

Beading as a Stabilising Element for Thin Wooden Panels

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Keywords: wood, beading, thin wooden panels, forming, prototyping.

Abstract. Beading has been used in metal construction for decades to reinforce and stabilize thin sheets of metal. In aircraft, washing machine and car manufacturing, this allows for cost-effective, lightweight and material-saving designs to be realized. These indentations are embossed into thin metal sheets to increase their rigidity and stability, thereby preventing fluttering or deformation. The bending stiffness is significantly increased by reshaping the material. The increased stability allows thinner sheets to be used, which reduces the overall weight of the structures and components. Beading is often used on larger surfaces to prevent fluttering or vibrations and to ensure greater dimensional stability. The combination of two old production processes, beading and steam bending for wood is examined in this paper. The use of beads to reinforce thin wooden panels saves material, resources and weight, thereby making production more sustainable. The investigations carried out examined the possibilities of introducing beads into thin panels made from different types of wood. The temperature, water content, water vapour content, soaking time and pressing pressure were varied. In a first step, a test specimen was produced that serves as a mould for the surround. This shape was pressed into the thin wooden panels when varying the processing parameters shown above. In a next step, the indentation depths achieved were measured. The deflection of the thin wooden panels was then measured under different loads and compared with the calculated results.

Introduction

Wood is one of the most important renewable raw materials and has been used in Europe for thousands of years. Wood is a renewable raw material that almost always comes from sustainably managed forests. Wood stores CO₂, which is removed from the atmosphere during tree growth. This remains bound in the wood as long as it is used as a building material, which contributes to reducing the carbon footprint. The importance of using wood as a construction material is steadily increasing in many areas of industry, not least in residential and modular construction. In order to expand the possible applications of wood-based materials and to continue to save materials in order to use natural resources responsibly, the corrugation of thin wood panels was investigated.

Beading is a channel-shaped indentation that is often used to reinforce thin-walled components, usually made of metal, against deformation or vibration. It is used in numerous areas such as mechanical engineering, aircraft construction and the automotive industry. Beading is also used to reinforce the outer walls of household appliances such as washing machines and dishwashers. One historically significant application of beads is in aircraft construction. All-metal aircraft such as the JU-52 were clad with beaded aluminium sheets to increase stability and reduce weight.

Beading improves the rigidity and strength of materials without the need for additional material. A well-known example of the use of beads in automotive engineering is the Citroën Transporter HY. Even today, beads are used in automotive engineering both as a design element and as a functional stiffening element. Beads can be used to create new design features while also providing stabilizing or functional advantages.

In order to be able to use these advantages for renewable raw materials such as wood, initial experiments were carried out on steam bending beads in wood.

2. Background and Related Work

Bending of wood.

Bending wood is one of the oldest woodworking techniques and has developed over thousands of years into a commonly used method for shaping solid wood. Two basic principles are used in this process: heat and water/water vapour. Either steam or direct heating of the wood over an open fire is used. Both methods are based on the same physical principles: heat makes the lignin and hemicellulose in the wood malleable, while moisture increases the elasticity of the fibres so that the wood can be permanently reshaped [8, 9].

Even in prehistoric cultures, wood was bent for use in tools, weapons and simple containers. Archaeological finds from this period indicate that steam was used to make wood more pliable so that it could be shaped [8, 9]. In Egypt and Greece, heated and watered wood was bent to form ship planks and furniture parts. In historical Greek shipbuilding, bent frames – probably bent over a fire – were used to make lighter and more robust hulls. Between the 10th and 17th centuries, wood bending over a fire reached its peak in European shipbuilding [8, 9]. Very old Viking ships with bent wooden planks have been found in Denmark. The age of these Viking ships has been estimated at 1000 years [1]. These early applications already demonstrate a basic understanding that wood becomes more malleable under heat and moisture. In the construction of cogs, galleons and later frigates, solid oak beams were heated over open fires until they could be bent under pressure. Fire was readily available and allowed for rapid heating, but the method required a great deal of experience to avoid charring or weakening the wood. In some regions, particularly Scandinavia, wood was prepared for bending by boiling it in water from an early stage. This results in better material quality and less tension in the wood [8].

In the course of industrialisation around 1800, steam bending became more precise and predictable thanks to the development and application of steam pipes and steam boxes. They enabled wood to be bent at constant temperatures and controlled humidity. This made it possible to plan bending times better and ensure consistent quality. This revolutionised many areas of industry – especially carriage and boat building [10, 11].

Furniture has been made from bent wooden parts for more than 200 years. The most famous piece of work in wood bending technology was developed by MICHAEL THONET. The bentwood chairs by MICHAEL THONET, also known as Viennese bentwood chairs or Viennese café chairs, which were made from bent beech wood, have become particularly well known. In the 1850s, he developed a bending process in which beech wood was plasticized with hot steam and then clamped into closed metal molds. Chair No. 14, designed in 1859, became a classic that was inexpensive to produce, extremely stable, and known worldwide. THONET's innovation made bent wood an element of modern design and later became the basis of modern series furniture production [10, 11, 12, 13, 14]. Figure 4 shows the THONET's chair number 14. However, THONET was not only involved in the manufacture of furniture, but also in the manufacture of wheels in his early days. He later combined his two developments and created the wheel shown in Figure 1.



Fig. 1. Thonet wheel with curved spokes from the estate of Viktor Thonet [2].



Fig. 2. Bending tool for yoke bows.

Wood steam bending was used in Southern Europe by many non-specialized craftsmen and even farmers to produce complex components quickly and cost-effectively. Figure 2 shows a simple wooden form for bending yoke bows for cattle. This form is approximately 120 years old.



Fig. 3. Single yoke bow with steamed bent yoke.



Fig. 4. Thonet Chair Nr 14 [25].

Steam bending of solid wooden parts is a well-established process in a wide variety of applications. Fig.3 shows a single yoke for draft cattle with U-shaped steam bent wooden yoke bows that were produced in Slovenia approx. 120 years ago.

In addition to the traditional methods of wood bending described above, new technologies were developed and used in the 20th century. These include laminated bending, in which layers of thin wood veneers are glued together and bent under pressure. Another method is form gluing, in which thin wood veneers are also placed in a mold and glued. This further development allows very stable curved wood components to be produced. Controlled steam boxes are also used, which enable precise temperature and humidity regulation [8, 15]. In addition to the possibility of using high-frequency fields to heat the wood, the possibility of using microwaves is also being discussed [11]. Despite numerous alternatives, steam bending still has a significant range of applications in boat building, instrument making, and the manufacture of high-quality furniture.

Beading.

Beading refers to elongated, channel- or ridge-like indentations or elevations in thin-walled components made of metal or plastic. They serve to increase local rigidity, reduce vibration, optimize material flow, and enhance the visual design of components. They are mainly used in car body construction, aviation, container construction, ventilation technology, and the food industry (cans). They are shaped using manual tools, beading hammers, beading sticks, beading machines, presses, or even during the injection molding of plastics. Beading was initially a purely manual technique. Before industrialization, reinforcements were hammered into sheet metal using a beading stick – a time-consuming, imprecise process that depended on the skill of the craftsman. The first applications were in sheet metal working, as sheet metal roofs, gutters, and containers required structural reinforcement at an early stage.

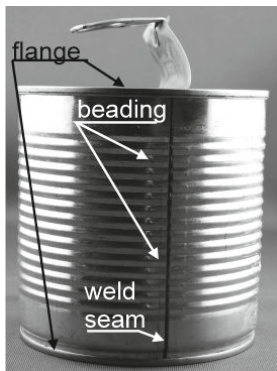


Fig. 5. Can with beads [20].

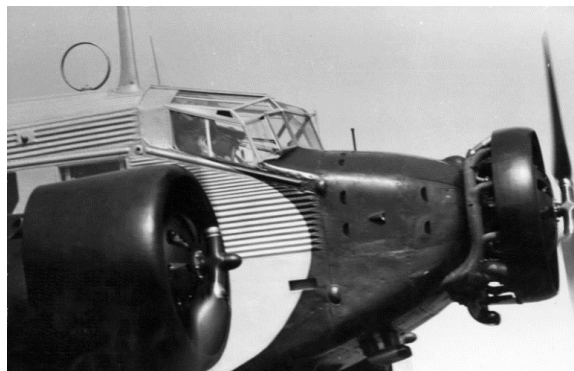


Fig. 6. Airplane Ju 52 with beads [23].



Fig. 7. Washing machine with beads.

The beads produced in this way were created by hand, which often allowed for only a low degree of uniformity. The use of beads was therefore functional, but not standardized. A key innovation in metal forming technology was the development of mechanical beading machines between 1861 and 1873 by the mechanical engineer CARL ERDMANN KIRCHEIS (1830–1894). His designs replaced the previously extremely laborious manual hammering technique with a roller system that produced uniform beads with significantly higher precision [17]. The early beading machines consisted of two rollers – a positive and a negative mold. The sheet metal was pulled through the rollers, which were gradually adjusted to increase the bead depth. This made beads a standardized, repeatable, and industrially usable structural form. With the growing importance of thin-walled sheet metal in mechanical engineering and vehicle construction, the function of the bead also evolved. Beads increase local bending stiffness, reduce shear sensitivity, and decrease the susceptibility of components to resonance and booming. Mainly in the automotive industry, equipment manufacturing, and the household goods industry, beads were also used for aesthetic reasons. A typical sample for beads on household goods shows Fig. 7, a washing machine with beads on the Side panel. These beads serve exclusively to stabilise the side panels of the washing machine. Fig. 5 shows a can with some beads for stabilising the thin edges around the tin can. The Fig. 6 shows a typical example of the use of beads in aircraft construction. This figure shows an aircraft, the Ju52, manufactured by JUNKERS FLUGZEUGWERK AG, Dessau. Beads were used very early on in this aluminum aircraft, which was developed in 1932, in order to save weight. Due to current requirements in lightweight construction (e.g., automotive engineering, mechanical engineering, aerospace), beads are also being used and investigated as an element for saving resources in the field of metal and plastic forming. Dissertations and research papers examine influencing factors such as shape, position, radii, material anisotropy, and component curvature in order to use beads specifically for component reinforcement [17]. Recent research approaches use topography optimization, AI-based bead patterns, and finite element analysis to automatically generate optimal bead layouts [21]. Such investigations enable predictable bead patterns that optimize mechanical performance, manufacturability, and material efficiency. Beads are used in many industries. In automotive engineering for body stiffening, crash performance, and drone reduction. In the aerospace industry for weight-efficient thin-walled constructions. In the construction industry, they are used to stiffen facade and roof panels. In the field of heating, air conditioning, and ventilation technology, they are used to reinforce and seal air ducts [19].

In the field of can manufacturing and container construction, beads increase the pressure stability of cylindrical cans and enable a significant increase in stability. The use of beads is a central component of lightweight construction. Today, beading is a highly optimized manufacturing process whose application goes beyond empirical rules and is determined by numerical simulation, algorithmic optimization, and digital manufacturing methods.

Principles of the thermoforming process of wood.

Wood is a natural composite material composed mainly of cellulose, hemicellulose, and lignin. The composition of different kinds of wood and bamboo is shown in table 1. The most significant component in wood is cellulose. The bending process of wood is usually divided into three steps: plasticizing (softening) - bending - stabilizing (drying) [11].

Table 1. Composition of wood [4,5,6].

Component [%]		Oak	Beech	Pine	Mahogany
Cellulose		47	41	41	45
Lignin		29	27	29	24
Hemicellulose	Xylan	22	13	9	28
	Mannan		18	18	
Pectin			1	3	

The glass transition temperature determines the softening temperature of the wood components lignin and hemicellulose. In the dry state, the softening temperatures of hemicellulose and lignin are 167–217 °C and 134–235 °C, respectively, while in the moist state they decrease to approximately 54–142 °C and 77–128 °C, respectively. This transition to the highly elastic state promotes the plasticity of the wood [7, 8]. Processes such as boiling, steaming, and electromagnetic waves are used to soften wood materials. While the mechanism of action is the same in these processes, the method of heat transfer is different. During boiling and steaming, the wood surface is gradually heated, softening the wood core and then bending it into the desired shape. Electromagnetic waves simultaneously heat the core and the outer surface of the wood, ensuring rapid and even heating [7].

Production of beading in thin wooden panels.

As described in the above sections, both wood bending and the beading of sheet metal, metals and plastics are manufacturing processes that have been known and established for a very long time. Thin wood-based materials, e.g. laminated veneer lumber, plywood or thin solid wood panels, have a favourable weight-to-load-bearing capacity ratio, but exhibit limited bending and torsional stiffness in flat areas. This leads to increased susceptibility to deformation, vibration and local instability, especially in large-area applications (interior design, furniture construction, acoustic panels, lightweight timber construction). The addition of corrugations offers a structural advantage here. As described above, this method is well established in metalworking, but has not yet been applied to thin wooden panels. The physical principles of form stiffening through the addition of corrugations can also be applied to wood-based materials. The mechanical advantages of this approach for thin wood panels are as follows: Stiffening of thin-walled structures, which have high potential for lightweight construction applications but exhibit low bending stiffness when the panel surfaces are slightly curved or completely flat. Beading improves stiffness through targeted geometric anisotropies. This principle is state of the art in sheet metal processing, but can easily be transferred to other materials as it is material-independent. Beading reduces free buckling lengths, increases buckling resistance and locally increases torsional and bending stiffness without the use of additional material [21]. The channel- or bead-like shape increases the cross-section of the wood panel. This results in significantly higher bending strength because the material is further away from the neutral fibre. Research into lightweight metal construction has shown that beads can significantly increase rigidity without adding weight. This principle can be applied 1:1 to thin wood-based materials. This paper examines the differences and challenges that can be expected when applying these principles to wood-based materials. Since beads increase the rigidity of a component without adding extra material, wooden panels can be made thinner. This principle is considered an essential design feature in lightweight construction. It enables increased load-bearing capacity with constant or lower weight. This behavior is used, among other things, in caravan/tiny house conversions, in the furniture industry, and in interior design with acoustic panels and ceiling coverings. Wooden panels with corrugations exhibit higher damping of structural vibrations, which is particularly relevant in acoustics, interior design or furniture back panels. Corrugations serve as structural dampers that reduce unwanted resonances.

3. Experimental Setup

Four different wood materials were used for the tests: oak, beech, mahogany and spruce. The materials were 150 mm long and 44 mm wide. The thickness of the individual materials is shown in Table 2.

Table 2. Thickness of tested materials.

	Oak	Beech	Pine	Mahogany
Thickness [mm]	1.4	1.3	1.5	1.45

Numerous preliminary test series were carried out in which the four different types of wood were softened at different water temperatures and for different lengths of time. The following were found to be suitable for initial tests for all types of wood. All materials were heated in a water-water vapor

mixture at a set temperature of 160 °C for one hour. The maximum pressure in the pressure vessel is approximately 1.8 bar. At this temperature, water has a boiling point of approximately 117 °C. The test components were then placed in various wire-eroded moulds and compressed to such an extent that the moulds were completely filled.

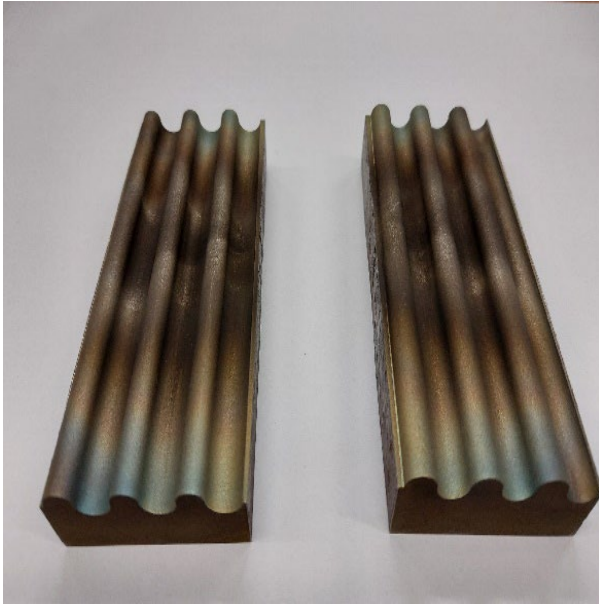


Fig. 8. Wire-eroded bending mould.



Fig. 9. Used bending mould (WEDM).

In order to determine the minimum possible bending radii, four different bending moulds were designed and manufactured using Wire Electro Discharge Machining (WEDM). A CUT P 350 Pro wire EDM machine from GF MACHINING SOLUTIONS GMBH, Schorndorf, was used to produce the various bending shapes. Two of different types of bending moulds are shown in the pictures 8 and 9. The bending mould shown in the figure 9 was used for the investigations presented in this article. The geometry of this bending mould shown in Figures 10 and 11. Small bending radii of less than 5 mm cannot be produced with the technologies currently under investigation.

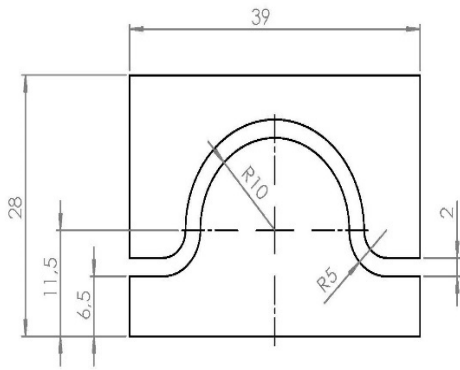


Fig. 10. Minimum bending radii used and shape for all wooden test pieces.

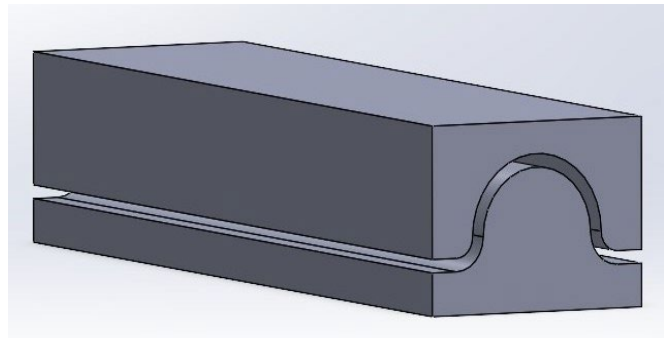


Fig. 11. Sketch of used bending mould.

The test components were then pressed and dried in the bending mould. Fig. 12 and 13 show the device for pressing and drying the thin wooden panels. As the steel mould used made it very difficult for the wooden test components to dry, they had to dry in the mould for at least 12 hours before the mould could be opened again. If the mould is opened too early, the components bent back very quickly. Fig. 20 shows the bending back of the test pieces after premature opening of the bending mold.



Fig. 12. Pressing of test Pieces.

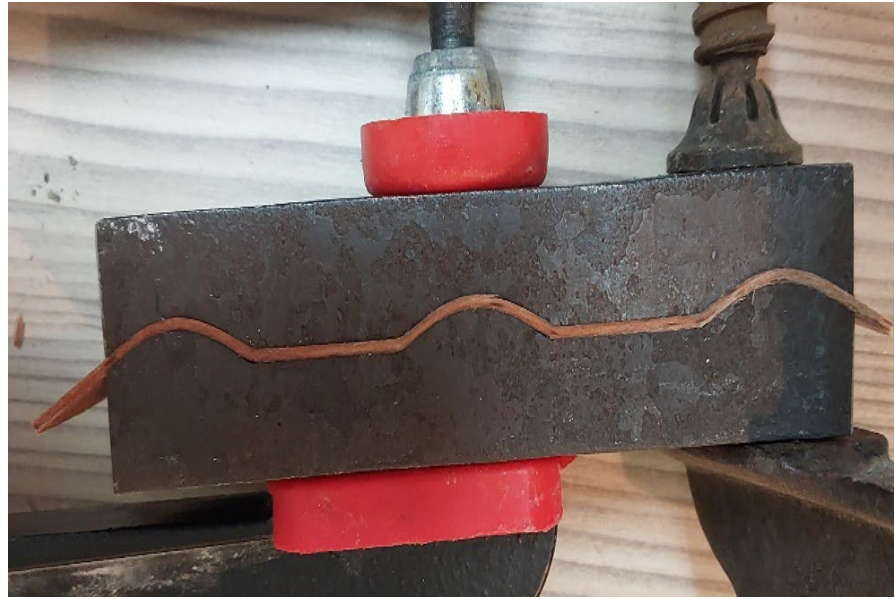


Fig. 13. Pressing and drying of multi-beads in bending moulds.

4. Measuring of Deflection

After the components had dried, the deflection was determined under various loads. For comparison purposes, the deflection of the thin, non-deformed wooden panels was also determined. The illustration shows the test setup for measuring deformation. The samples were tested in a three-point bending test. The samples were placed freely on the supports and loaded in the middle with a line-shaped force. The support spacing was 135 mm (Fig. 14, right). All samples were loaded with three different forces of 3.27 N, 5.45 N and 10.75 N and the deformation was measured. Subsequently, a simulation was performed in SolidWorks using these values.

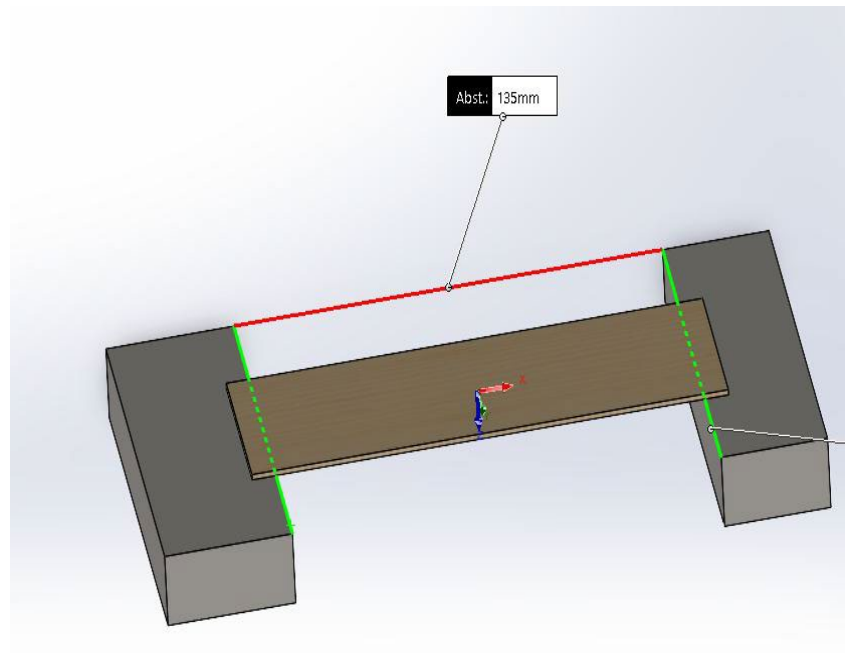


Fig. 14. Test setup for measuring deformation and distance between support, (distance 135 mm).

The results of the bending tests for the bevelled and non-bevelled wood samples are shown in Fig. 15. It is clear to see that the bevelled samples are stiffer.

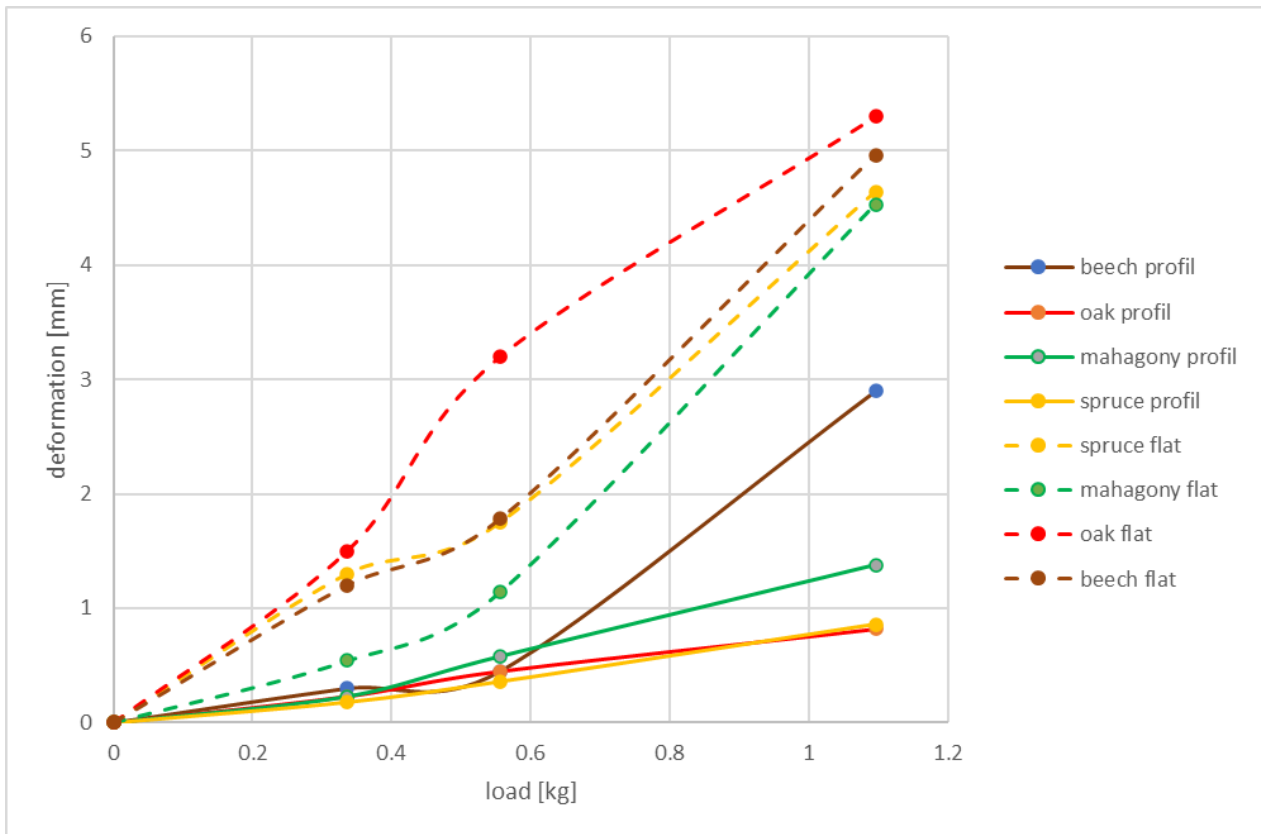


Fig. 15. Results of the bending tests.

5. Simulation of Deflection

An initial FEM simulation was performed using SolidWorks simulation tools. A linear elastic model with the smallest possible mesh was used. Type of networking used was a mixed curve-based network. Network quality was high with. The percentage of elements with an aspect ratio < 3 was 99.7 %. Figure 16 shows the used mesh for simulation of deflection tests. Since wood is a natural material with a very wide range of material properties, average material properties were always used. The supports are made of steel and are fixed in the simulation. The wood samples are in contact with the support, one side of the wood sample can slide, the force is applied centrally and the center of the sample can slide vertically. Figure 17 shows the results of simulation of flat pine sample.

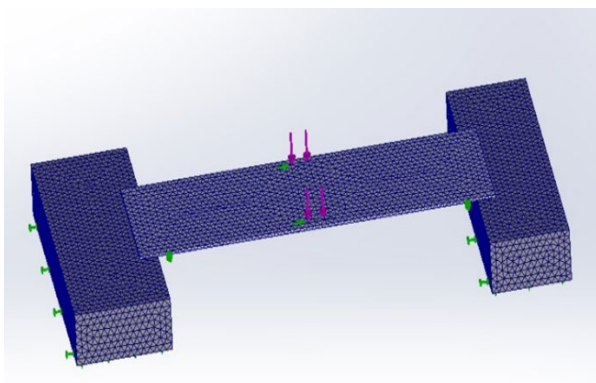


Fig. 16. Used mesh for simulation of deflection tests.

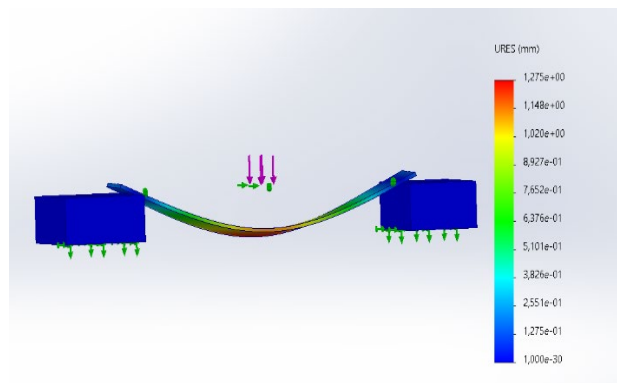


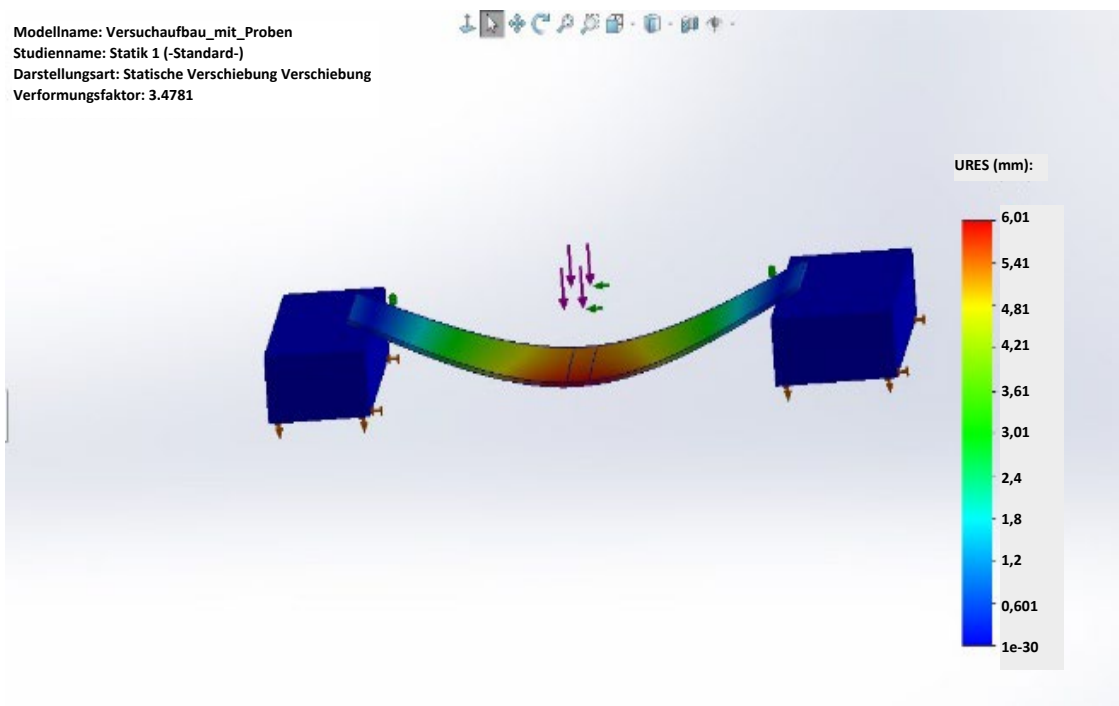
Fig. 17. Results of simulation of flat pine sample.

Table 3 compares the simulation results of flat pine with the test results of the same material. There is relatively good comparability between the two values. The error increases with increasing load, which can be explained by the errors in the natural material wood. Further investigations on this topic are still necessary.

Table 3. Comparison of simulation results with the test results of flat pine.

Test number	Material	Used E-Modulus [N/mm ²]	Deflection measured [mm]	Deflection simulated [mm]	Weight [g]	Force [N]
1	Pine flat	11000	1.3	1.27	333.6	3.27
2	Pine flat	11000	1.75	2.12	556	5.45
2	Pine flat	11000	4.64	4.19	1096	10.75

Fig. 18 shows the results of simulation of deflection of a flat oak sample with a load of 10.75 N.

**Fig. 18.** Results of simulation of flat oak sample.

The comparison of the simulation results for flat oak wood with the test results, also for oak wood. Unfortunately, the values from the simulation and the tests are not comparable. On the one hand, wood is a natural material with considerable variations in its material properties; on the other hand, wood is not an isotropic material, i.e. its properties, in particular its modulus of elasticity, are highly directional. It is easy to understand that the anisotropic properties of wood have a strong influence on the test results, especially in the case of curved components. In subsequent investigations and simulations, the simulation conditions must be further adapted to the anisotropic properties of the various types of wood and the wide range of properties of wood as a natural product. Figure 19 shows a result of simulation of deflection of beaded oak test sample with a load of 10.75 N.

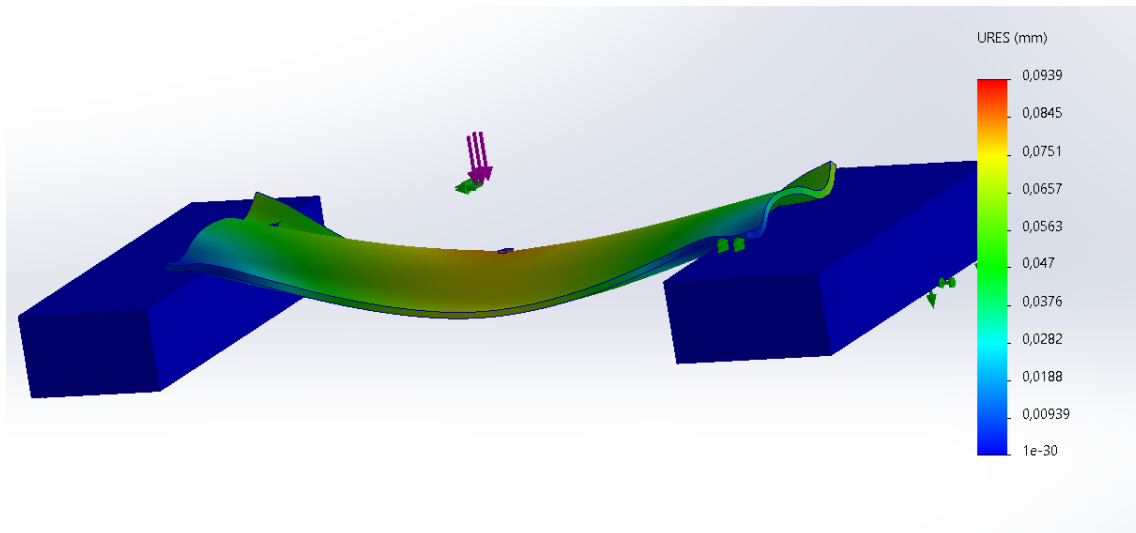


Fig. 19. Results of simulation of beaded pine sample.

The results of the simulation and the measurement of beaded pine test parts are not identical. Wood is a natural material whose material properties vary greatly. Furthermore, wood is not an isotropic material, which means that its properties are highly directional. This property has a strong influence on the simulation results. This plays a particularly important role in the corrugated or curved components examined here. The anisotropic properties of wood-based materials were evidently not sufficiently taken into account during the simulations carried out here.

6. Summary and Outlook

In the initial studies presented here, the two long established manufacturing processes of wood bending using steam and heat and corrugating materials to increase stability were combined to stabilise thin wooden panels. The studies show the great potential of beading thin wood panels to increase their stability. Experiments with different types of wood have shown that thin wood panels can be stabilised by beading with steam. However, the investigations also make it clear that there is still a considerable need for research in this area of production technology. On the one hand, the process parameters (e.g. pressure, temperature, time) for beading the different types of wood need to be determined more precisely, and on the other hand, further materials for the bending moulds need to be investigated. These must be pressure-resistant and breathable materials in order to significantly reduce the drying time. If the components are removed from the mould too early, they spring back. This process is shown in Fig. 20.



Fig. 20. Spring-loaded component after premature removal from the mould.

In addition, other, larger pressure vessels must be developed and used in order to soften the wood-based materials with different parameters and heat larger panel sizes so that they can be measured with standard measuring devices. Furthermore, the anisotropic material properties of the woods must be investigated more thoroughly. In further investigations and simulations, the simulation conditions must be further adapted to the anisotropic properties of the different types of wood and the highly variable properties of wood as a natural product. The behavior of the different types of wood must also be investigated and the transverse and longitudinal alignment of the wood fibres simulated. Furthermore, models must be found that describe the springback process of the various types of wood and enable the corrugation shapes to be designed accordingly. Other types of wood, wood-based materials and, if necessary, sandwich materials made of wood are to be investigated.

Acknowledgement

The authors gratefully acknowledge the extensive experimental contributions of MICHAEL STEINBRÜCK at Berliner Hochschule für Technik and JAN KLAMET the highly talented carpenter from Berlin.

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