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Advancing Timber for the Future Built Environment

INFLUENCE ON THE LOAD-BEARING BEHAVIOR OF SCREWS USING TOOTHED METAL INSERTS IN SHEAR PLANES

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ABSTRACT: In addition to economic efficiency, the performance of fasteners in timber structures is primarily determined by load-carrying capacity, stiffness, ductility, and the required minimum end and edge distances. Engineering-type fasteners can be distinguished between dowel-type fasteners, area-measured connections, and bonding systems. Actual timber constructions mainly use dowel-type fasteners, particularly self-tapping, fully- or partially-threaded screws. Screws offer many advantages, including their flexibility and versatility, as well as their reasonable load-carrying capacities. However, they have some disadvantages, including their relatively low stiffness, especially in shear load applications, and the requirement for relatively large end- and edge distances in timber elements. In contrast to dowel-type fasteners, toothed plate connectors and nail plates demonstrate considerably higher load-carrying capacities and stiffnesses. However, installing these shear connectors typically necessitates the use of hydraulic devices to press the teeth into the timber elements. The following work demonstrates a potential method for optimising the geometry and tooth shape of standard nail plates in a way that enables the generation of required press-fit forces by self-tapping partially-threaded screws with washer heads. The use of this technology, consisting of simple steel strips with toothed surfaces, to reinforce conventional screw connections in shear planes offers a wide range of potential applications with enhanced efficiency resulting primarily from a significant increase in stiffness.

KEYWORDS: timber structures, fasteners, shear forces, reinforcements, punched-metal-plate-fasteners

1 – INTRODUCTION

The quote »A chain is only as strong as its weakest link« illustrates the importance of connection technology in timber constructions. The connections between timber members are crucial for a structure's stability, robustness and durability. Nowadays, fasteners such as screws, dowels, and nails are commonly used, especially under shear stress. However, these mechanical connections have certain limitations, particularly in terms of load-bearing capacity, stiffness, and the required minimum distances to the ends or edges of the components. These factors can influence the dimensions of the structural members and make the construction more complex. Adhesive technologies offer the potential to overcome some of these challenges, enabling even force distribution and higher stiffness. However, the requirements for climatic conditions and processing are often so stringent that the practical use of adhesives is not always economical or feasible. Alternatives are so-called punched-metal-plate-fasteners (PMPF) [1] like conventional nail plates, which combine the ease of application of mechanical connecting elements with the load-bearing capacity and stiffness of bonded connections. Nail plates combine the benefits of both approaches by establishing a strong and stable connection without the complicated requirements of adhesive solutions. However, installing nail plates typically requires an extra tool to press the punched-out nails (teeth) into the wood surface. This can sometimes limit their application, especially when hydraulic presses are not easily accessible or straightforward to operate on construction sites.

In [2], the first attempts to modify the nailing plate in a way that reduces the press-fit resistance were made almost 90 years ago by developing the so-called »Krallenband« (cf. Fig. 1). This was achieved by lining up individual small, stamped press-fit dowels with triangular shapes to form a continuous strip.

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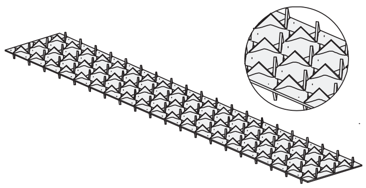

Figure 1: Thin metal strip with punched-out triangular-shaped teeth; German title: Krallenband [2]

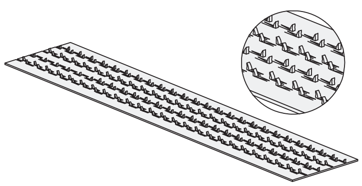

Figure 2: Toothed metal fastener (TMF) with scratched-out teeth on both sides

However, it was not possible to generate sufficient press-fit forces to connect the panel to the wooden part without additional hydraulic devices, and fasteners like screws that generate short-term preload axial forces during the insertion process were still not available at that time.

The presented research aims to develop a thin metal strip with small teeth on both sides, designed to reinforce screwed joints under shear loads and to be installed using partially threaded screws (cf. Fig. 2). The potential applications of these toothed surfaces were explored in preliminary tests, including obvious applications such as timber-to-timber single shear connections, potentials to reduce the minimum end distances and edge distances for dowel-type fasteners, ribbed floor constructions, timber frame elements, applications for aluminium system connectors, e.g. joist hangers, dovetail connectors (cf. Fig. 3), CLT edge connections (cf. Fig. 13) and also applications for timber-concrete composites. (cf. Fig. 14).

2 – METHODS AND MATERIALS

Using an innovative metal processing technique [3, 4, 5], which involves creating micro-teeth by scratching them out of any metal part, a new design of a PMPF was developed. This technology, derived initially from automotive brake plate applications, underwent an iterative development process to optimise the geometry, density, and layout of the teeth. These optimisations focused on achieving the required press-fit forces and shear performance. By doing so, the micro-tooth scratching technique was modified to create optimised serrated metal surfaces for timber connections in a way

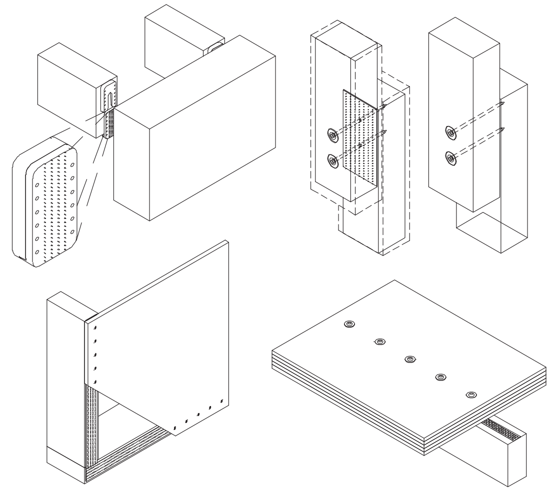

Figure 3: Exemplary applications for the surface treatment technology

to reduce the press-fit resistance to a level where joining timber components became feasible using only the axial preload forces generated by partially threaded screws with washer heads. After the fixation, the connection is a system of screws and a toothed thin metal fastener (TMF) to transfer shear forces, where (a) the toothed metal strip transfers the main shear loads and (b) the partial threaded screws support (b1) to press-fit the teeth of the metal strip into the timber surface and (b2) to ensure the clamping effects to keep the timber members closed. Also, an important design principle was to use thin steel sheets of ≤ 1.50 mm to drive the screws without any predrilling through the TMF.

Experimental investigations thoroughly analysed the optimised mechanical properties. Initial penetration tests were conducted to measure the required press-fit loads, followed by inclined-shear tests to evaluate the shear strength and, in particular, the slip modulus for comparison with existing solutions.

2.1 REQUIRED PRESS-FIT LOADS

To improve usage in the field of timber engineering and further minimise the required press-fit forces, the serrated metal surface requires further optimisation by varying the tooth geometry, height, and density without significantly reducing the shear strength. For this reason, preliminary penetration tests are carried out to analyse the behaviour of different TMF types when pressed into timber elements of varying densities and considering different grain directions. This investigation aimed to determine the load level to close the gap between the timber element and the toothed metal insert.

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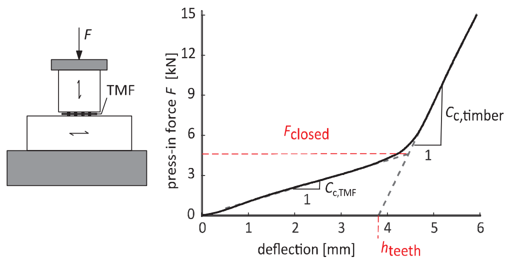

Figure 4: Penetration tests with samples of TMF dimensions 50x50 mm

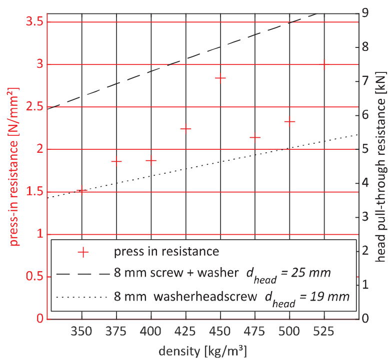

Figure 5: Influence of the gross density on the penetration (compressive) stresses in the side grain of softwood

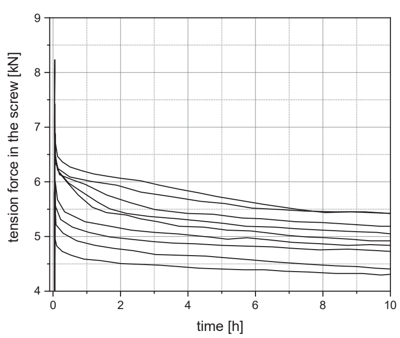

Figure 6: Tensile forces in a screw after screwing in, relaxation over a time period of 10 h

This is visible as a kink in the load-displacement curve with a subsequent increase in the gradient ($C_{c,0,TMF}$ and $C_{c,timber}$). As shown in Figure 4, the tests with TMF plates with a size of 50 x 50 mm² are repeated for timber densities with $350 \leq \rho \leq 525$ kg/m³ (in steps of 25 kg/m³) in the side and end grain of the timber members with different teeth types. Following this approach, a range of different required penetration forces appears, which in the second step can be compared with the pre-tensioning forces of screws [6]. After considering the effects due to relaxation in this test series, they come close to the head pull-through resistance of partially threaded screws (cf. Fig. 5 and Fig. 6) with washer heads, e.g. TBS screws or HBS with additional washers acc. [7].

2.2 SHEAR STRENGTH

In the first step, preliminary tests were conducted to demonstrate the capacity of the reinforcement by using TMF as an insert metal sheet in shear planes. For all shear tests, mainly specimens which fulfil the criteria of the gross density of C24 were chosen [8]. By using a screw connection to transfer, one has to consider the minimum distances to ensure the embedment strength of the fasteners. This leads by predrilling the screws to the dimensions of the timber parts of $l = 320$ mm, $b = 160$ mm and $t = 70$ mm. In a second step, tests on specimens were done with the exact dimensions but with the insertion of the TMF in the shear plane in combination with slotted holes in one timber member to avoid a contribution of the screws (cf. Fig. 7 and Fig. 8). Table 1 shows the results of these comparative inclined-shear tests. The shear load-carrying capacity of the TMF (measures 50 x 200 mm²) is a factor of 6 higher, and the slip modulus is a factor of 9 higher compared to the screwed connection. Following this proof of concept, additional tests are conducted to examine the influence of the angle between the TMF and the load direction concerning the grain orientation. Additionally, tests were performed on the end grain. Due to the high stiffness values, the length of the TMF, with a constant width of 50 mm, is varied from 50 mm to 1000 mm. To ensure uniform press-fit stresses, the screw spacing is set to the required minimum distance $a_1 = 12 \cdot d = 96$ mm for screws type TBS 8 x 160 mm ($d_{ef} = 5.4$ mm < 6 mm) according to Eurocode 5. The cross sections of the timber elements measure 60 x 100 mm² of the mounting part and 60 x 100 mm² of the supporting part. The density is chosen to match the reference density of C24 ($\rho_k = 350$ kg/m³), as specified in ISO 8970 [9].

The results of the test campaign for a TMF length of 500 mm are presented in more detail below. The load-displacement curves in Figure 9 and the values in Table 2 illustrate the results of the shear strength and the bedding modulus of the TMF depending on the number of screws. In total, 20 tests were conducted for each series, and $f_{v,0,max}$ is determined within a maximum differential deflection of the timber parts of 5 mm, divided by the area of 50 x 500 mm². The distances of the screws were set to a minimum of 96 mm and a maximum of 175 mm. The contribution of the screws is well visible. For the series »without screws«, screws were inserted in slotted holes to ensure the clamping effect but to avoid contributions to the shear load-carrying capacity. For the series with screws, the inclined-shear tests show a high ductility and also the rope effect of the screws. Due to the chosen test method of the inclined-shear tests and to ensure that the load transfer goes through the centre of gravity of the connection, an inclination of 7° was necessary. This results in additional compressive forces in the shear plane, which leads to a contribution to the shear load-carrying capacity parallel to the shear plane. To validate this effect, an additional test campaign using twin samples (where timber members are cut from a single timber beam) is conducted, including inclined-shear (compressive-shear) and classical push-out tests (cf. Fig. 10). The determined mean values from five samples in each series, as shown in Table 3, indicate a difference of 3.5 % in the shear strength. Especially the mean variation of the results is higher for the push-out test series, which ultimately results in a lower 5 %-fractile value compared to the inclined-shear tests (cf. Fig. 11). The mean values of the bedding modules show a difference of approximately 11 %.

Table 1: Preliminary shear tests with TMF 50 x 200 mm²: Comparison with single screw connection and the TMF

Series	Dimensions [mm]	F_{max} [kN]	f_v [N/mm²]	K_{ser} [kN/mm]
Screws only	8x120	2.43	-	6.64
TMF	50x200	15.80	1.58	54.60

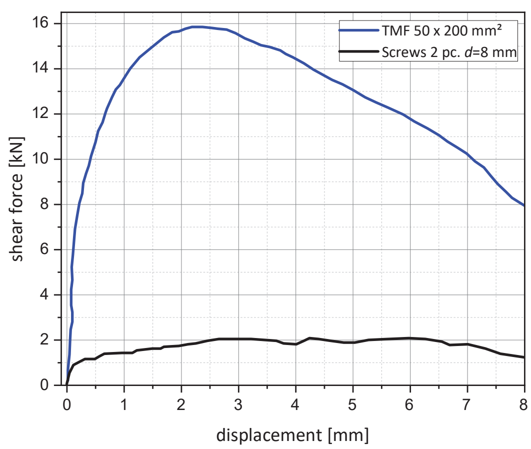

Figure 7: Load-deformation graphs: Comparison with a single screw connection and the TMF, preliminary tests

Table 2: Test results of the shear strength and bedding modulus, series 500 mm with screw distances 96 and 175 mm and without screws

Parameter		Series 500 mm	MEAN	COV
$f_{v,0}$	[N/mm²]	without screws	1.14	12%
		a_1=175 mm	1.54	10%
		a_1=96 mm	2.06	8%
$k_{v,ser}$	[N/mm³]	without screws	1.81	12%
		a_1=175 mm	2.30	31%
		a_1=96 mm	3.42	47%

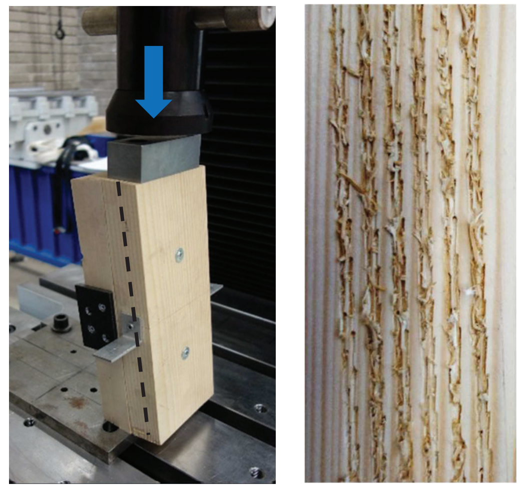

Figure 8: Preliminary inclined-shear tests: Comparison with single screw connection and TMF reinforcement and failure mechanism TMF

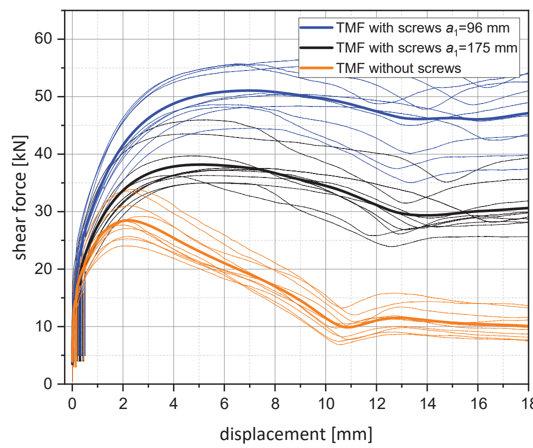

Figure 9: Load-deformation graphs: Shear tests with a length of 500 mm, with and without screws and varying amounts of screws

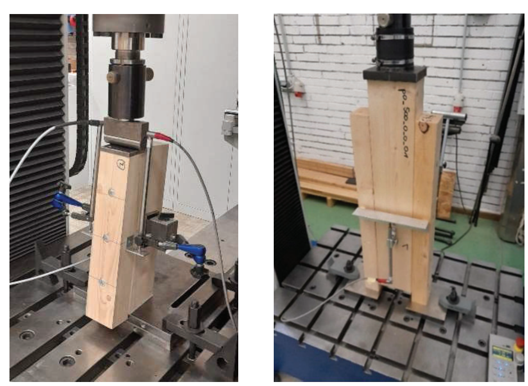

Figure 10: Different test methods: Inclined-shear (compressive-shear, left) and push-out tests (right)

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Table 3: Test results of the shear strength and bedding modulus of different test methods with TMF 500 mm and a_1=175 mm

Parameter		Series 500 mm	MEAN	COV
$f_{v,0}$	[N/mm²]	inclined-shear	1.46	3%
		push-out	1.41	7%
$k_{v,ser}$	[N/mm³]	inclined-shear	1.82	17%
		push-out	2.05	37%

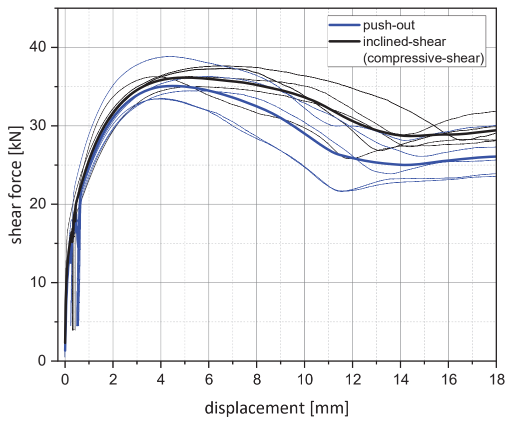

Figure 11: Load-deformation graph of different test methods: Inclined-shear and push-out tests (one and two-shear planes)

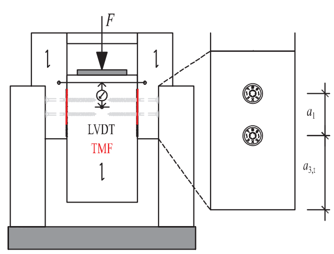

Figure 12: Shear tests with reduced minimum screw distances to the loaded end grain, $a_{3,t}$ (modified test setup for preliminary tests [10])

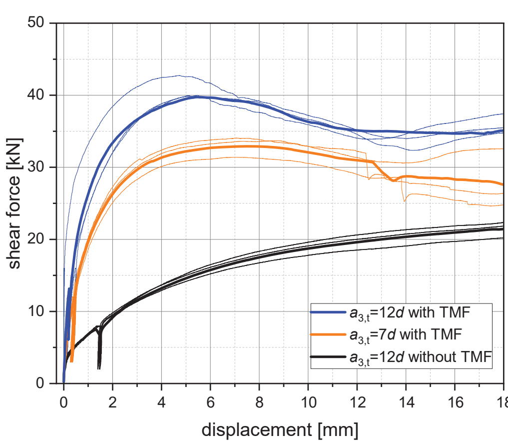

Figure 13: Results of shear tests with varying distances to the loaded end grain $a_{3,t}$=12·d and 7·d with and without TMF reinforcement

3 – APPLICATIONS

In the following section, a selection of applications with this innovative technology is presented. TMF can get inserted in all kinds of shear plane joints as long as the required penetration loads are obtained either by screws on-site or during assembly in a manufacturing plant using a hydraulic device. Whether reinforcement is applied over a large area, like in wall-to-wall or wall-to-slab connections, or selectively to transfer tension perpendicular to grain in notches, decrease screw distances, modify joist hanger connectors between beams, or in timber-concrete composites (TCC), it serves various purposes. The combination of screws with the TMF offers significant advantages due to its universal applicability and simplicity of use. It is essential to consider the precise arrangement of the timber elements before the penetration of the TMF teeth into the surfaces.

3.1 APPLICATION TO REDUCE THE MINIMUM DISTANCES OF LATERAL LOADED SCREWS

Beneath the simple reinforcement of a screwed connection in combination with the TMF, an additional effect gets visible on the required minimum edge distances and end distances according to, e.g. Eurocode 5. In many cases, the minimum distances within a connection are the limiting factor when designing a joint. The idea of the following examination is to lower brittle timber failure in connections with reduced screw distances using TMF.

The minimum distances a_1 and $a_{3,t}$ of screws with an inner diameter $d_{ef} \leq 6$ mm in grain direction are defined as follows ($\rho_k \leq 420$ kg/m³, predrilled): spacing parallel to the grain direction, $a_1 = (4+|\cos\alpha|)\cdot d = 5\cdot d$ and distance parallel to the loaded end grain with $a_{3,t} = (7+5\cdot\cos\alpha)\cdot d = 12\cdot d$. To obtain a reference value, a shear test without TMF is conducted using a modified test method described in [10]. This results in the black load-deformation curves shown in Figure 13. Afterwards, the same configuration is tested in combination with TMF strips on both sides between the timber surfaces (blue graph), as well as with a further reduced end grain distance of $a_{3,t}=7\cdot d$ = 56 mm (a_1 remains $5\cdot d$) and TMF reinforcement (orange graph). It is evident that even if the required minimum distances according to Eurocode 5 are not fulfilled, it is still possible to achieve a high load capacity with ductile failure using TMF as reinforcement. Compared to the standard configuration, the characteristic shear load of the samples with TMF reinforcement $F_{v,Rk}$=17.4 kN almost triples the initial value. After a further reduction to $a_{3,t} = 56$ mm, the connection still exhibits twice the characteristic load-carrying capacity, with $F_{v,Rk}$=13.8 kN, and also displays ductile failure. Additionally, according to [10], the requirement is that loads should not drop by more than 20 % before a deflection of 10 mm.

3.2 RIBBED SLABS

As described in the preliminary shear tests in Chapter 2, the aim of the following presented bending test series (cf. Fig. 14) with ribbed floor panels and different connection methods is to contrast connections with a maximum of screws possible and TMF reinforced screwed connections with a minimum number of screws [11]. For this reason, two test configurations are considered – the pure screw connection with a maximum of screws type TBS Max 8 x 240 mm (2 rows, a_1=12·d) and the reinforced connection (single row, a_1=20·d) with TMF stripes placed centrally between beam with the dimensions 120 x 240 mm² (GL 24h) and CLT panel, five-layer t = 120 mm and b = 580 mm with lamellas strength class T14 (C24). To compare the two screwed methods with a glued connection, three further tests are executed following the standards for screw-gluing according to ÖNORM B 1995-1-1 [12]. The maximum bending moments, regardless of displacement, as well as the initial effective bending stiffnesses, including the shear stiffness, are listed in Table 4.

Figure 14: Bending tests with ribbed panels, span 6 m

Table 4: Mean values of the load-carrying capacity and initial stiffness of screwed connections with and without TMF and glued ribbed panels

Series	M_{mean} [kNm]	$(EI)_{ef}^{*)}$ [MNm²]
Screwed Connection without TMF 125 screws type TBS Max 8x240	80.96	5.58
Screwed Connection with TMF 37 screws type TBS Max 8x240	80.89	4.81
Glued Connection Press gluing	136.92	9.14

*) Effective bending stiffness, including also shear deformations

All the load-carrying capacities of screwed connections without and with TMF reinforcement are settled approximately in the same range. Though, one must remember that the number of screws is lowered by 70 % in the TMF connection. Regarding stiffness, the glued ribbed panel elements are twice as rigid as those with a TMF connection, indicating that this aspect can be improved.

Consequently, this application presents an opportunity for further consideration. First of all, the TMF strips should only be placed in parts, not over the entire length of the beam, which means that only the parts with actual exposure to shear are strengthened. In a four-point bending test, this would entail that only the distance between the support and the load introduction is TMF reinforced, while the middle part remains unchanged. Moreover, the perfect amount and arrangement of screws (inclined screws) need to be figured out to find the most efficient solution with the lowest possible number of screws yet with increased values regarding load-carrying capacities and stiffness. Due to the minimum number of screws and the total length of TMF throughout 6 m, it was witnessed that the gap between the TMF and timber was not completely closed.

3.3 TIMBER FRAME ELEMENTS

An interesting application also emerges when considering TMF reinforcement in combination with industrial prefabrication. As more timber buildings are established using timber frame constructions, which entail that components such as walls are prefabricated in factories, TMF can be implemented within this industrial process. Consequently, a hydraulic device executes the press-fit process of TMF strips, which get positioned between the timber studs and the cladding. Within this test series [11], it must be considered that due to the quite hard surface as well as the low bending stiffness of the cladding panels, for this series one used OSB/3 panels, it was not possible to press-fit the TMF only with the help of screws. The first tests show an increase in diaphragm shear stiffness of 280 % (cf. Figs. 15 and 16) [11].

Figure 15: Frame of a wall element with TMF strips applied

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Figure 16: Diagonal test setup to determine the shear stiffness

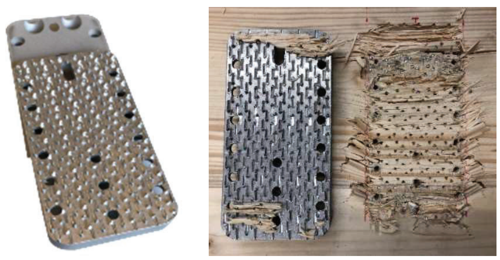

Figure 17: The modified surface of a joist hanger and failure mechanism after reaching the maximum load

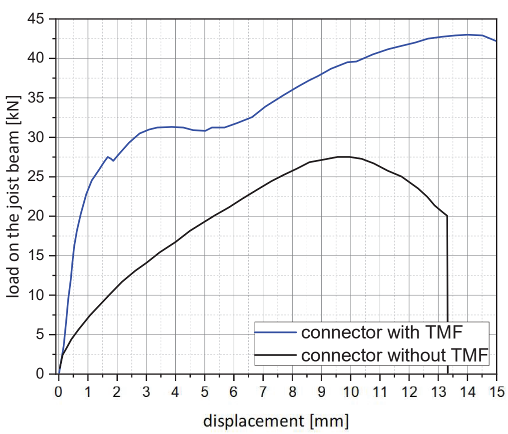

Figure 18: Shear tests of joist hangers with (blue graph) and without (black graph) TMF technology

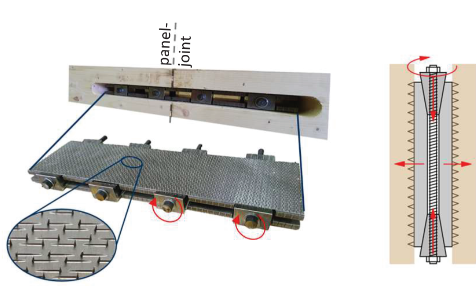

Figure 19: CLT edge connection with thicker metal plates and serrated surfaces

3.4 APPLICATIONS ON THE SURFACE OF JOIST HANGERS

One example of how a selective modification of a connector with a TMF surface can look is presented in the following preliminary tests with a dovetail-shaped joist hanger (cf. Fig. 17). By scratching up the surface of the connector part to be fixed on the beams, the load capacity can be increased by around 54 % (cf. Figs. 3 and 18). Again, the initial stiffness is increased compared to the standard connection, as shown by the curve gradient, followed by the obvious flat part and a renewed increase until the connection's collapse. Of course, this technique can be adapted to other kinds of timber connectors as well, improving the strength and stiffness of the respective joint.

3.5 APPLICATIONS WITH THICKER STEEL PLATES

The technology to scratch out teeth from a thicker steel plate offers new applications. One example of a game-changer in connecting CLT panels edgewise was already presented in [13, 14, 15]. It works in a way that two metal plates, with a thickness of, e.g., 12 mm, are placed into a vertical mill, arranged perpendicular to the edge side of the CLT slab (cf. Fig. 19). With the help of threaded rods and wedges, the teeth are pressed into the narrow surface of the CLT panel. The system was tested through four-point bending tests, which resulted in a rotational spring stiffness of approximately 5,000 kNm/rad/m. According to [14, 16] this is sufficient to build, for example, flat slabs with a column grid up to 7 metres.

Figure 20: Preparation of the punching specimen with Spider Connector [16] and radial arranged TMF strips on the top surface

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3.6 APPLICATION FOR TIMBER CONCRETE COMPOSITES

To demonstrate the potential application areas of timber-concrete composite construction (TCC) with TMF, initial shear tests have already been conducted [17,18]. A slightly modified teeth-shaped design is used to ensure higher penetration depths into the concrete member. As part of a master's thesis about the topic of point-supported flat slabs with TCC, the performance was also demonstrated for this application [cf. Fig. 20]. Preliminary shear tests indicated a shear strength of 3.5 N/mm².

4 – DISCUSSION AND OUTLOOK

The Timber Engineering Unit of the University of Innsbruck has been researching this connection medium since 2019 [19]. However, due to the COVID-19 crisis, the topic could only be intensively pursued again, starting around 2023, to investigate the basic concept of TMF through an extensive testing campaign to ensure a certified building product, such as an ETA. It was demonstrated that a highly efficient connection is created through the area-based micro-teeth combined with the clamping effects of screws. Screws with washer heads can produce the required press-fit forces for shorter lengths and gross densities up to 460 kg/m³. Due to the simplicity of the products, many applications can be strengthened with this technology. To ensure the connection remains stable over time, the impact of cross-sectional changes, which inevitably occur in timber construction due to variations in moisture content, must be considered. Extensive preliminary studies have captured these effects by taking into account the differential swelling and shrinkage rates, particularly in the radial and tangential directions, as well as variations in the orientation of the annual-year rings. Based on this, a screwing strategy is being developed to prevent the teeth, especially in the surface-near zones of the connection, from pulling out. A staggered arrangement of the screws has proven to be advisable and is currently being further investigated in experimental studies. The tests assume an initial installation moisture content of 12 %, which is then reduced in two stages to 6 %. Research on the impact of moisture changes on shear strength, without considering screwing strategies, has already been conducted by [20].

In addition to the wide range of applications (essentially anywhere timber components can be connected by using screws), there is also the possibility of integrating this technology into general steel components via inlays, providing maximum flexibility for structural designers.

Due to the numerous unanswered questions, several research projects are being conducted at the University of Innsbruck. The results will be published in more detail in the upcoming months. In agreement with our partners, these publications have been withheld until the first European Technical Assessment [21] is published, which will enable the development of the first simple applications for timber structures.

Further investigations are currently being conducted at the University of Innsbruck, focusing on long-term behaviour (creeping), as well as performance in the event of an earthquake. Additionally, the implementation of this technology on thicker metal plates is a focus [22].

5 – ACKNOWLEDGEMENT

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To protect intellectual property, invention disclosures have already been filed for several of the methods presented here in collaboration with our project partners.

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