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# Wood As A Technical Material For Structural Vehicle Components

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**Abstract**

The application of molded wood parts as an alternative, innovative and sustainable multi-material system (MMS) for structural, resource-efficient and sustainable components within the body shell is a new approach in light-weight constructions. In many of the cases where a structural application of FRP is being considered, they can principally be substituted by wood-based MMS. Although there are great challenges; wood has the potential to fulfill the demands of the present technical appliances and social requirements. Actual results offers the first systematic approach to use wood in structural applications. The main properties and demands, which correspond with those of the specific original structural components, could be met. So, as regarding performance and reproducibility, it is possible to apply a wood-based material in technical appliances. Furthermore, material models have been designed and concepts for the repair and recycling of the wood-based MMS were developed.



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*Keywords:* wood; technical material; automotive; multi-material-systems, lightweight construction

## 1. Introduction

Lightweight constructions that aim to reduce weight and be ressource-efficient are and will be of great importance for traffic-related technology. In most cases, the mere substitution of materials is not the best economic and technical solution. Instead, a more holistic approach should be taken to meet the increased demands on driving comfort and security within a vehicle, but also to meet the targets for the reduction of $CO_2$ emissions [1]. Especially for traffic-related technology, multi-material-systems (MMS) have great potential for the application within light-weight constructions. However, these MMS demand an appropriate combination of materials that serve the specific application and, for this, the specific joining technologies need to be refined.

Here, the research project which is funded by the Federal Ministry of Education and Research 'Moulded Wood Parts as Multi-Materials Systems for the Applications in Car-Bodies' could help to face these challenges by defining the potential for wood as a material for car-bodies. The main goal is to develop a structural application of moulded wood parts as an alternative, innovative and ressource-efficient MMS for structural and sustainable light-weight components of car-bodies.

This design could be used for conventional but also for electric vehicles, giving this research project a long-term perspective and good economic implementation possibilities. [2] In the following, we would like to present the tests that have been performed within this project so far, and, subsequently, we would like to introduce their results.

## 2. Potential and Challenges for Wood in Car-Body

There is no doubt that the application of wood in car-bodies poses great challenges; apart from the purely mechanical compatibility, further characteristics such as reliability, process compatibility and reproducibility are highly relevant. Wood is, on the other hand, one of the oldest materials, a material with attractive potential and possibilities for today's technological appliances.

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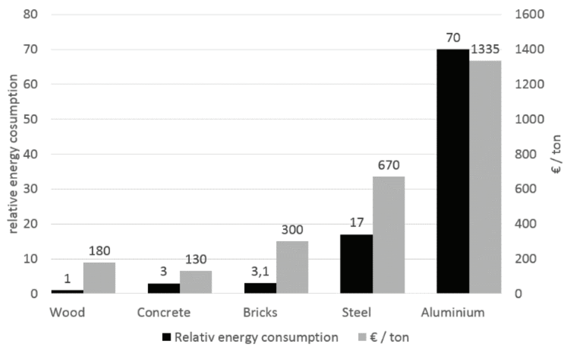


*Figure 1: Average relative energy consumption of the production of a tonne of selected raw materials, with wood as reference (=1) [modified from 6] and prices.*

### 2.1. Potential Weight, Emissions and Energy

Apart from the specific drive technology, the weight of a vehicle has a great influence on its $CO_2$ emissions [3]. The applied materials, the specific joining method and joining technology have a strong impact on this weight. As an example, a weight reduction of about 100 kg leads to a mean reduction of $CO_2$ emissions of about 13.9 % [4]. Current research shows that the substitution of steel with wood-based multi-material systems leads to a reduction of weight of about 15-20 % and still allows for the same performance. The comparision between usual materials and beech wood is shown in table 1.

Table 1: Comparision of relevant material properties with regard to the strength/density proportion. [3,13]

| **Material** | **Density [g/cm³]** | **Tensile Strength [N/mm²]** | **Tensile Strength/Density** | **Properties** |
|---|---|---|---|---|
| Beech | 0,54-0,91 | 135 (longitudial) | ~187 | anisotropic |
| Steel | 7,85-7,87 | 340-1,250 | ~44-160 | Isotropic |
| Aluminum | 2,3-2,8 | 45-500 | ~20-217 | isotropic |

As Germany has large woods of high-quality beech trees, short transportation routes improve the value chain right at the beginning. As wood is available nationally and regionally, this material offers a first ressource-efficient advantage in comparison to materials that need to be imported [5]. Furthermore, in comparison to materials such as steel or aluminium, the relative energy input for the production and provision is clearly lower, as shown in Figure 1.

This advantage would be even clearer, if the comparison had included high-strength and super high-strength steels as are currently used in the automotive industry as they can only be produced using highly energy consumpting forming processes [7].

In addition to the energy-related $CO_2$-emissions, table 2 compares the environmental impact of 1 kg of beech veneer plywood with urea-formaldehyde binder to aluminium.

Table 2: Impact on the environment when producing a kilogram of beech veneer-plywood with urea-formaldehyde adhesive and aluminium [8]

| Impact Categorie | Aluminium Mix | Veneer Plywood | Unit |
|---|---|---|---|
| Photochemical ozone creation potential (POCP) | 0,0069 | 0,0005 | kg Ethen-equiv. |
| eutrophication potential (EP) | 0,004 | 0,0006 | kg PO4-equiv. |
| Acidification Potential (AP) | 0,054 | 0,0025 | kg SO2-equiv. |
| Ozone-depleting potential (ODP) | 3,056E-06 | 9,4E-08 | kg R11 |
| Global warming potential (GWP) | 17,122 | -1,21 (-1,84) | kg CO2-equiv. |
| Excavation | 27,35 | | kg/kg |

### 2.2. Potential Price and Availability

Apart from the aforementioned potentials, wood is an attractive material as regard feasability in comparison to conventional materials. The price range of wood per tonne is listed in Figure 1. For metal, Germany is dependant on imports of the raw materials which makes it vulnerable to price fluctuations and supply shortages [9]. In Germany, woods cover an area of approx. 111 billion $m^2$, about 31 % of the entire country. Thus, with approx. 3.4 billion $m^3$, Germany has one of the biggest timber ressources in Europe. In addition, this amount increases by about 107 million $m^3$ every year whilst the total annual cut is about 56.8 million $m^3$ (mean value of the years 2003 to 2012) [10, 11]. Sustainability is embedded safely in the German forest management values, thus, the cultivation and cut cannot be increased to an endangering limit, even if the demand on wood should increase.

As the demand for finite ressources, especially in developing countries, will increase in future, this will inevitably lead to rising prices for these raw materials. Furthermore, the prices for raw fossile materials have always been liable to price fluctuations. Wood, however, is a renewable and quite often a regional raw material, therefore it offers a certain reliability and price stability [12]. And, as already mentioned, much of the transport costs can be saved due to the regional supply.

### 2.3. Challenge Process Chain

As the automotive industry has focused mainly on the processing of metal materials for the last decades, established and refined processes and methods that have grown through continuous optimisation dominate the field as they are highly efficient and economical. Thus, the process chain for car-bodies is adapted to the processing of steel-dominated structures. This becomes aparent when looking at the design of the car-body, where steel sheets in different strengths are applied in accordance to the specific demands on the constructional element.

Furthermore, the trend to design integral constructions leads to the production of few separate constructional elements that are highly complex; thin steel elements that have to withstand tensile strengths of up to 1500 MPa. These constructional elements are hot-worked and lead to a high reduction of weight and offer an optimal crash performance.

Apart from the challenges in the specific design of the car-bodies, there are further challenges for the application of wood in car-bodies and their processing; as an example, the individual metal sheets are joined by automatic welding robots that are an integral element of the existing process chains.

Furthermore, as a protection against corrosion, the car-bodies run through a cathodic dip painting. Here, the specific requirements such as media and temperature stability need to be taken into account when implementing wood structures into car-bodies.

### 2.4. Challenge Production and Design

As regards deep drawability, the possibilities to form wood are strongly limited, therefore complex geometries can only be achieved to a limited degree. As a consequence, steel cannot be substituted directly by wood. Priorily, the geometry has to be adapted to the limited forming possibilities of wood as regards the bending radius, handling properties or the susceptibility to skewing and springback. Thus, the design of the surrounding constructional elements must be adapted to these specific material and applicational demands. And, this should also take into account the interaction and reciprocal effects between these surrounding elements and the production environment.

### 2.5. Challenges Material Properties and Parameters

For the correct wood-adapted design of constructional elements, the material properties and parameters are fundamental. However, the parameters as mentioned in research so far differ very strongly in parts and are therefore only of very limited use. Furthermore, wood is a heterogeneous natural material, factors such as growth, location and time of harvest should be considered when establishing the parameters [13]. And, as regards a multi-material compound, there are many compound-related parameters such as the amount of layers, their orientation and strength and the choice of adhesive to be determined. This, in turn, necessitates an elaborate and extensive investigation of the tensile, bending and shear strength as well as modulus.

Taking this into account, it is clear that a mere substitution of 'steel with wood' would be misleading. The approach should be to closely examine the compound and define at which place wood can be intregrated with regards to its specific material requirements. Once these challenges have been met by adapting the process chain, the potentials of wood; low energy consumption, $CO_2$ emissions, general impact on the environment and sustainability can play an important role in the automotive industry.

## 3. Reinforced Wood for the Use in Technical Appliances

### 3.1. Wood-Based Multi-Material Systems

Wood is already applied in vehicles today, however, mainly as non-structural fibre mouldings or decorative elements. In the serial production of cars, wood is rarely used in structural, crash-relevant components due to its anisotropy, inhomogeneity and strength. To promote the integration of the natural material wood, wood-based multi-material systems need to be investigated.

By combining wood with other materials, the potential of these synergies can be taken advantage of and the deficiencies are balanced [14]. A possible combination is the adhesively joined compound of beech wood veneers with technical textiles or metal foils. Earlier research of the authors has shown that such a multi-material system can balance the wood-specific deficiencies and that these reinforced multi-material systems can be used in technical appliances. The test samples for this research project were compounds comprised of three layers of plywood and two reinforcement layers (Figure 2).

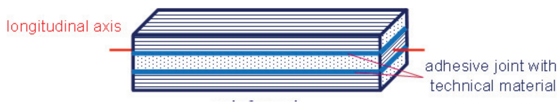


*Figure 2: Schematical specimen design of reinforced plywood layers.*

The overall amount of reinforcement in the samples that were reinforced with aramid was 16 wt% and for those that were reinforced with stainless steel, the amount was 37 wt%. With this compound design and an insert of stainless steel, a bending strength of up to 180 $N/mm^2$ (aramid up to 130 $N/mm^2$) could be achieved, this is an increase by up to 395 % in comparison to non-reinforced moulded wood. The bending modulus of elasticity of the test samples was up to 15.5 GPa (aramid 14 GPa). Furthermore, the tensile strength of the samples was up 160 $N/mm^2$ (aramid 100 $N/mm^2$) which is an increase of about 191 % in comparison to non-reinforced moulded wood. The tensile modulus of elasticity was up to 20 GPa (aramid 11 GPa) [15].

In addition, the fracture behaviour can be modified by the various material combinations so that specific requirements - such as a high force absorption together with a high containment performance for the absorption and the redirection of crash energy - can be met. Another advantage is that the reinforcement layers help to compensate the anisotropic behaviour of individual veneer layers so that the orientation of these layers does not need to be reciprocal, nearly allowing for a unidirectional structure of the various veneer layers [16].

### 3.2. Analysis of the Process Parameters

In technical appliances, one of the greatest challenges for the integration of new products is the reproducibility of specific characteristics as these are influenced by the kind and sensitivity of the influencing variables. For this reason, the influence of specific process parameters on wood-based multi-material systems - setting variables (direct, adjustable parameters) as well as disturbance variables (random, not directly influenceable parameters) - on the production process was investigated.

These parameters are listed within the investigated range of values in Table 3. Veneer waviness was kept at the lowest possible rate, thus, there can be no further reduction. The moisture content in wood was also only investigated for higher amounts as we assumed that a lower moisture content was unlikely.

The data was evaluated relatively to the strength values that were gained with the help of the average values.

All test samples had two parallel layers and one layer that was transversal to the tensile direction (Figure 4). The specimen geometries are shown in Figure 5.

Table 3: Overview of the Process Parameters.

| Process Parameters | Range of Values I | Average Range of Values (ACTUAL-Value) | Range of Values II |
|---|---|---|---|
| Moisture Content [%] | 16 ± 1 | 8 ± 1 | 8± 1 |
| Veneer Waviness | strong | minimal | minimal |
| Pressing Force [N/cm² ] | 120 | 200 | 360 |
| Pressing Temperature [°C] | 80 | 100 | 150 |
| Pressing Period [min] | 7 | 10 | 10 |
| Time before Grouting [min] | 3 ± 1 | 5 ± 2 | 15 ± 2 |

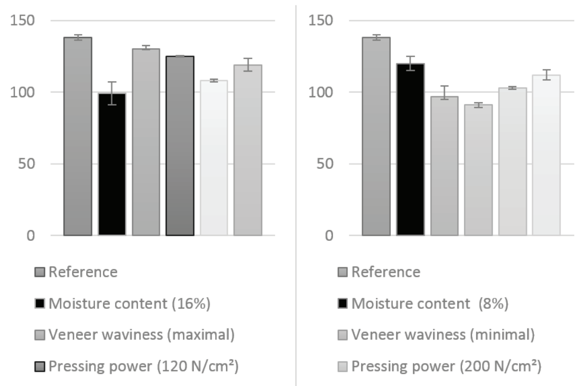


Figure 3: Tensile Strength [N/mm²], (left) when varying one parameter on the value of Range I, (right) when varying one parameter on the value of Range II, Reference = medium value (see Table 3).

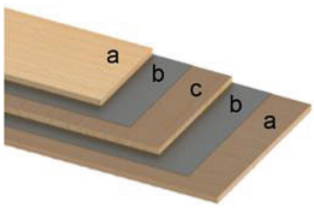


*Figure 4: Structure: Wood-Parallel-Layers a, Steel-Layers b, Wood-Transversal-Layer c.*

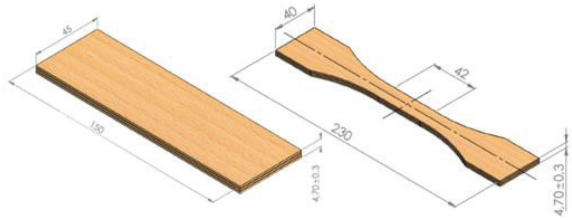


Figure 5: Specimen geometry: (left) bend specimen; (right) tensile specimen.

First, the major influences of the setting and disturbance values were determined, allowing us to establish which specific parameters crucially influence the production process. Then, the setting values were varied, especially in ranges that had not been investigated before. In a second phase, the process optimum was determined, here the leading question was whether the setting values could be varied so that the process results could be improved or whether the process was already in an optimal range.
The tests showed that only the moisture content had a significant impact on the achievable strength values. Figure 3 exemplarily show the influence on the tensile strength. Furthermore, these results show the substantial dependence between the moisture content in the wood and the resulting strength values. Thus, a high moisture content in the wood leads to significantly lower strength values than a low moisture content.

The analysis of the test results on the parameters waviness, pressing force, pressing temperature, pressing period and time between the application of the adhesive and grouting allowed for no clear estimation of the extent and kind of impact on the process results. Additionally, all parameters apart from veneer waviness can be influenced directly.

In a second phase, the setting values were analyzed as regards possible process optimizations. Here, the parameters pressing temperature, pressing period and pressing force were examined on two factor levels. The leading question was whether there was a general potential for optimization. This could be answered.

Under the condition that the moisture content is taken into account, the best results were achieved by applying the average values, changes of these values lead to a decrease of strength rather than to an improvement.

In addition, it is an important prerequisite that impurities or faults that occurred within the wood during growth need to e sorted out in order to facilitate the production of wood-based MMS.

### 3.3. Repair

In order to develop a holistic approach for the application of wood-based constructional elements in car-bodies, we would also like to present first concepts for repair. Following "best practice" methods from the field of FRP, first concepts of repair were developed for typical damages. For this, MMS-test samples were damaged by punctuation [Figure 6 (a)], by notching [Figure 6 (b)] and by a defined break [Figure 6 (c)].

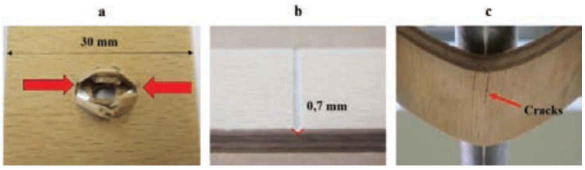


*Figure 6: Defects: (a) punctuation, (b) notch, (c) defined break.*

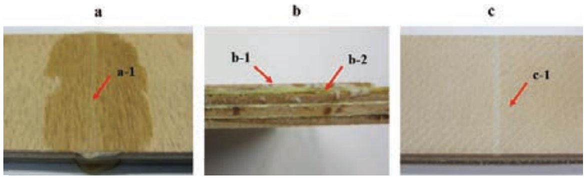


*Figure 7: (a) adhesive filled defect (a-1 notch), (b) double layer patch (b-1 wood layer, b-2 aramid layer), (c) single layer patch (c-1 layer).*

Then, they were repaired using different approaches and tested together with reference samples.

The basic test samples were composed of three veneer layers and two reinforcements inserts. The different orientations were also taken into account.

The created cracks and faults were repaired using adhesive fillers, a double-layered patch and a one-layered patch.

The adhesive filler was a 2c-epoxy resin which was grouted to the specific spot of the test sample at a temperature of 100 °C and a pressure of 200 N/cm² for ten minutes. However, this method of repair can only be applied to certain, fillable damages such as a punctuation or a notch.

Applying layers for repair can be used for all sorts of damages. The double-layered patch is created by combining a layer of the specific reinforcement material with a layer of wood [Figure 7 (b)]. Here, the adhesive is also cured for ten minutes at a temperature of 100 °C and a pressure of 200 N/cm². The one-layered patch only consists of the reinforcement layer.

Table 4 shows the results for an aramid-reinforced compound.

Table 4: Bending strength after overhauling.

| Defect | Single-Layer Patch | Double-Layer Patch | Adhesive Filling |
|---|---|---|---|
| Notch | 178 N/mm² | 157 N/mm² | 114 N/mm² |
| Puncture | 181 N/mm² | 137 N/mm² | 153 N/mm² |
| Defined Break | 209 N/mm² | 118 N/mm² | ----- |
| Reference Value | 108 N/mm² | 108 N/mm² | 108 N/mm² |

## 4. Conclusion and outlook

As one of the oldest building materials, wood offers many attractive possibilities for today's technical appliances. These appliances also need a high degree of reliability, process compatibility and reproducibility, especially in the automotive industry.

Our results are part of a first systematic approach to apply wood as a structural element in future car-body designs. Going beyond the development of design studies and concept-cars, the holistic implementation of wood with regards to the industrial process chain is the aim of this project. Therefore, this study wants to open up a comprehensive starting point from which the environmentally important substitution of steel with wood can be promoted rather than giving a fully developed concept for serial production.

Thus, the foremost aim must be to establish wood as an equal, if not superior, material and not just as a "measure to gain prestige". However, this can only be achieved by balancing the potential and by reducing the disadvantages bit by bit as this material is not yet established for technical-structural appliances.

These results can serve as a starting point for further and more specific research and development which might open up new perspectives and can therefore loosen old ways of thinking.

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