necessary to meet sound insulation requirements.

2.3 SOUND PROTECTION

In addition to structural and fire safety, sound insulation is a crucial factor in the construction of multi-storey timber buildings, especially for living and working areas. For this reason, sound insulation tests were carried out on the test rig to simulate real conditions in construction projects. This means that sound insulation was measured including flank transmission. The same floor construction was used for comparison with the conventional construction (Figure 2).

By using the wood-wood connection (double dovetail), the ceiling is not supported but hung from the side. This results in changes in the connection area of the ceiling. From a structural point of view, there is no transverse pressure in the support area of the ceiling, as the wall elements can be placed directly on top of each other. A continuous wall element that extends over several storeys can also be used. In the investigations selected here, the storey-by-storey structure was chosen in order to install sound decoupling strips between the storeys. These serve to reduce sound transmission via the flanks. Due to the storey-by-storey construction, the wood-wood connectors can be installed at a slight angle (Figure 16). The inclined installation of the connectors makes it easier to hang the ceiling elements and create an airtight layer between the storeys. Compared to conventional installation with a supported ceiling, a vertical, narrow gap is created when hanging the ceiling elements, which is necessary to compensate for dimensional tolerances in the wood and to be able to assemble the elements. It is essential that this joint be sealed airtight, as airtightness is a key factor in achieving high sound insulation values requirements in addition to the required construction layers and decoupling. It should also be mentioned that airtightness in this area is also essential for fire protection.

Sound insulation requirements in Austria

In Austria, sound insulation is regulated in OIB Guideline 5, in the building regulations and in the technical building regulations (standards). For airborne sound insulation, a weighted standard sound level difference of $D_{nT,w} \geq 55$ dB must be achieved for flat partition walls and ceilings. A weighted standard impact sound level $L'_{nT,w} \leq 48$ dB is required for impact sound. Basic principles, terms, measures and examples of sound insulation can be found in the various parts of ÖNORM B 8115.

Acoustic ceiling test stand at the University of Innsbruck

The special feature of the ceiling test stand for airborne and impact sound measurements is that the flanking transmission via the component connections can also be measured (research test stand). This design of the sound test stand makes it possible to carry out airborne sound measurements according to ÖNORM EN ISO 16283-1 and impact sound measurements according to ÖNORM EN ISO 16283-2, i.e. like in situ measurements (as shown in Figure 15). This way, practice-relevant results are achieved. In addition to the standard measurements for airborne and impact sound insulation, the sound bypasses (flank transmission) can be measured with accelerometers.

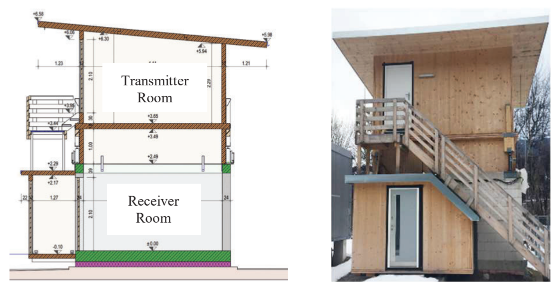

Figure 15. Acoustic ceiling test stand

The measuring rooms (transmitter room, receiver room) have a floor area of 21.5 m² (5.24 m long; 4.10 m wide).

Investigation of sound insulation and results

The investigations focussed on impact sound insulation. A particular focus was placed on the enhancement of the floor construction layers. The airborne sound measurements are not shown because they do not represent any meaningful results due to the chosen test setup (external walls only made of 120 mm CLT elements, no facing shells).

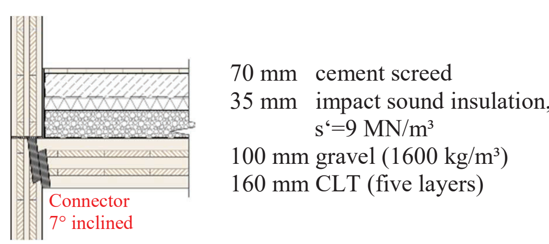

Figure 16. Built-in connectors and floor construction

A standard sound level difference $L_{nT,w}$ = 46 dB was measured with the floor structure shown (compare Figure 16). The measurement result for impact sound insulation shows that the impact sound insulation $L_{nT,w} \leq 48$ dB required in Austria can be achieved with the proper coordination (selected masses, dynamic stiffness of the impact sound insulation, etc.) of the component layers in

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the ceiling area, despite low sound insulation quality of the flanking components.

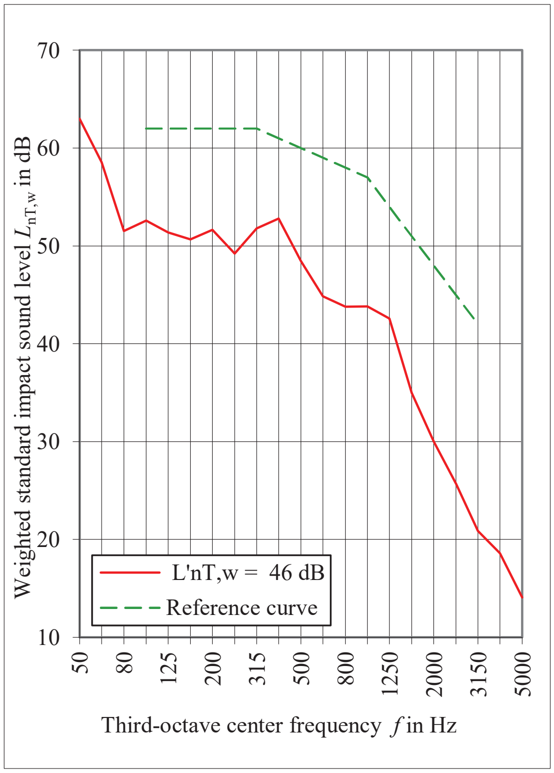

Figure 17. Measurement diagram of the impact sound measurement

The tests show (compare Figure 17) that when using the double dovetail connector, comparable sound insulation qualities can be achieved as with the conventional construction method (with installed ceiling).

3 – RESULTS

The investigations show that the solid wood connector fulfills the static, fire protection and sound requirements and can therefore be used in multi-storey timber construction.

The results of the structural analyses of variants 1 and 3 (Tables 2 + 3) show that the individual connectors can transfer very high loads. This means that for the loads typically occurring in buildings, only two connectors would be sufficient for the static load of CLT ceiling elements (125 cm wide). For safety reasons (robustness), however, three connectors are recommended for the CLT ceiling elements in question. When using wider ceiling elements (wider than 125 cm), the spacing can therefore be increased in accordance with the loads that occur.

The results on the fire protection of solid wood-to-solid wood connections in multi-storey timber construction also show that they fulfil the fire protection requirements when designed accordingly. The investigation of the fire resistance of the connecting element itself shows that it can withstand a fire resistance of 25 minutes. When installed with the necessary fire protection measures, which depend on the BC, the required fire resistance is generally met. This means that the fire protection measures applicable in Austria for R90 did not require any additional measures specifically for the fire protection of the connector. The same applies to the fire protection measure R60 with a facing shell on the wall side. Additional fire protection measures are only required for direct wall panelling and suspended acoustic ceilings.

The results of the sound tests with the wood-wood connector show that the impact sound insulation required in Austria for residential and office buildings is met. The sound insulation quality is comparable with the measurements for conventional construction methods. To achieve the sound insulation quality, however, particular attention must be paid to airtightness in the connection area of the ceiling elements.

4 – CONCLUSION

The wood-wood connector (double dovetail tenon) has been rethought and developed as a system connector for flat timber elements such as the CLT as a system connector from a historical connection. As the results of the tests show, this wood-to-wood connection fulfils the three essential requirements – static properties, fire protection and sound insulation - for multi-storey timber construction. This makes the double dovetail joint a good alternative to metal fasteners. As it is a pure wood-wood connection that is suspended and does not require any metal fasteners, this is a sustainable and resource-efficient solution. Dismantling can be carried out in a similar way to that already known for log buildings. This means that when dismantling, the elements only need to be unhooked again. The wood-wood connector is already patented. Serial production is to follow.

5 – ACKNOWLEDGEMENT

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