Characterization of Laminated Bamboo Lumber Using Digital Image Correlation in Mechanical Testing

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Abstract

The purpose is to investigate the use of bamboo as an outstanding material in terms of sustainability in various technical fields, such as civil engineering. Therefore, the Phyllostachys edulis (Carrière) J. Houz. (Moso) culms are further processed into laminated bamboo lumber (LBL) to bring the material closer to technical applications according to European standards. The testing program was divided into three parts. First, LBL was examined in its initial condition. Computed tomography (CT) was applied to detect pores and other defects. In particular, the visualization of potential bonding defects between the individual laminate layers of bamboo was of key importance, as this type of defect is expected to have a major impact on the mechanical properties of LBL. Afterwards, the bamboo specimens underwent mechanical testing, including compressive and shear testing. The results were promising for the intended technical applications. The engineered bamboo product LBL exhibited strengths comparable to those of wooden products already used in the targeted areas. Material reactions were recorded during the tests using appropriate measuring devices. In particular, the digital image correlation (DIC) was applied to record deformations and strains on the surface of bamboo specimens. This measuring technology enabled a subsequent visualization of the influence of the applied loads, highly loaded areas, and resulting crack progression. During compressive testing, it was observed, that the failure of the specimens often began at the nodal area of the bamboo culm, still clearly visible in the engineered bamboo product. The moisture content of specimens was determined using the oven-dry method, as moisture has a proven influence on material properties. After completing the mechanical characterization, the third phase of the study began, including analytical tests of damaged specimens. The focus was on examining the damaged areas and fracture surfaces to identify the operating damage mechanisms. The research indicates that LBL shows promise as a sustainable alternative to commonly used building materials.

Keywords: *Sustainability, Engineered bamboo, Climate-friendly building, Mechanical properties, Digital image correlation, Computer tomography*

1. Introduction

Civil engineering can be cited as one of the technical fields where considerations of renewable resources in material selection have become one of the most central aspects. Bamboo is a sustainable and renewable alternative to proven materials such as concrete, making it an excellent material for the investigations in this work. It provides an enormous potential for the eco-restoration of degraded lands [1], as it is creating opportunities for other plants to thrive in the landscapes once again. Additionally, the ability to absorb high levels of CO2 makes it a significant contributor to addressing global issues such as climate change and global warming. Bamboo´s widespread growth already had a significant impact on various countries, particularly developing countries. Implementing an extended use of bamboo in those countries will undoubtedly enhance both the industry and the standard of living for the local population. Furthermore, it will play a crucial role in promoting indigenous construction methods.

Bamboo is one of the fastest-growing plants in the world. Meaning that the gigantic culms are growing to a height of multiple meters in a short time. The culms can be harvested after 4-6 years, when the lignification of the bambooculm is completed, demonstrating a growth rate ten times faster than the average tree. In addition, the culm is confidently cut near the ground during harvesting, leaving the root firmly in the soil. The growth process of bamboo restarts continuously without the need for replanting.

Further, bamboo has excellent mechanical properties, comparable to those of wood [2–4]. Due to its low weight, the material has significantly higher specific mechanical properties than concrete, that is commonly used in civil engineering. Bamboo is a fibrous material and because of the alignment of fibers, there is an anisotropy of material properties. This leads to higher characteristic values parallel to the fibers compared to those perpendicular to the grain. Manufacturing bamboo into engineered bamboo material, such as laminated bamboo lumber (LBL), can significantly enhance its mechanical properties. This can be referred to the elimination of naturally grown flaws and misalignments of the culms. LBL is produced by splitting the bamboo culm into lamellas, shaping them into rectangles, and bonding them to a homogenous material using adhesive, high pressure, and elevated temperatures. Research activity on bamboo and engineered bamboo has significantly increased in recent years. However, there are still many questions concerning the material properties of bamboo, and this research should contribute to the increasing use of bamboo in various technical fields. Thus, the mechanical properties were investigated in compressive and shear tests and the material reactions were recorded using appropriate measurement equipment during the tests.

2. State of the Art

Bamboo and engineered bamboo products have gained significant attention in recent years due to their exceptional mechanical properties and potential for sustainable application in various technical fields. In the following, a concise summary of selected research findings is presented.

Bamboo contains cell fibers aligned in a particular direction, resulting in strong anisotropy. This is the reason for varying mechanical properties depending on the direction the load is applied [4–6]. The culm has a graded structure of the fiber arrangement, with the majority of fibers located in the outer zone of the culm wall, resulting in a higher density and greater strength of the outer culm skin. The density and stiffness of the bamboo culm decrease as the fibers become less at the inner culm wall. The distribution of fibers is leading to a nearly linear increase of the mechanical properties in the outer culm wall [7, 8]. The fiber distribution in the raw bamboo culm as and the engineered LBL product can be seen in Figure 1.

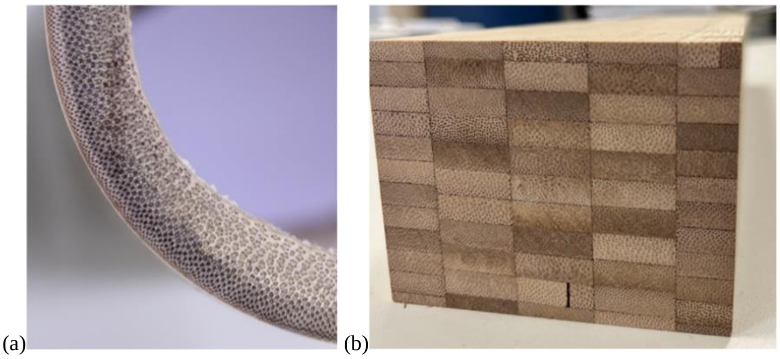

(a) (b)

Fig. 1. Distribution of the fibers in the (a) raw bamboo culm and (b) laminated bamboo lumber.

There are naturally grown flaws e.g., the eccentricity of the culm, as the bamboo is never growing straight up in the air nor in a perfectly circular way. The flaws have an important influence on the material properties of bamboo and have to be carefully considered when planning to build with raw bamboo culms. In addition, the hollow sections of the culm, also known as the internodal areas, are separated by nodes, which ensure greater stability of the very tall plants. The effect the node has on the mechanical properties is not clarified conclusively. On the one hand, the nodes help to stabilize the hollow structure of the culm, but on the other hand, mechanical investigations conclude that the nodes are a point of weakness since the straight course of the bamboo fibers is distracted and thus failure often starts in the nodal area [9].

Because of the high amount of hemicellulose bamboo contains, it is a highly hygroscopic material [10], meaning it interacts strongly with the moisture of the surrounding environment. If the moisture content of the bamboo is lower than the surrounding environment's moisture, it tends to absorb water until the state of equilibrium is reached. If the surrounding environment is dryer, the material releases water into the atmosphere. Research found that the moisture content has a direct impact on physical properties, such as culm dimensions, and further on the mechanical properties [11, 12]. Thus, a proper method of drying the bamboo for further processing steps is essential, as well as a regulated climate for conditioning the LBL before use.

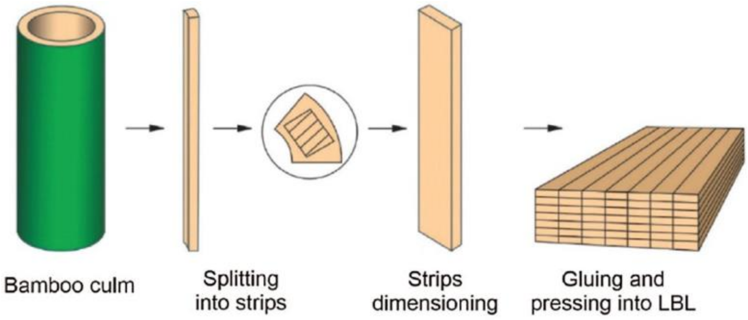


Fig. 2. The manufacturing process of laminated bamboo lumber [13]

As previously mentioned, in present time there is a strong focus on engineered bamboo, such as laminated bamboo lumber. It provides a possibility of eliminating natural-grown flaws described earlier, as well as shaping the bamboo into beams and thereby bringing them closer to possible applications, e.g., in the context of civil engineering. Figure 2 shows the fabrication process of LBL from the raw bamboo culm to the engineered product.

For fabrication, the culms are split into strips. Because of the round shape of the raw material, the strips are not rectangular after the first step of production. Hence, the next step is dimensioning the strips. There are two possibilities for dimensioning the strip, that have a varying influence on the mechanical properties of the material. First, the rectangle shape can be cut out of the strip as implied in Figure 2, meaning that the hardest part of the culm, i.e. the outer wall, is detached and the strip allegedly loses strength. Therefore, the approach of flattening the whole strip was invented. Luan et al. found, that flattening the single bamboo strips at a temperature from 170 to 190 °C for 20 min has a positive influence on the mechanical properties by obtaining the outer culm wall. Following the hot-pressing during the flattening process, the density of the bamboo was increased, which can be directly linked to an increase in the mechanical properties. During the subsequent mechanical tests the bending properties, such as modulus of elasticity (MOE) and modulus of rupture (MOR) increased, as well as different types of fracture mechanisms were seen for the two differently pre-treated bamboo strips [14].

In the next step, the bamboo strips are glued together and pressed into the desired LBL compound afterwards. In the majority of applications, the strips are pressed under high pressure and elevated temperatures. Recent research activities have proven, that especially the high-temperature exposure once again has a significant influence on the mechanical properties of the resulting LBL. Nugroho and Ando found, that hot-pressing of bamboo differs from the well-known pressing process of wood because the bamboo is a little waxier and thus needs a longer processing time. The temperature also influences the density of the LBL, meaning a higher temperature leads to a higher density. They also did fundamental testing in the form of bending tests and the LBL provided very promising results comparable to those of laminated veneer lumber (LVL) made from wood [15]. Mahdavi et al. engaged the process of LBL production with a lower technology approach, meaning they used simple machines and production processes. Due to the highly technological machines needed for the production described above, there is a high energy consumption that should be minimized with their approach. In addition, the low technology approach was investigated to be implemented on-site at the regions where the bamboo grows, as these regions often do not have access to these types of machines. By potentially creating a solution to process the bamboo directly in the growing area, the transport costs and expenses could be negated [16].

After the manufacturing process of LBL is finished, there are some further treatments with a possible influence on the properties of the engineered material. Another temperature treatment could lead to a positive change in the compressive, bending, and shear properties of the material. Simultaneously the tensile properties are slightly deteriorated. Furthermore, the heat treatment contains an optical aspect due to the caramelization of the bamboo, as the outer appearance of the material is positively influenced [4]. A treatment with high-temperature water leads to a change in the chemical composition of the bamboo. The lignin proportion is enhanced, while cellulose and hemicellulose are reduced. This leads to a less pronounced hygroscopicity and at the same time slightly decreased mechanical properties [10].

3. Experimental Setup

The experimental setup contained different testing methods and rigs. In the following, the experimental design and the measurement devices used for recording the material responses to the different loads are described in detail.

3.1 Specimen Preparation and Analytical Investigations

The LBL made from Phyllostachys edulis (Carrière) J. Houz. (syn.: Phyllostachys pubescens Mazel ex J. Houz.) (Moso), were supplied in two different cross-sections. One was 86×82 mm and the other was 120×60 mm, while both beams had a total length of 5,900 mm. The specimens required for the two different testing methods were cut from those beams. The different types of specimens are shown in Figure 3.

(a) (b) (c)

Fig. 3. Specimens for the testing methods, (a) compression, (b) shear, and (c) representation of the front side of the laminated bamboo lumber with the two dimensions of shear specimen.

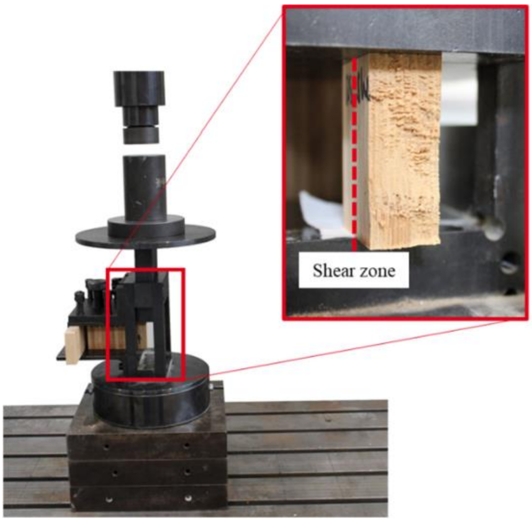
The specimens were manufactured according to European/German standards for wood, due to a lack of normative requirements for engineered bamboo products, such as LBL. The compressive specimens were dimensioned according to the requirements of DIN 52185 and the shear specimens in correspondence with DIN 52187 and DIN EN 14080.

Following the preparation, the specimens were investigated utilizing non-destructive analytical testing methods. Hence, the specimens were further investigated using computer tomography (CT), i.e., CT model XT H 160 from Nikon with a maximum voltage of 160 kV and a 5-axis manipulator allowing a 360° rotation of the sample. During the CT scan, the specimens were rotated and the generated X-ray beams radiated through the material and were deflected in various ways, resulting in different gray values of the beams recorded on the detector. Through a computer-aided subsequent aggregation of the images recorded, it is possible to reconstruct a 3-dimensional illustration of the specimens.

3.2 Mechanical Testing Setups

The shear testing of the LBL was conducted using the testing device shown in Figure 4. Generally, two different types of shear zones were considered. As shown above in Figure 3 (a) and (c), the “Length” (L)-direction, meaning the adhesive line on the long side of the lamellas, was tested. The specimens were cut out of the LBL to obtain a single row of lamellas that was extracted. Thus, the adhesive joint between the single lamellas was tested. For the “Cross”(C)- direction the specimens were excised so that the perpendicular glue line was tested. In this case, a compound of several lamellas were loaded on the lamella’s short side.

For the shear experiments an universal testing system D-400-D from walter+bai was used. With the help of the device in Figure 4, the applied compressive force led to a shear loading in the glue line between the LBL lamellas. The test execution was carried out in displacement control at a speed of 0.75 mm/min and the machine recorded data, e.g., force and displacement, at a rate of 1 Hz. In advance of the shear test, the machine approached an initial load of 200 N. The testing parameters are listed in Figure 4.

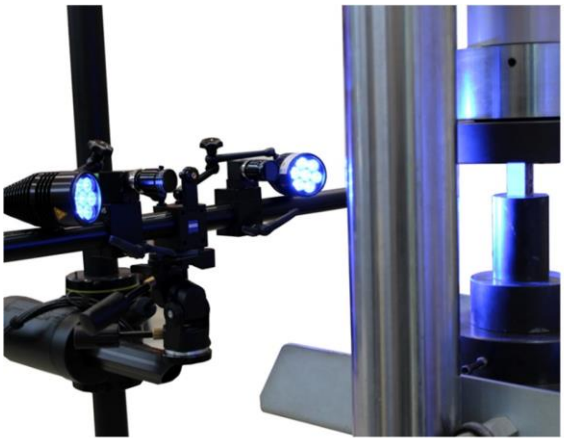


Testing parameters:

Direction of load: Compression → Shear
Regulation: Displacement control
Testing speed: $v_c = 0.75$ mm/min
Inital force: $F_{init} = 200$ N

Recording rate: f = 1 Hz

Fig. 4. Testing setup for shear testing of the laminated bamboo lumber.



Testing parameters:

Direction of load: Compression
Regulation: Force control
Testing speed: $v_c = 0.1$ kN/s
Inital force: $F_{init} = 400$ N
Testing time: t = 300 ±120 s

Recording rate: f = 0.5 – 5 Hz

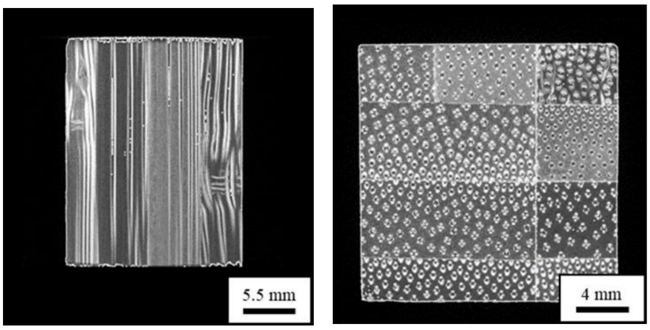
Fig. 5. Testing setup and parameters for compressive testing including the video system for subsequent DIC analysis.

The compressive testing of the LBL was conducted on the same universal testing machine. In advance to the tests, the machine approached an initial load of 400 N and afterwards the test was carried out in force control at a movement speed of 0.1 kN/s. This led to a testing time of 300 ± 120 s, as is required in the normative standards. The camera system for subsequent DIC analysis (Figure 5) was calibrated for the specimen size of 20×20×40 mm³ and 60 mm respectively and recorded at a rate of 0.5 Hz at the beginning of the tests. After surpassing a defined force threshold of 20 kN, the recording rate was increased to 5 Hz in order to record as many pictures of the failure of the specimens as possible. With a high number of pictures recorded, the chance of displaying the crack initiation and propagation for the brittle material bamboo during quasi-static testing could be maximized.

4. Results and Discussion

4.1 Computer Tomography

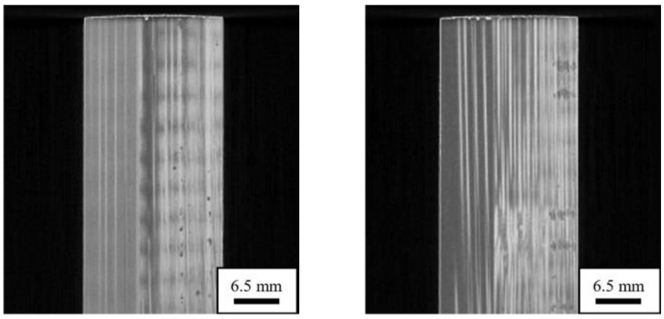
First analytical analyses of the LBL material were conducted on the CT and some representative images are presented below. Because bamboo only absorbs a small amount of the X-rays, the CT scans showed promising results with a relatively low voltage.



(a) (b)

Fig. 6. CT reconstruction of a laminated bamboo lumber compressive specimen.

In Figure 6 (a) the fibers of the initial bamboo culm are visible. The fibers are still aligned in a preferred direction, leading to the anisotropy the LBL shares with the raw material. Furthermore, on the right side of the compressive specimen radiated in the exemplary representation, a former node of the bamboo culm can be seen. The area is characterized by a deflection of the straightly aligned fibers. There is a reasonable suspicion that the deflection of the fibers serves as a weakening point of the LBL and thus is an initial point for fracture propagation. Figure 6 (b) shows the top view of a LBL specimen. On the one hand, the single strips connected to homogenous material can be seen, as well as the small glue lines between the strips. On the other hand, the sectional view of the bamboo fibers can be seen. The CT representation shows the mentioned graded structure and the naturally uneven distribution of fibers still visible in the engineered bamboo product. Additionally, an assignment of the position the strips were cut out of the bamboo culm can be seen. The arrangement of the strips with the harder and softer side seems to be randomized in this example.



(a) (b)

Fig. 7. CT scan of the laminated bamboo lumber with connection errors between the bamboo strips.

Initially, the CT scans should be used to identify internal errors and especially bonding errors between the single bamboo strips. Figure 7 shows two images recorded of a specimen later investigated in compressive tests. It shows

two different glue lines and it becomes obvious, that there are bonding errors such as pores or inclusions. In Figure 7 (a) the pores are small and due to their form, they seem to be air bubbles trapped in the adhesive during fabrication of the LBL. The picture on the right shows a different type of connection error, as the pores are bigger and have an indiscriminate form. This type of error is more likely to be found in areas where the penetration of the adhesive was not possible and thus the areas are not covered with adhesive. A possible influence of the pores determined during a first CT scan series on the mechanical properties emerging from subsequent material tests has to be further observed.

Bamboo is a very porous material and thus the subsequent defect analysis was difficult. There were a great number of pores determined within the bamboo fibers, causing long computing times and an overlooking of real connection errors between the strips.

4.2 Compressive Testing

The compressive testing was performed according to the parameters described earlier. A total of 25 experiments were conducted on two different specimen heights: 40 mm and 60 mm. The specimens were aged in an environment of 20°C and 65% humidity for 14 days each. Exemplary results are shown in Figure 8. The results showed a negligible influence of the varying specimen height, since the compressive strength was fc,40= 70.36 ± 1.04 MPa for the 40 mm specimen, and fc,60= 71.47 ± 2.62 MPa for the 60 mm specimen, respectively. Since all specimens had the same cross- section of 20×20 mm, the maximum force Fmax for both types of specimens was around 28 kN. The strain was recorded using a virtual extensometer (Figure 8) placed within the subsequent DIC recordings. Therefore, the DIC system captured two defined facets and their movement in relation to each other as a result of the applied compressive load. The 40 mm specimens on average had a higher strain of 15-19% and the 60 mm specimens had a lower average strain of 8-12%. To record the moisture content of the LBL specimens, there were comparative samples, that underwent the same number of days in the aging environment. On the testing day, the moisture specimens were put into the oven to dry them according to the oven-dry method described in ISO 22157. After 24 hours at a temperature of 103 ± 2°C the samples were dry and an average moisture content of 7.2% could be determined.

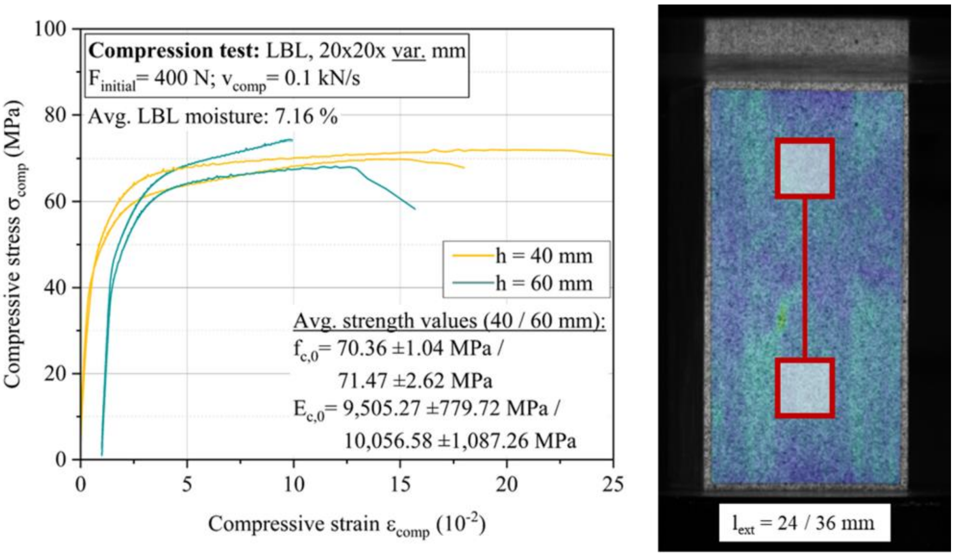
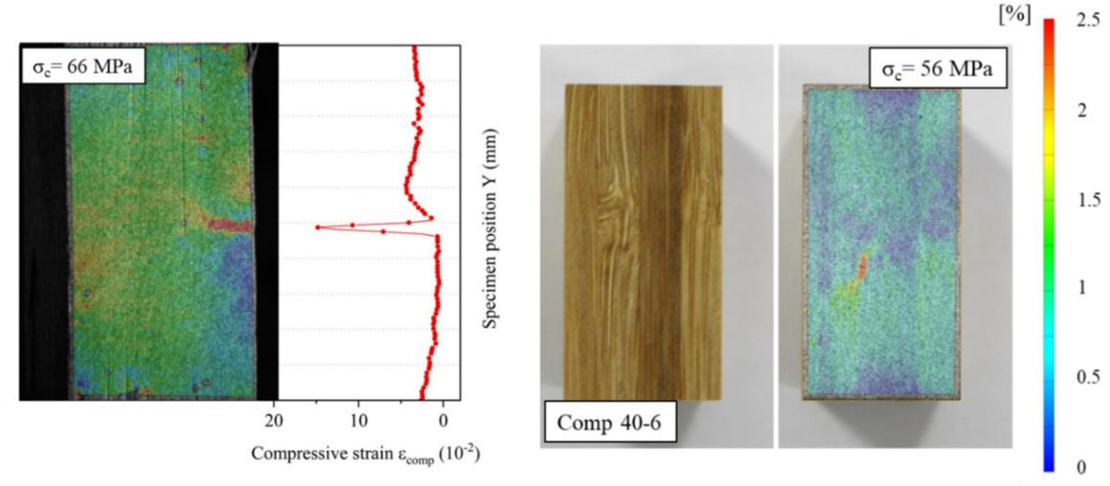


Fig. 8. Compressive stress-strain-diagram for the different laminated bamboo lumber specimens and virtual extensometer for the strain evaluation using the subsequent DIC analysis.

In addition to the strain evaluation described above, the virtual extensometer was used to determine the elastic modulus of the LBL. The length of the extensometer was chosen to be 0.6 times the height of the specimen to avoid potentially occurring unusual deformations in the edge area. For the two heights inspected, that means an extensometer length of 24 mm and 36 mm, respectively. According to the standard for testing bamboo culms, the values of load and strain should be taken from 20% and 60% of the compressive strength. For the tests, the standard was not applicable, since the selected points did not meet the criterion of a linear progression between them. This indicates an elastic- plastic material response at 60% of the maximum load applied. Hence, the European standard for testing engineered woods was taken into consideration. DIN EN 408 prescribes the two points at 10% and 40%, respectively. As the linear progression was given for the points, the modulus of elasticity was calculated in between. The results have shown a spread between 8 and 11 GPa. On average, the 40 mm specimen showed a value of Ec,40= 9.51 GPa with a standard deviation of 0.78 GPa. Regarding the 60 mm specimen an average modulus of elasticity of Ec,60 = 10.06 GPa with a standard deviation of 1.09 GPa could be determined. The spread of the modulus can be explained because bamboo is a naturally grown plant and the specimens vary strongly from each other. Nevertheless, the range of the calculated values can be considered valid and allows a first tendency of the material parameters of engineered bamboo. The modulus of elasticity and compressive strength are comparable to, or even higher than, those of wooden products commonly used in technical fields such as civil engineering. Bamboo, particularly engineered bamboo, can therefore be said to be fundamentally suitable for usage in these technical applications.

The DIC analysis was also used to determine the surface strain distribution during the compressive tests and particularly to identify highly loaded areas. Figure 9 (a) shows a LBL specimen during the test and based on a virtually added section through the specimen, the strain distribution can be identified. It can be seen, that in the area of a node, still contained in the engineered LBL, the compressive strain is remarkably high compared to the rest of the specimen. This means, that the compressive load applied to the specimen produces a material reaction in the node first. The stronger reaction can then be linked to a destruction of the material and a buckling failure of the specimen. It can be emphasized, that the nodal areas within the LBL seem to be favoring failure when applied to compressive load.



(a) (b)

Fig. 9. (a) DIC analysis of a compressive testing specimen with the location of a highly loaded area and (b) surface strain contribution for different laminated bamboo lumber specimens during compressive testing.

Figure 9 (b) shows the surface strain contribution for a 40 mm specimen. On the left-hand side, the specimen surface can be seen before the speckle pattern, the DIC system needs to track changes on the surface, was applied. It's observable, that the specimen surface contains two nodal areas of the initial bamboo culm. When looking at the strain distribution at a stress of 56 MPa on the right-hand side, it becomes apparent, that the nodal area again is a point showing a stronger material reaction, as the surface strain is the highest right below the node. The highest strain is occurring along a bamboo fiber that is deflected due to the node towards that it converges. Because the fibers are leaving their straight course in the nodal areas, these can often be considered as highly loaded areas, which are predetermined breaking points. Since the nodes are frequently present in the LBL, their effect on the mechanical properties of the material has to be investigated more closely in further investigations.

4.3 Shear Testing

The results of the shear testing series are compiled in Table 1. The two investigated directions show differences in the maximum force appearing during the tests. The L-dimension reached an average maximum force of 11.52 kN with a standard deviation of 2.22 kN, and the C-specimens reached 37.06 kN with a standard deviation of 2.62 kN.

Due to the significant difference in the cross-section of the two types of specimens, the shear strength fV was calculated according to DIN EN 14080. It becomes obvious, that the directions only differ slightly when compared geometry- independent, with an average shear strength of 16.24 MPa for the L-specimens and 17.91 MPa for the C-specimens, respectively. The shear specimens possessed an average moisture content of 7.4%, that has also been determined using the oven-dry method.

Tab 1. Results of shear tests along the two mentioned directions.

Shear zone dimensions	Max. force Fshear (kN)		Shear strength fv (MPa)	Fiber content (%)
Length (L) 1)	15×45 mm	11.52	16.24	97
Cross (C) 2)	45×45 mm	37.06	17.91	98

1) Average values of 8 shear tests along the long side of the lamella
2) Average values of 6 shear tests along the short side of multiple lamellas together

(a) (b)

Fig. 10. Representation of the shear zone of the “Length”-specimens, (a) bamboo failure, and (b) bamboo and glue line failure.

The examination of the shear surfaces was conducted to determine the fiber content contained in the shear zone, which can be directly linked to the quality of the adhesive bonding. Figure 10 shows representations of two shear surfaces of the L-specimen. Figure 10 (a) shows bamboo failure as a consequence of the applied shear load, which occurred in about 90% of the shear tests conducted. In the fracture zone, the bamboo fibers are still clearly recognizable. As mentioned earlier, the fibers are decisive for the strength of the material and can be considered the strongest component of bamboo. Between the fibers, the parenchyma of the culm is located. It is responsible for the storage of nutrients and has a sponge-like property. The parenchyma can be seen in the shear zone as well. Since it is a weaker material than the fibers, it reacts stronger to the shear load, and the parenchyma material is compressed due to the applied load. At a certain point, it breaks as a result of overloading and leaves the wave-like eruptions that can be seen in the upper part of the shear zone. The lower shear zone in Figure 10 (a) shows a material breakout of the bamboo, that results from a naturally grown node, still included in the LBL material. In the nodal area, the bamboo fibers are deflected from their strictly straight course, which can be observed in the internodal area. As a consequence the fibers tend to possibly buckle out due to the shear loading and the material breaks out more strongly.

In Figure 10 (b) a different failure mode occurring during the testing of the L-specimen is shown. In the represented shear zone, the adhesive was causative for the failure. It can be seen, that there are adhesive residues on about 50% of the shear surface, recognizable as the dark areas. Nevertheless, there are still some bamboo fiber and parenchyma attachments that can be seen on the surface, meaning that the failure can be considered a bamboo- adhesive-failure. The described adhesive-bamboo-failure only occurred in a small number of experiments.

Figure 11 (a) shows the failure modes for the C-specimen with a larger 45×45 mm cross-section. The failure occurred in the bamboo material and the glue line between the lamellas as well. The majority of the shear area exhibits material failure with the characteristic failure pattern of the parenchyma described above. In addition, about 5-10% of the area shows a glue line failure recognizable by the darker coloration. The proportion of the glue line failure compared to the bamboo failure is so small, that the latter can be described as the main failure mechanism.

(a) (b)

Fig. 11. Representation of the shear zone of the “Cross”-specimens, (a) bamboo and glue line failure, and (b) bamboo failure in the nodal area.

A different type of shear zone is shown in Figure 11 (b), meaning the failure runs exclusively through the bamboo material. As described earlier the bamboo fibers as well as the parenchyma material, which was compressed due to the shear loading, can be observed on the whole surface shown. It once more becomes obvious, that the breaking out is more pronounced in the nodal areas, as can be seen in the top right area of the shear zone presented.

The shear tests showed a capable bonding of the bamboo lamellas, since in the majority of the tests the glue line was not responsible for the failure of the LBL. The bamboo material, particularly the parenchyma, failed due to the applied loads.

5. Conclusions

The material tests conducted have shown, that LBL made from Moso bamboo possesses good material properties when exposed to compression and shear loading. Additionally, the radiation of the LBL showed first promising results. It was possible to visualize defects contained in the glue line between the lamellas. Despite this, the calculation and description using the program-based defect detection should be specified to define the exact shape and size of the defects. Furthermore, the impact of the pores detected has to be studied in further investigations.

The compressive results showed a certain reproducibility and the influence of the two different heights examined was not extensive, as all specimens have failed at a comparable load. The nodal areas still contained in the LBL tend to have a major influence on the mechanical properties of the engineered bamboo. The results have shown that the nodal areas have a larger deformation and often serve as an initiating point of failure.

Moreover, the shear results of the glue line were promising, since the majority of the specimens failed in the bamboo material and not the glue line. It became apparent, that mostly the parenchyma surrounding the bamboo fibers failed and that the nodal areas once more appeared to play a failure-supporting role.

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