TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 65, Issue Special I, February, 2022

THE OPTIMIZATION OF COSTS FOR THE THERMOFORMED FRAMES FROM NATURAL FIBER COMPOSITES

Emilia CIUPAN, Ioan CIONCA, Mihai CIUPAN, Emilia CÂMPEAN

Abstract: *Recent years have seen an increasing focus on the environment which has led to replacing traditional materials with newly developed composites. These composites are environmentally friendly and are made using raw materials from renewable resources. This is the case for composites made of plant fibres and different polymer matrices which are more and more common in the furniture industry. Companies are looking for ways of reducing manufacturing costs due to the market competition. The current paper aims to develop a method of optimizing the cost of products by considering the factor of safety and the stiffness. These dimensions depend in turn on the composite's ultimate tensile strength and Young's modulus. The study was conducted as part of a research program led by Taparo S.A., an upholstered furniture manufacturer.*

Key words: *optimization, cost, factor of safety, composites, plant fibres, thermoforming.*

1. INTRODUCTION

The current paper is the result of research completed within the project entitled "The Realization of a Centre of Excellence within the Field of Composite Material at TAPARO Ltd."

A great part of the upholstered furniture items has a resistance structure made of wood. Although wood has very good properties from a manufacturing, aesthetic and functional point of view, the excessive exploitation of forests has a strong negative impact on the environment.

Romania has a tradition in wood manufacturing, especially as far as furniture industry is concerned. A proportion of 12.7% of the wood assigned to this industry is used to produce upholstered furniture [1]. Due to excessive exploitation, Romania's woodland decreased to a point below the mean of 31% of the European countries [2].

The European Union imposed strict laws to stop deforestation and harmful impact upon the environment [3]. This led to a reduction of the offer of wood and, implicitly, a significant increase in the price of wood.

Under these circumstances, the producers of furniture have been looking for solutions to replace wood, one of them being the use of natural fiber composite materials. The properties and the fibers structure of regenerable materials like flax, banana, jute, kenaf, nettle, hemp, and bamboo is presented in [4]. The authors observed that biomaterials have a lower density of fibres than synthetic fibres.

The current paper aims at the optimization of the costs of the frames obtained from materials of this type, through the appropriate choice of the composite material, depending on its properties. The cost optimization is the subject of many articles. Paper [5] studies the effects of the flax fibre on the design of composite plates taking into account the maximum buckling and minimum cost. Different material configurations were studied. The article showed that including flax into the composition of the plate improve both cost and buckling load factor. Another paper that analyses costs is [6]. The authors studied the optimization of hybrid natural laminated composite beams for a minimum weight and cost design, varying the material of the fibre, the volume fractions, thicknesses, and the fiber orientations. The results showed that using flax into the composite material reduces the costs and the weight of the beams, compared with the beams composed of carbon/glass/epoxy.

Another study of our team members involved the requirements imposed to the composite materials in order for them to comply with the replacement of wood in the resistance structures of the upholstered material. This research is not published yet, it is under review. A research methodology consisting of the following steps was devised in order to identify requirements for composite materials:

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

The methodology of optimization of the costs used in the current paper uses the stages a-d of the methodology presented above, to which stages e-f are added. They are described as follows:

e. The interpretation of results and collection of the data necessary in order to determine the costs:
    i. The graphic representation of the variation of the safety factor depending on the characteristics of the material and the thickness of the frame's wall;
    ii. The determination of the accepted minimal safety factor (FOS);
    iii. The determination of the material's weight for the previously established values.
f. The determination of the costs based on the results obtained through numerical simulation:
    i. The establishment of a method of calculation of the price of the mechanically consolidated composite material, depending on its physical and mechanical properties.
    ii. The determination of the costs for each significantly consolidated frame, based on the weight established in stage e.
    iii. The choice of the option that ensures the minimal price and complies at the same time with the deformation restrictions.

2. RELATIONS FOR THE DETERMINATION OF THE DEPARTMENT COST

The department cost $CS_{i,j}$ of the frame is determined as follows:

$$CS_{i,j} = M_{i,j} + S_{i,j} \cdot \left(1 + \frac{Rs}{100}\right) \qquad (1)$$

where:

$M_{i,j}$ = the costs of the material [lei/piece], when composite material which has the elasticity modulus E_i and the ultimate tensile strength Rm_j is used.

$S_{i,j}$ = the costs with direct labour [lei/piece], when composite material which has the elasticity modulus Ei and the ultimate tensile strength Rm_j is used.

Rs = department costs [%].

The cost of the material used for the realization of the frame is determined as follows:

$$M_{i,j} = m_{i,j} \cdot p_{i,j} - \left(m_{i,j} - mn_{i,j}\right) \cdot pd_{i,j} \qquad (2)$$

where:

$m_{i,j}$ = the raw mass of the material used for the frame [lei/kg]

$mn_{i,j}$ = the net mass of the frame [lei/kg]

$p_{i,j}$ = the unitary price of the material [lei/kg]

$pd_{i,j}$ = the price of waste [lei/kg].

Initially, there will be determined, through real facts or a method of calculation, the costs of the mechanically consolidated composite material, depending on its properties.

There is assumed that there are m x n materials, where m is the number of materials that have a different elasticity modulus (E_i, i=1, m), and n is the number of materials with a different ultimate tensile strength (Rm_j, j=1, n). There was decided that the method of calculation of the cost of the price of the raw composite be influenced both by the ultimate tensile strength Rm_j, as this parameter influences the safety factor, and the elasticity modulus (E_i), which ensured the rigidity of the frame, that is the maximum deformation.

Table 1 illustrates the above-mentioned values.

In the cases where not all the prices of the materials in Table 1 are known, they can be estimated based on the price of a material known, upon a scenario. Let us consider as known the price of material $p_{1,1}$ in table 1 and, if the costs of the materials $p_{i,j}$.

Table 1

The price of the mechanically consolidated composite material $p_{i,j}$ [euro/kg]

Elasticity modulus E_i [MPa]	Direct material costs [Euro/kg]			
	Ultimate tensile strength Rm_j [Mpa]			
	Rm_1	Rm_2	…	Rm_n
E_1	$p_{1,1}$	$p_{1,2}$		$p_{1,j}$
E_2	$p_{2,1}$	$p_{2,2}$	…	$P_{2,j}$
…	…	…	…	…
E_m	$p_{i,1}$	$p_{i,2}$	…	$p_{i,j}$

Increase proportionally with the characteristics (elasticity modulus and ultimate tensile strength), the price of the materials can be calculated through the following formula:

$$p_{i,j} = p_{1,1} \cdot a^{i-1} \cdot b^{j-1} \qquad (3)$$

where a and b represent the coefficients of increase of the costs depending on the improvement of the properties of the materials (E_i, and Rm_j, respectively).

In order to establish the manufacturing cost of the frame, it is necessary that we determine, in addition to the material costs, the direct costs with labor. The determination of the costs with labor implies knowing the amount of time necessary for each stage of the transformation of the mechanically consolidated composite in finite product.

It is known that the technology of thermic consolidation of the composite in molds implies the completion of the stages 1-5 in table 2.

Table 2

The stages of realization of a thermoformed mould

No. of the stage	Stages	Thickness of the material $g^*_{i,j}$			
		$g^*_{1,1}$	$g^*_{1,2}$	…	$g^*_{i,j}$
1.	Turning (1 worker) [min/piece]	t1	t1	…	t1
2.	Cutting out (1 worker) [min/piece]	t2	t2	…	t2
3.	Heating the press (2 workers) [min/piece]	t31,1	t31,2	…	$t3_{1,j}$
4.	Pressing in the mould (2 workers) [min/piece]	t41,1	t41,2	…	$t4_{i,j}$
5.	Trimming (1 worker) [min/piece]	t5	t5	…	t5
	Total amount of time per operation	$Top_{1,1}$	$Top_{1,2}$		$Top_{i,j}$

The thermic consolidation implies heating the material over the melting temperature of the thermoplastic matrix (polypropylene), which is followed by the pressing and cooling in the mold, and the duration of these operations is influenced by the thickness of the frame. The thicker the wall, the more the amount of heating and cooling time.

In order to determine the cost of the frame, there will be considered the following simplifying hypotheses:

- The amount of time necessary for heating the composite material to the temperature of thermoforming and the amount of time necessary to cool and consolidate it are directly proportional with the thermically consolidated thickness of the wall;
- The amount of time necessary for the other operations is not influenced by the thickness of the wall of the finite product;
- The amount of the mechanically consolidated material (the raw mass of the material) is by 15-20% greater than the final weight of the frame (the net mass);
- The average price of the material recovered from thermoformed waste and cutting out waste is 30% of the price the virgin composite.

The costs with direct labor ($S_{i,j}$) are determined through the following relation:

$$S_{i,j} = \frac{Top_{i,j} \cdot S}{60} \quad (4)$$

where:

$Top_{i,j}$ = the total amount of time of manufacturing the significant frame using the material with the properties E_i and Rmj;

S= hourly price of the operation.

3. CASE STUDY. THE OPTIMIZATION OF COSTS OF AN ARMCHAIR SHELL

There was chosen as a representative model the shell of an upholstered armchair. Figure 1 and 2 illustrate the state of tension and the deformations resulting from the FEA analysis of the model. The shell should correspond to the functional requirements imposed by the testing standards (the test of stress upon the seat of 1300 N and of stress upon the back of 350 N).

The simulation program followed the variation of the safety factor and of the deformation depending on the variation of the parameters of the material (ultimate strength Rm_j and elasticity modulus E_i) and on the thickness g of the wall, g having values of 5, 6 or 7 mm (tables 3 and 4). For the variation of the ultimate resistance strength there were chosen four values 15-45 MPa (table 3), and for the elasticity modulus E_i, four values in the range 1000-2500 MPa (table 4). When choosing the values described above, there were considered the materials realized and characterized by Taparo, whose properties belong to the range E=1000-1500 MPa, Rm=15-25 MPa [4].

Table 3

Study of the safety factor of the shell

No.	Thickness of the wall g [mm]	Ultimate tensile strength Rm_j [MPa]			
		15 MPa	25 MPa	35 MPa	45 MPa
		Minimal safety factor FOS_{min}			
1	5	0.99	1.62	2.35	3.03
2	6	1.17	1.63	2.71	3.15
3	7	1.43	2.39	3.35	4.31

Table 4

Study of the deformation of the shell

No.	Thickness of the wall g [mm]	Elasticity modulus E_i [MPa]			
		1000 MPa	1500 MPa	2000 MPa	2500 MPa
		Maximum deformation [mm]			
1	5	22.15	15.97	12.15	9.91
2	6	20.36	14.28	11.01	8.40
3	7	18.34	12.75	9.78	7.93

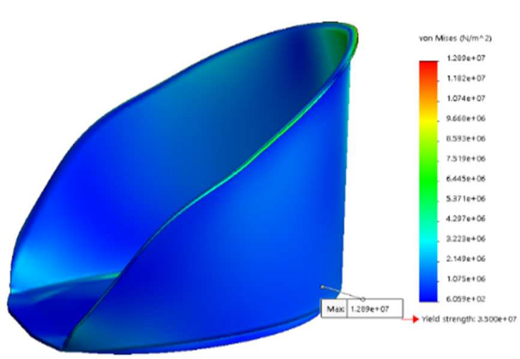

Fig. 1. The equivalent von Mises stress (g=6 mm, Rm=35 MPa; E=2000 MPa)

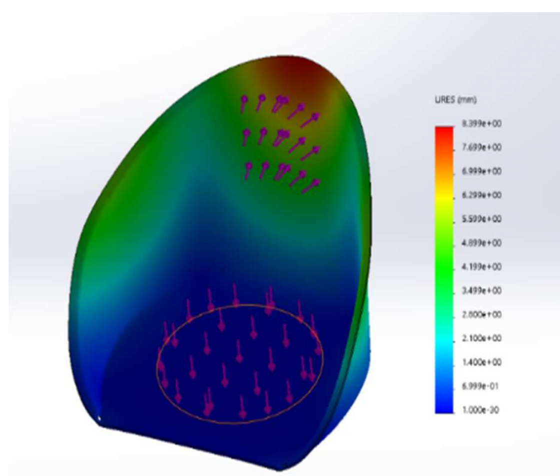

Fig. 2. State of shell deformation (g=6 mm, Rm=35 MPa; E=2500 MPa)

Fig. 3 shows the maximum deformation of the shells at the test of combined pressure on the seat and the back (data based on the analysis completed by TAPARO Ltd.). It was noticed that for the same thickness of the material, the maximum deformation is reduced to below 50%, when E increases from 1000 to 2500 MPa.

The safety factor increases with the thickness of the wall and the ultimate tensile strength of the material (fig. 4). Based on figure 4, there was determined the necessary wall thickness so that there is obtained the safety factor FOS=2 (Fig. 5).

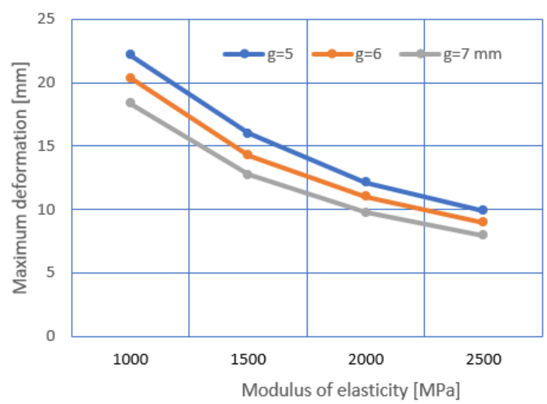

Fig. 3. Maximum deformation depending on the elasticity modulus

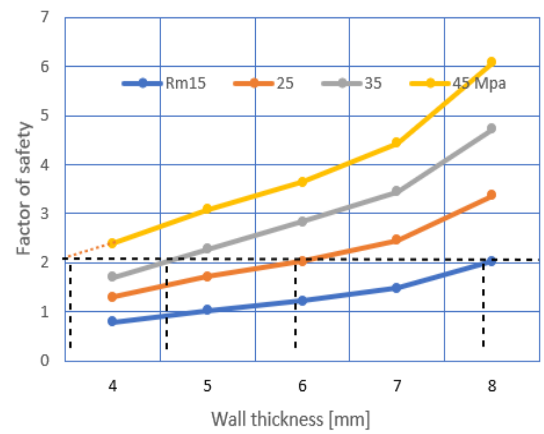

Fig. 4. Wall thickness for FOS=2

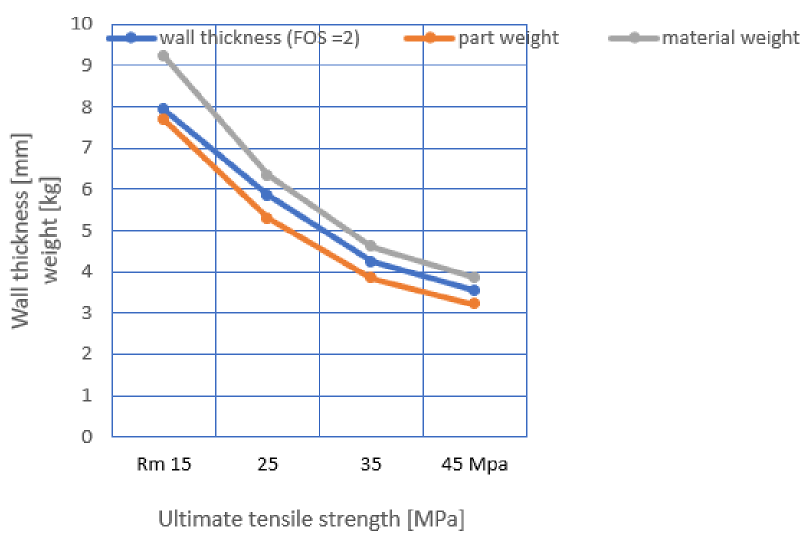

Fig. 5. Material weight for FOS=2

Using the relation (3), for a=1.05 and b=1.07, there was obtained the price of the composite material in table 5.

Fig. 6 showed the department costs of the chair shell, for each of the 16 variants of the composite materials in table 5. When calculating the costs, the following parameters were considered:

-
- hourly price S=41 lei/hour
- department costs Rs=300 %.

The results from figure 6 were presented in percentages in figure 7. The standard (100%) was considered to be the one of the materials currently used by TAPARO, with Rm=15MPa and E=1000 MPa.

Table 5

Price of the mechanically consolidated material [euro/kg]

Elasticity modulus E_i [MPa]	Direct material costs [euro/kg]			
	Ultimate tensile strength Rm_i [Mpa]			
	15	25	35	45
1000	1.50	1.58	1.65	1.74
1500	1.61	1.69	1.77	1.86
2000	1.72	1.80	1.89	1.99
2500	1.84	1.93	2.03	2.13

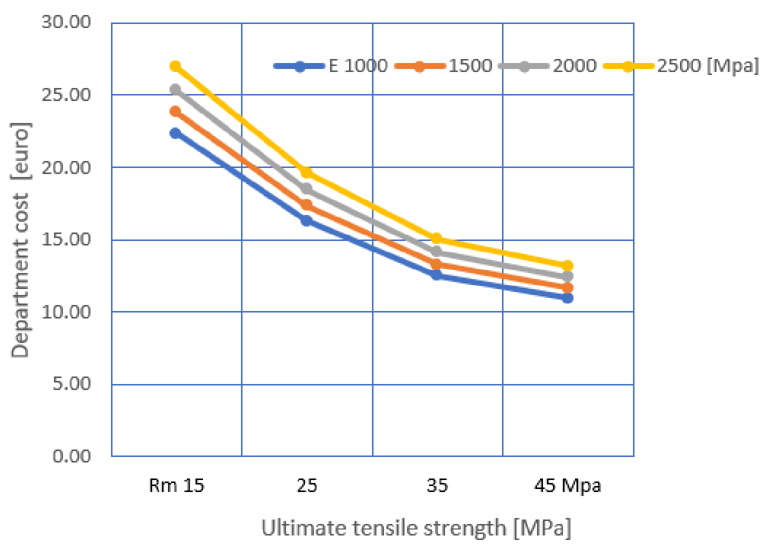

Fig. 6. Department costs depending on the properties of the material

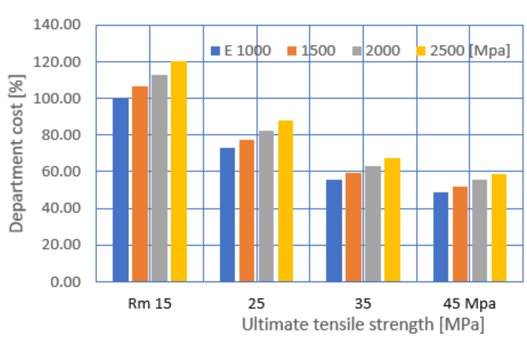

Fig. 7. Percentage variation of a department costs depending on the properties of the material

4. CONCLUSION

The method presented here can be used to minimize the department costs. In the first stage, there is chosen the material that grants the minimal cost and the accepted safety factor. Then the product is analyzed from the point of view of the minimal accepted deformation, and a material that meets this criterion as well is chosen, having in view the decrease of the costs.

From the research completed there can be drawn the following conclusions regarding the requirements imposed in terms of composite materials for upholstered products:

1. The ultimate tensile strength should be above 15 MPa. At the minimal value of 15 MPa, for a number of products the thickness will be excessive and difficult to realize. For example, in the case of the chair shell, when using a material with an ultimate tensile strength of 15 Mpa, a thickness of the wall of 8 mm is necessary, which leads as well to a greater amount of time needed to heat the material for the thermoformation, and a cost

of about 22 euro. On the other hand, when using a material with properties Rm=45 MPa, there is achieved a reduction of the thickness of the wall to la 4.5 mm, and a cost of 11 euro/piece.

2. For values of the elasticity modulus of E=1000 Mpa, there are obtained greater deformations, even when the safety factor is the appropriate one, and in some situations, there will be necessary to increase the thickness of the wall and, implicitly, the costs.

3. For the analyzed products, when increasing the value of the elasticity modulus E from 1000 MPa to 2500 MPa, the deformation is reduced to 50% (Fig. 3). This is why it is recommended that the quality of the materials be improved by adding agents of compatibilization between the natural fibers and the connection matrix and/or additivation agents.

4. The increase of the ultimate tensile strength of the material leads to the decrease of the thickness and weight of the product, for FOS=2.

5. There was noticed that for composites with the same elasticity modulus, there is obtained a reduction by about 50% of the cost of the product if the ultimate tensile strength of the product increases from 15 to 45 MPa.

5. REFERENCES

[1] Dinu E., *Industria mobilei din Romania.* Available online: https://biblioteca.regielive.ro/referate/contabilitate/industria-mobilei-din-romania-11117.html.

[2] *Institutul National de Statistica. Anuarul Statistic al Romaniei—Serii de Date 1990–2016*; Institutul National de Statistica: Bucuresti, Romania, p. 526, 2018.

[3] Report with recommendations to the Commission on an EU legal framework to halt and reverse EU-driven global deforestation, European Parliament, 2020.

[4] Das P. P., Chaudhary V., *Moving towards the era of bio fibre-based polymer composites*, Cleaner Engineering and Technology, Vol.4, 2021.

[5] Jalili S., Khani R., Hosseinzadeh Y., *On the performance of flax fibres in multi-objective design of laminated composite plates for buckling and cost,* Structures, no. 33, pp. 3094-3106, 2021.

[6] Megahed M., Abo-bakr R. M., Mohamed S.A., *Optimization of hybrid natural laminated composite beams for a minimumweight and cost design,* Composite Structures, 239, 2020.

[7] Ciupan E., Lăzărescu L., Filip I., Ciupan C., Câmpean E., Cionca I., Pop E., *Characterization of a thermoforming composite material made from hemp fibers and polypropylene*, The 13th Modern Technologies in Manufacturing, Cluj-Napoca, MATEC Web of Conferences, Volume 137, DOI: 10.1051/matecconf/201713708003, WOS:000426604200079, 2017.

Optimizarea costurilor pentru repere termoformate din compozite pe bază de fibre naturale

Rezumat: *Preocupările crescânde din ultimii ani privind problemele mediului înconjurător au dus la manifestarea tendinţei de înlocuire a unor materiale tradiţionale cu materiale compozite noi. Fabricarea acestora din urmă se bazează pe materii prime obţinute din surse uşor regenerabile şi prietenoase cu mediul inconjurator. Acesta este şi cazul materialelor compozite obţinute din fibre vegetale în amestec cu diferite matrice, adecvate înlocuirii lemnului din componenţa unor produse de mobilier. Într-o piaţă concurenţială, întreprinderile caută soluţii de reducere a costurilor de fabricaţie. Lucrarea de faţă are ca scop crearea unei metode de optimizare a costului unor produse luând în considerare, ca şi criteriu, factorul de siguranţă şi rigiditatea. Aceste mărimi depind la rândul lor de rezistenţa maximă Rm şi de modulul de elasticitate E al materialului compozit. Studiul s-a realizat în cadrul unui proiect de cercetare al cărui beneficiar este Taparo S.A., producător de mobilier tapiţat.*

Emilia CIUPAN, PhD, Assoc.prof, Technical University of Cluj-Napoca, Management and Economic Engineering Department, emilia.ciupan@mis.utcluj.ro, +40-264-401642, B-dul Muncii 103-105, 400641, Cluj-Napoca.

Ioan CIONCA, PhD candidate, TAPARO S.A., 43562 Village Borcut, No. 98, Maramureş County, Romania

Mihai CIUPAN, PhD, Assistant, Technical University of Cluj-Napoca, Design Engineering and Robotics Department, mihai.ciupan@muri.utcluj.ro, +40-264-401200, B-dul Muncii 103-105, 400641, Cluj-Napoca.

Emilia CÂMPEAN, PhD, Assoc.prof, Technical University of Cluj-Napoca, Design Engineering and Robotics Department, emilia.campean@muri.utcluj.ro, +40-264-401200, B-dul Muncii 103-105, 400641, Cluj-Napoca.