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Self-tapping screws as reinforcement for timber structures

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Abstract

Modern self-tapping and continuously-threaded woodscrews enable new methods for strengthening and joining timber and glulam construction elements. As these screws have a high axial strength and an excellent continuous bond to the wood they can be used similar to steel reinforcement in concrete construction. Different from concrete the natural construction material timber shows a high grade of anisotropy, resulting in low values of strength and stiffness for tension and compression perpendicular to the woodfibre and for shear forces parallel to the woodfibre. Self-tapping screws can be systematically used to reinforce these 'weak' directions either in sections of load concentration, e.g. bearing areas, or to increase strength and stiffness of whole structural elements. In several series of tests conducted by the Chair of Structures and Structural Design at the RWTH Aachen University, screws forming an internal truss system improved the shear stiffness of glue-laminated timber beams. Similarly the reinforcement of the flexural tension zone by steel plates attached with screws in a truss arrangement significantly increased the bending stiffness and ultimate load of the beams. A second field of the application of reinforcing screws are high-performance joints. Tests on rigid frame corners connected with self-tapping screws proved a significant higher load bearing capacity compared to conventional joints with dowels or glued finger-joints. The layout for the configuration of the screws was done by modelling the internal flow of forces with strut-and-tie-models in a related way to reinforced concrete design. The presented reinforcing method with self-tapping screws opens new perspectives for joining and upgrading all kinds of timber elements creating innovative engineering solutions for challenging high-performance timber structures.

Keywords: timber construction, self-tapping screws, reinforcement, strengthening, timber joints

1. Introduction

Screws as connectors in timber construction have gone through a significant development that widened the fields of use and greatly improved the performance of the woodscrews.

Conventional woodscrews, e.g as in German standard DIN 571, are partially threaded and normally used for shear-connections similar as nails or steel dowels. These types of screws need pre-drilled pilot holes for installation and thus were not used very frequently in timber construction. New types of screws with self-drilling or self-tapping heads could be fitted fast and easily with electrical tools and are commonly used for fixing board materials in wall and floor constructions. To open new fields of use the screw sizes were increased. At the moment the maximum available size of self-tapping screws with continuous threads is 12 mm diameter of the thread and a length of 800 mm. Even bigger lengths up to 2.0 m can be reached with threaded rods with a diameter of 16 mm that need of course a pre-drilled hole. Figure 1 shows examples of self-tapping screws and threaded rods.

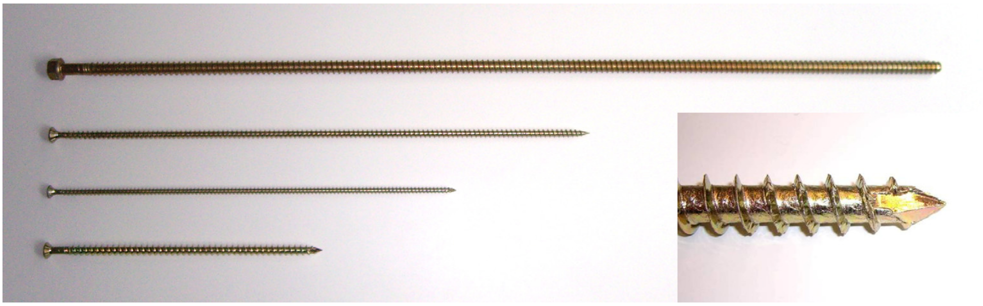


Figure 1: Self-tapping continuously-treaded screws and threaded rods of different size

The self-tapping continuously-threaded screws have significant advantages compared to conventional standardized woodscrews. They are specially hardened to reach a high tensile strength of over 800 N/mm² and thus can bear high axial load even with small core diameters, reducing the danger of splitting. The improved thread geometry and bigger share of the thread enables an excellent bond to the wood and very a high pull-out strength. A comparison of modern self-tapping woodscrews with conventional woodscrews is given in Figure 2.

Type of screws	**Core-Ø/ Thread-Ø**	**$f_{u,k}$ [N/mm²]**	**Core-section/ Nominal section**	**Edge of threads**
Standardized Woodscrews (e.g. for threads: DIN 7998)	0,68 – 0,75	300	0,46 – 0,56	60º
Self-tapping completely-threaded woodscrews (general technical approval)	~ 0,6	860 - 1000	0,37 - 0,4	~ 40º

Figure 2: Comparison of the properties of conventional and self-tapping screws

The high strength and continuous bond enables the use of these screws for reinforcing and joining timber elements similar as in reinforced concrete construction.

The approach for using continuously-threaded screws for reinforcing timber elements is based on the special structure of the wood which has a distinctive anisotropy. The cellular structure implies a low weight and the longitudinal fibres provide a high strength parallel to the grain, enabling a high efficiency of structures stressed in the direction of the woodfibre. Perpendicular to the grain wood shows a rather poor performance regarding both strength and stiffness. Especially the tensile strength orthogonal to the fibres is very low giving the danger of splitting failure. The shear stiffness and shear resistance of the wood is also relatively low compared to the longitudinal stiffness and strength. The performance of structural timber elements can be increased by systematically reinforcing these ‘weak’ directions with continuously threaded screws. The screws are used to carry tension and compression loads rectangular to the fibre direction as well as shear forces diagonal to the grain. In this respect the reinforcement of timber elements differs from the reinforcement of concrete where the reinforcement bars are mainly used to bear the tensile forces which the brittle concrete cannot conduct. The reinforcement screws can be applied both locally in areas of load concentrations and globally to raise the strength and stiffness of the whole element.

Another important characteristics of wood is a high grade of inhomogeneity which causes in natural timber a high margin of deviation of strength and stiffness parameters. Natural local growth defects like knots and pitch pockets as well as seasoning checks strongly reduce the effective load-bearing capacity of timber elements compared to the performance of flawless small-size specimens. The grading procedure of sawn timber used for further processing, e.g. the production of glue-laminated timber, leads to a homogenization of the material and reduces the range of variation. Still the remaining natural defects and new artificial ‘defects’ as glued finger-joints have a significant influence on the structural behaviour of load bearing elements. Placing an internal reinforcement with screws is suitable to canalize the flow of internal forces, thereby reducing the negative effects of local material deficiencies and the risk of unpredictable failure causes.

Compared to flawless small-size specimens the local deficiencies mainly reduce the tensile and bending strength of structural elements, while the compressive strength is not affected significantly. Thus for timber beams under bending loads an additional reinforcement of the tensile bending zone can be an effective measure to raise the load bearing capacity.

2. Design models and dimensioning of screw reinforcement

The layout and configuration of reinforcing continuously-threaded screws has to be adapted to the individual task of strengthening or connecting timber elements. So far a number of solitary solutions have been developed, for example for bearings or connections of main and subordinate girders. These ways of use have been integrated in the general technical approvals of the screws or dimensioning aids. To promote a broad use of continuously-threaded screws as reinforcements in timber construction a general dimensioning concept is necessary which enables the engineer to easily adapt the layout and positioning of the screws to any given task of reinforcement and joining. A basic need for that is the knowledge of the flow of forces within the structure or connection. Because of the anisotropy of wood the classical analytical methods based on technical mechanics can only be used to a limited extent. The complex boundary conditions, for example in areas of bearings or load transfer, the dependency of material properties from the direction of the grain and the composition of compound systems build from different materials, i.e. wood and steel, enforce the use of numerical calculation methods. A detailed numerical analysis, for example using finite elements method is very time-consuming. Thus for practical application a simplified design method is needed, allowing the dimensioning of reinforcements with simple means.

A promising approach to describe the structural behaviour of screw reinforcement is the use of strut-and-tie-models as used in reinforced concrete construction for the layout and dimensioning of bearing or notch details. These strut-and-tie-models allow an idealized modeling of the internal flow of forces by assigning them to the elements of the virtual truss inside the timber beam or joint. In Figure 3 examples for simple strut-and-tie-models are shown.

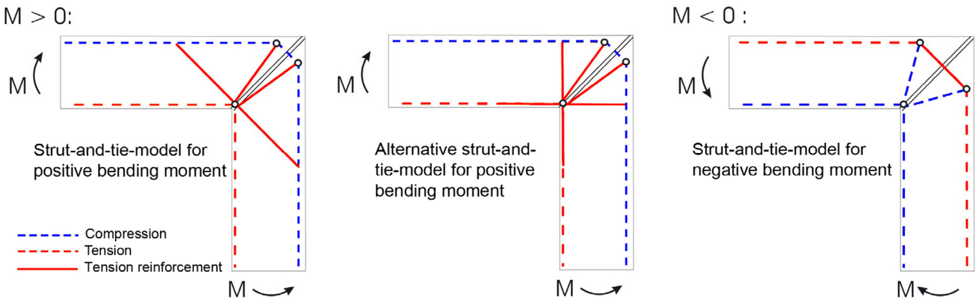
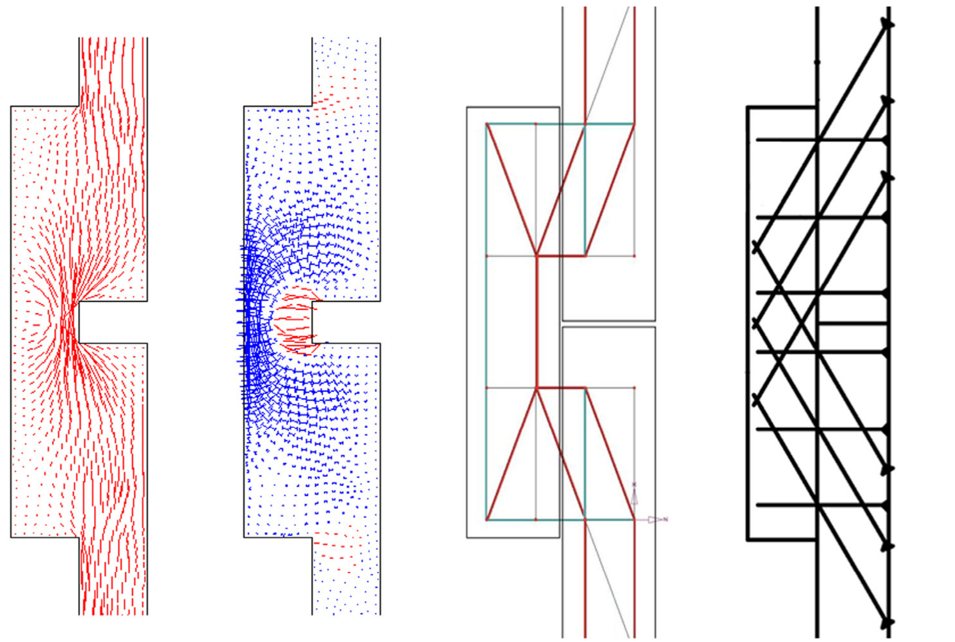


Figure 3: Simple strut-and-tie-models for the layout of screw reinforcements for rigid frame corners with positive and negative bending moments

Nevertheless the principles for positioning reinforcements according to the strut-and-tie-models as known from concrete design have to be adjusted to the special properties of wood. As concrete is an isotropic and brittle material with a unidirectional very low tensile strength the reinforcements in concrete design have to carry all internal tensile forces while the compressive forces are conducted by the concrete itself. In contrast to this timber is in general capable of bearing tensile forces parallel to the direction of the woodfibre without additional reinforcements. On the other hand it can be reasonable to assign reinforcement screws to compression members of the virtual truss that run perpendicular or diagonal to the fibre direction in order to raise the stiffness and strength in these 'weak' directions.

The strut-and-tie-models reflecting the internal flow of forces can be constructed based on engineering experience or existing models and examinations of the flow of internal forces. For more complex systems a preliminary analysis using finite elements method might be necessary to construct the strut-and-tie-models according to the directions of the principal stress. Figure 4 shows the development of a screw configuration on basis of principal stress analysis. Nevertheless it can also be reasonable to modify the internal truss system by concentration of stiff reinforcement elements in order to specify load channels. Such modification can for example be used to optimize the lever of internal forces in joints or to release load concentrations from highly stressed areas of the timber element.

The forces of the members of the strut-and-tie-models can easily be calculated with usual manual methods or basic engineering software. The dimensioning of the reinforcement screws can then be derived from the forces of the virtual truss members. If there is no risk of brittle failure, for example by lateral tension or shear stress, the forces of the truss members can be allocated to both timber and reinforcements.



Principal stress from FEM-analysis (tension red, compression blue)

Strut-and-tie-model with tension and compression members

Derived configuration of reinforcement screws

Figure 4: Development of a screw layout using FEM-analysis and strut-and-tie-model

Setting up detailed construction and dimensioning rules for the use of strut-and-tie-models is subject to further research activity. In particular in the course of the studies the level of accuracy of this simplified and idealized approach compared to more detailed numerical analysis has to be evaluated.

3. Fields of application for reinforcement with screws

Self-tapping continuously threaded screws can be efficiently used in many applications of strengthening and joining timber structures and also be combined with additional structural measures like steel connectors lamellas.

Some individual solutions of reinforcement are already established in timber construction. Examples are lateral reinforcements of heavily stressed bearing areas or reinforcements for lateral tension around notches and load inductions. In rehabilitation measures threaded steel rods have already been used as reinforcements for shear forces. Figure 5 depicts examples of usual applications of reinforcement screws.

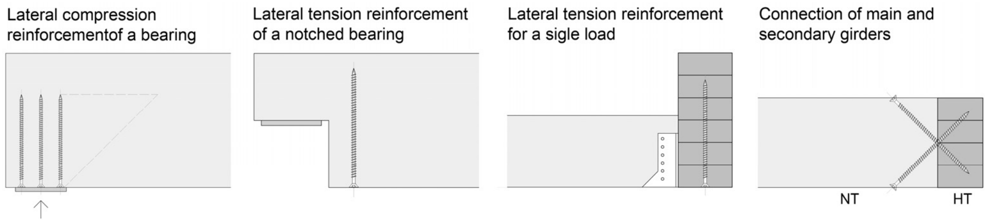


Figure 5: Examples for possible applications of continuously-threaded screws as reinforcements and connecting members

The Chair of Structures and Structural Design at RWTH Aachen University conducted two research projects in the years 2007 and 2008 to examine different reinforcement types for beams and structural joints.

3.1. Tests on reinforcement of timber beams

Continuously-threaded screws were used in different configurations of internal truss systems to increase the shear stiffness of girders. The tests were set up according to the measuring methods in DIN EN 408 with glue-laminated beams of GL 24 quality and a cross-section of 16 by 32 cm. A considerable shear stiffening effect could be shown especially for configurations with truss models where both tensile and compressive forces of the system were conducted by screw reinforcements. A truss system with a combination of diagonal tension members formed by screws and idealized vertical compression members of not reinforced wood had a much lower performance due to the low compressive rigidity of the timber lateral to the fibre. Figure 6 shows two of the examined truss systems and their shear stiffening effect compared to a timber beam without reinforcements.

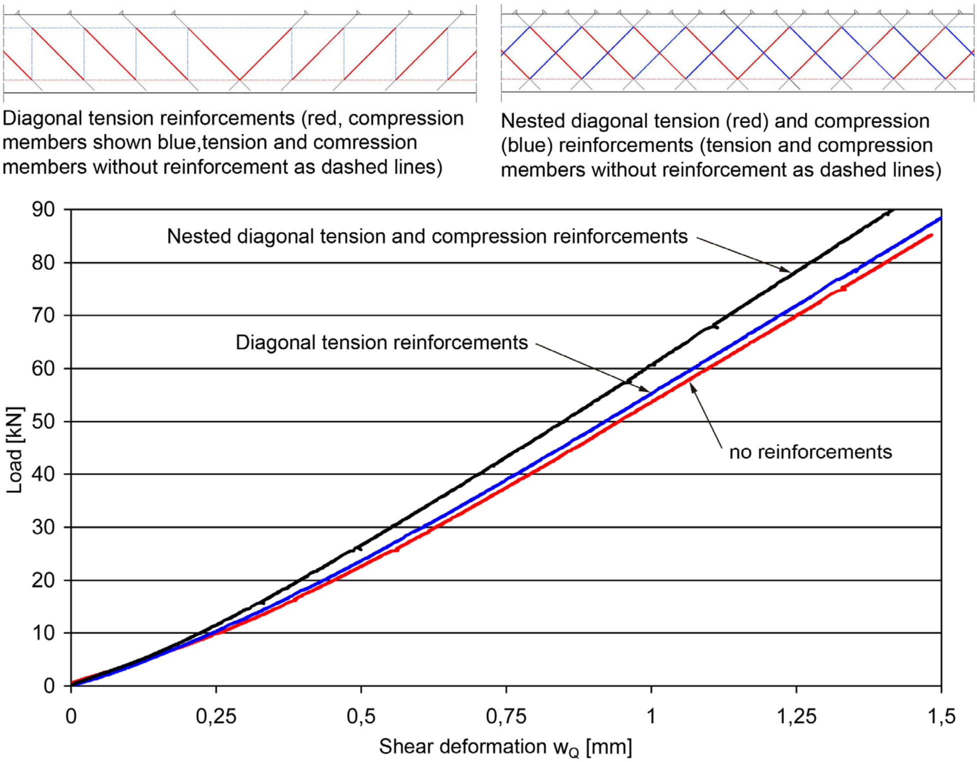


Figure 6: Effect of different screw reinforcements for shear stiffening of glulam elements

The logical next step was to complement the diagonal and lateral shear reinforcements with longitudinal reinforcement elements to raise the bending stiffness and flexural load bearing capacity. The first approach was to install long threaded steel rods parallel to the grain. As the drilling of the necessary holes for installation had a certain deviation from projected position the rods had to be placed with sufficient distance from the beam surface. Therefore the measured effects regarding stiffness and load bearing capacity of the beam did not meet the expectations. Hence it was decided to use external steel elements for bending reinforcement. The high strength and modulus of elasticity of steel allows an efficient strengthening of timber beams even with small profiles. Thus steel lamellas were preferred to woodbased materials such as laminated veneer lumber.

The steel lamellas were fixed to the timber beams with diagonal screws and the help of special anchoring chocks. As the lamella and the beam form a flexibly connected compound system the stiffness of the interface is crucial for the performance of the reinforced beam, regarding both load bearing capacity and flexural rigidity. The high axial stiffness of the screws and the slip-free design of the anchoring chocks resulted in a high compound stiffness. The test setup with steel lamella and anchoring is shown in Figure 7.

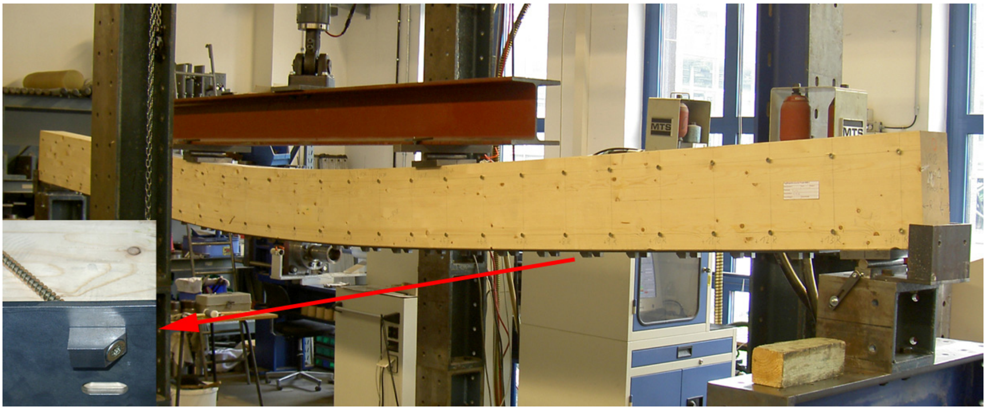


Figure 7: Glulam beam with external lamella and internal screw reinforcement in bending test, down left detail of the anchoring chock to fit the screws to the lamella

Two different lamella configurations were examined for strengthening glue-laminated beams of the dimensions 16 by 32 cm and a single span of 5.76 m: a 6 mm thick lamella made of steel quality S 235 and an 8 mm thick lamella made of steel S 355. The structural behaviour of the reinforced beams compared to a reference beam without reinforcement can be seen from Figure 8.

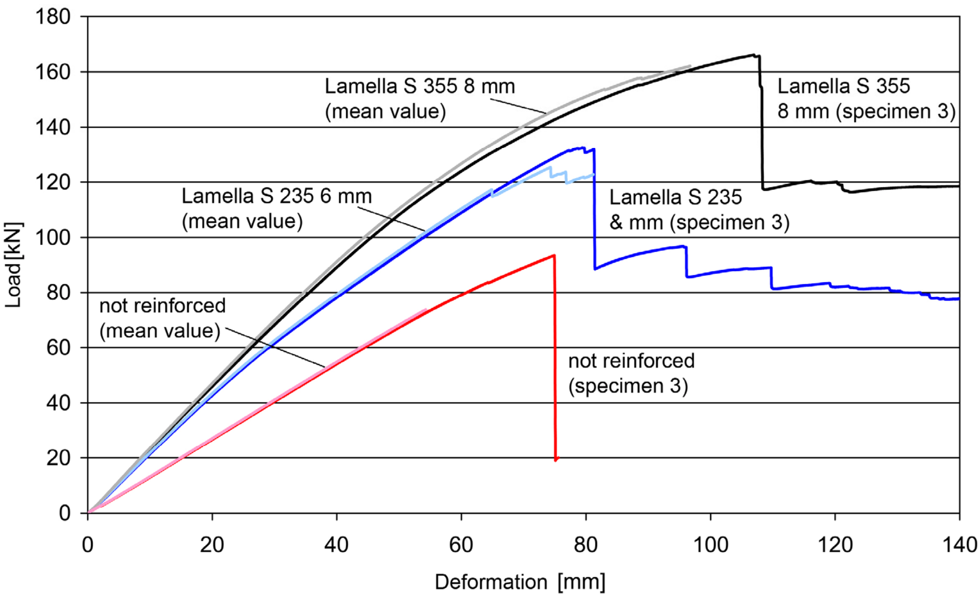


Figure 8: Load-deformation-diagrammes for beams with lamella reinforcements

The 6 mm lamella increased the ultimate load by 45% and the bending stiffness by 39%. For the 8 mm lamella an average increase of the ultimate load of almost 80% and a rise of bending stiffness of 49% was measured. The fracture mode of the reinforced beams was characterized by a ductile behaviour of the steel lamellas as well as the compression zone of the timber, what is a big advantage against the brittle failure mode of normal timber beams. The truss-like reinforcement screws secured the anchorage of the lamella even in the state of initial failure and prevented large-scale delaminations and shear fractures of the timber beam.

The test results underline the high performance of the combined reinforcement with internal truss-like screw configurations and external steel elements. This method is especially suitable for a posteriori reinforcement of beams and girders in renovation and rehabilitation of structures because it can be applied in situ and relatively unaffected by moisture content and surface quality of the timber and the external climatic conditions.

3.2. Tests on joints connected with continuously threaded screws

On the field of connections of structural elements in a first series of tests tension members with an square cross-section were joint with a one-sided fish-plate and tilted screws. The basic layout and the screw configuration can be seen from Figure 4. Compared to a conventional reference joint connected with the maximum number of geometrically applicable steel dowels the screw joint had an 18% higher load bearing capacity and a notably higher longitudinal stiffness. Furthermore the connecting reinforcement screws channeled the internal flow of tensile force within the wooden fish-plate so that the excentricity of the load was reduced and a flexural fracture of the plate prevented. Two exemplary states of fracture for the dowel and the screw joint are depicted in Figure 9.

Figure 9: Exemplary states of fracture of one-sided fish-plate joints connected with dowel (left) and with continuously-threaded screws (right)

A main field of research on screw connections have been rigid frame corners constructed as one-layered mitre-joints. The joints were designed for positive and negative bending moments. The basic strut-and-tie models for the layout of the reinforcement can be seen in Figure 3. The corresponding screw configurations as well as the test settings are show in Figure 10.

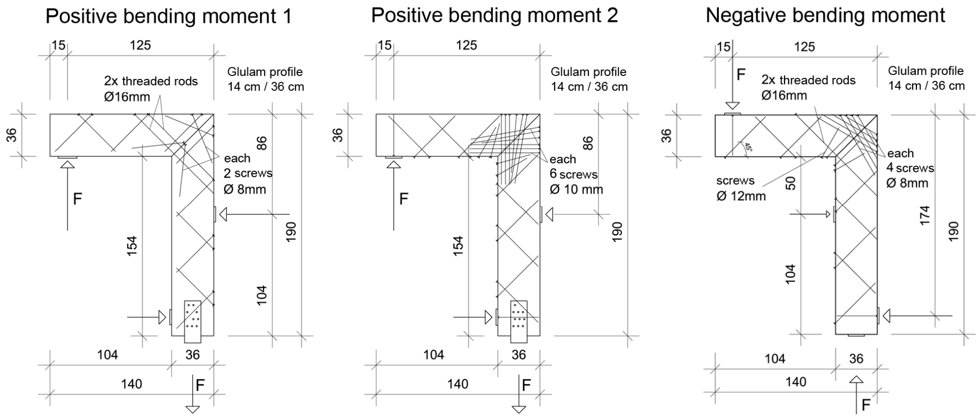


Figure 10: Configurations of screw reinforcements for rigid corner joints

The load bearing capacity of the joints could be raised in the course of the two research projects by improving the layout and maximizing the number of screws for the connection. Both for negative and positive bending moments the ultimate load was significant higher than the characteristic values of calculated conventional corner joints such as steel dowels arranged in a circle or glued finger-joints. A table with load bearing capacities, comparing the quantile values from the tests with the characteristic values of the calculated reference joints and the 'pure' glulam profile is given in Figure 11.

Type of joint		**Negative bending moment**			**Positive bending moment**		
		Load F [kN]		**Moment M [kNm]**	**Load F [kN]**		**Moment M [kNm]**
Glued finger joint	X_k	25,59	37,8%	27,38	5,12	8,2%	5,48
Dowel ring	X_k	17,02	25,2%	18,22	17,02	27,1%	18,22
Screw joints	$q_{0,05}$	59,04	87,3%	63,18	43,60	69,5%	46,65
'pure' gluelam	X_k	67,62	100,0%	72,35	62,71	100,0%	67,10

Figure 11: Comparison of characteristic ultimate loads for calculated conventional joints with 5%-quantiles of tested ultimate loads for screw joints

It can be seen that the screw joint for negative bending moment could bear almost 90% of the calculated ultimate load of the used profile. In the load tests this configuration reached failure by bending fracture of the vertical leg of the test specimens as shown in Figure 12. In configurations containing a lower number of screws, tensile fracture of the screw material was the typical failure cause, resulting in an extremely low statistical spread of the ultimate loads. In those cases the measured failure load coincided perfectly with the values calculated from the used strut-and-tie-model. The used strut-and-tie-models hence proved to be a suitable method for dimensioning and layout of the examined frame-corners. The concentration of stiff reinforcement elements to direct internal forces onto a predefined path was also used in the design of the corner joints. By installing very stiff threaded steel rods close to the inner corner of the joint for negative moment, the lever of forces in the mitre cut could be maximized thus raising the transferable bending moments. At the same time the indentation of the wood at the inner corner was reduced, leading to an increased rigidity of the whole connection.

The high load bearing capacity of the tested rigid corner joints enables the development of light and lean frame structures with high architectural quality.

Figure 12: Failure of rigid frame corners connected with screws: left under positive moment, right under negative moment

4. Conclusions and outlook

The concept of reinforcing and joining timber elements with self-tapping continuously-threaded screws offers efficient engineering solutions for many tasks in timber construction. The conducted research projects proved the high performance of the examined reinforcements and connections. To enable a general use of the proposed construction and design methods further research has to be done on a number of topics. An important aspect is the long-term behaviour of reinforced elements under different climatic conditions as well as under changing and dynamic loads. Especially the dry-out shrinkage of the wood has to be examined regarding the development of seasoning checks in reinforced timber elements and their influence on the bond between the wood and the screws. The applicability of the simplified design approach using strut-and-tie-models as an easy-to-handle instrument for dimensioning the reinforcements should be verified in further examinations. Extensive development to decrease the admissible minimum angle between screws and woodfibre would greatly increase the field of possible applications, especially for the design of innovative joint details.

The introduced reinforcing and joining methods open many fields of new design approaches in construction and rehabilitation of high-performance timber structures.

Acknowledgements

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