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DEVELOPMENT OF A NEW WOOD-BASED MODULAR FURNITURE SYSTEM – EVALUATION OF SUITABLE MATERIALS FOR CONNECTORS

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Abstract

Concepts for modular furniture systems are of growing interest from the perspective of both producers and customers, and they are now entering the area of mass customization. Modularity and standard interfaces eliminate the interdependency of the components of a product, and allow the manufacturer and customer to change components without affecting the product architecture. In this context, the connectors between components of the modular furniture systems are essential for the systems. The objective of this study was to evaluate the suitability of different wood-based materials for the connectors of the modular furniture system, the focus being on the strength properties.13 different types of wood-based material were tested in three-point bending tests, and the modulus of elasticity (MOE) and the modulus of rupture (MOR) were determined. The tested materials incorporated wood modifications such as compression, heat treatment and impregnation, as well as different types of adhesives. It could be concluded that birch plywood bonded with soybean glue, and solid cumaru wood are the most suitable types of wood-based material for the modular furniture system. Compressed plywood generally exhibited better strength properties than ordinary plywood, and the type of adhesive had no significant influence on either MOE or MOR. Self-bonding plywood had a high MOE, but a comparably low MOR. Solid cumaru wood exhibited both a high MOE and a high MOR. Materials which had reasonable strength properties and a comparably low environmental impact were considered suitable for the connectors of the modular furniture system, which meant that non-formaldehyde-emitting adhesives were favoured.

Key words: *product development; modularity; lean; plywood; innovation.*

INTRODUCTION

Mass customization is a well-known buzzword in the modern marketing landscape. On the one hand, customers are no longer satisfied with standard off-the-shelf products. As individuals, they want to set themselves apart from the ever increasing uniformity of today's society. On the other hand, most customers are not willing to spend more money on a given type of product than they did before (Piller 2009). Mass customization is considered to be a solution to this dilemma.

How can mass customization be achieved in the furniture market? How can a company offer a piece of furniture tailored to the needs of a specific customer at a price similar to that of a generic bookshelf? Modularity is an answer.

Product modularity means that the components of a product are not interdependent (Ulrich and Eppinger 2012). This is achieved by incorporating standardized interfaces. Furniture components with standardized interfaces allow the manufacturer to offer products in which each component can be varied without changing the overall product architecture. By offering various material options, surface finishes, or ways of assembly, the number of possible combinations easily reaches four digits.

Coming back to buzzwords, *green thinking* is another one. Clearly, it is not a new, but an important one. The development of modular products can have a positive impact on the utilization of resources. Offering modular products instead of products with highly interdependent components, can increase the market responsiveness of the organization. A high responsiveness supports the implementation of a production system which is based on market pull, a central principle of lean manufacturing (Bicheno and Holweg 2009). The overriding concept of lean manufacturing is the eliminating waste, which eventually leads to a more efficient use of resources, and closes the circle from green thinking to lean thinking.

Recently, a new type of modular furniture concept, 'Modos' (2015) was revealed to the world, Fig. 1, consisting of wooden boards and aluminium connectors. The design is sleek and appealing.

There are two features which set this product apart from all others: simplicity and flexibility. The parts can be assembled and disassembled rapidly, and without any tools. Other modular furniture systems such as the “Build” shelving system by Movisi (2015) or the modular coffee table designed by James Howlett (2015), do not offer the same level of flexibility.

Fig. 1.
The Modos modular furniture system (Modos 2015) consists of standardized aluminium connectors and wooden boards. Various types of furniture can be assembled without tools

Despite its great potential, the Modos furniture system has some weaknesses. First of all, like many other high quality furniture products, it is rather expensive. The high costs somewhat defy the purpose of a modular system. It takes the word *mass* out of *mass customization*. Secondly, aluminium as the connector material is certainly not the best choice from an environmental perspective, even though it can be recycled. According to Slavid (2005), the production of aluminium raw material consumes about 20 times more energy than the production of sawn timber.

For these reasons, concepts of an entirely wood-based modular furniture system, based on the functionality of Modos, were developed. Aluminium has a higher strength-to-volume ratio than wood. Hence, the challenge was to adapt the wood-based system so that a sufficient strength could be obtained without compromising its aesthetic appearance. In order to overcome this challenge, two aspects needed to be addressed: the geometry and the choice of material of the connectors.

OBJECTIVE

The aim of the study was to evaluate the suitability of different wood-based materials for the connectors of the modular furniture system, the focus being on the strength properties.

MATERIAL, METHOD, EQUIPMENT

This study covered the selection of suitable materials for the connectors of the modular furniture system. The geometry of the connectors has an influence on the material evaluation. Fig. 2 shows the design of the two connectors on which the material evaluation was based. The first design is to be made of laminated veneer, and the second is to be made of three parts of solid wood, in order to achieve the optimal strength in each connection direction. As eco-friendliness is an important feature of the modular furniture system, endangered wood species must not be used. In addition, the use of formaldehyde-emitting adhesives should be avoided.

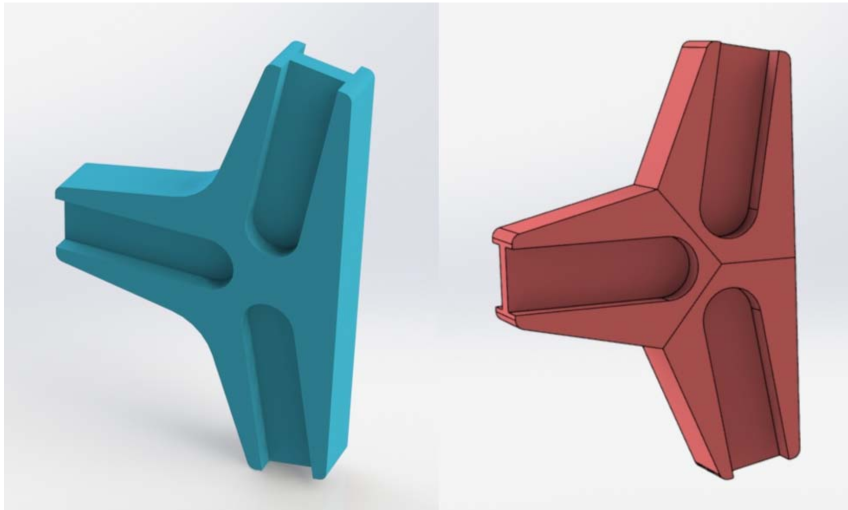

Fig. 2.
The study was based on two connector designs: a) a one-part connector of laminated veneer and b) a three-part connector of solid wood

Based on a literature search and applying the wood selection tool presented by Neyses and Sandberg (2015), various types of wood-based materials, modifications, and adhesives were chosen as being potentially suitable, and the woo- based materials described in table 1 were further evaluated and tested.

Beech (*Fagus sylvatica* L.) or Birch (*Betula pubescens* L.) veneer with a thickness of 2 mm was used as raw material for the different types of laminated panels produced and tested as indicated in Table 1. The only solid wood material tested was Cumaru (*Dipteryx odorata* (Aubl.) Willd.*).* Beech veneer was used for all the panels categorized as compressed plywood or LVL. Regular plywood specimens were manufactured of both beech and birch veneers. In the case of the plywood and LVL specimens, a Fjellman 2-89200 hot press was used for panel production. Afterwards, the panels were cut into specimens for bending tests. Between three and five specimens of each type of material were tested.

The following types of adhesive were tested: (1) a melamine-urea-formaldehyde adhesive (Casco Adhesives 1247/2526), (2) a two-component epoxy adhesive (275A Epoxy resin & 275B Hardener, Nils Malmgren AB), (3) a single-component polyurethane adhesive (Cascol Polyurethane 1809), and (4) a soy-based adhesive (Soyad, Solenis AB).

Three-point bending tests were performed on a Hounsfield 0133 Model H25KS testing machine. The modulus of elasticity (MOE) and the modulus of rupture (MOR) were determined. All specimens were tested parallel to the grain. In the case of plywood, the grain direction of the outer veneers determined the grain direction of the panel. It was not possible to manufacture the specimens according to the standard EN 310, but the ratio of length to thickness was kept within the range of 18 to 22. The standard specifies a ratio of 20. In all cases, the ratio of specimen width to specimen thickness was close to 1. The moisture content (MC) of the specimens was determined with the oven-drying-method.

The bond lines of the laminated panels were oriented parallel to the load direction during the bending test, Fig. 3. This bond line orientation during testing is unusual according to EN 310. In the present case, however, it is similar to the orientation of the connectors under real application conditions. For comparison, some specimen groups were tested with the bond lines perpendicular to the load direction. This was of particular interest in the case of the novel and uncommon materials such as self-bonding plywood or compressed plywood.

Table 1

Wood-based materials tested for the connectors of the modular furniture system. MC – moisture content

No.	Specimen group	Description	Pressing/ gluing	Bond-line orientation	MC [%]	No. of specimens	Level of densi-fication [%]
1	Comp Ply V Beech MF	Compressed plywood; 5 layers of 2 mm beech veneer; Melamine formaldehyde adhesive	4.5 MPa, at 220°C, for 450 s	Parallel to load direction	5.8	4	33
2	Comp Ply H Beech MF	Compressed plywood; 5 layers of 2 mm beech veneer; Melamine formaldehyde adhesive	4.5 MPa, at 220°C, for 450 s	Perpendicular to load direction	5.8	4	33
3	Comp Ply V Beech SB	Compressed plywood; 5 layers of 2 mm beech veneer; Self-bonded without adhesive	5 MPa, at 250°C, for 330 s	Parallel to load direction	5.6	3	51
4	Comp Ply H Beech SB	Compressed plywood; 5 layers of 2 mm beech veneer; Self-bonded without adhesive	5 MPa, at 250°C, for 330 s	Perpendicular to load direction	5.6	3	51
5	Comp LVL V Beech SB	Compressed LVL; 5 layers of 2 mm beech veneer; Self-bonded without adhesive	5 MPa, at 250°C, for 300 s	Parallel to load direction	5.6	3	50
6	Comp LVL H Beech SB	Compressed LVL; 5 layers of 2 mm beech veneer; Self-bonded without adhesive	5 MPa, at 250°C, for 300 s	Perpendicular to load direction	5.6	3	50

7	Comp LVL H Beech MF	Compressed LVL; 5 layers of 2 mm beech veneer; Melamine formaldehyde adhesive	5 MPa, at 250°C, for 330 s	Perpendicular to load direction	5.6	3	27
8	Compreg Ply V Beech E	Compressed impregnated plywood; 5 layers of 2 mm beech veneer; Epoxy resin and hardener	6.5 MPa, at 120°C, for 10 000 s	Parallel to load direction	5.6	3	15
9	Solid Cumaru	Solid cumaru wood	-	-	5.7	4	-
10	Ply V Beech PU	Plywood; 5 layers of 2 mm beech veneer; Polyurethane adhesive	24 h curing time	Parallel to load direction	5.6	4	-
11	Ply V Birch PU	Plywood; 5 layers of 2 mm birch veneer; Polyurethane adhesive	24 h curing time	Parallel to load direction	5.0	4	-
12	Ply V Birch Soy	Plywood; 5 layers of 2 mm birch veneer; Soybean adhesive	Curing at 220°C for 500s	Parallel to load direction	5.0	5	-
13	Ply V Birch SoyS	Plywood; 5 layers of 2 mm birch veneer; Soybean adhesive	Curing at 220°C for 500s; plywood panel was soaked in water for 3 days, and oven-dried at 103°C for 24h	Parallel to load direction	Oven dry	3	-

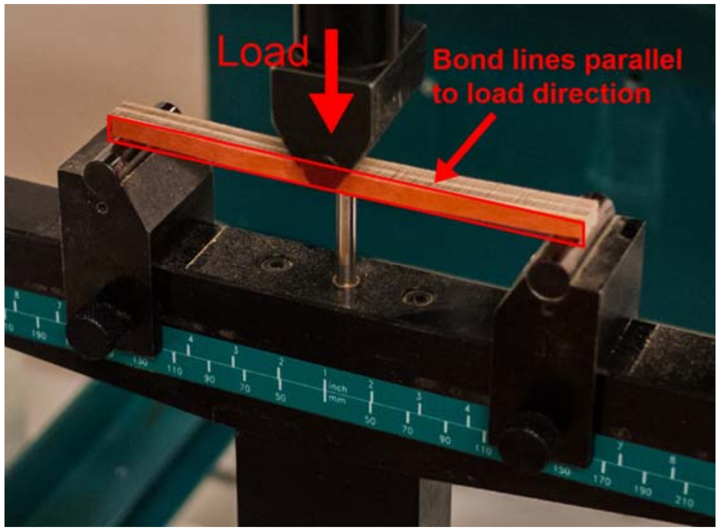

Fig. 3.
Setup for the three-point bending tests, with the bond lines of the specimen parallel to the load direction

RESULTS AND DISCUSSION

In most cases, the production of the specimens went well. The production process parameters of group 7 were, however, too aggressive. Either the pressing time was too long or the pressing temperature was too high. As a result the panel literally exploded after the 5 MPa pressure was released, Fig. 4. A gradual reduction of the pressure towards the end of the pressing process might have perhaps avoided this problem. Nevertheless, half of the panel remained undamaged, making it possible to cut out three specimens for the strength tests.

The boards using polyurethane adhesive in combination with compression of the veneer layers could not be bonded. After the pressure has been released, the panels fell apart, indicating that the combination of compressed plywood and polyurethane adhesive is not a viable alternative for the modular furniture system.

Fig. 4.
Exploded panel of specimen group 7. Apparently, the pressing time was too long, or the pressing temperature too high

Table 2 and Figure 5 show the results of the three-point bending tests. The scale of the MOR values was adjusted to match the magnitude of the MOE values. The purpose of the figure is to facilitate the comparison of the tested types of material.

Table 2

Results of the three point bending tests. All values are mean values

No.	Name	MOE [GPa]	MOR [MPa]
1	Comp Ply V Beech MF	10.3	103.6
2	Comp Ply H Beech MF	13.4	160.4
3	Comp Ply V Beech SB	12.2	104.4
4	Comp Ply H Beech SB	16.6	90.0
5	Comp LVL V Beech SB	10.1	86.3
6	Comp LVL H Beech SB	17.8	104.1
7	Comp LVL H Beech MF	17.0	127.5
8	Compreg Ply V Beech E	14.5	135.3
9	Solid Cumaru	14.9	148.7
10	Ply V Beech PU	7.3	74.6
11	Ply V Birch PU	10.8	103.9
12	Ply V Birch Soy	10.9	103.7
13	Ply V Birch SoyS	10.8	100.0

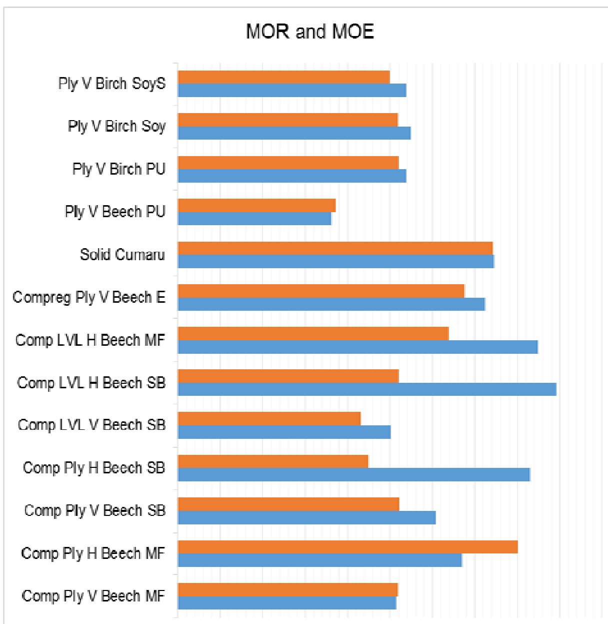

Fig. 5.
Results of the three point bending tests:
MOR (upper bar) and MOE (lower bar). The scale of the MOR values was adjusted to facilitate a visual comparison

Densification of the plywood and LVL panels (groups No. 1-7) during manufacture had a positive impact on the strength of the specimens, regardless of whether adhesives were used or not. As the strength properties of wood are strongly correlated to the density, these results were expected (Dinwoodie 2000). It seems, however, that the strength increase is in most cases less than proportional to the level of densification, probably because of a reduction in thickness as well as thermal degradation. The thickness of the panels was 10 mm before pressing, and 5 mm to 7 mm after pressing. This corresponds to a densification of 50% to 30%.

It is interesting to see that the self-bonding compressed plywood and LVL specimens (group No. 3-6) exhibited a high MOE, but a comparatively low MOR. The specimens were stiff until they suddenly broke due to failure in the bond line. This behaviour was more pronounced when the bond line was oriented perpendicular to the load direction. In contrast, all the plywood and LVL specimens which were bonded with adhesives, broke due to failure of the wood material. It was concluded that the maximum strength of self-bonding plywood is determined by the strength of the bond line, whereas the stiffness is determined by the strength of the wood material.

The specimens in group 8 (*Compreg Ply V Beech)* exhibited the best combination of MOE and MOR of all veneer based specimens, i.e. a high MOE as well as a high MOR. Unfortunately the use of epoxy resin is questionable from an environmental perspective.

It was concluded that the type of adhesive had no great impact on the strength. All the specimens broke due to failure of the wood rather than the bond line. Exposing the specimen group 13 (*Ply V Birch SoyS)* to a complete wetting and drying cycle reduced neither the MOR nor the MOE. The strength of the panels glued with formaldehyde-free soybean adhesive (groups 12-13) showed that this is a promising adhesive.

In the uncompressed plywood, birch panels were about 40% stronger than beech panels. Of all the specimens, cumaru wood had the best combination of MOR and MOE. If the MOR is high but the MOE is low, the connector will withstand a high load until failure, but it will deform a lot. If the MOE is high but the MOR is low, the connector will not deform much, but it will fail under relatively low loads. Other species with similar strength properties to cumaru are certainly suitable for use in the modular furniture system.

CONCLUSIONS

In this study, 13 types of wood-based materials have been evaluated regarding their suitability for the connector components of a novel modular furniture system. Three-point bending tests were carried out in order to determine the MOE and MOR of the tested materials.

It can be concluded that birch plywood bonded with a soybean adhesive, and solid cumaru wood are the most suitable types of wood-based material for the modular furniture system. They exhibited reasonable strength properties, while being environmentally friendly, which is an essential feature of the product. Self-bonding plywood has the potential to be an alternative in the future if the process parameters can be controlled so that a consistently strong bond line can be ensured.

It was possible to produce comprehensive prototypes of the product, and further tests on the prototypes confirmed the suitability of the materials identified in this study. Before the modular furniture system is ready to be launched, fatigue tests must be performed.

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