# INTRODUCTION OF NON-DESTRUCTIVE TESTING FOR NOVEL COMPOSITES AND JOINTS OF TIMBER AND BAMBOO

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**ABSTRACT:** Due to increasing demand for sustainability, manifold efforts are made to reduce  $CO_2$  emissions. Renewable raw materials such as timber and bamboo even have a negative carbon footprint when it comes to procurement, making them very attractive for industrial use in terms of environmental targets. New material concepts with these renewable materials or combinations of both, additionally, a particular visually appealing alternative with glass fibre reinforced polymer, are analysed to develop adequate NDT (Non-Destructive Testing) solutions for the quality control in later production processes. NDT offers special opportunities in terms of cost savings compared to destructive testing procedures. The presented efforts to develop solutions for new renewable material applications are embedded in a comprehensive proceeding for NDT introduction to later series production. Prior evaluation of selected NDT methods with particular potential for testing renewable material concepts like radiographic computed tomography, ultrasonic testing, microwave or terahertz testing as well as thermography clarify the general suitability of different excitation sources that can be used for timber and bamboo. Practical results provide information about detectable material inhomogeneities and structural defects. The findings are supplemented by finite element calculations to estimate corresponding defect characteristics. Finally, main influences on thermographic testing that need to be considered in order to achieve robust quality control are pointed out as a preview of the next steps required to complete NDT qualification.

**KEYWORDS:** renewable materials, sustainable composites and joints of timber and bamboo, active thermography, qualification of non-destructive testing (NDT), quality control, thermal finite element analysis

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# **1 – INTRODUCTION**

The emerging challenges brought about by sustainability requirements are leading to new applications of renewable raw material resources. Manifold trends exist, for example highly advanced construction materials to improve the capabilities of building materials in the construction industry [1]. Recent development of material concepts with timber, bamboo or a combination of both, also with natural or glass fibres, open new paths for sustainable solutions, e.g. as construction material in architecture or even as design elements. As renewable materials and composites can make a significant contribution to the overall goal of decarbonisation, such material concepts are in the focus of this research. A successful introduction of new materials in the industry always needs to provide capable testing concepts for quality control. Despite the introduction of nondestructive testing (NDT), solutions often involve a high level of effort e.g. for process qualification. Due to their significant advantages like reducing costs or higher product reliabilities, the aim of this work is to find most targeting NDT methods, further develop them and to show up a procedure for its reliable implementation.

#### 2 – BACKGROUND

This research continues previous investigations of nondestructive characterisation of renewable materials [2], deepening the findings for its novel composite and joint applications. It points out the framework for an effective procedure to introduce NDT solutions. The considered raw materials and corresponding composites and joints are described, followed by its typical defect appearances, so far as it is relevant for NDT evaluation.

## 2.1 NDT IMPLEMENTATION

Bringing new products to market or even implement new material concepts, it is always accompanied by the need of reliable quality assurance production process control. Especially NDT methods offer both opportunities to get more detailed information about material's quality in early stages of production and great potential to generate cost savings in context with quality assurance. That makes their use very attractive, although NDT methods are often complex, and they must be well qualified for later use in series manufacturing. The successful introduction of NDT solutions requires to fulfil a variety of tasks and specifications. Issues as in the beginning "the smallest reliably detectable failures", later "the robustness of test equipment" or "the manifold disturbances, that influence the measurement" and not least towards the end "the training and providing of specialised test personnel" are important aspects to handle with, before NDT can come to use. Several steps of a systematic approach to qualify NDT solutions, ensuring the accordance with industrial regulations, are shown in Fig. 1. Increasing phases of test method development require more in-depth analyses or further focus. Contents of 'Task Definition', 'Principle Test', 'Laboratory Test', 'Serial Test' and 'Pilot Application' together with a checklist to guide the proceeding and examples can be found in [3, 4].



Figure 1: Qualification steps for the implementation of non-destructive testing methods for industrial applications.

## **2.2 RAW MATERIAL PROPERTIES**

The novel material and joining concepts considered in this paper consist of renewable raw materials like timber, bamboo or a combination of both or with glass fibre reinforced polymer. In some areas used adhesives play a subordinate role. <u>Timber</u> is an organic material consisting of cells and chemical compounds such as cellulose, hemicellulose and lignin. The cell wall is composed of many layers: Microfibrils in a lignin matrix glued together by polyoses. The microfibrils make up approx. 40-50 % of the timber mass and are oriented roughly in the direction of the fibres. They are responsible for the very high



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tensile strength up to 1000 MPa. The lignin content is approx. 25-30 % and fills the cavities between the fibrils, acting as a supporting material and providing the compressive strength, which is increased by the layered cell wall structure [5]. Fig. 2 shows the inner structure of frequently used timber species spruce (softwood) and oak (hardwood). The illustration exemplifies the large differences in structure between different types of timber. The annual rings shown in Fig. 3 for pine can be found in general, they complement the foregoing statement for timber materials.



Figure 2: Inner structure of soft- (left) and hardwood (right) [5].



Figure 3: Tree slice with annual rings.

<u>Bamboo</u> is a fast-growing plant of the grass family with timber-like properties. There are over 1250 species worldwide with different properties. Fig. 4 gives an impression of the wide variety of different bamboo kinds.



Figure 4: Bamboo variety [9].

The anatomical structure of bamboo appears relatively uniform compared to timber. The bamboo culm consists of nodes and internodes, the intermediate sections. The lengths of the internodes as well as the thickness of the culm walls differ considerably between the different bamboo species. Fig. 5 shows the culm arrangement with nodes and internodes. A microscopic intersection illustrates the inner structure in an internode section. The bamboo culm consists of approx. 50 % parenchyma cells, 40 % fibres and 10 % vascular bundles. The cross-section shows the dark vascular bundles with their fibre agglomerates in the parenchyma tissue. All bamboo species show an analogous pattern in the distribution of their cells.



Figure 5: Culm structure [10], apud [11].

The advantage of bamboo is its great hardness, but the origin, moisture content, age and diameter of the cane have a great influence on the material properties [6, 7, 8].

<u>Glas fibre reinforced polymer</u> (GFRP) in detail is a composite, but in this paper, it is simplified as one material component. It consists of a polymer matrix (polyester or epoxy resin) and glass fibres of different sizes, from approx. 1 mm up to more than 50 mm length. The glass fibres serve as reinforcement and give the material high strength and stiffness combined with low weight. The material is also characterised by its corrosion resistance and good thermal insulation. Due to its mouldability it can be brought into different shapes and enables complex designs. GFRP is used in many areas, including vehicle construction, aerospace, boat building and sports equipment manufacturing.

Adhesives glue components together in a materially bonded manner without the need for further mechanical fasteners. The interaction of surface adhesion and the internal strength of the adhesive (cohesion) results in a force-transmitting effect. The structure of the parts to be joined remains essentially unchanged. Depending on the use of the respective timber material, different types of adhesives are used. In general, adhesives consist of nonliquid components such as binders, fillers and extenders, and volatile components such as solvents, thinners and dispersants. Adhesives are classified into physically setting and chemically reacting adhesives [12]. The adhesive used was a glue on a 1-component polyurethane basis OTTOCOLL® P84 [13].

#### 2.3 NOVEL COMPOSITES AND JOINTS

To identify a promising non-destructive testing solution and further development the composite concepts with its geometric and joining conditions must be defined. The previously described properties of the individual material components have a major influence that can lead to enormous anisotropic behaviour of a sustainable composite both in relation to the usage properties and for NDT testing. <u>Composites of renewable materials</u> are already widely used as for example building material. Cross laminated timber (CLT) is a typical material for load-bearing constructions. It is a layered construction of solid timber boards in different orientations as schematically shown for five layers in Fig. 6.



Figure 6: Structure of 5-layered cross laminated timber [14].

A new type of sandwich composite structure is built up with a bamboo-based core material consisting of a honeycomb-like arrangement of bamboo ring sections covered with various top and bottom layers. Fig. 7 shows the structure of a so called Comboo composite: the inner bamboo comb layer and the section of a 3- or 11-layered Comboo composite with two or ten cover layers of timber. This is called CCLT like Comboo cross laminated timber.



Figure 7: Structure of central layer in CCLT (top) and 3- or 11layered samples with cover layers of timber.

The use of different face layers thus results in stiffer or more ductile composites. Results of previous tests with the novel bamboo honeycomb arrangement show that excellent mechanical properties can be achieved compared to conventional materials [15, 16]. Another composite that is recently under investigation consists of inner bamboo rings and GFRP outer layers (see Fig. 8+9). Since round structures can also be reproduced with this material and transparent structures are also possible, this material is already gaining a high level of attractiveness for decorative purposes [17].



Figure 8: Structure variability with GFRP Comboo [17].



Figure 9: Comboo with GFRP top layer for "bamboo design" [17].

<u>Joints of renewable materials</u> are important to be able to produce more complex components, to build up structures. In this paper novel friction welded samples are considered as shown in Fig. 10 for timber and bamboo. For such samples initially determined toughness showed promising results compared to ordinary connection types like glued joints. Currently, up to 60% of the final strength of timber-based materials is achieved by friction welding joints. The advantage of friction welding is the absence of chemical, possibly toxic, substances that make sustainable use difficult or impossible.



Figure 10: Friction welding on bars of timber (left), bamboo (right).

Due to the lignin present in both bamboo and timber (different types such as ash, spruce, pine, beech or oak), they can be joined together without adhesives. In order to be able to reliably assess the quality of the friction welded joint, non-destructive material testing is needed, especially for safety-related applications.

#### 2.4 CHARACTERISATION AND DEFECTS

For later use of the considered materials and joints it is important that no defects impair the properties. Defects must be monitored in later production processes or during possible life cycles of e. g. load-bearing structures. For this purpose particular NDT applications are essential. Specific defect patterns that influence mechanical properties and may reduce strength are illustrated: For the different composites, these are horizontal delamination from layer to layer and differently oriented cracks within the layers (Fig. 11-13).



Figure 12: Delamination, cracks in Comboo with timber top layer.



Figure 13: Delamination in Comboo with GFRP top layer.

Fig. 14 shows cross-section surfaces of samples after tensile tests. Adhesion defects would arise in the fracture plane area, where the connection is partially interrupted.



Figure 14: Fracture surface after tensile test of friction welded joints in beech and pine timber (left) and bamboo (right).

These defect characteristics, together with individual material properties of renewable raw materials are mostly unfamiliar compared to conventional NDT tasks, posing specific new challenges for inspection.

# **3 – PROJECT DESCRIPTION**

As part of the step '*task definition*' at the beginning of a process qualification (see chapter 2.1), typical test tasks for a later quality control of the renewable material

components are derived from previous considerations. Non-destructive testing methods are evaluated with regard to their test capability. Based on findings from literature and own experiments in the context of the step 'principle tests' promising NDT methods are selected and further investigated. More extensive analyses at the step 'laboratory tests' provide more detailed information about the method testabilities. Particularly active thermography appears to be suitable, not least due to its various process variants. The appropriate excitation and evaluation the best test procedure configuration should be found and adapted. In order to provide an outlook including the tasks that are still open to finalise the NDT introduction. The interference influences are shown in a so called ISHIKAWA diagram, created with help of an influence and effects analysis.

## 4 – EXPERIMENTAL SETUP

For the experimental investigations the defects, that should be detected are clearly defined. Most promising NDT methods to continue the NDT process development are selected. The experimental setups for computed tomography as well as for active thermography are briefly described.

# 4.1 TESTING TASKS DEFINITION

A schematic description of relevant testing tasks, derived from previous considerations (see chapter 2.4) can be found in Tab. 1. The categorisation considers types of material combination, sample geometries and specific defect patterns. The dimensions are variable and can be scaled to almost any size. The geometries have the proportions shown here or similar ratios.

Table 1: Variants of inspection tasks.

	Geometry	Material(-combination)	Failures
1	~	timber	cracks
2		timber / timber + adhesive (cross-laminated timber)	delamination, cracks
3		timber / bamboo + adhesive (comboo)	delamination, cracks
4		cross-laminated timber / bamboo + adhesive (comboo)	delamination, cracks
5		glass fiber reinforced polymer / bamboo (comboo)	delamanation, cracks
6		timber / timber or bamboo / bamboo	no adhesion, cracks

#### **4.2 NDT METHOD PRESELECTION**

There are a lot of non-destructive testing methods in use, all with their specific capabilities, limitations, advantages and disadvantages. The consideration of their testing principles shows which methods are generally unsuitable for the considered renewable materials and which should be further investigated, because they show potential to solve the testing tasks listed before. The analysis of NDT capabilities, taking both experimental results from principal tests as well as findings from recent research into account, leads to a preselection of NDT methods for subsequent *'laboratory tests'* in context with the NDT qualification. Tab. 2 summarises the evaluation of the mentioned NDT methods and points out specific application aspects.

Table 2: Estimation of test suitability for NDT preselection.

NDT Method	Suitable?	Remarks
Visual Test	-	only surface inspection
Ultrasonic Test	(+)	e. g. humidity detection
Acoustic Test	(+)	e. g. crack monitoring
Penetration Test	-	no high absorbing materials
Magnetic Particle Test	-	only permeable materials
Eddy Current Test	-	no electric induction possible
Radiographic Test	(-)	limited to volume failures
Computed Tomography	+	expensive, long test duration
Thermography	+	many test configurations
Microwave Test	(+)	resolution is limited
Terahertz Test	(+)	more decreasing precision,
		increasing penetration depth

As computed tomography and thermography are expected to have promising capabilities to control the integrity of renewable components, NDT qualification continues with them. High costs, mostly long test durations associated with computed tomography, let this method be less attractive for serial inspections. On the other hand, the excellent resolution makes this method predestined as a reference method for NDT qualification. Thermography is selected because of promising results in principal tests. In particular, its multiple variations, which use different physical principles to make defects visible, increase the interest in investigating this method.

Opportunities of ultrasonic testing can be the detection of humidity or decay in timber [18]. Acoustic testing is estimated to be a helpful method for health monitoring, due to the fact that beginning cracks in bamboo can be listened early. The comparison of applications of microwave and terahertz testing with testing tasks in this work, indicates somehow potential to test renewable materials as timber and bamboo [19]. Both methods should be pursued. While microwave testing uses longer electromagnetic waves, terahertz testing could be an adequate compromise to achieve better resolutions. On the other hand, worse penetration depths of terahertz radiation compared to microwaves must be sufficient for defect detection. These methods will not be further discussed in this article.

## **4.3 COMPUTED TOMOGRAPHY**

Among the industrially applied NDT methods, 3D computed tomography (CT) plays a significant role, as it

allows very precise insights into the internal structure of almost all materials. Unfortunately, however, it is also one of the most cost-intensive due to the need for extensive testing technology and peripherals. The application for timber or bamboo materials enables high penetration depths into the interior of the material and also excellent resolution capabilities down to the nanometre range. Pure detachments can only be detected with a high resolution, as there are hardly any density differences and thus only the smallest of contrasts when layers lie closely together. Testing times are considerably long and depend strongly on the desired resolution. The friction welded samples were analysed, before tensile tested, with a 3D CT system (phoenix nanotom® m, GE Sensing & Inspection Technologies GmbH), see Fig. 15.



Figure 15: Pine sample in computed tomography system.

#### 4.3 ACTIVE THERMOGRAPHY

The test setup for active thermography includes an infrared camera to record thermal radiation of the specimens surface. Excitation sources induce a heat flow into a specimen interacting with inner properties and structure, so that resulting infrared surface pattern can make failures visible. Fig. 16 shows the test principle of active thermography with exemplary heat, respectively excitation sources.



Figure 16: Test setting for active thermography.

The infrared camera used in the experiments is a T1020® microbolometer from FLIR Systems. Optical, convective and ultrasonic excitation are investigated using the following heat sources:

- halogen lamp Hensel C-Light 1000, max. 1.000 W
- flash light Hensel EH Pro 6000, max. 3.000 W
- hot air dryer Bosch GHG 23-66, max. 2.300 W
- ultrasound generator Sonikks Sonobonder US 6015, max. 15.000 W

## 5 – RESULTS

From the testing perspective, the defect types shown in Tab. 1 can be reduced to three categories. The current possibilities and new development approaches of NDT are discussed for the following cases:

- 1. cracks in base material (timber, bamboo, GFRP)
- 2. delamination in CLT (timber to timber) or in Comboo (bamboo to timber, GFRP)
- 3. no adhesion in friction welds (timber, bamboo)

First, the defect types that are unfavourable for thermographic testing are visualised non-destructively using computed tomography. Afterwards, the progress in testing with active thermography and the promising test configurations are presented. For a better understanding of the experimental phenomena a finite element model is introduced and important influences for further NDT qualification are identified.

#### **5.1 COMPUTED TOMOGRAPHY RESULTS**

Testing the adhesion quality of friction welds in bars of timber or in bamboo described as '*case 4*' (see position 6, Tab. 1) is actually not possible to realise with thermography. The cost and time intensive method 3D computed tomography is needed to characterise it non-destructively. Even when the adhesion force cannot be measured, due to the high resolution, irregularities in the bonding plane are clearly visible and correlations with bonding strength quality can be estimated. The relatively even, compressed lignin layer is responsible for the bond strength. The pin diameter can be measured in a 3D CT scan (Fig. 17). The reliability detecting damage or leck in the layer or even adhesion strengths will be continued.



Figure 17: Pin diameter measurement in CT image of a pine sample.

Alternative NDT methods for this testing task could work with low frequent ultrasound or maybe microwaves [3, 18, 19]. This will be a subject of other continuing work.

## **5.2 ACTIVE THERMOGRAPHY RESULTS**

Thermal excitation sources, that seem to be suitable for thermographic inspection of timber or bamboo material, are optical (e. g. with lamps or flashes), convective (e. g. with hot or cold air) or even mechanical (e. g. with highpower ultrasound) heating. Beyond that, the excitation can be realised homogeneously, i. e. in more extended areas, or the surface. Another way is to excite the defects selectively. Optical excitation with halogen lamps heats up the entire surface and the internal effects starts to interact with the induced heat wave. Contrasts on the surface are effected through reflections at inner material interfaces. Whereas Ultrasonic excitation can heat up the defect itself by friction between the crack surfaces making the crack visible through hot areas on the surface. The results of various new approaches with active thermography, evaluated by its potential for testing the failure structures in 'cases 1-2' (see positions 1-5, Tab. 1) are shown next. The result images will show snapshots of recorded infrared sequences, without temperature scale. They only show measurable infrared contrasts. For the detection of cracks in base materials ('case 1') different excitations offer useful test results. Selective crack heating was realised with ultrasound excitation. Cracks become visible as hot spots in infrared images (Fig. 18).



Figure 18: Selective crack heating in timber with ultrasound.

In Fig. 19 the deviation from undisturbed heat dissipation after an areal heating in a sample indicates the presence of a crack in timber. The contrasts are moderate yet so that for a robust failure detection the excitation and evaluation procedure will be further optimised.



Figure 19: Deviation of heat flow due to a crack in timber after ultrasound heating.

Most promising excitations for testing delamination in CLT or combo ('case 2') as slow conducting materials may be slow acting heating sources or even pulse excitations as well. Heat excitation with ultrasound is only possible, if surfaces are close together. A principle test in order to excite delamination in timber with typical gaps selectively with ultrasound was not successful. Delamination from the GFRP layer in Comboo material can be made visible in an infrared image after continuously convective heating in transmission mode (Fig. 20). The heat transfer is locally disturbed, resulting in a thermal contrast with a "cold area" at the surface towards the infrared camera. Testing times are relatively long because of the heat transmission duration through the specimen. Due to the heat dissipation in all directions of the material, the contrast image is relatively blurred.



Figure 20: Thermal image of GFRP Comboo material with delamination after industrial dryer heating in transmission mode.

For a homogenous, relatively slow heating of the specimens surface also optical sources like halogen lamps can be used to receive comparable results. Fig. 21 shows the infrared contrast after continuously heating measured in reflection mode, i. e. excitation and camera are positioned at the same side. Unlike the result in transmission mode, the delamination appears as a "warm area" in the infrared image. The reflection mode can be beneficial for accessibility issues.



Figure 21: Thermal image of GFRP Comboo material with delamination after continuously halogen lamp heating in reflection mode.

For delamination check in reflection mode optical flashlight excitation is another established option, which in some cases can also shorten testing duration. Experiments in this configuration result in different, all barely recognisable, contrasts over the time. Fig. 22 shows a slight contrast appearing at later inspection times.



Figure 22: Thermal image of GFRP Comboo material with delamination after flashlight excitation in reflection mode.

The investigations carried out in the '*Principle*' and '*Laboratory Test*' form the basis for the ongoing thermography development and its application to the specific testing tasks. Development will continue to determine the most effective excitation and evaluation modes, including thermal finite element analysis.

#### **5.3 FINITE ELEMENT SIMULATION**

For a better understanding of the experimental findings and to be able to make more targeted adjustments to the test method excitation and evaluation, a finite element model with a single row delamination was developed for a transient thermal analysis of a GFRP Comboo material (Fig. 23) in comparison with the practical results.



Figure 23: Finite element model for GFRP Comboo material.

The middle row of bamboo rings is detached from the surface to capture a separation from the GFRP. The excitation applies a thermal load in form of an adjusted heat flux density. The remaining surfaces are subject to heat transfer to the environment. The consideration of two excitation variants with different optical sources shows that this makes it possible to display a temperature contrast. Both test setups are considered for the reflection mode. Fig. 24 shows the temperature results for continuous halogen lamp and after flashlight excitation at inspection times of 10 s, where particular contrasts (high enough or highest possible) were calculated.



Figure 24: Simulated temperatures for GFRP Comboo material with delamination after halogen lamp (left), flashlight (right) excitation.

Higher temperature gradients are achievable with continuous halogen lamp heating (approx. 0.3 K). Flashlight excitation maps the delamination even sharper, but with temperature differences smaller than 0.01 K. For this numerical experimental setup delamination can only be recognised from a detachment width of approx. 0.4 mm for both, continuous halogen and flashlight excitation. The results were confirmed to be in approximate agreement with the experimental measurements. Even if the absolute temperature differences for flashlight heating seem to be too small, it must first be clarified to what extent of delamination the received contrasts in practice depend on. The geometric deviation of the model from the real delamination has not yet been taken into account. The comparison with defined samples will help to prove the reliability of the model or for its further optimisation.

## **5.4 MEASUREMENT INFLUENCES**

All important influences and faults on a thermographic measurement must be identified and appropriately analysed, before they can be controlled in the serial production. The following ISHIKAWA diagram illustrates the relevant influences and disturbance variables that must be comprehensively taken into account to receive robust series processes and a cost saving quality assurance method. For the final NDT introduction, there is still a lot of analysis to be done in the concluding *'Laboratory Test'*, *'Serial Test'* and *'Pilot Application'*. The analysis of the effects of the disturbances can be supported and accelerated by using the developed finite element model.



Figure 23: Ishikawa diagram as result of an influence and effects analysis for thermographic applications.

#### **6 – CONCLUSION**

Natural renewable materials and their composites pose a challenge when it comes to installing NDT for serial production. Physical test principles need to be harmonised with special material and internal structure properties, which are often inhomogeneous and highly anisotropic. Thermography shows good approaches as a test solution for selected categorised defects. The costintensive computed tomography is less attractive for a series solution, but for butt-welded timber bars as one of the analysed use cases, it is recently the only suitable NDT method. Furthermore, due to its high resolution, it is also the preferred method of comparison when qualifying other NDT solutions. Thermography offers promising opportunities for crack and delamination testing in timber and GFRP Comboo material. Convective (hot air), mechanical (ultrasound) and optical (halogen and flashlight) heating were identified as suitable excitation sources. Cracks in timber can be detected selectively by ultrasonic excitation. Delaminations in GFRP Comboo material become visible after convective and optical excitation. Continuous halogen lamp heating offers significant higher temperature contrasts, flashlight heating induces only slight contrasts but sharper images. Both optical excitation methods should be further pursued in order to implement most effective heating modes (e.g. time modulation) as well as the best evaluation algorithm for the infrared signal data. Here, the findings to date content essential information for subsequent steps. The developed thermal finite element model additionally helps enormously for a more in-depth understanding and for a reliable parameter adaption of the test method. Initial statements on testability and limits of thermographic testing could be accomplished. At a later stage of the NDT qualification, the finite element model

effectively supports the analysis of the disturbance influences. By analysing some variables virtually, the effort of NDT qualification can be considerably reduced. While simulations already provide a good support, the model will be further developed to increase its reliability for even more statements.

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## 8 – REFERENCES

[1] B. F. BuFAS & A. e. V.. "Baustoffe im Fokus - von Bambus bis Beton." In: Proceedings of 29.
Hanseatischen Sanierungstage, Heringsdorf/Usedom.
Fraunhofer IRB Verlag, 2018.

[2] U. Siemer, R. Förster, T. Borsoi Klein, and A. Loth. "Use of non-destructive testing (NDT) methods for the characterization of novel sustainable composites and joints in renewable raw materials." In: Proceedings of 27th ABCM International Congress of Mechanical Engineering COBEM 2023. Florianopolis, Brazil, 2023.

[3] U. Siemer. "Einsatz der Thermografie als zerstörungsfreies Prüfverfahren in der Automobil-industrie: Entwicklung einer Ingenieurplattform." Dissertation. University of Saarland, Saarbrücken, Germany, 2010.

[4] U. Siemer, R. Förster, T. Borsoi Klein, and A. Loth. "Non-destructive testing (NDT) for industrial applications – Systematic approach to implementation, opportunities and limitations of novel NDT methods, new trends." In: Proceedings of 27th ABCM International Congress of Mechanical Engineering COBEM 2023. Florianopolis, Brazil, 2023.

[5] J. Bühler. "Holz als konstruktiver Baustoff." Holzbau Handbuch. HOLZABSATZFONDS, Absatzförderungsfonds der deutschen Forst- und Holzwirtschaft, 2008.

[6] W. Liese, M. Köhl. "Bamboo - The Plant and its Uses, Tropical Forestry." Vol. 10, Springer Switzerland, 2015.

[7] G. Minke. "Building with Bamboo: Design and Technology of Sustainable Architecture." Third and revised edition. Berlin, Boston: Birkhäuser, 2023.

[8] A. Ziani, Y. Yulianto, R. Förster, D. L. Zariatin. "The Effect of Mesh Size on Mechanical and Thermal

Properties of Bamboo Composites." In: JEMMME Journal of Energy, Mechanical, Material, and Manufacturing Engineering, Vol. 4., 2019.

[9] C. Tönges. "Mechanical properties of bamboo, Construction with Bamboo." In: online report, 2002. Available: https://bambus.rwth-aachen.de [Accessed 25.03.2025].

[10] Y. Goh, S. Yap, T. Tong. "Bamboo: The Emerging Renewable Material for Sustainable Construction." Elsevier Inc., 2019.

[11] J. F. Correal. "14 - Bamboo design and construction, Nonconventional and Vernacular Construction Materials." Elsevier Ltd., 2016. http://dx.doi.org/10.1016/B978-0-08-100038-0.00014-7 [Accessed 25.03.2025].

[12] A. Wagenführ, F. Scholz. "Taschenbuch der Holztechnik." Edition: 3, aktualisierte Auflage, Carl Hanser Verlag, 2018.

[13] H. Otto. "Technical data sheet OTTOCOLL® P 84, Otto Chemie Dichten & Kleben." Available: https://www.otto-chemie.de/bau/ottocoll-p-84.pdf, 2022. [Accessed 25.03.2025].

[14] DIN, German Institute. "Holzbauwerke-Brettsperrholz-Anforderungen." Beuth Verlag GmbH, EN 16351:2021-06. 2021.

[15] A. Loth, R. Förster. "Usage of Bamboo Honeycomb Structure (COMBOO) in Timber Architecture." In: World Conference on Timber Engineering (WCTE 2023), Oslo, 2023.

[16] A. Loth, R. Förster. "COMBOO – properties of a novel bamboo based honeycomb core material for composite sandwich structures." In: International Conference on Composite Materials (ICCM 2022), Lausanne, 2022.

[17] A. Loth, R. Förster. "Advanced qualification of COMBOO - a bamboo based core material." In: 22. International Conference on Composite Materials (ICCM 2019), Melbourne, 2019.

[18] A. Hasenstab. "Integritätsprüfung von Holz mit dem zerstörungsfreien Ultraschallechoverfahren." BAM-Dissertationsreihe, Band 16, Bundesanstalt für Materialforschung und -prüfung Berlin, 2006.

[19] J. H. Hinken, A. Gopalan. "Microwave testing with the pitch-catch method, e-Journal of Nondestructive Testing." Vol. 25(9), 2020. Available: https://www.ndt.net/?id=25462 [Accessed 25.03.2025].