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# OPTIMIZATION OF THERMOFORMING OF POLYPROPYLENE AND HEMP FIBER COMPOSITE MATERIALS EGG CARTON SHAPE PARTS BY RADIUS PROFILE AND PITCH

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***Abstract:*** *This paper aims to develop new possibilities for improving mechanical performance in the field of composite materials reinforced with plant fibers. Parts made with an egg carton-shape of different radii and pitches are investigated. These parts will be implemented in chairs. The main goal is to improve the mechanical resistance, since specialized studies have shown that parts with different profiles are more resistant than parts with a flat shape. The egg carton shape in the stool-type chair will not be visible after it is covered with a textile material.*

***Key words:*** *thermoforming, polypropylene and hemp fiber composite, natural fiber composite, profiled board.*

## 1. INTRODUCTION

The furniture industry is a big consumer of wood and boards made of wood material. Because natural resources are limited, furniture manufacturers are continuously looking for solutions to replace the wood in the structure of an upholstered product with recyclable composite materials [1].

The interest and necessity of replacing wooden items in the structure of upholstered furniture, without affecting the external appearance of the product and its functional requirements, were presented in more detail in the papers [1], [2] and [3].

Many types of composite materials are known, and according to the consolidation method there are two large groups:

- Thermosets: composites that consolidate by heating and which practically cannot be recycled;
- Thermoplastics: composites that melt when heated and harden upon cooling, making them easy to recycle [4].

Authors have collaborated on the design and production of composite products for the upholstered furniture industry. Upholstered furniture manufacturers supply products to vendors operating in a global market. For this reason, they are constantly looking for solutions to reduce costs and improve quality. One such solution is the replacement of wood with composite materials with natural fibers (flax, hemp, willow, poplar, coconut, etc.), mixed with other matrices, especially thermoplastics. Under these conditions, the partial replacement of wood and wood-based products in the structure of an upholstered article with composite materials with polypropylene matrices, reinforced with natural fibers, presents a number of significant advantages. These include the preservation of existing forests, the reduction of pollution and greenhouse gas emissions, the preservation of flora and fauna, the increase in the productivity of fiber-producing crops, and the reduction of costs [1], [4]. Due to the continuous increase in competitiveness in this field of upholstered products, mass-produced products, manufacturers are continuously looking for ways to reduce costs. In the case of replacing wood with thermoplastic composite materials, cost reduction can be achieved by: - increasing the physical and mechanical properties of the material (Yield strength, ultimate tensile strength, Young's modulus, and elongation) - using ribbed parts that lead to a

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reduction in the weight of the parts. The properties of the material can be improved by modifying the network (type, quality and proportion of natural fibers, type of matrix and its proportion in the composite material) or by using compatibilizing agents or natural adhesives. The use of polypropylene as a thermoplastic matrix provides advantages regarding product recycling. For this reason, market requirements aim to decrease the percentage of polypropylene and increase that of natural fibers. The properties of the material can also be improved by using compatibilizing agents such as lignosulphates, maleic aldehyde, etc. In this paper, the authors aim to reduce the weight of the material by using parts with corrugated surfaces similar to those used in egg formwork.

The present paper explores the impact of using an egg carton-shaped chair seat surface as a replacement for the conventionally used flat surface. This type of shape could lead to increased mechanical performance, less material and smaller costs of upholstered furniture products. The chair is covered with a piece of foam with a profile similar to that of the egg carton piece, so that the final product has a normal shape and the profile inside isn't observed.

The modeling of the profiled parts and the finite element analysis were performed using SolidWorks CAD and CAE. The Dynaform software was used for the numerical simulation of the thermoforming process.

## 2. STATE OF THE ART

Up to the present, several attempts have been made to consolidate various complex shapes built of natural fiber composite materials which were used in upholstered furniture.

The use in various fields such as the automotive industry, the furniture industry and even civil engineering of composite materials reinforced with natural fibers through various consolidation processes such as thermoforming, injection or extrusion, has attracted an increased interest due to recyclability and increased mechanical performance.

There are numerous papers which have attempted to obtain complex shapes by thermoforming composite materials reinforced with natural fibers.

Paper [5] studied the effect of using two types of lignin (lignosulfonate and soda lignin) on the properties of hemp fiber reinforced polypropylene composites for furniture applications. An addition of 20% soda lignin or lignosulfonate (relative to the nonwoven mass) was used and a significant improvement in the mechanical properties of the material was found.

Paper [6] investigated the behavior of polypropylene reinforced with wood fibers composite materials and analyzed the influence of the fiber mass in the thermoforming process on hemispherical parts. It found that an appropriate quantity of fiber was between 30% and 40%, later mentioning that in order to obtain a defect free part (wrinkles or tears) the maximum percentage of the fiber was 25%. Even though for simple shapes a blend of 50% fiber with 50% polymer works in order to obtain parts with complex shapes it is necessary to reduce the amount of fibers.

The present paper investigates how an egg carton shaped part made of a polypropylene and hemp fiber composite can be obtained while considering the following parameters: the profile radius, the step and the thickness.

The egg carton type part that is researched in this paper contains between 40% and 50% hemp fibers to ensure mechanical strength since the part will be used in the furniture industry. We use this percentage of fiber according to paper [7] which studied various hemp composite material formulations with fiber oriented in two different directions.

Paper [8] analyzed the sustainability of using composite materials reinforced with plant fibers. The Figure below presents the manufacturing process briefly from obtaining the raw materials (hemp, jute, polypropylene, flax) to the final thermoformed product.

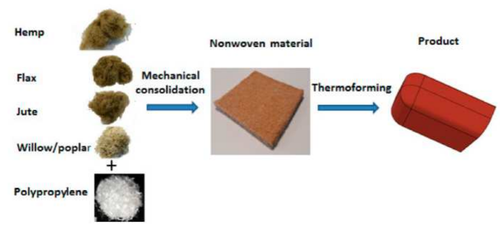


**Fig. 1.** The process of obtaining a natural fiber composite product through thermoforming [1]

The analysis carried out in the mentioned paper found that it is advantageous to use fiber-reinforced composite materials to replace wood in the furniture industry. The use of fiber-reinforced composite materials represents an attractive direction in furniture making because these materials can be recycled. The natural fibers currently used in these composites require a reduced land area compared to wood grown in forests.

A model of a chair made of composite materials covered with textile material is presented, the only wooden components remaining being the legs because they represent highly stressed components.

**Fig. 2.** Chair with backrest made of polypropylene and hemp composite [1]

To simulate the thermoforming process, the material characteristics from [9] and the egg-shell shape model from [10] will be used.

Paper [9] provides the necessary data for the simulation of thermoforming using LSDYNA, such as Young's Modulus, Poisson's ratio, and the necessary points on the stress-strain curve at a temperature of 160°C, for a polypropylene material that has been tested for the thermoforming process

Paper [10], the authors carried out a comparative analysis of a part with an egg-shell shape. They thermoformed a part made of nonwoven fiber composite material and compared it with the numerical model obtained using the LSDYNA program.
This research aimed to validate the accuracy of the numerical simulation by comparing it with a part obtained through thermoforming. The thermoforming simulation in LSDYNA involves moving the mold cavity towards the fixed core while applying a pressing force. This process shapes the semi-finished product to conform to the profile defined by the two mold components.

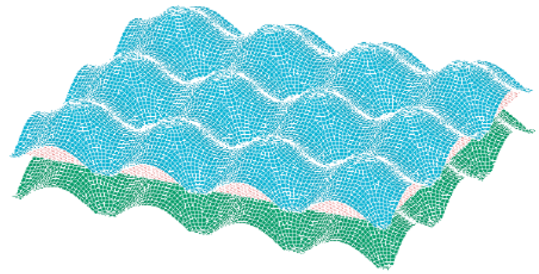

**Fig. 3.** Finite element discretization of the thermoforming process in LSDYNA [10]

The authors of paper [10] compared the dimensional results of the egg-shaped part shown in Figure 4, obtained through the thermoforming of a nonwoven fiber composite, with a numerical model created using LSDYNA. They noted that the numerical model represents progress, as the simulated part's shape exhibits similarity to the physically produced part, although it lacks correlation in terms of dimensional accuracy.

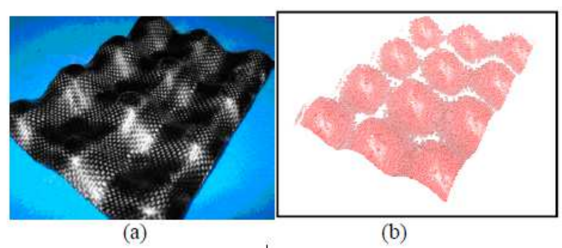


**Fig. 4.** Piece with an egg-shaped form made of nonwoven fiber composite (a) and numerical model made by numerical simulation (b) [10]

In eta/DYNAFORM [11], there is a user manual specifically designed to enable users to create numerical models useful for simulating the thermoforming process. The 3D models of the mold and the semi-finished product are imported in the .IGS format, containing only material surfaces relevant to the thermoforming simulation. Using eta/DYNAFORM version 5.6.1, the gravitational deformation of the semi-finished product is initially simulated. Subsequently, the shape of the gravitationally deformed semi-finished product is imported into the program to perform the thermoforming process simulation. Eta/Post [12] facilitates a detailed analysis of the thermoforming process, providing the necessary results for process validation. These results include the thickness distribution and the prediction of the force required for thermoforming the part, which will also be analyzed in this study.

## 3. PROPOSED REINFORCEMENT SHAPES

The authors propose the use of egg carton shaped boards instead of plain flat or curved boards for chair surfaces. This is predicted to increase the strength and stiffness of the products without a significant increase in price. The final exterior design of the furniture piece remains the same since this structure is covered with foam and textile material.

According to Figure 5, we investigated the influence of variations in the profile radius and pitch. The analysis included different egg-crate configurations, defined by the following parameters:

- radius of 15, 20 or 35 mm;
- pitch of 30, 50 and 70mm;
- thickness of 1, 2 or 3 mm.

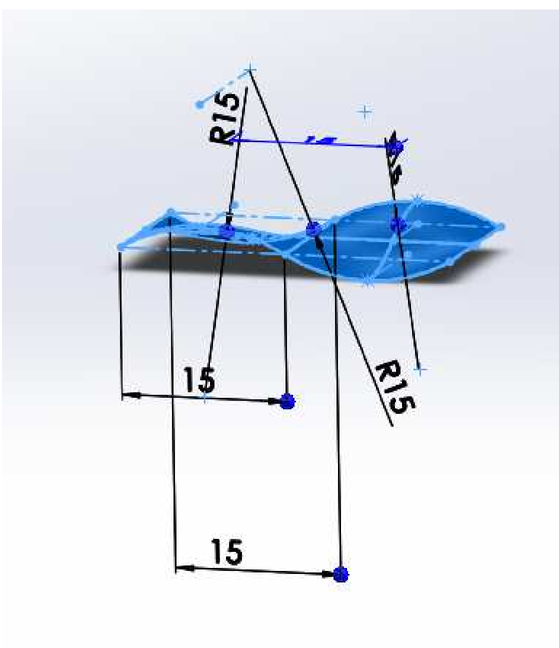


**Fig. 5.** Basic egg carton pattern

The egg carton shaped plate is shown in isometric view in Figure 6. Its size is 300 by 300 mm.

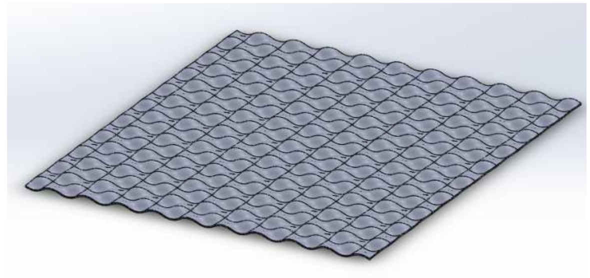

**Fig. 6.** Egg shaped board

The part profile was designed starting from the initial sketch with a simple shape consisting of two arcs of the same radius and a pitch of double the arc radius. The three values used for the radius are sequentially combined with the three values of the thickness so that a total of 9 board variants are considered. The results of the finite element analysis simulation are found in Table 2 and Table 4.

## 4. NUMERICAL SIMULATIONS

### 4.1. THERMOFORMING PROCESS SIMULATION

The thermoforming process was simulated using the Eta/Dynaform program.

The parameters of the polypropylene material can be found in paper [8], [9] and are summarized in table 1 for a temperature of 160°C. The stress-strain curve for different temperatures of a hemp and polypropylene composite are presented in Figure 7. The mechanical behavior of polypropylene reinforced with various fibers is mentioned in paper [4]. The material parameters were taken from these two papers and used for the simulation of the thermoforming process.

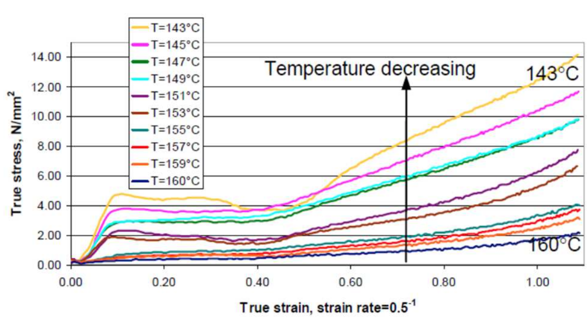


**Fig. 7.** Stress-strain curves for polypropylene between the temperatures of 143°C and 160°C [8], [9]

*Table 1*

**Table 1. Parameters of the composite material made of polypropylene reinforced with hemp fibers [3]**

| Plastic strain [-] | Yield stress [N/mm2] |
|---|---|
| 0 | 0.2 |
| 0.2 | 0.35 |
| 0.4 | 0.43 |
| 0.6 | 0.71 |
| 0.8 | 1.1 |
| 1.0 | 1.73 |

The stages of the thermoforming process are as follows:

- gravitational deformation starting from the initial thickness (1, 2 or 3 mm) of the composite layer;
- thermoforming of the composite material by moving the mold cavity towards the core; the core is fixed and placed below the cavity; only the cavity moves.

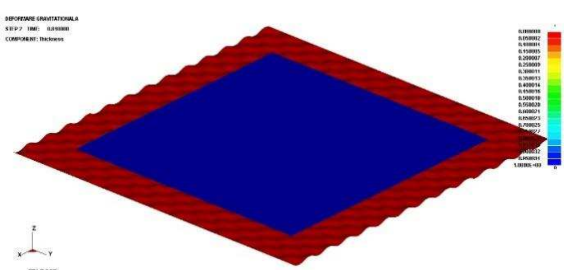

**Fig. 8.** Gravitational deformation in Eta/Post

To solve the simulation in Eta/Dynaform, the CAD models of surface type were imported using the .igs extension. This .igs extension is recognized by the Eta/Dynaform software. For this analysis, the mold core and the 300x300 semi-finished product were imported, and the cavity was generated by copying the discretization elements in the Auto-setup menu in Eta/Dynaform, which established a mesh size according to the thickness of the part.

For each piece, we used the process that involved gravitational deformation and thermoforming of the material. The material thicknesses and the material parameters from Table 1 were established using the Auto-setup menu in Eta/Dynaform. The Eta/LS-Dyna solver was used with double precision for the gravitational deformation simulation and with single precision for the thermoforming simulation.

The simulation of the thermoforming process in Eta/Dynaform is shown in Figure 9 and consists of moving the mold cavity on the Z-axis towards the mold core; this procedure deforms the semi-finished product into the shape of the molds.

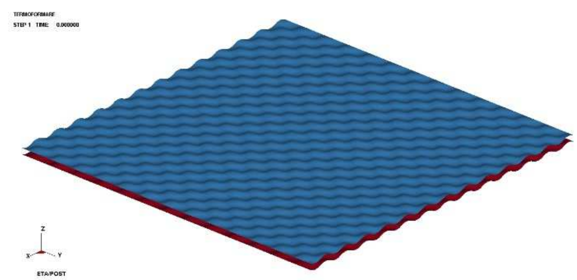

**Fig. 9**. Thermoforming process simulation using Eta/Post-Processor

In Figure 10 is shown the distribution of thickness of the egg carton shaped piece. In the figure, it can be observed that the center of the part is the area where the material thins and is marked in red. This phenomenon is repeated for all simulation models, regardless of the thickness, radius, or pitch of the part.

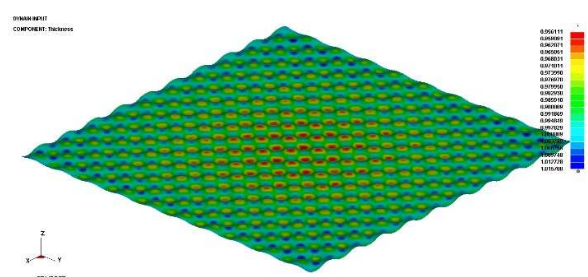

**Fig. 10**. The thickness variation of part R15p30g1 with an initial thickness of 1 mm

The results of the thermoforming process simulation research, including the initial thickness, minimum thickness, maximum thickness, and required force, are presented in Table 2. The table contains data for each part, categorized by thickness, pitch, and radius, and denoted as RXXpXXgXX, where R represents the radius, p represents the pitch, and g represents the thickness. The study examines the influence of the thermoforming process on the minimum and maximum thickness compared to the initial thickness.

*Table 2*

**Table 2. Results of the numerical simulations of the thermoforming process**

| Part code | Initial thickness [mm] | Minimum thickness [mm] | Maximum thickness [mm] | $F_{max}$ [N] |
|---|---|---|---|---|
| R15p30g1 | 1 | 0.95 | 1.01 | 469,04 |
| R15p30g2 | 2 | 1.89 | 2.02 | 1247,83 |
| R15p30g3 | 3 | 2.81 | 3.03 | 2230,15 |
| R25p50g1 | 1 | 0.96 | 1.02 | 216,25 |
| R25p50g2 | 2 | 1.91 | 2.03 | 604,11 |
| R25p50g3 | 3 | 2.84 | 3.04 | 1113,91 |
| R35p70g1 | 1 | 0.97 | 1.03 | 141,55 |
| R35p70g2 | 2 | 1.93 | 2.05 | 349,64 |
| R35p70g3 | 3 | 2.88 | 3.05 | 637,36 |

## 4.2 CHAIR SEAT LINEAR SIMULATION

The simulation of the mechanical behavior of the finished product, the thermoformed board, was carried out with two fixed supports, which are actually the places where the seat is fixed to the frame and a 200 mm (can be seen in Figure 11) circular surface which is approximately the surface where a person sits on the chair. The force on the circular surface is 1000 N, corresponding to an approximately 100 kg person. The actuation force for testing is on the upper side of the part, and the fixed supports (can be seen in Figure 12) are on the lower side of the part.

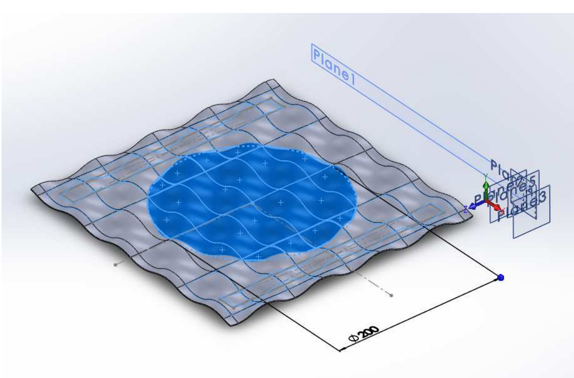


**Fig. 11.** The circular area where the force is applied is 200 N.

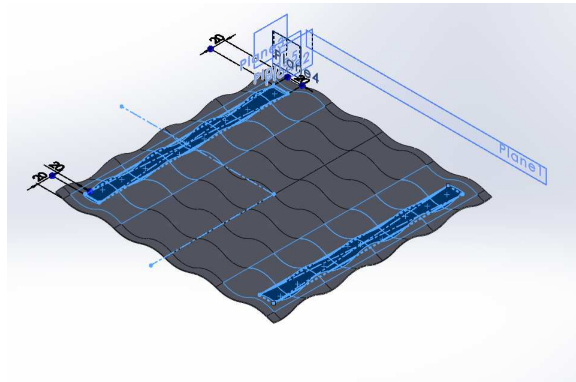


**Fig. 12.** Fixed Geometry of part for simulation

The properties of the composite material made of 50% polypropylene and 50% hemp fibers are shown in table 3, the main properties are the modulus of elasticity, Poisson's ratio, density and tensile strength.

*Table 3*

**Table 3. Properties of the composite material**

| Property | Value | Units |
|---|---|---|
| Elastic Modulus | 316000000 | N/m^2 |
| Poisson's Ratio | 0.35 | - |
| Mass Density | 740 | kg/m^3 |
| Tensile Strength | 27300000 | N/m^2 |

These types of numerical simulations were used to improve the strength of the chairs. The parameters that underlie the testing were taken from the standards of global furniture manufacturers.

The simulation results are found in table 4 with the following parameters: initial thickness, displacement and mechanical stress.

*Table 4*

**Table 4. Stress and displacement for the different seat shapes**

| Part code | Initial thickness [mm] | Displacement [mm] | VonMises stress[MPa] |
|---|---|---|---|
| R15p30g1 | 1 | 29.15 | 24.91 |
| R15p30g2 | 2 | 24.48 | 20.99 |
| R15p30g3 | 3 | 17.67 | 17.89 |
| R25p50g1 | 1 | 31.07 | 26.90 |
| R25p50g2 | 2 | 22.63 | 19.07 |
| R25p50g3 | 3 | 18.60 | 16.82 |
| R35p70g1 | 1 | part break | part break |
| R35p70g2 | 2 | 24.29 | 23.91 |
| R35p70g3 | 3 | 19.95 | 21.06 |

For part R35p70g1, the simulation program in the SolidWorks CAD software crashed at 89.4%, as can be seen in Figure 13. It can be seen in the Figure 13 that there are large displacements which are most likely the cause of the finite element analysis simulation running stops. The result in Figure 14, which shows the displacement analysis of the finite element simulation of the part, is partial, with values of 12% and 39% of the simulation. Therefore, it is considered a part break that cannot be compared in the table with the other parts. For the other parts, the simulation proceeded normally, without error messages. The most likely error that caused this simulation failure can be attributed to the eggshell shape profile which has a larger radius, which could lead to bending sensitivity under force.

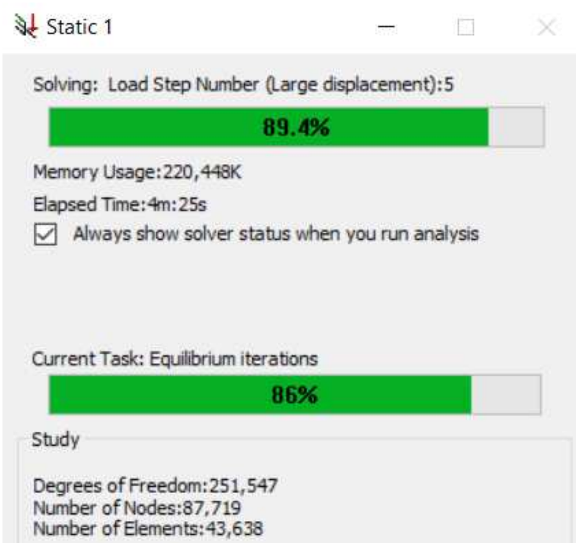


**Fig. 13.** Part Break R35p70g1 of Static simulation

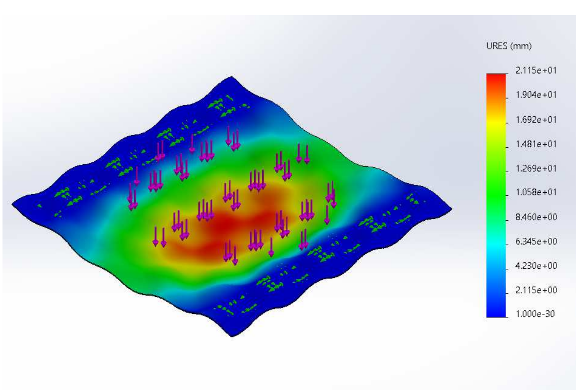


**Fig. 14.** Part Break R35p70g1 of Static simulation, with partial results

## 5. CONCLUSIONS

The pressure required for thermoforming of the part is directly proportional to its thickness, but inversely proportional to the pitch and radius of the egg carton profile.

The thickness of the part is almost unchanged in the center of the part where there are higher tensile stresses in the thermoforming process. The thickness variation is between -0.16 mm to +0.05 mm compared to the initial thickness.

Following the analysis performed, it was found that the deformation expressed in mm in Table 3 decreases for the same profile with increasing thickness, regardless of the profile radius or pitch, and so does the breaking force. The results also show that as the pitch increases the von Mises stress also increases, which is clear because the shape tends towards a flat board. The idea is during the design phase to find a pitch that is small enough to obtain small stresses, but not to small so as to consume too much material or to be difficult to manufacture.

The limitations of this paper is that, due to the two parameters, the pitch and the radius of the profile, the surface on which the fixed support is placed can influence the results leading to a lack of correlation between the increase in pitch and the radius of the part profile.

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**Optimizarea termoformării unor piese tip cofraj de ouă din materiale compozite de polipropilenă armată cu fibre de cânepă, în funcție de raza și pasul profilului.**

Această lucrare își propune să dezvolte noi posibilități de îmbunătățire a performanțelor mecanice în domeniul materialelor compozite armate cu fibre vegetale. Sunt investigate piese cu o formă de tip cofraj de ouă, cu diferite raze și pasuri ale profilului. Acest tip de formă va fi implementat în scaune. Scopul principal este de a îmbunătăți rezistența mecanică, deoarece studiile de specialitate au arătat că piesele cu diferite forme și profiluri sunt mai rezistente decât cele cu formă plană. Forma profilului de tip cofraj de ouă pentru scaunul tip taburet nu va fi vizibilă după ce va fi acoperit cu un material textil.

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