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DEVELOPMENT OF A PREFABRICATED ADHESIVELY BONDED JOINT FOR BAMBOO STRUCTURES

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ABSTRACT:

Despite ecological benefits, bamboo applications in modern construction are limited due to the complexities of connecting round cross-sections. The construction industry is a significant contributor to global warming due to its environmental impact. As a result, responsible builders are implementing sustainability measures to limit their carbon footprint and improve other environmental aspects of their operations. Continuing our previous research on connecting Douglas fir (*Pseudotsuga menziesii* Franco) roundwood in a material-appropriate way for large-span truss structures, the promising results led to an expansion of the round-to-round truss connection topic to other renewable building materials with a particular emphasis on sustainable bamboo structures made from *Guadua angustifolia* Kunth bamboo species. This paper explores the development and testing of adhesive bonding techniques combined with mechanical interlocking for grouted bamboo joints, focusing on the inner layer bonded with biocomposites. The research includes the implementation of ecologically harmless adhesives and experimental research of the bond strength between biocomposite and inner bamboo layer and results in a grouted joint that avoids punctual splitting by the absence of fasteners. Results were obtained in push-out tests and the strain fields were evaluated by using Digital Image Correlation. The results demonstrate a robust bond, especially when using concrete-type adhesive with high shear strength.

KEYWORDS: bamboo, connection, biocomposite, adhesive bond, DIC

1 – INTRODUCTION

1.1 STRUCTURAL ASPECTS

Bamboo, a perennial evergreen that is actually a type of grass, has been used to build houses since ancient times. In certain parts of the world, it remains the building material of choice. Given suitable soil and climate conditions, the bamboo plant can grow more than one meter in a single day, making it one of the fastest-growing plants in the world. The bamboo culm is hollow but reinforced with rigid cross-sectional partitions (nodes), giving it superior transversal tensile strength and stability.

Bamboo is increasingly recognized as a valuable building material due to its high strength-to-weight ratio, lightness and sustainability [1]. The natural appearance and design, combined with low effort in construction, makes bamboo the material of choice in design of eco-friendly constructions. Despite its numerous advantages, the widespread adoption of bamboo in structural applications faces several challenges, where a primary obstacle is the development of reliable and durable connections or joints between bamboo culms and structural members [2]. The inherent characteristics of raw bamboo, such as its hollow and thin-walled nature, variations in diameter, and susceptibility to splitting, complicate the creation of

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strong and stable joints using traditional methods or even modern fasteners. The technology of connecting round sections in-plane is a main problem for roundwood in construction, and a challenge relevant for bamboo [3]. To overcome these limitations and enhance the efficiency and reliability of bamboo in construction, prefabricated structural elements and new jointing techniques are crucial and innovative methods for joining bamboo culms are needed.

1.2 ECOLOGICAL ASPECTS

The buildings and construction sector is responsible for 37 % of global carbon dioxide emissions, mainly due to the high carbon footprint of materials such as cement and steel [4]. This has led to an urgent search for sustainable alternatives that not only reduce emissions but also actively capture and store carbon. Among these alternatives, bamboo stands out as a material with exceptional potential, thanks to its rapid growth, high density, and great ability to convert atmospheric carbon dioxide into biogenic carbon.

As an example of its crucial role in carbon sequestration throughout history, DULL et *al.* [5] conclude that natural reforestation resulting from the depopulation of the Americas by Old World diseases after European colonization, which led to a decline in agriculture and deforestation, played a decisive role in the cooling during the "Little Ice Age" (16th to 18th centuries), see also Figure 1. Studies by KING et *al.* [6] measuring the total ecosystem carbon (TEC) in bamboo forests indicate a storage capacity of between 94 and 392 tons of carbon per hectare - values that are lower than those of natural forests are (126-699 tC/ha) but comparable to tree plantations (85-429 tC/ha) and higher than grasslands or pastures (70-237 tC/ha).

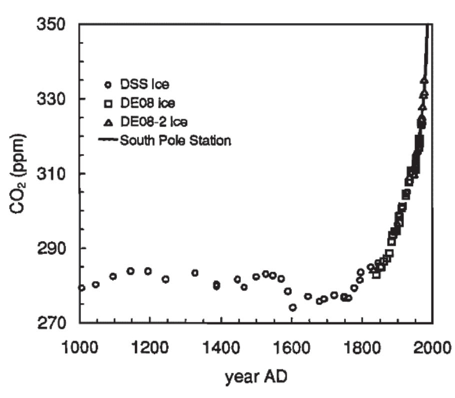

Figure 1: Carbon dioxide mixing ratios from several ice cores and the modern atmospheric record from South Pole [7].

Additionally, storing carbon in durable products as well as replacing conventional building materials when appropriate, bamboo not only serves as a carbon sink but also prevents the emissions associated with the production of these materials. To maximize these benefits, proper management is essential. This includes harvesting every 3 to 4 years to prevent the release of stored carbon through decomposition and to ensure storage in durable products. A side effect of proper management is the utilization of erosion control and water retention capabilities of the bamboo plants, making it an ideal option for restoring degraded land [8]. Considering the mechanisms of storing carbon, bamboo stands out among other natural building materials in the contribution mitigating climate change. Moreover, with its excellent carbon sequestration, combined with rapid regeneration and structural efficiency, bamboo can attain a key position under building materials in the transition towards a more sustainable built environment.

2 – BACKGROUND

Today, *Guadua angustifolia* Kunth (GaK), a giant bamboo species, has become a key resource for sustainable architecture. This native Colombian species, which can grow up to 30 m in height with diameters usually ranging from 60 to 160 mm and a wall thickness of up to 25 mm, offers significant structural advantages. Its high strength-to-weight ratio, natural flexibility, and rapid regeneration make it an efficient and eco-friendly alternative to conventional building materials.

Unfortunately, bamboo still faces challenges in the widespread adoption within contemporary architecture. Historically regarded as a low-cost material, its use in a large-scale project has been limited due to concerns about durability, standardization, and regulatory acceptance. However, advancements in prefabricated connections, engineered bamboo products, and modern construction techniques have transformed its perception. These innovations are positioning bamboo as a high-performance, structurally reliable and sustainable alternative for modern construction.

Traditional jointing methods such as lashings and bindings, which rely on friction and locking mechanisms, and later on screws and point connections, have been widely used due to their cost-effectiveness, simplicity and a lack of engineered solutions. Lateral loads and deflections lead here into splitting, a reduced capacity and low durability. The advent of modern engineering approaches has addressed these limitations through the introduction of bolted connections, capped connections and grouted systems (Figure 2) [9]. Bolted connections, while widely used, tend to generate stress concentrations leading to splitting. Capped connections distribute forces more uniformly, reducing localized failures and extending the service life of the material. With this type of joint, the dimensional inaccuracy and shrinkage behaviour of bamboo pose a challenge. Meanwhile, grouted or filled connections, which involve injecting materials such as resins or mortar into the bamboo plant's hollow section, possibly enhance joint performance by creating a composite system that improves both, durability and mechanical strength. Adhesive bonding in general presents a promising approach for creating strong and efficient joints in bamboo structures.

Figure 2: Some examples of engineered bamboo joints [9].

Engineered bamboo products and bamboo scrimber already utilize adhesives to create composite materials with enhanced and consistent mechanical properties. SCHOBER et *al.* [10], [11], [12] developed a design approach for modified bonded-in rods to enhance the performance of encapsulated systems and composite technologies for round wood connections. By increasing the bondline thickness and using concrete-type adhesives (CTA), they were able to increase the load-bearing capacity of modified bonded-in rod connections by a factor of three compared to glued-in rod connections with the same boundary conditions. Due to the fracture behaviour of the CTA, stress concentration occurred in a critical zone about 60 mm from the loaded end within a total embedment length of 250 mm. These results can be further improved by using ring reinforcements within this critical zone. It is concluded that this design approach for modified bonded-in rods can provide joint capacities equivalent to the capacities of wood parallel to the grain.

These findings not only improve the load-bearing capacity of timber structures, but also form the basis for a re-evaluation of these emerging technologies in conjunction with bamboo, transforming this material from an outdated choice to a new, flexible and sustainable building choice. The development of international standards for the modeling and design of bamboo structures, including connections, is essential for the further dissemination of bamboo in construction.

3 – PROJECT DESCRIPTION

3.1 OBJECTIVE

Different problems have been addressed so far and need to be solved. Rethinking the spatial connection of round cross-sections, preventing splitting of the raw material and using adhesive bonding in bamboo connections are the main tasks of investigations and source of research questions. The objectives of the work presented are (i) the identification of ecologically harmless bonding agents, suitable for the application goal in terms of robustness and durability, (ii) the description of their behaviour under typical load scenario's depending on joint configuration and degree of composite action, and (iii) the experimental validation of the bondline between grouted hollow pole section and the bamboo pole inner wall.

To start, a (partially) prefabricated joint suitable for lightweight structures and modular housing has been developed, suitable grouts determined and the quality of bond to the inner bamboo layer has been tested and investigated for uniaxial loading in growth direction. The basis of investigations was the transfer of the approach given by SCHOBER et *al.* [10], [11], [12] for modified bonded-in rods to grouted bamboo connections. While cylindrical timber sections allow that the prefabricated joint geometry is directly connected to solid wood, bamboo exhibits a hollow profile cross-section.

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Key innovations of the research project will include the use of biocomposites, surface treatments enhancing adhesion bonding as well as mechanical interlocking, and internal or external ring reinforcements to counteract splitting effects. These approaches ensure reliable structural load-bearing capacity and superior durability under the effects of climate exposure. In addition, research is being carried out into an easy-to-assemble plug-in connection as a modular system, consisting of a moulded-in adapter and an adapter receptacle, in order to bring together all the components of a flat truss construction with different angles in one plane.

3.2 MATERIALS

Among the most studied species, *Guadua angustifolia* Kunth, native to Central and South America, stands out for its exceptional mechanical performance. It has been the subject of numerous studies as a potential species for structural engineering and sustainable building applications. The plant's mechanical properties are significantly influenced by the species of bamboo (i), growth site (ii), culm density (iii), height position in the culm section (iv), fibre orientation (v), age (vi) and moisture content (vii). Table 1 shows mean values of mechanical properties of Colombian GaK.

Table 1	**Mean values of mechanical properties of GaK**		
	CORREAL et *al.* [13]	CORREAL & ARBELÁEZ [14]	SÁNCHEZ E. et *al.* [15][a]
f_c [MPa]	73.64	40.40	22.86 – 45.99
f_{c90} [MPa]	7.01 (52.22)[b]	-	4.42 – 7.81
f_t [MPa]	120.50	-	42.53 – 56.58
f_{t90} [MPa]	1.23	-	-
f_v [MPa]	10.81	7.70	3.95 – 7.82
f_m [MPa]	83.00	98.50	38.88 – 72.82
E_c [GPa]	21.84	17.20	15.00 – 34.51
E_t [GPa]	13.87	-	9.43 – 19.49
E_m [GPa]	18.07	17.40	11.57 – 14.93

[a] value ranges due to varying growth sites of the bamboo used
[b] values in [kN]

f_c	Compression strength parallel to fibres
f_{c90}	Compression strength perpendicular to fibres w/o mortar filling and with mortar filling (bracket values)
f_t	Tension strength parallel to fibres
f_{t90}	Tension strength perpendicular to fibres
f_v	Shear strength
f_m	Bending strength parallel to fibres
E_c	Compressive modulus of elasticity
E_t	Tensile modulus of elasticity
E_m	Bending modulus of elasticity

The values given were all determined on test specimens from the growth site in Colombia, although the mechanical properties vary greatly even within the region. The influencing factors of culm density and height position were covered by a representative sample size selection. The fibre orientation was taken into account by the laboratory tests and the specification of corresponding strengths. With regard to age, optimum performance was found to be achieved with 3 to 4 year old specimens, which where the basis for the quoted properties. With a moisture content of more than 12 %, the strength can be reduced using a modification factor in accordance with NSR-10, Table G.12.7-5 [16]. With the exception of [13], the strength was determined on test specimens with MC ≥ 12 %, making modifications unnecessary.

Furthermore, GaK has an uneven distribution of the vessels across the wall thickness (Figure 3). As it turned out, this property makes it difficult to predict a failure load in push-out tests with test specimens in which the load transfer between the CTA and the bamboo wall takes place partially via milled grooves. A holistic understanding of the failure modes can be achieved only through future push-out-tests using specimens with an accessible cross-section and an evaluation by means of Digital Image Correlation (DIC).

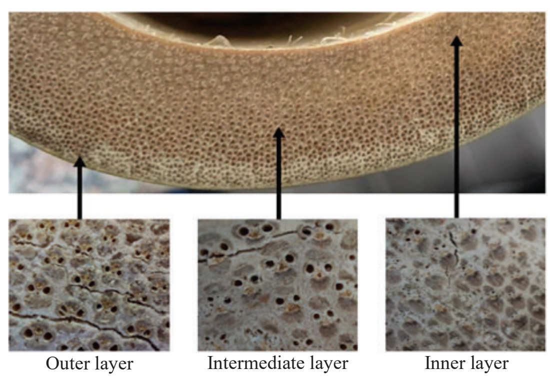

Figure 3: Distribution of the internal vessels or vascular of a Guadua angustifolia culm [17].

After evaluating target properties and other requirements, the commercially available low-viscosity 2c-EP resin system HP-E56L (HP-Textiles) with a resin-initiator ratio of 100:40 by weight has been chosen for the EP-series and investigations. It was selected on the basis of previous studies by CHAHADE & SCHOBER [12]. For the PU-series, a bio-based derived polyol with 65 – 80 % renewable natural oil content fulfilled the selection requirements [18]. The chosen system consists of the 2c-PU commercial bio-resin Sovermol® 750 (BASF) and the

PMDI-initiator ASTI-TECH® B (Beil), mixing ratio 100:88 by weight. It was selected with focus on a sustainable bio-CTA and a promising study by MURCIA et *al.* [18]. The raw material selection for the grout formulation has been completed with a poorly-graded gravel as mineral additive, grain size 0 - 5.6 mm.

3.3 TEST SPECIMENS

GaK was used for all 24 test specimens. The raw material was supplied by the project partner Guadua Bamboo SAS, taken from altitudes between 1,200 and 1,600 m above sea level in Valle del Cauca, Colombia. Only 4-5 years old specimens from the bottom part of the culm were used since these are usually used for construction purposes due to greater wall thickness and short internodes. For the immunization process, disodium octaborate tetrahydrate, a non-toxic alkaline salt was used, dissolved in water at a concentration of 5 %. It consists of a combination of boric acid and borax in a mixing ratio of 1:1.5 by weight. The immersion tank is equipped with a heating system that reduces the normal immunization time from 4 days to only 8 hours.

Following the treatment process, the poles were sun bleached for 2-4 weeks while rotating every 1 to 2 days in order to prevent cracking and to acquire a pleasant beige colour. Afterwards they are washed and air dried for about 4 months in a well ventilated and covered area so that the moisture content at the time of loading in Colombia ranges between 15 % and 18 %. Arrived in Germany, the poles were stored indoors with climate conditions according to service class (SC) 1, defined in ISO 22156:2021-06 [19], which is representative of indoor air-conditioned or heated environments to a temperature of 20 °C in which relative humidity is maintained below 65 %. At the time of infilling, the bamboo to be infilled had reached its equilibrium moisture content (EMC) of less than 12 % measured. The push-out tests itself were also performed in European normative indoor climate (20°C, 65% rH). As a result, it can be assumed that the mechanical properties of the test specimens are comparable with the mean values given by CORREAL et *al.* [13], Table 1.

Table 2 and Figure 4 show the specimen geometry for the push-out tests. Due to the shape inaccuracy of bamboo poles, the test specimens were captured and measured using Scaniverse (Niantic Inc.). It uses Light Detection And Ranging (LiDAR) to create 3D objects. The accuracy of the geometric dimensions was set to millimetres due to the limits of the scanning device and the application algorithm. Due to the dense and smooth surface of bamboo, the test specimens were milled to increase the failure load by mechanical interlocking. Depth and width of the milling could not be ensured exactly (Figure 4), due to the use of a hand-held router and shape inaccuracy of the specimen. To solve this problem and to ensure a high quality standard of the millings, it is planned to use computer numerical control (CNC) milling machines with prior scanning of the test specimens in future investigations.

The samples for the push-out tests were produced in three series. In two series, the cavity in the bamboo was filled with 2c-EP CTA with a mixing ratio between the mineral additive and resin components of 7:1 and 2.5:1 by weight, respectively. The third series was filled with 2c-PU CTA with a mixing ratio of 7:1. The test specimens are named resin type – aggregate ratio – sample no.

Table 2	**Geometric dimensions of the test specimens in [mm] and irregularities**					
	Length	***Outer diameter***	***Inner diameter***	***Wall thickness***	***Node***[a]	***Cracks***[b]
EP-71-1	160	93-96	70-72	10-12	115	0
EP-71-2	160	90-92	67-71	10-12	135	0
EP-71-3	160	104-106	82-84	9-12	135	1
EP-71-4	160	99-101	79-81	9-11	135	1
EP-71-5	160	100-101	76-77	11-12	-	0.5
EP-71-6	160	98-99	81-82	8-9	-	1
EP-71-7	160	102-103	84-86	8-9	-	1
EP-71-8	160	95-96	79-80	6-8	-	0
EP-71-9	160	91-92	65-68	11-14	-	0
EP-71-10	160	90-91	68-70	8-12	160	0
EP-71-11	160	99-101	71-74	11-14	-	0
EP-71-12	160	101-102	83-85	8-10	65	1
EP-251-1	160	91-92	76-77	7-9	-	0
EP-251-2	160	93-95	74-76	8-11	-	0.33
EP-251-3	160	94-97	66-69	12-16	-	0
EP-251-4	160	93-95	69-74	9-12	135	0
PU-71-1	160	94-98	71-73	11-13	145	0
PU-71-2	160	97-99	76-79	9-11	160	0
PU-71-3	160	93-94	70-73	9-13	110	0
PU-71-4	160	85-87	71-72	7-9	-	0
PU-71-5	160	92-94	65-70	11-14	-	0
PU-71-6	160	92-95	75-77	7-9	110	0
PU-71-7	160	96-101	76-81	9-10	-	0
PU-71-8	160	96-98	71-73	10-14	125	0

[a] centreline of the node measured from the loaded upper end of the bamboo pole [mm]

[b] number of longitudinal shrinkage cracks along the entire length; floating point numbers mean a partial crack

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4 – EXPERIMENTAL SETUP

Uniaxial compression tests have been performed to obtain the load-displacement behaviour. The load application was primarily done by DYNA-MESS universal test machine (hydraulic), max. load application 165 kN. Due to a higher load-bearing capacity, the push-out tests with the series EP-251 were carried out by FORM+TEST universal test machine, maximum load application 600 kN. The load application was done in two steps. Step 1 was force controlled, speed 0.5 kN/s until a load level of 50 kN was reached. In step 2 the speed changed to 0.1 kN/s until the failure load was reached. The force application was controlled by a proportional integral (PI) controller where both were set to 0.5. A load distribution plate made of S235 structural steel (Figure 4) ensured even force transmission in all the tests examined.

To record the displacements in the longitudinal and transverse direction, Digital Image Correlation was used. Surface displacement was measured optically by two camera pairs with a subsequent numerical calculation of the corresponding strain fields. The surface displacement measurement was done two- and three-dimensionally. Two camera pairs detected the displacements, covering one quarter each of the curved outer bamboo surface with an image resolution of 4000 x 3000 px, 25 mm lens and a stereo angle of approximately 25°. A black coloured pattern (speckle image) was applied to the surface. The specimens were washed first to achieve a preferably clean surface with no irregularities. Thereafter, the outer bamboo surface was primed white to create a better contrast with a subsequent application of the speckle image by the airbrush technique. The DIC tracked the displacement of each speckle and evaluated displacements with the integrated software Vic-3D®-system from Correlated Solutions, Inc. The target parameters in the data processing were longitudinal and tangential strains in the bamboo outer surface, which Vic-3D® provided automatically as a direct output by transforming the coordinate system from Cartesian to cylindrical coordinates. The measurement tolerances of Vic-3D® were smaller than 0.01 ‰ and can be neglected.

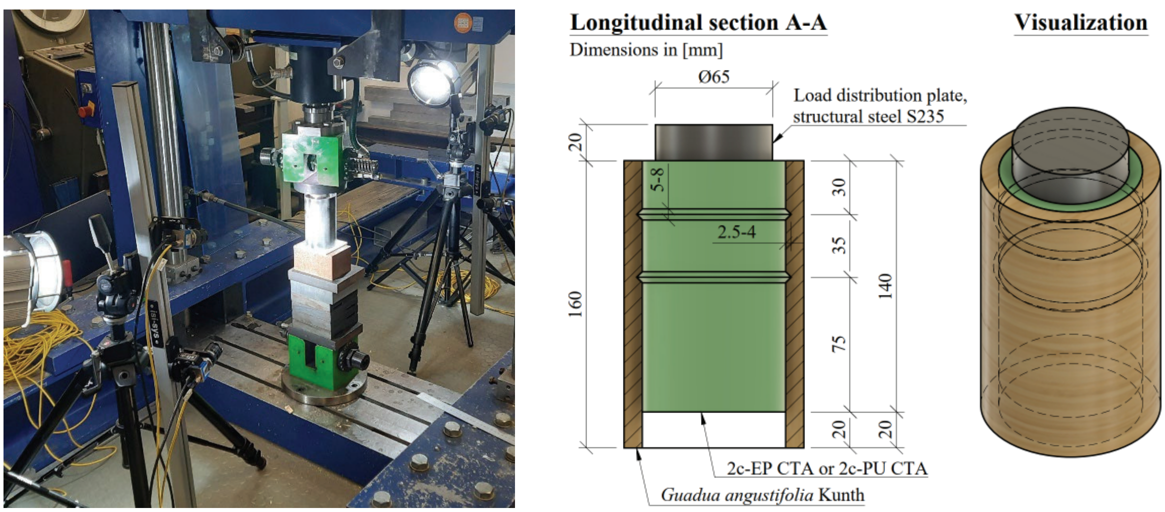

Figure 4: Test set-up for push-out tests using DIC for the evaluation (left) and corresponding geometry of the test specimens (right).

5 – RESULTS

A brittle fracture without significant post-fracture behaviour resulted in all the test specimens examined. The brittle failure results on the one hand from the sudden shear failure of the CTA at the milled grooves (SF-CTA) and on the other hand from the splitting failure of the bamboo wall due to transverse tensile failure (SF-B). For example, the failure load of test specimen PU-71-5 is higher than of test specimen PU-71-4 (Table 3) due to the higher transverse tensile bearing capacity as a result of greater wall thickness (Table 2). It can be assumed that the SF-CTA leads to SF-B in general due to tilting of the CTA with resulting radial expansion forces. Only test specimen EP-251-4 exhibited a limited SF-CTA exclusively at the first milling and achieved by far the highest failure load of 180.89 kN. This indicates that the mixing ratio between mineral additive and epoxy of 2.5:1 has an increased shear strength and is promising for further investigations.

Within the same mixing ratio of 7:1, Table 3 shows a slightly better adhesive bond between bamboo and

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polyurethane compared to epoxy, which can also be seen on the fracture inner bamboo surface after test (Figure 5). The cohesive bamboo failure (CBF) when using 2c-EP CTA was in most cases practically 0 % or only affected the thin inner bamboo skin (< 10 %) whereas the use of 2c-PU CTA enabled true activation of the bond in half of the test specimens. The better bonding behaviour of polyurethane-based systems can be attributed on the one hand to the lower modulus of elasticity resulting in increased transverse elongation. On the other hand, a study by JIMENEZ & RAMOS [20] show a comparatively low contact angle and thus a high wettability for polyurethane adhesives on bamboo surfaces. This leads to higher bond shear strength of approximately 6 MPa on average and an associated higher CBF of approximately 65 % on average for untreated bamboo. Additionally, the load-longitudinal strain-behaviour of four samples (Figure 6) evaluated by using DIC, shows a more even distribution of strains when using polyurethane. The force transmission at the milled grooves is significantly more pronounced using epoxy due to the higher stiffness.

If a CBF occurred in the test specimens with a mixing ratio of 7:1, it only occurred above the milling or nodes, which indicates a shear failure within the bamboo wall due to the short loaded end distance. On the other hand, test specimen EP-251-4 with a mixing ratio of 2.5:1 and a node in the lower part of the specimen exhibits a CBF of approximately 100 %. The governing failure mode for this specimen was also SF-B, but caused by a shear failure within the bamboo wall regardless of the loaded end distance.

Furthermore, a comparison of the failure loads (Table 3) with the geometric dimensions and irregularities of the test specimens (Table 2) shows a significant positive influence of the node when its centreline is in the range of 125 mm to 145 mm from the loaded upper end of the bamboo pole. In addition, the failure load tends to increase with greater wall thickness due to the increased transverse tensile capacity.

Table 3	**Load-carrying capacity and failure of the test series**				
	Failure Load [kN]	***CBF[a] [%]***	***SF-B[b]***	***SF-CTA[c]***	***CF-CTA[d]***
EP-71-1	-78.21	< 10	✓	✓	-
EP-71-2	-131.28	< 10	✓	✓	-
EP-71-3	-108.38	< 10	✓	✓	-
EP-71-4	-98.35	< 10	✓	✓	-
EP-71-5	-84.66	< 10	✓	✓	-
EP-71-6	-95.86	< 10	✓	✓	-
EP-71-7	-71.10	< 10	✓	✓	-
EP-71-8	-84.77	< 10	✓	✓	-
EP-71-9	-68.85	< 10	✓	✓	-
EP-71-10	-60.17	~ 50 (above 1st milling)	✓	✓	-
EP-71-11	-50.37	< 10	✓	✓	✓
EP-71-12	-75.06	~ 50 (above node)	✓	✓	-
EP-251-1	-83.83	< 10	✓	✓	-
EP-251-2	-114.78	< 10	✓	✓	-
EP-251-3	-135.53	~ 25	✓	✓	-
EP-251-4	-180.89	~ 100	✓	(✓)	-
PU-71-1	-98.83	~ 30 (above 1st milling)	✓	✓	✓
PU-71-2	-62.83	< 10	✓	✓	✓
PU-71-3	-59.88	< 10	✓	✓	✓
PU-71-4	-72.92	< 10	✓	✓	✓
PU-71-5	-94.55	~ 50 (above 2nd milling)	✓	✓	✓
PU-71-6	-83.41	~ 50 (above node)	✓	✓	✓
PU-71-7	-73.22	< 10	✓	✓	✓
PU-71-8	-109.57	~ 50 (above node)	✓	✓	✓

[a] CBF = Cohesive Bamboo Failure according to ISO 12466-1:2007 [21] by visual inspection; < 10 % means only shear off the thin inner bamboo skin

[b] SF-B = Splitting failure of the bamboo wall due to exceeding the transverse tensile strength

[c] SF-CTA = Shear failure of the CTA at the milled grooves

[d] CF-CTA = Compression Failure of the CTA (fracture in the core of the CTA)

Figure 5: Specimen EP-71-9 with CBF < 10 % (left), specimen PU-71-5 with CBF ~ 50 % (middle) and specimen EP-251-4 with CBF ~ 100 % (right).

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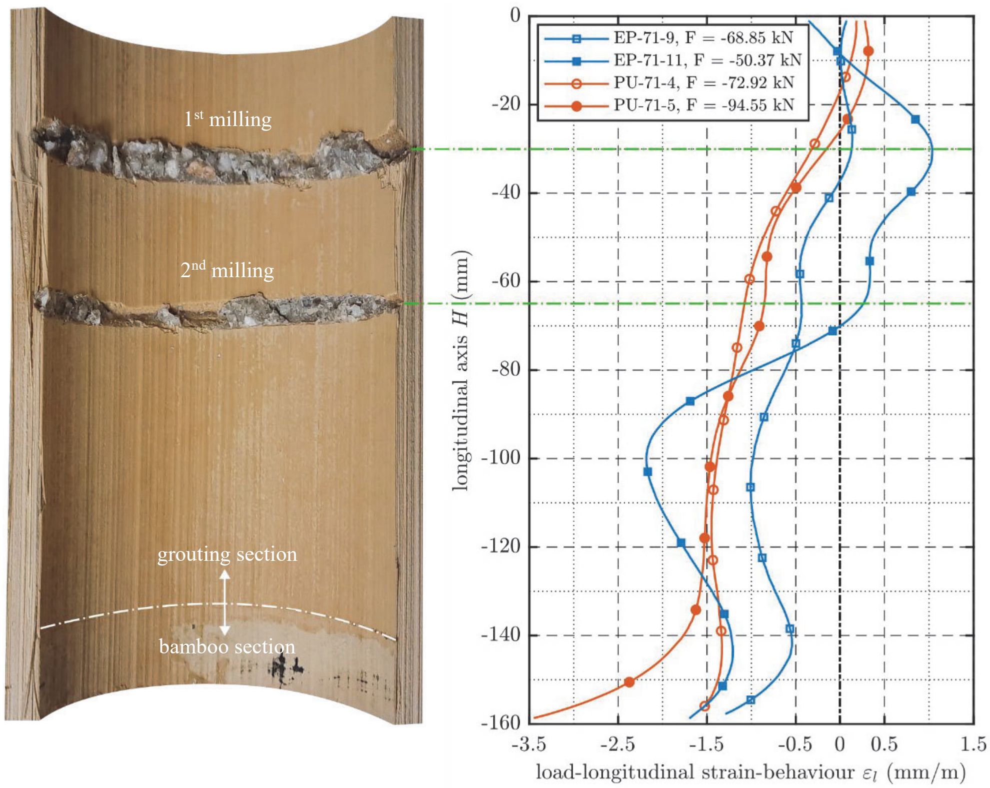

Figure 6: Part of inner bamboo layer (specimen EP-71-8) after testing (left), load-longitudinal strain-behaviour in the outer bamboo layer of four specimens shortly before failure (right).

In accordance to ISO 22156:2021-06 [19], the allowable joint design load-bearing capacity shall be determined by applying all relevant adjustment factors to the calculated characteristic joint strength as given by (1).

$$F_y = F_{yk} \cdot C_{DF} \cdot \left(1 / FS_j\right) \quad (1)$$

F_y	Joint design capacity
F_{yk}	Characteristic joint capacity (5 % - fractile with 75 % confidence)
C_{DF}	Modification factor for service class and load duration
FS_j	Joint factor of safety

The 5th percentile characteristic joint capacity with 75 % confidence can be calculated according to DIN EN 14358:2016-11 [22] as given by (2) - (4). As recommended in this standard, a log-normal distribution is assumed.

$$\bar{y} = \frac{1}{n} \sum_{1}^{n} \ln m_i \quad (2)$$

$$s_y = \sqrt{\frac{1}{n-1} \sum_{1}^{n} (\ln m_i - \bar{y})^2} \quad (3)$$

$$m_k = \exp\left(\bar{y} - k_s(n) \cdot s_y\right) \quad (4)$$

$\bar{y}$	Average Failure Load
n	Number of specimens
m_i	Failure Load of specimen
s_y	Standard deviation
m_k	Characteristic Failure Load (5 % - fractile)
$k_s(n)$	5 % - Fractile factor (75 % confidence)

Table 4 shows the statistical evaluation of the characteristic failure load (m_k) or the characteristic joint capacity (F_{yk}) determined separately according to the CTA used and the irregularities of the test specimens (Table 2). The evaluation confirms the positive influence of a node in the test specimen. The 2c-EP CTA with a mixing ratio of 2.5:1 seems to be the most promising, especially when considering the high mean values and the increased fractile factors due to low sample numbers.

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Table 4	Statistical evaluation of the characteristic joint capacity (5 % - fractile with 75 % confidence)					
	n	*Mean [kN]*	$\bar{y}$	s_y	$k_s(n)$	m_k or F_{yk} *[kN]*
EP-71	12	-83.92	-4.40	0.26	2.03	-47.85
EP-71 w/o node	6	-75.94	-4.31	0.23	2.34	-43.68
EP-251	4	-128.76	-4.82	0.32	2.71	-51.85
EP-251 w/o node	3	-111.38	-4.69	0.24	3.15	-50.68
PU-71	8	-81.90	-4.38	0.22	2.18	-49.90
PU-71 w/o node	3	-80.23	-4.38	0.15	3.15	-49.84

6 – CONCLUSION

The research results in a grouted joint, that avoids punctual splitting of the bamboo pole wall by the absence of doweling, thus significantly improving the performance and durability compared to previous connection systems. The results demonstrate that the failure load is highly influenced by the shear strength of the CTA due to tilting after SF-CTA resulting in splitting of the bamboo wall. In this respect, the 2c-EP CTA, mixing ratio 2.5:1 with a failure load of up to 180.89 kN was the most promising CTA. In contrast, 2c-PU CTA tend to provide a better bonding behaviour. Both systems are under further investigation. Due to the low ductility of the joint, a joint factor of safety (FS_j) of 3.0 must be taken into account in line with (1). Furthermore, a modification factor for service class and load duration (C_{DF}) must be taken into account, which additionally reduces the joint design capacity (F_y) by a factor of up to 1.8. In the worst case, this leads to a resulting safety factor of 5.4, by which the characteristic joint capacity (F_{yk}) must be reduced. For this reason, F_{yk} must be increased by future research and reliably predicted with less scatter. The following criteria can contribute to this.

1. Quality control of the milling geometry to uniformize the load-bearing capacity.
2. Use of a CTA with superior shear strength, e.g. 2c-EP CTA with a mixing ratio between mineral additive and resin system of 2.5:1.
3. Chemical pre-treatment of the inner bamboo layer, e.g. by means of mercerization in order to increase the bond strength due to an improved fibre-matrix adhesion [23].
4. Using the positive influence of a transverse expansion restraint on the SF-B either by means of a ring reinforcement applying an external casing or by increasing the transverse tensile load-bearing capacity using the natural bamboo nodes in the critical area near the end of the grouting section.

If the aforementioned points are achieved, the load-bearing capacity of the connection can be predicted more reliably and thus the governing failure mode can be designed specifically for the moulded-in adapter. This would result in a ductile connection and reduce the joint factor of safety (FS_j) from 3.0 to 2.0, so that the resulting safety factor decreases significantly from 5.4 to a maximum of 3.6.

Furthermore, due to the hidden bond line, the evaluation of strain fields using DIC could only be carried out on the outer bamboo surface. In order to gain a holistic understanding of the force transmission at the bond line area and within the materials, specimens with an accessible cross-section will be used in future laboratory tests. This will also enable an evaluation of the effects resulting from the uneven distribution of the vessels across the wall thickness of the bamboo culms (Figure 3). Additionally, a third camera system will be used in tests with inaccessible cross-sections, which records the radial deformation.

In order to achieve the goal of developing a (partially) prefabricated bamboo joint, there is a need for further research into an easy-to-install plug-in connection as a modular system, consisting of a moulded-in adapter and an adapter receptacle. In addition to push-out tests, the joint should also be validated in pull-out tests and under climate exposure according to SC 2 and 3.

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