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ASSESSING THE INFLUENCE OF MECHANICAL PROPERTIES OF A POLYPROPYLENE AND HEMP COMPOSITE ON THE DESIGN OF UPHOLSTERED FURNITURE

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Abstract: *The current paper studies the influence of some of the mechanical properties of a polypropylene (PP) and hemp composite on furniture products. Different values were given to the mechanical properties starting with the ones measured in the laboratory for a composite made by the company Taparo SA (Romania) in an attempt to identify the most desirable properties from new blends of PP and hemp composite. The results show which parameters are relevant to the design process and in what way.*
Key words: *polypropylene, hemp, plant fiber composite, wood alternative, furniture design.*

1. INTRODUCTION

The upholstered furniture industry is a large consumer of wood and engineered wood products such as particleboard, laminated veneer lumber etc. Partially replacing the wood and the engineered wood materials in the furniture's structure with composites would contribute to the conservation of existing forest resources, to the decrease of pollution and the greenhouse effect, to the development of a more competitive industry and to the development of new jobs [1].

Most upholstered furniture, such as sofas and chairs, are currently made from a frame which is then padded with foam and finally covered with textile material for a pleasant look and feel (figure 1). The frame is the element that gives the product its main shape and supports the loads. The surfaces don't have to be class A or even class B surfaces because they are covered by foam and textile material and are never in plain sight.

A number of composites have been considered over the years to replace wood. The most promising of them have been those consisting of a polymer matrix and natural fiber reinforcements. Natural fibers have several advantages over artificial ones even though they are weaker: they are very abundant in nature, they are biodegradable and they don't require human produced energy to form. Their main disadvantages are the fact that they are weaker than artificial fibers such as carbon, glass or aramid fibers and the fact that their properties vary greatly depending on factors such as place of growth.

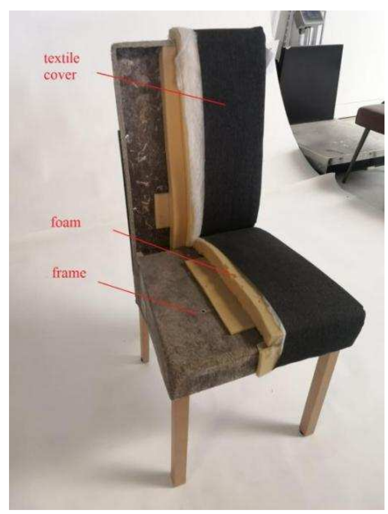

Fig. 1. Composite chair structure

Taparo SA, a Romanian company, has developed a composite made of polypropylene (PP) and hemp that corresponds to the new ecological requirements of the furniture industry. The material contains PP fibers as the matrix that are mechanically consolidated with hemp fibers as reinforcement. The result is a

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flexible cloth that can be cut into different shapes and transformed into products by thermoforming in a mold.

The company currently manufactures a number of composite products. The PP and hemp cloth is unwound from a roll, cut according to different patterns and stacked in more layers where it is necessary to have greater strength or stiffness. This package made of multiple layers is then heated in a hot plate press so as to melt the thermoplastic matrix. Next it is moved into a mold fitted to a press where it is formed into the products final shape. The mold is kept closed until the polymer cools enough to retain shape. The composite part is then trimmed to size and is ready to undergo fitting of the foam, textile materials and feet to become a finished piece of upholstered furniture.

The "green" character of this composite material is represented by the multiple recycling possibilities. It can be shredded and blended with new PP and hemp by mechanical consolidation and transformed into a new roll of composite material or it can be recycled into granules suitable for injection molding.

The labor required to make an upholstered product drops by replacing the large number of wooden structural elements with fewer composite ones. Paper [2] shows that 21 different parts are required in order to manufacture a classical sofa side, but only 2 when using composites. This drop in labor leads to a significant decrease in time and costs.

Paper [3] shows that biocomposites contribute to large weight savings in furniture due to their lower density compared to conventional materials and a superior strength to density ratio. This means easier and more cost effective handling and transportation. Biocomposites retain good mechanical properties even after several recycling cycles, which means they can be reused multiple times compared to engineered wood designs.

Even though there are numerous composite materials with superior mechanical properties, such as carbon or glass fiber composites, these use thermosetting matrices which prohibit their recycling. The build up of nondegradable waste would become a serious problem if these materials would be applied to mass production. Two major problems would remain even if the thermosetting matrix would be replaced by a thermoplastic one: the artificial fibers' lack of biodegradability and their high price.

The current paper studies the influence of the mechanical properties of a PP and hemp composite on furniture items. The mechanical properties determined in the laboratory for Taparo's material are varied and used to identify other possible blends with better results from a performance or economical point of view. Future research into developing better blends of PP hemp composites could be guided by these results.

2. DEFINING THE RESEARCH METHODOLOGY

A research methodology consisting of the following steps was devised in order to identify requirements for composite materials:

- selecting a product that is representative and constructing its CAD model;
- preprocessing the CAD model for the finite element analysis (FEA) by simplifying the shape, checking the geometry for errors and meshing the model;
- defining the experimental program: choosing which material properties are varied and their values;
- conducting the FEA according to the experimental program and postprocessing the data;
- interpreting the results.

Taparo's products, including the ones that aren't currently manufactured of composite, were analyzed. A sofa side, Tapcomp, was chosen as a representative product. It is shown in figures 2 and 3.

Solidworks Simulation was the FEA software used. The model was simplified compared to the actual sofa side in order for the numerical simulations to run more efficiently. The side was modeled as a single piece even though it consists of two halves. This simplification offered accurate results since the actual manufacturing would have implied gluing the two parts together. The current technology of thermoforming implemented by the company cannot be used to manufacture the sofa side as a single piece. A one piece design would be possible by extrusion if the ribbing and the front and back walls would be removed.

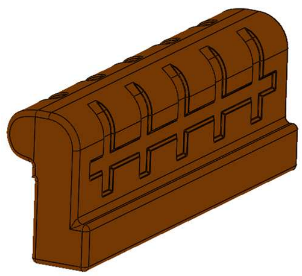

Fig. 2. Tapcomp sofa side

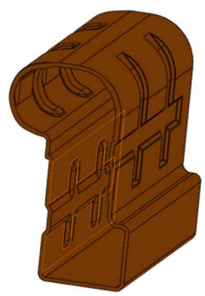

Fig. 3. Section through the sofa side

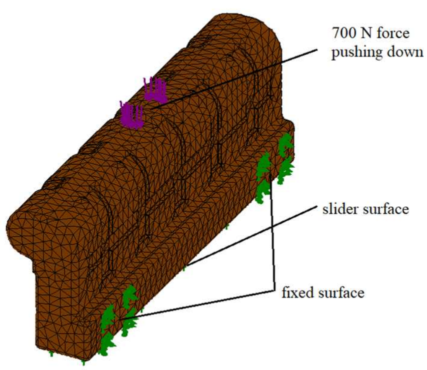

Fig. 4. The preprocessed sofa side (mesh, fixtures and load)

Figure 4 shows the meshed part with the fixtures and the loads applied. The fixtures were defined as fixed for the place where the side intersects the frame of the couch, and roller/slider for the base because it is free to slide on the floor.

The forces and their place of action were chosen according to the standards set forth by a large furniture retailer, the main customer of these products. It was concluded that the test that consists of a 700N force pressing on the top leads to the largest stresses and displacements following some initial simulations conducted in order to rule out any errors and check the accuracy of the results.

The experimental program was designed to offer an idea on how the composite material's properties impact the stresses and displacements. The parameters used by Solidworks Simulation for linear analyses are Young's modulus, Poisson's ratio. The Shear modulus is an optional parameter, which if not specified by the user, is automatically calculated by the software based on the first two. Poisson's ratio was he first property to be varied and then Young's modulus. For each value of Young's modulus different material thicknesses were analyzed.

The decision to run the FEA on multiple material thicknesses is based on a number of reasons even though thickness is not a material property:

- the wall thickness has a direct influence on the stresses and displacements of the parts;
- the weight of the part is almost directly proportional to the thickness of the wall because the PP and hemp composite is manufactured as a textile;
- the time needed to heat the composite for thermoforming is proportional to the thickness of the material;
- because the thickness of the part has a direct influence on the amount of raw material and the heating time, it also influences the cost and quality of the final product significantly.

The experimental program consists of the following phases:

- the influence of Poisson's ration is assessed for the the 4 mm thick sofa side;
- a value for Poisson's ratio is chosen and Young's modulus is varied for different material thicknesses: 2.5, 3, 3.5, 4, 4.5, 5 mm;
- the tensile strength is varied for the previously analyzed Young's modulus and thickness combinations in order to determine the factor of safety (FoS).

The previous theoretical and experimental research conducted at Taparo and at the Technical University of Cluj-Napoca was used to establish the interval in which the material parameters could vary. Ciupan et al (2017) ran tensile tests on the composite material, which consisted of a blend of 50% PP and 50% hemp,

made and supplied by Taparo. The ultimate tensile strength was measured as 18.30 MPa. The material used in the tests came from a thermoformed sheet that consisted of 4 layers oriented in the same direction.
The samples that were cut from the sheet had an average thickness of 2.13 mm. Young's modulus was measured to be between 976 and 1013 MPa. These properties are lower than the properties of each of the composite's constituents.
This could be due to a heterogeneous blending of the constituents during the production of the material or to a weak bond between them during thermoforming. Poisson's ratio was measured as 0.41 during the same set of experiments.

3. THE INFLUENCE OF MECHANICAL PROPERTIES ON THE DESIGN OF FURNITURE

3.1.The influence of Poisson's ratio

Table 1 shows the results of some FEAs which study the influence of Poisson's ratio on the stresses and displacements of the Tapcomp sofa side. In order to conduct a linear static study the other required parameter, Young's modulus, was chosen to be 1000 MPa, close to the average of the laboratory testing.

Table 1

FEA results of Poisson's ratio influence on the stresses and displacements of the sofa side

No.	Young's modulus E [MPa]	Poisson's ratio	Max. von Mises stress [MPa]	Max. displacement [mm]
1	1000	0.30	12.56	8.13
2	1000	0.35	12.71	7.94
3	1000	0.40	12.89	7.70
4	1000	0.45	13.04	7.41
5	1000	0.49	12.88	7.044

The results in table 1 show that as Poisson's ratio increases, the maximum displacement decreases. A Poisson's ratio of 0.4 was chosen for the following FEA. This value is close to the one obtained during during the tensile testing of the composite samples.

3.2 The influence of Young's modulus

Young's modulus was varied between 1000 and 2500 MPa with an increment of 500 MPa. Young's modulus for PP is approximately 1950 MPa [4] and of hemp fibers 9500 MPa [5]. Even if the chosen value of 2500 MPa is higher than that of PP, it is still close to it and it could be obtained in the material development process due to the fact that a composite is an average of its constituents.

Table 2

FEA results for the 4.0 mm thick Tapcomp sofa side

No.	Young's modulus E [MPa]	Poisson's ratio	Max. von Mises stress [MPa]	Max. displacement [mm]
1	1000	0.4	10.14	6.61
2	1500	0.4	10.14	4.40
3	2000	0.4	10.14	3.30
4	2500	0.4	10.14	2.64

Table 2 shows that a change in Young's modulus doesn't affect the maximum von Mises stress, but the deformation decreases inversely proportional to it.

3.3 The influence of the ultimate tensile strength

A factor of safety is used in dimensioning the furniture's components, just as it is when designing other mechanical parts. It is expressed as a ratio between the maximum stress and the yield strength or the ultimate tensile strength of the material. Taparo uses a FoS between 1.8 and 2.2 calculated using the ultimate tensile strength, even though there isn't a specific requirement. The minimum value of 1.8 represents a minimum value for which most of the products will not fail because of the prescribed loads and their variations encountered in real use or because of fatigue during the lifetime of the product. The maximum value of 2.2 prevents the oversizing of components and thus the unnecessary increase of raw material use.

Table 3 expands the results in table 2 and shows that the FoS isn't influenced by Young's modulus, only by the ultimate tensile strength. It also shows that the FoS criterion isn't always sufficient when designing furniture, but the displacements should be also considered so as to prevent them from becoming excessive and making the products seem low quality.

Table 3

The influence of the ultimate tensile strength on the FoS

No.	Young's modulus E [MPa]	Poisson's ratio	Ultimate tensile strength R_m [MPa]	Max. von Mises stress [MPa]	Max. displacement[mm]	FoS
1	1000	0.4	15	10.14	6.61	1.47
2	1500	0.4	15	10.14	4.40	1.47
3	2000	0.4	15	10.14	3.30	1.47
4	2500	0.4	15	10.14	2.64	1.47
5	1000	0.4	25	10.14	6.61	2.46
6	1500	0.4	25	10.14	4.40	2.46
7	2000	0.4	25	10.14	3.30	2.46
8	2500	0.4	25	10.14	2.64	2.46
9	1000	0.4	35	10.14	6.61	3.45
10	1500	0.4	35	10.14	4.40	3.45
11	2000	0.4	35	10.14	3.30	3.45
12	2500	0.4	35	10.14	2.64	3.45
13	1000	0.4	45	10.14	6.61	4.43
14	1500	0.4	45	10.14	4.40	4.43
15	2000	0.4	45	10.14	3.30	4.43
16	2500	0.4	45	10.14	2.64	4.43

3.4 The influence of the side's wall thickness

Multiple FEAs were conducted for wall thicknesses between 2.5 and 5 mm with an 0.5 increment according to the experimental program. This meant that 6 analyses were carried out for the following thicknesses: 2.5, 3, 3.5, 4, 4.5, 5 mm.

Figure 5 shows the maximum displacement of the Tapcomp sofa side based on its wall thickness and the material's Young's modulus. Figure 6 shows the variation of the FoS based on the wall thickness and the material's ultimate tensile strength.

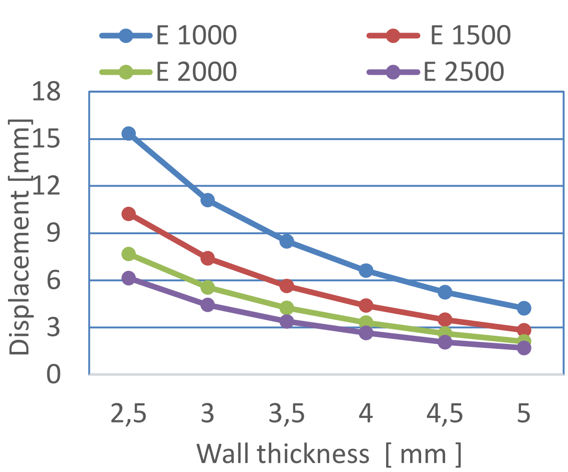

Fig. 5. The influence of the side's wall thickness and Young's modulus on the displacement

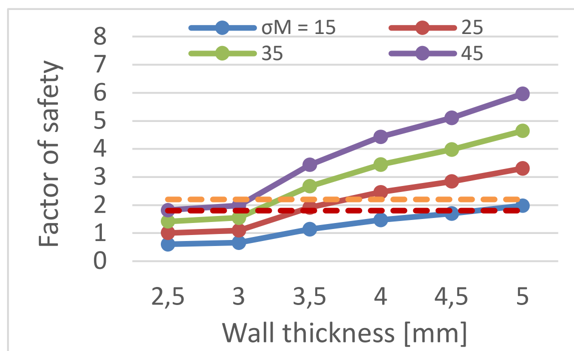

Fig. 6. The influence of the side's wall thickness and the ultimate tensile strength on the FoS

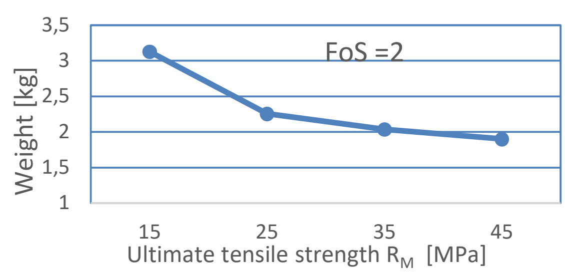

Fig. 7. The influence of the ultimate tensile strength on the weight of the sofa side for a FoS of 2

Figure 7 presents the change in the weight of the sofa side as a function of the material's ultimate tensile strength. The design of the side was based on a FoS of 2, the average between 1.8 and 2.2, and was obtained by changing the thickness of the CAD model wall.

Figure 7 presents the change in the weight of the sofa side as a function of the material's ultimate tensile strength. The design of the side was based on a FoS of 2, the average between 1.8 and 2.2, and was obtained by changing the thickness of the CAD model wall.

7. CONCLUSIONS

There are two main design criteria used when designing furniture: the factor of safety and the maximum displacement. The FoS is the main one that is considered, but this is not enough if excessive displacements appear as these lead to design changes.

There are a few measures that can be taken is excessive displacements are measured: a different material with a larger Young's modulus or a larger Poisson's ratio can be selected. A different approach is to increase the thickness of the material or add ribbing to the shape.

If the displacement is satisfactory, but the calculated FoS is smaller than the required one, then a different material with a higher ultimate tensile strength should be selected or the product should be redesigned with a greater material thickness or extra ribbing.

The results show that different blends of PP and hemp composite materials could be an excellent substitute for wood and wooden products in the furniture industry. The paper can serve as a guide both for the design of furniture, but also for the development of new natural fiber composite blends.

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Evaluarea influentei proprietatilor mecanice ale unui compozit din polipropilena si canepa asupra proiectarii mobilierului tapitat

Prezenta lucrare are ca obiectiv studiul influentei unor proprietati mecanice ale compozitelor din polipropilena si canepa asupra produselor de mobilier. Proprietatilor mecanice ale compozitului li s-au atribuit diferite valori pornind de la datele masurate in laborator pe un amestec de compozit din polipropilena si canepa realizat de compania Taparo SA (Romania). Rezultatele analizelor cu element finit indica care parametrii de material sau de forma sunt relevanti in procesul de proiectare.

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