WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

ROTATIONAL BUTT FRICTION WELDING OF BAMBOO AND WOOD

Ralf Förster[1], Andreas Loth[2], Ulrike Siemer[3] Annette Juhr[4]

ABSTRACT: Natural, renewable raw materials such as wood or bamboo are increasingly important for industrial applications as they are environmentally friendly to produce and dispose of. The use of renewable raw materials allows for substitution of petroleum-based products and can significantly reduce CO_2 emissions. Renewable raw materials generally decompose much faster than most petroleum-based plastics, provided that no chemical adhesives are used to bond the natural, renewable raw materials. In order to reduce the proportion of petroleum-based adhesives, investigations into the rotational butt welding of bamboo and wood were carried out. This article presents further fundamental investigations of rotational butt welding of various woods, bamboo and their joints.

KEYWORDS: rotational butt welding of wood and bamboo, pine, beech, oak, mahogany

1 – INTRODUCTION

Wood is one of the most important renewable raw materials and has been used in Europe for thousands of years. In Asia, next to wood, bamboo is also frequently used as a building and construction material. Unlike wood, bamboo (Bambusoideae) belongs to the family of sweet grasses (Poaceae). Asia has the worlds largest bamboo reserves. China has the largest cultivation area with 1/3 of the world's supply of bamboo [1]. There are about 500 different bamboo families worldwide and hundreds of subspecies. These are native to every continent except Europe and Antarctica (Fig. 1).

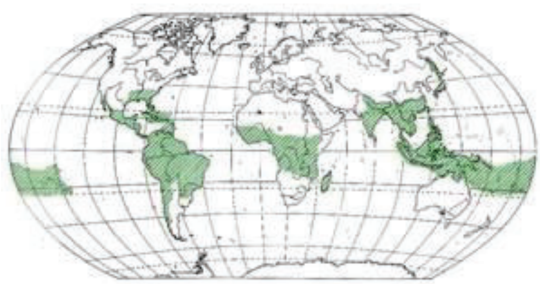

Figure 1 Natural distribution area of bamboo [2]

Wood and bamboo bind not only water but also a great deal of CO_2 as they grow. Bamboo is one of the fastest growing plants on earth and is characterised by its very good mechanical properties. The world record for plant growth is held by Moso bamboo, which can grow up to 114,5 cm per day [15]. Heights of up to 35 m and culm diameters of up to 45 cm are reached. However, the average length growth of all bamboo species is only 25 cm per day [3,4]. Bamboo, like wood is used as a construction material for building houses, bridges and furniture. Wood is usually joined using nails, screws, dowels, etc. Glues and adhesives are also frequently used for secure wood joints. One disadvantage of these joining techniques is that the volatile components of the adhesive can be highly toxic even in small quantities. Another disadvantage are the long curing times. In most cases, glued joints require several hours of curing time, sometimes under high pressure, to achieve their final strength. Bamboo is traditionally often bonded with ropes, fibres or wires.

2 - BACKGROUND

Friction welding has been an established process in the field of metal and plastic processing for a very long time. In 1891, the American James Bevington filed a patent in Chicago describing the process of friction welding metals using a test set-up [5]. In friction welding, the components to be joined are joined by a relative movement against each other and by applying pressure to

[1] Ralf Förster, Dept. of engineering, Berliner Hochschule für Technik (BHT), Berlin, Germany, rfoerster@bht-berlin.de

[2] Andreas Loth, Dept. of engineering, Berliner Hochschule für Technik (BHT), Berlin, Germany, aloth@bht-berlin.de

[3] Ulrike Siemer, Dept. of engineering, Berliner Hochschule für Technik (BHT), Berlin, Germany, usiemer@bht-berlin.de

[4] Annette Juhr, Dept. of engineering, Berliner Hochschule für Technik (BHT), Berlin, Germany, ajuhr@bht-berlin.de

https://doi.org/10.52202/080513-0583

the joining surfaces. The relative movement can be rotational, linear, orbital or by an angular oscillation.

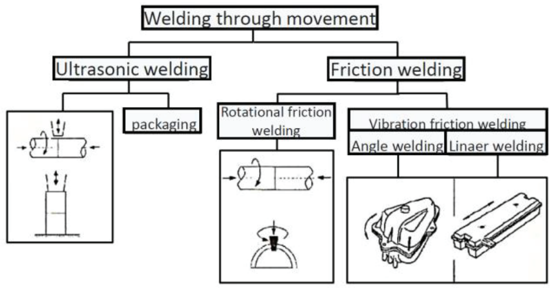

Figure 2 Friction welding process [6]

Due to the interaction of a component- and material-specific speed or frequency and friction time as well as a surface-related, linear friction force, the joining surfaces heat up as a result of friction. If, after a defined time, a braking process to a standstill takes place with a simultaneous increase of the frictional force to the contact pressure, the resulting upsetting pressure causes the actual welding [7]. The process of rotary friction welding begins with the clamping of two components in a rotary friction welding machine. One component is clamped firmly (fig.3 nr.6) and immovably and the other is set in rotation (fig.3 nr.5). Figure 3 shows the principle of rotary welding. In this figure, the numbers the show the structure of the system (1 drive motor, 2 brake, 3-rotating clamping device, 4 fixed clamping device, 5 rotating workpiece, 6 fixed workpiece, 7 pressure cylinder).

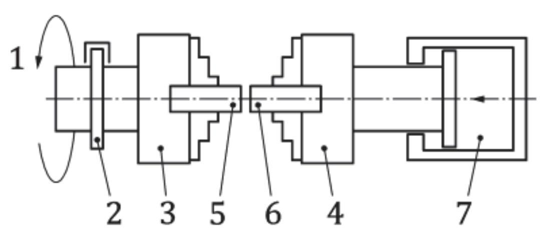

Figure 3 rotarry butt friction welding principle [16]

During the friction or heating phase, the two workpieces are pressed against each other with a defined, linear frictional force. The friction heats up the welding area and the components can be joined. The heating of the weld seam results from the surface-related frictional force and friction time, which depends on the nature of the joining surfaces, the material and the temperature distribution in the workpieces. Friction butt welding is an excellent method for joining bamboo to bamboo, wood to wood and bamboo to wood components without petroleum-based adhesives. Such friction welded connections enable a reduction of the CO_2 footprint and a significant improvement of the recyclability of the components manufactured in this manner.

2.1 FRICTION WELDING PROCESS OF WOOD

The technology of friction welding has so far mainly been used for joining thermoplastics and metals. During the friction welding process of wood, the connection of the individual parts is achieved through the combination of pressure and heat both generated by a linear friction movement. This produces short time local temperatures of up to 350°C. In 1993, GANNE-CHEDEVILLE examined the friction of thermoplastic and thermoset adhesives and found that the lignin contained in wood has thermoplastic properties [8]. First investigations on linear friction welding of wood and wood dowel welding were presented by GANNE-CHEDEVILLE in 2008 [10,11,12] The first studies on linear wood friction welding were carried out using ultrasonic actuators. Furthermore, the linear friction welding of wooden parts without the addition of binding agents was investigated [9,10,11,12]. Due to the frictional heat, a temperature of over 200°C was reached at the connection points in a short time. As a result, the lignin liquefied and subsequently solidified [8,9,10,11].

2.2 ROTATIONAL BUTT FRICTION WELDING PROCESS OF WOOD AND BAMBOO

First investigations of rotary butt friction welding with a standard lathe and special rotary butt friction welding machine was presented 2016 and 2023 [13,14]. Fig.4 shows a typical friction welded pine wood bar.

Figure 4 friction welded pine timber bars [according to 25]

The process of rotary butt welding is comparable to linear friction welding in terms of heating and processes in the material. However, the components are heated by rotating them against each other. The suitability of bamboo for friction welding has so far only been investigated using rotary butt welding [13,14]. Wood is a very popular building material as it has a low volume weight with relatively high strength and easy workability. Cellulose is a main component of plant cell walls and serves as a scaffolding material. Lignin is an organic filler that is incorporated into the cell walls and thus leads to lignification of the cell. Other components of wood are resins, minerals and tannins. The structure of wood is fibrous and consists of tubular cells that are arranged radially. The strength values are mainly influenced by the direction of the fibres and the moisture content of the wood. The type of wood also plays a decisive role due to the different cell structures. The highest tensile strengths are achieved when stress is applied in the direction of the fibres. The inhomogeneous fibre structure means that both the compressive strength and the bending strength are lower than the tensile strength. The structure of bamboo is similar to that of wood and has similar properties. However, bamboo belongs to the grass family. Bamboo consists of about 50% cellulose and 30% lignin, it is hard on the outside and soft on the inside. The very tear-resistant fibre strands are arranged on the outside. Most bamboo plants are divided by nodes. The tensile strength of bamboo can reach values of up to 40 $kNcm^{-2}$. From a botanical point of view bamboo belongs to the Garmineen (grasses). Chemically, bamboo is similar to wood and consists of cellulose, hemicellulose and lignin. Its environmental performance is also positive because it store a lot of carbon dioxide. Of particular note are its material properties, such as light weight, high strength to pressure, train and bending as well as the fact that it's relatively easy to machine. For these reasons, it is recommended as a modern building material.

3 – PROJECT DESCRIPTION

The following materials and material combinations were examined as part of the investigations of rotary butt friction welding of wood and bamboo:

- Pine with Pine, Oak, Mahogany;
- Beech with Beech, Oak, Mahogany;
- Oak with Oak, Mahogany;
- Mahogany with Mahogany;
- Bamboo with Bamboo, Pine, Beech, Oak, Mahogany

As already mentioned above, the polymers hemicellulose, cellulose and lignin are also present in different distributions in the various types of wood and bamboo. The polymer lignin is important for friction welding. Table 1 shows the composition of the materials analysed. Different diameters of the samples were used. The oak rods had a diameter of 12 mm. The mahogany samples had a diameter of 8 mm and the pine, oak and beech samples had a diameter of 10 mm, the diameter of the bamboo samples varied between 10 and 16mm.

Table 1 Composition of wood and bamboo[17,18,19]

Component [%]		Oak	Bamboo	Beech	Pine
Cellulose		47	40,7	41	41
Lignin		29	27.1	27	29
Hemicellulose	Xylan	22	23.6	13	9
	Mannan		0,6	18	18
Pectin				1	3

The mechanical properties of the various materials analysed are shown in Table 2. As these are natural materials, the values vary considerably. Furthermore, these materials are very anisotropic and have significantly different properties in the fibre direction than in the tangential or radial direction. The values shown in Table 2 are average values or value ranges measured in the fibre direction of the materials.

Table 2 Mechanical properties of bamboo, pine and beech [20,21,22,23].

	Young's Modulus N/mm²	Com-pressive strength N/mm²	Tensile strength N/mm²	Flex-ural strength N/mm²	Shear strength N/mm²
Bam - boo	20000	62-93	148-384	76-276	20
pine	6900-20000	35-94	35-169	41-200	6-14
beech	10000-18000	41-99	57-180	74-210	6-19
oak	11500	60	88	95	11,5
Maho-gany	95000	45	100	80	11

4 – EXPERIMENTAL SETUP

The investigations were carried out using a machine specifically designed for rotary butt welding of wood and bamboo.

Figure 5 CNC-controlled Rotational friction welding machine

As part of a research project funded by the AiF e. V. (German Federation of Industrial Research

https://doi.org/10.52202/080513-0583

Associations), a CNC-controlled rotary butt friction welding machine (see Fig. 5) was developed to carry out friction butt welding processes of wood and bamboo. Figure 6 shows a view into the working area of the rotary welding machine with a welded test component. The possible setting parameters of the machine are shown in Table 3.

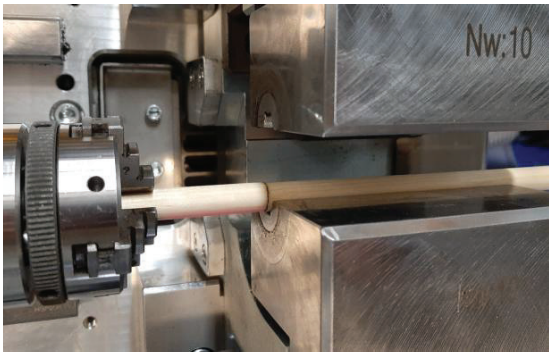

Figure 6 View into the working area of the friction welding machine with a welded sample

The setting parameters shown in Table 4 were used for the investigations of friction welding process.

Table 3 Setting parameter of friction welding machine

Parameter	Unit	min. value	max. value
Rotational Speed	min^{-1}	1	4000
Force (start)	N	140	790
Force (cooling)	N	140	790
Cooling time	s	0,1	60
Press path	mm	1	10
Linear Press Speed	mms^{-1}	5	50

The smallest diameter of the samples involved or the circular ring area of the bamboo samples were used to calculate the area of the friction welded joint.

Table 4 used setting parameter

Parameter	Unit	V 1	V 2	V 3	V 4	V 5
Rotational Speed	min^{-1}	800	1600	2400	3200	4000
Force (start)	N	140	270	400	530	660
Force (cooling)	N	150	280	410	540	670
Cooling time	s	0,1	15	30	45	60

Table 5 shows the setting parameters of the tests carried out with the different wood-wood and wood-bamboo pairings. The first number refers to the test results shown in Figures 8-10. The tests of the different material pairings were carried out with the same parameters.
As mentioned above, the frictional heat on the components to be joined must reach a temperature of over 200°C in a very short time for the lignin to become liquid. After liquefaction, the lignin must solidify. During this time, the samples must no longer rotate against each other. The components must be pressed against each other with a holding force (cooling force) for a certain time (cooling time). After the friction welding process, all welded samples were tested on a tensile testing machine. The workpiece holders on the tensile testing machine had to be modified for the different diameters of the samples. However, this modification has no influence on the measurement result.

Table 5 Parameter settings of the investigations carried out [according to 24]

Number	Rotational Speed	Force (start)	Force (cooling)	Cooling time
Unit	min^{-1}	N	N	s
1	800	140	150	0,1
2	800	270	280	15
3	800	400	410	30
4	800	530	540	45
5	800	660	670	60
6	1600	140	280	30
7	1600	270	410	45
8	1600	400	540	60
9	1600	530	670	0,1
10	1600	660	150	15
11	2400	140	410	60
12	2400	270	540	0,1
13	2400	400	670	15
14	2400	530	150	30
15	2400	660	280	45
16	3200	140	540	15
17	3200	270	670	30
18	3200	400	150	45
19	3200	530	280	60
20	3200	660	410	0,1
21	4000	140	670	45
22	4000	270	150	60
23	4000	400	280	0,1
24	4000	530	410	15
25	4000	660	540	30

The tensile tests were carried out on a Zwick/Roell ProLine Z050 universal testing machine. The maximum applied force can reach 50 kN. The accuracy of crosshead is up to 0.1 N and drive speed can be set to 0.01 mm/s. Fig. 7 shows the tensile test of a bamboo oak sample in the tensile testing machine.

Figure 7 Tensile stress test of a bamboo-oak joint [according to 24]

5 – RESULTS

Figures 8-10 show the tensile strengths achieved by the tested joints. Figure 8 shows the tensile strengths of wood-wood joints of similar types of wood. Figure 9 shows the tensile strengths of wood-wood friction welded joints of woods of different species. Figure 10 shows the results of the tests on wood and bamboo friction welded joints. Figure 8-10 show that no welding could be achieved with the small parameter sets. The low setting parameters did not lead to the required temperature to liquefy the lignin.

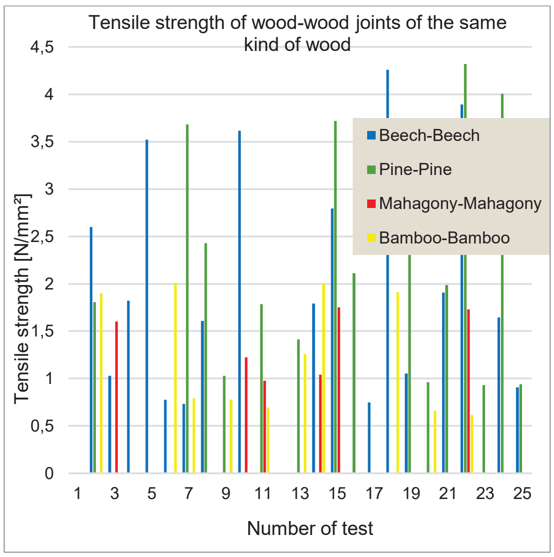

Figure 8 Tensile strength of wood joints of the same kind of wood [according to 24]

Figure 10 shows that the material combination of mahogany and bamboo led to the highest strength values. The value of 4.99 N/mm² was achieved using a speed of 2400 min^{-1}, a starting force of 660 N, cooling forces of 280 N and a cooling time of 45 s. It should also be noted that a connection between bamboo and beech led to several tensile strengths above a value of 3 N/mm². The highest tensile strength determined for this joint, 3.94 N/mm², was achieved at speeds of 4000 min^{-1}, a starting force of 530 N, cooling forces of 410 N and a cooling time of 15 s. As can be seen in figure 9, the material combination of oak and mahogany achieved the highest strength values. The sample with the highest strength value of 7.52 N/mm² was produced at a speed of 800 min^{-1}, a starting force of 400 N, cooling forces of 410 N and a cooling time of 30 s. This was closely followed by the sample with a strength value of 7.51 N/mm², which was welded at speeds of 2400 min^{-1}, a starting force of 140 N, cooling forces of 410 N and a cooling time of 60 s. The third highest value with a strength of 6.54 N/mm² was achieved with the material combination of oak and beech. These workpieces were welded together at speeds of 1600 min^{-1}, a starting force of 140 N, cooling forces of 280 N and a cooling time of 30 s.

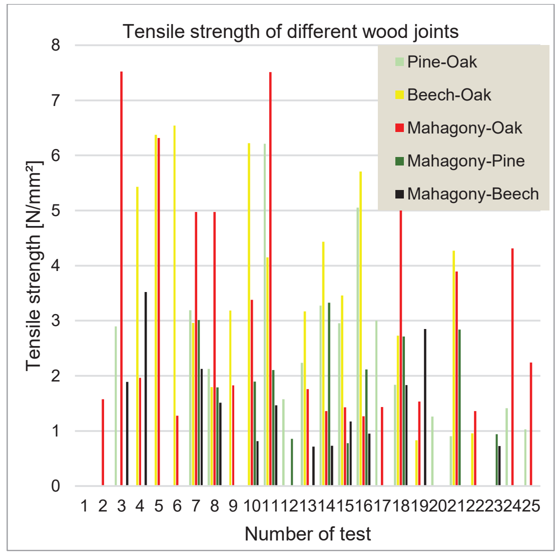

Figure 9 Tensile strength of wood joints of different kind of wood [according to 24]

The material with the least successful friction welds among the same material pairings is mahogany (fig.8); of 25 attempts, only six welds were successful. This may be due to the hardness of mahogany.

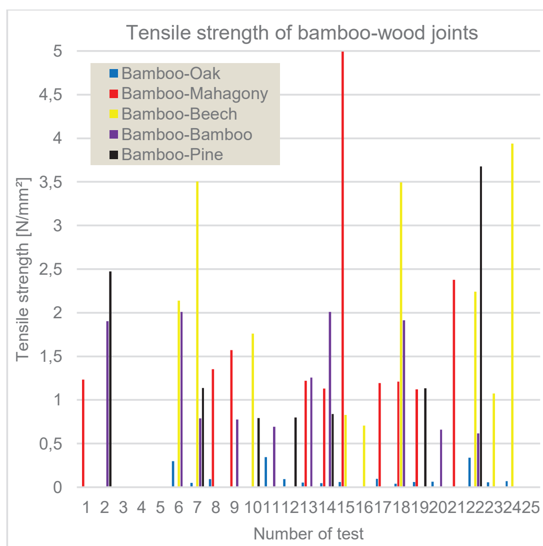

Figure 10 Tensile strength of Bamboo-wood joints [according to 24]

During the tests with mahogany, numerous samples were destroyed. Figure 11 shows some of the failed mahogany welds. It can be seen that high compressive forces were particularly responsible for the destruction of the workpieces. Investigations to clarify the behavior of this

https://doi.org/10.52202/080513-0583

mahogany wood are currently ongoing. On the other hand, the material combination mahogany-oak (Figure 9) was able to be joined 21 times out of 25 attempts. In the attempt to weld two workpieces made of oak together, this was successful in 20 attempts.

Figure 11 Failed mahogany welds [24]

The joints of mahogany and bamboo are also comparatively stable and often successful. The material combinations with oak wood, both with bamboo and in combination with other wood materials, have achieved the most successful welds.

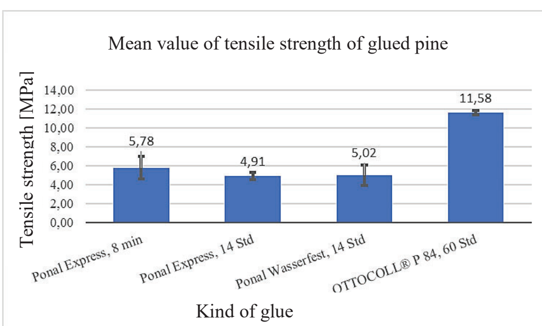

Figure 12 Mean value of tensile strength of glued pine [according to25]

In order to obtain comparative values of the tensile strength of glued joints to rotational friction welded joints, pine rods were glued using different glues (see Figure 12). The PU glue OTTOCOLL® P 84 with a pressing time of 60 hours achieved the highest average tensile strength with a value of 11.58 MPa. The highest individual tensile strength value was 11.90 MPa. The wood glue Ponal Express with a pressing time of 8 minutes achieved the second best result with an average tensile strength of 5.78 MPa. With an average tensile strength of 5.02 MPa, the wood glue Ponal Waterproof with a pressing time of 14 hours performed third best. The adhesive joints made with Ponal Express wood glue with a pressing time of 14 hours could only achieve an average tensile strength of 4.91 MPa. Basically, the glued joints had a much lower standard deviation than the rotational friction welded joints. This illustrated the high process capability of gluing with wood glues compared to the still high optimisation potential of rotary butt friction welding of renewable raw materials under given condition.

6 – CONCLUSIONS AND RECOMMENDATIONS

The results show that a wide variety of wood and bamboo can be reliably joined by rotary butt friction welding. This process can be used to join lignin-containing materials such as wood or bamboo without the use of adhesives (**Fehler! Verweisquelle konnte nicht gefunden werden.** shows as example connection of oak and mahogany). Very promising tensile strengths can be achieved.

Figure 13 Friction butt welded connection of oak and mahogany [24]

This enables sustainable production and also recycling of the products after use without the generation of hazardous waste. By using wood and bamboo, CO_2 can be significantly reduced, furthermore, oil-based adhesives can be avoided. With the adhesive-free joining method rotary friction welding, it is possible to join different types of wood and bamboo. Raw materials can thus be used for new applications (bamboo scaffolding tubes) and their specific properties can be exploited. In addition, wood scraps can then be reused as no adhesives are involved. The results presented in this article provide a first insight into the possibilities of rotary butt welding of wood and bamboo. Further investigations will and must be carried out. In particular, the results of the investigations carried out with the conventional friction welding machine cannot be compared with the results of the specially developed friction welding machine, as the lathe does not switch off quickly enough after the end of the joining process. Furthermore, numerous investigations must be carried out in order to increase the reliability and statistical validation of the previous test results. Friction welding can also be used to successfully join different types of wood and bamboo. It is possible to join different types of wood and bamboo with this glue-free joining method. This provides a process with which renewable raw materials can be used for new applications (bamboo scaffolding tubes) and their specific properties can be exploited. Furthermore, wood residues can be reused, while at the same time reducing the use of adhesives. The results underline the applicability of developments auch as, e.g., honeycomb core of bamboo rings called COMBOO which is currently under investigation. The approach called CCLT (COMBOO Cross Laminated Timber) can reduce timber consumption and weight using hollow bamboo combs [26].

7 – ACKNOWLEDGEMENTS

We would like to thank the Bundesministerium für Wirtschaft und Klimaschutz der Bundesrepublik Deutschland (BMWK) for funding and financial support of the research work in the project 'Cross laminated timber sandwich panels with bamboo core' CCLT. We would also like to thank the Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e. V. (AIF) for funding and supporting the development of the rotary butt friction welding machine for wood and bamboo. We would also like to thank BMWK for supporting our participation at the WCTE 2025 in Brisbane.

8 – REFERENCES

[1] Li, S., et al.: Study on the Bonding Performance of the Moso Bamboo Dowel Welded to a Poplar Substrate Joint by High-Speed Rotation (Journal of Renewable Materials, 2020)

[2] https://bambus.rwth-aachen.de/de/referate2/baumaterial/bambusalsbaumaterial.html, 2023

[3] Holzmann, G.; Wangelin, M.; Bruns, R.: Natürliche und pflanzliche Baustoffe, Rohstoff - Bauphysik - Konstruktion, Wiesbaden: Springer Vieweg, 2012, pp. 73-99, 139-154.

[4] „BAMBUS WISSEN," [Online]. Available: https://bambus-wissen.de/bambus/tag/moso/?cn-reloaded=1. [07. 10. 2019].

[5] Patent US463134A, https://patentimages.storage.googleapis.com/c1/10/44/79c8d8ff336c7b/US463134.pdf [02. 03. 2025].

[6] Michel, P.: Schweißverfahren in der Kunststoffverarbeitung, Grundlagen und Aspekte zur Serienfertigung, DVS-Berichte Band 203, Düsseldorf: DVS-Verlag GmbH, 1999, pp. 1-29.

[7] Schuler, V.; Twrdek, J.: Praxiswissen Schweißtechnik, Werkstoffe Prozesse Fertigung, 6. vollständig überarbeitete Auflage, Wiesbaden: Springer Vieweg, 2019, pp. 142-147, 239-242.

[8] Ganne-Chedeville, C.: Zukunft Holz: Verbindungstechniken – 10.3 Fügetechniken Schweissen von Holz (2009)

[9] Ganne-Chedeville,C.: Schweissen von Holz – Innovationstagung IPEK, Rapperswil (2008)

[10] Župčić, I.; Vlaović, Z; Domljan, D.; Grbac, I.: Influence of Various Wood Species and Cross-Sections on Strength of a Dowel Welding Joint. Drv. Ind. 2014, 65, 121–127

[11] Ganne-Chedéville, C. Soudage linéaire du bois: étude et compréhension des modifications physico-chimiques et développement d'une technologie d'assemblage innovante. PhD Thesis, Nancy-Univerité 2008

[12] Ganne-Chedeville, C.; Pizzi, A.; Thomas, A.; Leban, J. M.; Bocquet, J. F.; Despres, A.; Mansouri, H., 2005: Parameter interactions in two-block welding and the wood nail concept in wood dowel welding. J Adhesion Sci. Technol., 19 (13-14): 1157-1174. http://dx.doi.org/10.1163/156856105774429037

[13] Förster, R., Berwing, M.; Loth, A., Böhlke, T. Friction welding of bamboo
European-Latin-American Conference of Theoretical and Applied Mechanics (ELACTAM-2016), February 22-24, 2016, Havana, Cuba

[14] R. Förster, A. Loth, T. Borsoi Klein, and U. Siemer. "ALTERNATIVE BONDING OPTIONS FOR RENEWABLE RAW MATERIALS." In: Proceedings of 27th ABCM International Congress of Mechanical Engineering COBEM (2023). Florianopolis, Brazil.

[15] Chen, M. et. Al. Rapid growth of Moso bamboo (Phyllostachys edulis): Cellular roadmaps, transcriptome dynamics, and environmental factors; The Plant Cell, Volume 34, Issue 10, October 2022, Pages 3577–3610, https://doi.org/10.1093/plcell/koac193.

[16] DIN EN ISO 15620 (2019): Schweißen – Reibschweißen von metallischen Werkstoffen, Berlin, Wien, Zürich: Beuth Verlag, 2019

[17] Timell, T.E. Recent progress in the chemistry of wood hemicelluloses. Wood Sci.Technol. 1, 45–70 (1967). https://doi.org/10.1007/BF00592255

[18] Leenakul, Wilaiwan & Tippayawong, Nakorn. (2010). Dilute Acid Pretreatment of Bamboo for Fermentable Sugar Production. Journal of Sustainable Energy & Environment. 1. 117-120.

[19] Szatkowski, Piotr & Szatkowska, Martyna & Gralewski, Jacek & Czechowski, Leszek & Kedziora, Slawomir. (2022). Biocomposites with Epoxy Resin Matrix Modified with Ingredients of Natural Origin. Materials. 15. 7167. 10.3390/ma15207167.

[20] Lohmann, U.: Holz- Handbuch. DRW-Verlag, Rosenheim, 4. völlig überarbeitete Auflage (1990) 13-56.

https://doi.org/10.52202/080513-0583

[21] Dunkelberg, K.: Bambus als Baustoff, in IL 31 Bambus. Karl Krämer Verlag, Stuttgart (2005) 46-91.
[22] Şeker, Sedanur & Koc, Kucuk. (2023). Engineering Analysis Application in Furniture Making: Deformation Equivalent Stress. Drewno. 66. 1-10. 10.12841/wood.1644-3985.406.07.
[23] DIN 68364:2003-05 Kennwerte von Holzarten - Rohdichte, Elastizitätsmodul und Festigkeiten, Berlin, Wien, Zürich: Beuth Verlag, 2003
[24] Sakran, R. J.: Untersuchung des Rotationsreibschweißen von Holz & Gräsern BA-Thesis, Berliner Hochschule für Technik (BHT), Berlin, University of Applied Sciences, 2023
[25] Niebergall, M. Untersuchung eines temperaturgeführten Fügeverfahrens von nachwachsenden Rohstoffen. Master thesis, Berliner Hochschule für Technik (BHT), 2020
[26] A. Loth, and R. Förster. “Usage of Bamboo Honeycomb Structure (COMBOO) in Timber Architecture.” In: Proceedings of World Conference on Timber Engineering WCTE (2023). Oslo, Norway.