GROUTED JOINTS FOR MODERN ROUND WOOD BRIDGE AND TRUSS STRUCTURES

LIGAÇÕES MOLDADAS PARA ESTRUTURAS MODERNAS DE TRELIÇAS E PONTES EM ROLARIA DE MADEIRA

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Abstract

Natural dried logs have outstanding mechanical values and an excellent eco and energy balance. Nevertheless, in most countries using round timber in construction is not considered. The main problem is caused by the joining technology of round-to-round sections. Innovative composite materials and Advanced Manufacturing Technology processes allow the design and manufacturing of connecting systems with difficult geometry and different section types in wooden truss structures. The design process from the Architects idea to the final building is accompanied by the Engineers focus on easy-jointing techniques.

The presented work is based on the grouting technology used in reinforced concrete structures, where structural parts are force- and form-fit connected by a combination of starter bars and a backfitting grouting material. For timber bridges, the presented grouting joints follow this technology, where the joints are prefabricated and assembled first by technical approved adhesives or screws. Afterwards on site they are coupled with rods, straps or stamped parts and additional grouted. As grouting material a polymer concrete is used with high compression strength and high adhesive bond to timber as well to steel.

Keywords: round timber; advanced manufacturing technology; wood adhesives; green buildings; high performance polymer concrete; cohesive zone modeling; delamination

Resumen

Os troncos secos naturalmente têm elevados valores de resistência mecânica e um excelente balanço energético e ecológico. No entanto, o uso de rolaria em construção não é tido em conta na maior parte dos países. O principal problema é o da tecnologia de ligação entre secções circulares. Materiais compósitos inovadores e processos de Tecnologia Avançada de Fabrico permitem o projeto e fabrico de sistemas de ligação com geometrias difíceis e tipos diferentes de secções circulares em estruturas treliçadas de madeira. O processo de projeto, desde o conceito inicial da Arquitetura até à construção final, é acompanhado pela Engenharia, focada em técnicas simples de ligação.

O trabalho apresentado baseia-se na tecnologia de moldagem usada em estruturas de betão armado, nas quais as forças e formas das partes estruturais a unir são compatibilizadas por ligações constituídas por uma combinação de armaduras e argamassa de enchimento. Para pontes de madeira, as ligações moldadas apresentadas seguem esta tecnologia, sendo pré-fabricadas e montadas inicialmente com recurso a colas ou parafusos tecnicamente aprovados. Posteriormente, em obra, a união é completada com varões, cintas ou chapas estampadas, e enchimento adicional. A argamassa de enchimento utilizada é um betão polimérico de alta resistência à compressão e elevada aderência, tanto à madeira como ao aço.

***Palabras clave**: rolaria de madeira; tecnologia avançada de fabrico; colas para madeira; edifícios verdes; betão polimérico de alto desempenho; modelação da zona coesiva; delaminação*

1 INTRODUCTION

Timber has been used as structural material for centuries and numerous examples demonstrate its durability if properly designed and built and adequate maintenance has been applied. The use of timber in structures has become increasingly important, considering that it is the only truly renewable building material.

One approach which offers potential for increased use of timber involves the notion of "timber-based hybrid structures". These structures integrate wood with different materials, thereby significantly increasing the applications of timber in structures beyond current limitations. The hybrid design framework is particularly interesting for its ease of assembly and the resulting reduced construction times and improved building physics performance. Additionally, modern manufacturing technologies have the potential to drive structural improvements, for example, by enabling the accurate shaping of complex products and the precise creation of ready-to-install factory-built components.

Over the last decade, several innovative hybrid systems were developed to promote the use of timber [1], but round timber as construction material is still not very common in structural timber engineering. However, some good examples are available, where architects introduce natural dried round wood for larger structures and buildings, e.g. WholeTrees® Architecture & Structures, Madison, WI. Buildings made of round timber have the aesthetics of a transparent structure by use of eco-efficient round timber and are lightweight with minor material consumption.

Modern timber architecture, probably best illustrated by Shigeru Ban [2], increasingly moving towards free forms, for which currently used timber joining methods do not offer fully adapted solutions. Consequently, the use of adhesive bonding is described as one of the most interesting fields of development: "just as adhesives have freed timber of its structural and size limitations, adhesives can free timber of the metal needed presently to make joints" [3]. Adhesive bonding can be used to form load-bearing joints in timber structures, both in new-build applications and in repair, and provide an efficient and durable method provided that: i) the joints are correctly designed; ii) suitable specifications are adopted; iii) the work is done by experienced operatives; and iv) strict quality control is exercised [4].

To conceive large-span trusses, the structural system, the load distribution within the joints and restrictive regulations in design codes have to be considered in the design process. Furthermore, an innovative design of the joint is needed, focusing on efficient load-distribution in the structure and geometrical conditions of the round timber members. One possible solution is shown below, introducing round wood for modern bridge and truss structures with concrete-type adhesive joints (CTA) made of high-performance polymer concrete.

2 GENERAL DESIGN ASPECTS

Hybrid composite structures made of round timber are not only eco-friendly and energy-efficient by their use of untapped round timber, which is fabricated in terms of sustainability under low process-energy. They also provide a much higher stiffness in comparison to sawn structural timber and engineered wood products. This result in a design of truss structures with wider spans in comparison to conventional timber trusses under retention of the ratio between strength and bulk density. Especially adult-tree trunks have a high-pressure resistance in external fiber areas. In an ordinary sawing process, these areas are normally removed. Investigations of Teischinger [5] show, that full sized timber-diameters have their highest density in the outlaying areas of the logs.

Nevertheless, wide spanning round timber constructions are not usually considered in timber engineering. The main cause is the lack of an efficient joining technology for round-to-round sections (Fig. 1). Further significant reasons why round wood is rarely used in timber engineering are unavailable mechanical strength values and joint slippage when using conventional connecting techniques.

Figure 1: Conventional round-to-round timber joint

The new design solution consists of three essential parts:

a) Spatial round timber as structural girder
b) Assemblage point made of high-performance polymer concrete
c) Timber-HPC connection with glued-in rods (GIR)

Conventional glued-in rod joints deal with very thin glueline thicknesses up to 2.0 mm [6] or up to 6.0 mm when using particle-filled epoxy resins [7], which can still be considered as thin glue lines. The applied adhesives tend to exhibit strength-reducing effects in the bondline during the initial hardening shrinkage and limited gap-filling qualities. To overcome this shortcoming, new-type connections using grouting technology with concrete-type adhesives (CTA) have been developed, accounting different mechanical behavior and manufacturing technology compared to conventional glued-in rods.

Grouted joints use modified adhesives with dried fillers to create a concrete-type connection for enclosed timber members. The CTA is able to overcome disadvantages of traditional adhesives for glued-in rod joints, e.g. stringent quality control, high assembling effort and geometrical restrictions. Consequently, structures that are more complex can be developed, like grid-shells, modern reproductions of tree structures (Fig. 2).

Figure 2: Spatial timber tree structure

Fig. 3 and 4 shows the initial design of a timber foot bridge using the new composite design concept with grouted joints and the foot bridge under construction (clear span 13 m / 43 ft).

Figure 3: Composite timber truss bridge with grouted joints

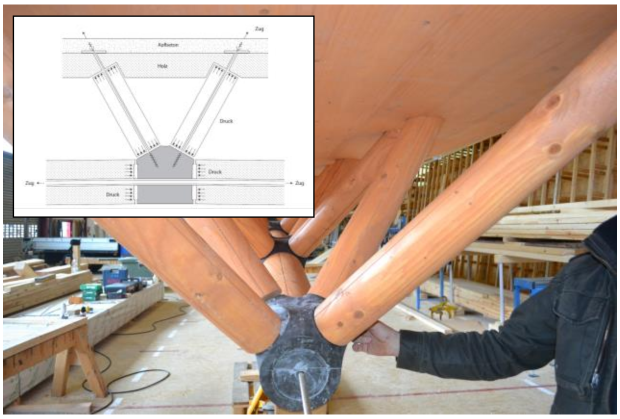

Figure 4: CTA joint connecting six truss members

3 CTA-JOINT DESIGN

3.1 Grouting material

Several materials have been studied and analyzed to identify a suitable material for the compound. The best suited CTA is a two-component BPA EP-bound concrete with mineral aggregate. The hardener adapted for the product is a fluid polyamine adduct, which holds an average reactivity for the interlacing of the resin. The mineral additive is composed of well-graded gravel with a grain size of max. 6 mm. A comparison of the CTA with common construction reinforced concrete C25/30 is shown in Table 1.

Table 1: Comparison of material properties with reinforced concrete

Material property	Unit	CTA	RC 25/30	Comparison CTA/RC
Density	g/cm³	2.3	2.4	0.95
Compression MOE	MPa	32,000	30,000	1.07
Bending strength	MPa	40	5.5	7.27
Compressive strength	MPa	150	30	5.00

The high compressive strength of CTA results from the bonding behavior of the polymer binder material and the mineral fillers, which leads to a high packing density. With regard to the stress strain behavior of the composite material, an ideal elastic behavior with a semi-ductile hardening rule was observed in material tests (which were also used to calibrate the subsequent numerical model). The failure behavior under consideration of tension or shear loading is more brittle compared to the failure under compression loading. Due to the high content of gravel in this composite, it is possible to assimilate a large amount of concrete, e.g. for much bigger drill holes compared to conventional drill hole diameters when dealing with glued-in rods, without creating exothermic chemical reactions like higher-content resin and curing agent adhesives compositions.

3.2 Grouting technology

Over the last 15 years, rapid prototyping has been an integral part of the design process in the car and aerospace industry. Recently the architecture profession has started to use these techniques in its design process [8], [9] and some architecture schools have begun experimenting with these technologies, as they allow a cost-effective way from design to production of complex geometries.

Advanced design and manufacturing are used in the production of the grouted joints. The form of the joint following the distribution of forces and are modeled to gather all members with the given axis, length and angle. The manufacturing takes place in a digital fabrication process. Supported by a plug-in for the free-form modeler Rhinoceros® [10] the necessary machine operations are exported from the design to the interface of the joinery machines for production of the members.

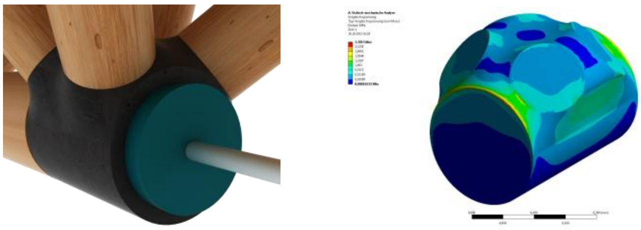

Figure 5: Digital design of the CTA-joint

A volumetric model (Fig. 5) serves as the basis for a prototype, which is subsequently milled on a 5-axial portal-milling machine in a PU-foam. This prototype is used as a “positive” in the manufacturing. The necessary joint shape can be cast in the finished multi-part silicone mould by grouting and reaches its final strength after 24 hours [11], [11]. The pre-manufactured parts can, according to size, be mounted in the factory or on-site through screwing, plugging and gluing, whereas manufacturing, gluing-in of steel rods into the timber and into the grouted joint take place under controlled conditions. The enclosed members are simply cut at the according length and milled with the fitting drill holes and recesses (Fig. 6).

Figure 6: Finished CTA-joint with fitted trusses

3.3 Experimental characterization of the timber-CTA compound

Laboratory tests were conducted for model verification and investigation of the embedding stiffness. The experimental investigations consisted of push-out and pull-out tests analyzing large drill holes (the grouting chamber) to activate the much larger lateral surface in comparison to conventional dimensions for drill holes in glued-in rods. The push-out tests allowed determining the shear-slip relationship between timber and CTA for further numerical investigations. In further pull-out tests, a single 12 mm diameter steel rod was put into a drill hole and grouted with CTA (Fig. 7).

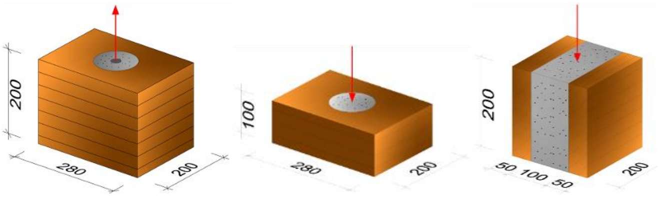

Figure 7: Push- and pull-out testing: tensile behavior (left); shear-slippage (middle), rolling shear behavior (right)

For all test series, the drill-hole depth was chosen to 150 mm with a glued-in length of 120 mm. All specimens consisted of glued laminated timber, European strength class GL24h. They were tested according to EN 338:2009 with a MC 12 ± 1% during manufacturing and testing, measuring the load-slip behavior between timber and CTA, GIR and CTA in loading direction and the strain between timber and CTA and GIR and CTA perpendicular to the loading direction (radial to the glued-in rod). One result example is shown in the following figures, where PO-0 denotes push-out parallel to grain and PO-90 denotes perpendicular to grain. A comparison of the test results with the calculated characteristic value is shown in Table 2 and Figures 8 and 9. A detailed description of the tests and the results are given in [12], [13], [14].

Table 2: Push-out tests: mean values in MPa

series	specimen	ultimate strength	characteristic strength [1]
PO-0	6	6.83	3.50
PO-90	6	4.93	1.00

[1] DIN EN 1995-1-1/NA:2013-08, DIN EN 14080:2013-09

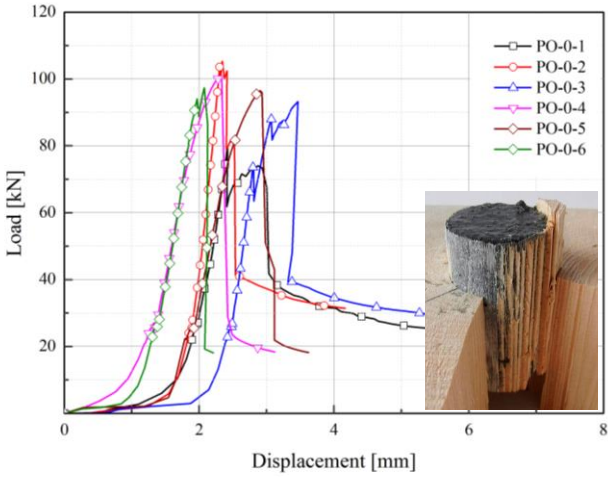

Figure 8: Push-out test parallel to grain (PO-0), load-slip curve

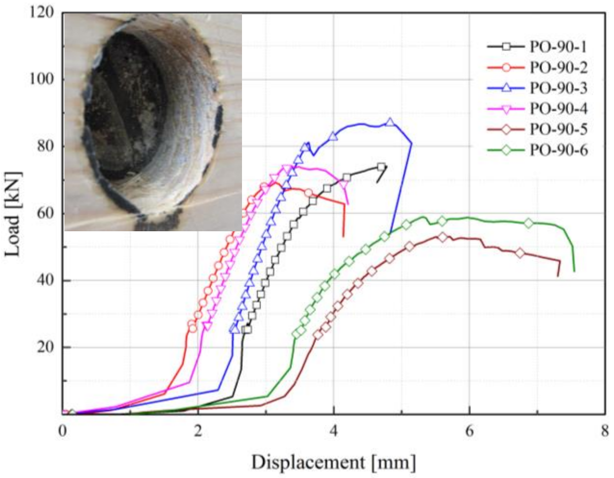

Figure 9: Push-out test perpendicular to grain (PO-90), load-slip curve

3.4 Experimental characterization of the connector-CTA compound

In tensile tests, glued-in rods with a female thread M16 embedded in CTA cylinder *d* = 120 mm have been tested to obtain the withdrawal resistance. The embedding length was chosen to 135 mm. All specimens failed around 100...110 kN by concrete cracking near the loaded edge (Fig. 10). After opening the specimen (Fig. 11) it could be observed that most of the glued-in rod was still in service with full compound to the CTA. The experimental obtained ultimate load was more than double than the design value given by the producer. The high ultimate loads and the uncracked specimen demonstrate clearly that the CTA can bear much higher tensile loads than common reinforced concrete and the compound between glued-in rod and CTA can be defined as rigid. In all tests the compound was not a weak spot in the joint design.

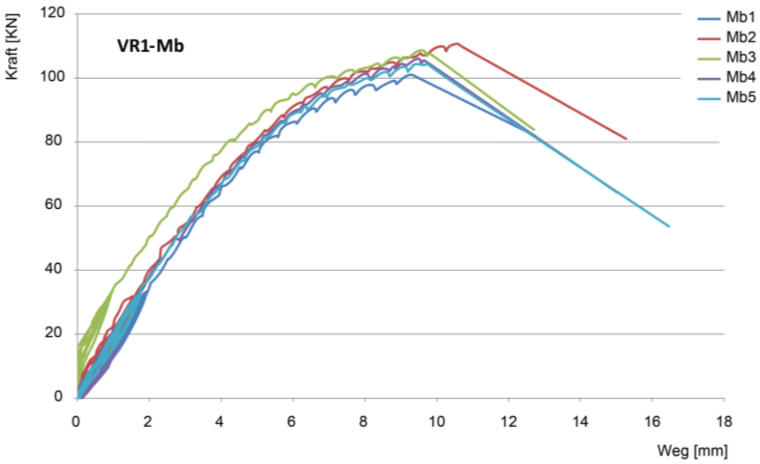

Figure 10: Load-slip relationship of the compound between glued-in rod and CTA

Figure 11: Opened specimen after testing

3.5 Numerical characterization of the bondline

To describe the debonding behavior within the bondline, a cohesive-zone model was applied, considering the delamination process in a fracture mechanics damage model [16], [17]. Based on the consideration of the specialties in near surface mounting on wood adhesives, a 3D numerical model was created and calibrated with lab tests addressing the structural and material nonlinearities of wood and CTA as well as damage and debonding behavior in the joint. The material properties of the threaded rod and structural steel have been assumed as isotropic and multi-linear-elastic. The numerical modeling of the used concrete-type adhesive is based on the fracture model for concrete of WILLAM & WARNKE [18] which describes brittle materials under multi-axial loading. In this model, yielding criteria are the uniaxial tensile and compression stiffness with shear transmission factors. If stresses exceed the yield criterion crushing occurs under compression (loss of stiffness) and smeared cracking occurs under tension (loss of stiffness perpendicular to the crack layer). A comparison of the experimental results and the numerical values of the bond-line behavior are shown in Figure 12 and Figure 13.

Referring to the results of the experimental investigations, the structural behavior of the compound between timber, GIR and CTA can be described as rigid and shear-resistant until the crack propagation in the bondline starts. The numerical model showed a good agreement with the lab results and correctly reflected structural nonlinearities with debonding [12], [13], [14].

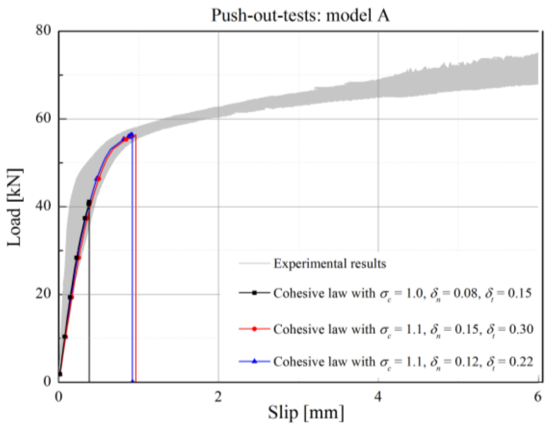

Figure 12: Comparison of test results with delamination-law softening effects

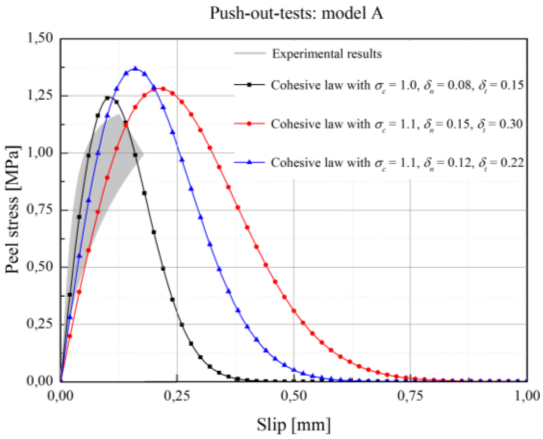

Figure 13: Comparison of peel stresses

The design and modeling of the CTA joint has been done using Rhino® 3D. Thereafter, the geometry data have been transferred into ANSYS® Rev. 17 finite element package for structural optimization. An appropriate mesh geometry have been applied first (Fig. 14 left) and openings as well as connecting surfaces adjusted to the geometry model. The mechanical model was chosen as quasihomogeneous and multi-linear isotropic with a damage behavior for brittle materials in dependence on the triaxial failure behavior of concrete. Due to asymmetric loading of the joint surfaces in girder direction of the bridge local stress concentration in the inner joint occur especially in the connecting areas of the truss diagonal members. Here, the maximum stresses have been calculated to 14 MPa, which is around 35% of the maximum material capacity (Fig. 14 right).

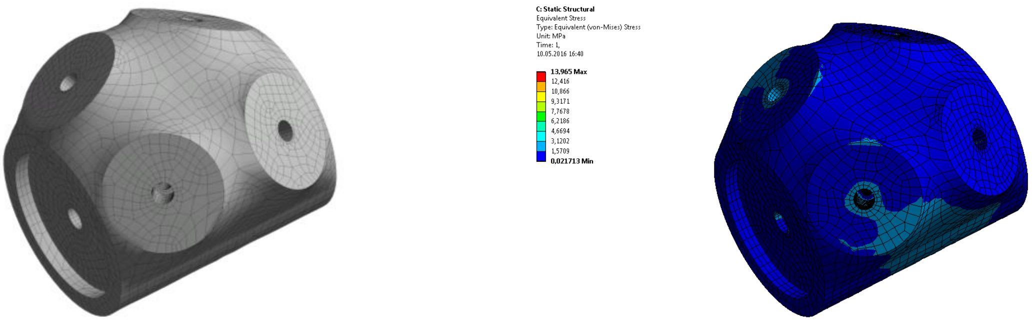

Figure 14: FE-model of the joint (left); max. equiv. stresses under service load of ~14 MPa (right)

The outer surface of the joints is nearly free of stresses. The stress distribution inside the joint is quite smooth in all elements; the adaptive mesh allows good results nondependent from the mesh geometry (Fig. 15).

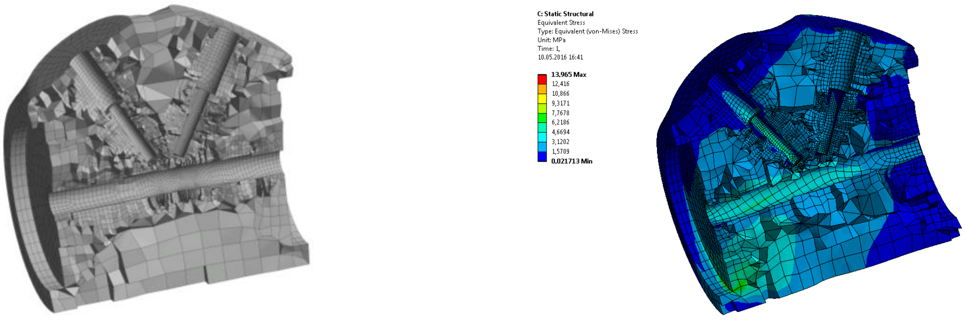

Figure 15: FE-model within the joint (left); max. equiv. stresses under service load (right)

4 CONCLUSIONS

Apart from the traditional jointing categories for timber structures (wood-to-wood, mechanical fasteners, adhesive bonding), novel solutions for hybrid joints have been the focus of recent research. Research on grouted joints demonstrated that conventional wood adhesives used with glued-in rods can be substituted by a composite material. One solution of grouted joints in inlay technology has been developed at Trier and Mainz University of Applied Sciences. The technique overcomes some shortcomings of traditional adhesion when used on-site. It is suitable for large-scale truss structures, such as grid-shells, trusses and timber bridges.

Especially for geometrical demanding joints and connections the application of grouted joints is the key technology for economical and efficient structures. With this technology, timber structures can be better introduced to architecture with complex geometrical shapes in digital design, as well as for sophisticated large scale timber buildings with complex loading conditions (interaction of shear, normal and bending loads, parallel and perpendicular to the grain).

A numerical model based on experimentally determined parameters displayed the structural response realistically when compared to experimentally obtained data. The presented new-type joint solutions made from a virtually isotropic, cost-effective material in combination with threaded or glued-in steel rods allow completely new, high-performance connection technologies in timber engineering. This can lead to new eco-efficient timber structures introducing natural dried round wood for larger structures and buildings by minor material consumption.

5 OUTLOOK

Further research will deal with the influence of outdoor exposure and changing MC to the compound as well as the long-term behavior of the composite joint. First test results of test specimen under all service classes with an appropriate climate exposure of 720 days show promising results with the expected reduced load-carrying capacity (Fig. 16). In all test series, the compound between the CTA and timber was not affected but a slightly different fracture behavior could be observed (Fig. 17). Those tests are currently going on and contribute to recommendations for outdoor use of grouted joints under different climate conditions.

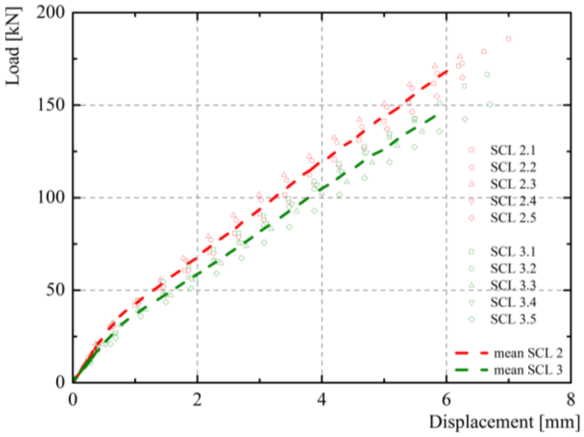

Figure 16: Comparison of the load-carrying capacity; pull-out tests in service class 2 and 3 after 720 days

Figure 17: Service class 3 test specimen 365 days outdoor exposure (left), 720 days exposure after test (right)

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