Furniture use safety at early design stage

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Abstract: *Furniture use safety at early design stage.* This paper presents a virtual method of determining the usage safety of a bed frame. The aim of the study was to investigate the influence of different external loads dictated by standards on the newly designed bed structure. Furthermore, it was decided to take into consideration unusual ways of acting load. Finally, the test of dynamic load was carried out. The analysis was executed by means of Finite Element Method in Computer Aided Engineering software. Results of stress distribution and displacements were compared to previously investigated mechanical properties of the used materials, such as elastic plywood and pine wood rigidity. Based on compared data, the safe use of bed frame was determined. The numerical calculations performed proved that there are possibilities of design changes to improve user safety and/or reduce production costs while ensuring sufficient mechanical properties of the furniture. Conclusions of the analysis suggested a possibility to sub-optimize the tested solution.

*Keywords***:** FEM, bed, stress, displacement, dynamic

INTRODUCTION

Each product on the market should guarantee safety to customers in accordance with the General Product Safety Directive (2001/95/WE). A safe piece of furniture is designed and produced in line with the requirements and conditions described by European standards. Obviously, the safety of furniture depends primarily on such factors as shape of the piece, the used materials and their mechanical characteristics or the kinds of joints. On the one hand, during the design process there is a number of ideas connected with technology and materials. Engineers are obliged to immediately find out the option that provides the demanded stiffness and durability. On the other hand, making physical models and conducting physical tests takes lots of time and has a significant influence on production costs increase. That is why there is a need for virtual tools allowing designers to verify their construction solutions in a quick and efficient way at early stages of the design process.

The Finite Element Method (FEM), developed more than 50 years ago, allows engineers to predict the behaviour of the designed structures during usage, with the help of numerical calculations. The essence of FEM is to discretize the analyzed object. It is a process of transferring continuous models and equations into discrete counterparts - finite elements. The use of software with FEM ensures a fast and convenient way of verifying the mechanical properties of new construction designs, although specialist knowledge is required.

Over a dozen years after the appearance of FEM, numerous computer analysis were undertaken in terms of furniture durability. Subsequent promising results of chair construction test executed by Smardzewski (1990) with a simple application PANDA-1 paved a new and constantly evolving direction in the development of furniture design. In the following studies, a numerical model designed for determining the durability of skeleton furniture constructions was also developed by Smardzewski. Smardzewski and Prekrat (2002) used FEM software to evaluate stress distribution in disconnected furniture joints. Smardzewski and Papuga (2004) assessed stress distribution in angle joints of skeleton furniture subsequently. Smardzewski and Ożarska (2005) tried to investigate the rigidity of cabinet furniture with semi-rigid joints of the confirmat type. Smardzewski and Kłos (2011) presented alternative methods of numerical modelling of dowel joint rigidity of board elements, using for this purpose nodes of substitute linear elasticity modulus. Strength analysis methods included in the design phase

contributed effectively to optimizing the construction. Smardzewski and Gawroński (2001) presented FEM algorithms for chair construction optimization. Subsequently, they developed a method of gradient optimization for skeleton furniture with different connections. Smardzewski and Prekrat (2009) successfully performed the optimization of a sofa frame in the integrated CAD-CAE environment. While designing, every aspect of furniture construction has to be taken into consideration at an early stage of prototyping. In relation to attempts of suboptimization, reference was made to the criteria described by Ostwald (1987) and Smardzewski (2008). The idea of this paper is to pay attention to a method that allows to determine the mechanical properties of a structure globally, at an early stage of the design process and, based on the results, propose design changes in order to suboptimize the construction.

MATERIALS AND METHODS

Material characteristics

The bed frame shown in figure 1 was made mainly of pine wood elements. Only the head and foot of the bed were made of glued and bent elastic plywood veneers made of Fuma (exotic wood species) - the head was made of three veneers 8 mm thick and the foot was made of four veneers 5 mm thick. In numerical analysis wood was considered as an orthotropic material. Elastic plywood was analyzed in regard to two major axes of orthotropy. Thus, in a 3D model of the bed, there were spatially oriented elements, and the values of their mechanical properties depend on the anatomical direction of the wood and wood-based material.
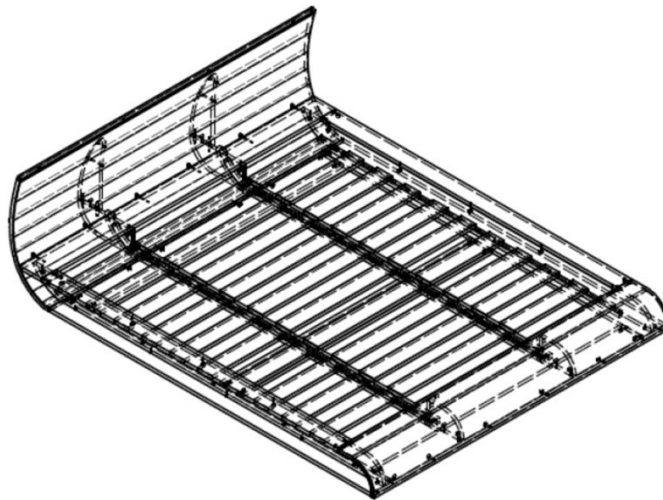

Figure 1. Tested bed structure

Hence, it was necessary to investigate the mechanical properties of the used materials. Samples of pine wood were prepared accordingly, in order to determine their flexural rigidity (Rg) in three point bending and their Modulus of Elasticity (MOE) in the longitudinal anatomical direction (longitudinal-tangential - LT and longitudinal-radial - LR surfaces). There were ten samples for each surface series. Flexural rigidity of wood and MOE tests were carried out in accordance with PN-77/D – 04103 and PN-63/D-04117 standards, respectively. The tests of flexural rigidity and MOE of plywood were conducted along with the PN-EN 310 standard, although it was impossible to determine the flexural rigidity of the samples in which the grain was oriented in parallel to the acting force. Examined specimens did not shutter under the acting load even when a small bending radius value was obtained. Ten samples were tested for each material - elastic plywood 5 mm and 8 mm thick with grains running in

parallel and in perpendicular to the acting force. Figure 2 presents the stiffness characteristics of pine wood samples during flexural tests.
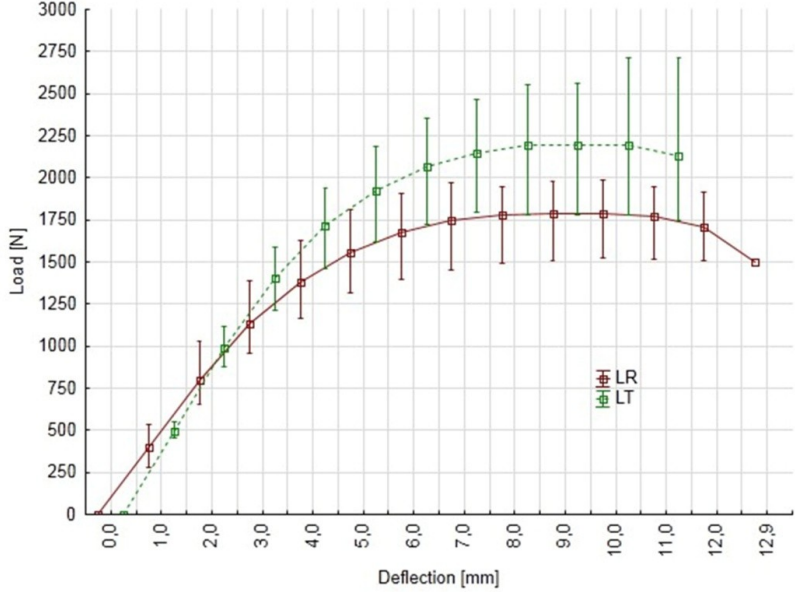

Figure 2. Stiffness of the pine wood used in the experiment

Clearly, pine wood in LT surface is characterized by maximum stiffness value about 37% higher than LR surface. Comparable data gained from flexural experiment conducted on elastic plywood are presented in figure 3. The elastic plywood with 8 mm thickness is stiffer by about 42% than the 5 mm plywood.
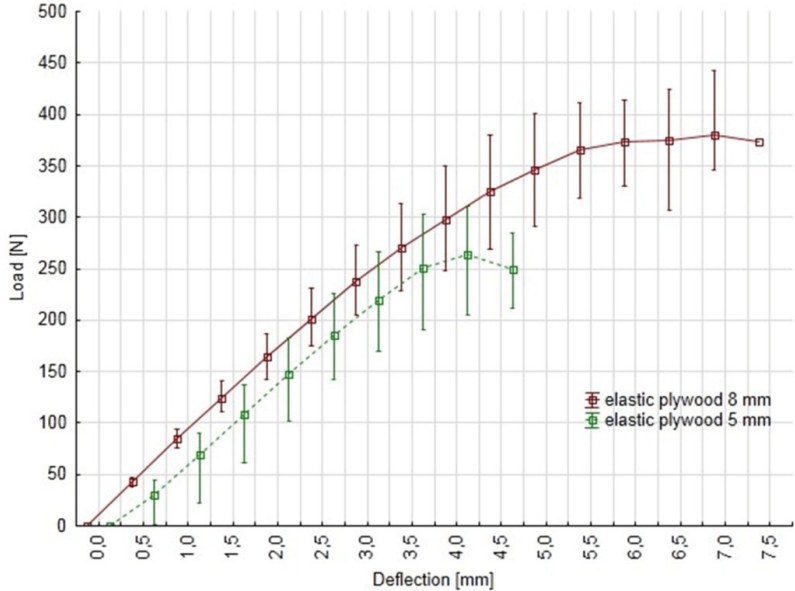

Figure 3. Stiffness of the elastic plywood used in the experiment

The characteristics of pine wood and plywood presented above are not sufficient for a full description of orthotropic properties. They refer to elastic properties in the longitudinal direction (wood) and two major directions of orthotropy (flexible plywood). The heterogeneity of the used materials is characterized by the three main directions of orthotropy. In addition, it was necessary to specify the value of Poisson's ratios in the individual

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anatomical planes. Based on the data gathered by Hearmon (1948) and mentioned by Smardzewski (2008), the missing properties of wood were adopted. Figure 4 shows the main axes of orthotropy of flexible plywood conventionally referred to wood anatomical directions - longitudinal (L), tangential (T) and radial (R).
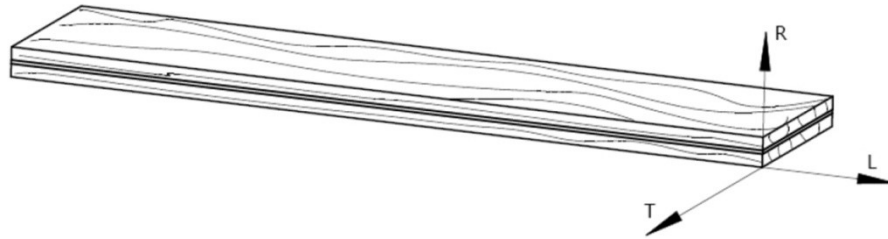

Figure 4. Adopted main axes of orthotropy for elastic plywood

Noted the fact that elastic properties of plywood take extreme values in the main two mutually perpendicular directions, it was assumed that the most important Poisson's ratios will be determined in plane LT. It was also assumed that the omission of Poisson's ratios for the planes containing the direction of the thickness (R) will not have a significant impact on the quality of the results. To fulfill those assumptions, it was relevant to use the equation mentioned by Smardzewski (2008) and Gerrard (1987). Adjusted to the requirements of this paper, it presents as follows:

$$\frac{v_{LT}}{MOE_{LT}} = \frac{v_{TL}}{MOE_{TL}} \qquad (1)$$

Where:
v_{LT} - Poisson's ratio for LT surface,
MOE_{LT} - Modulus of Elasticity for longitudinal direction,
v_{TL} - Poisson's ratio for TL surface,
MOE_{TL} - Modulus of Elasticity for tangential direction.

The shear modulus was calculated in accordance with the equation presented by Smardzewski:

$$G_{yx} = \frac{MOE_y}{2(1+v_{yx})} \, (MPa) \qquad (2)$$

Where:
G_{yx} – Shear modulus in chosen surface (MPa),
MOE_y – Modulus of Elasticity in chosen direction (MPa),
v_{yx} – Poisson's ratio for chosen surface.

Table 1. Selected properties of pine wood used in the tests

	Density [kg/m³]	Rigidity, Rg [MPa]		Modulus of Elasticity, MOE [MPa]				Shear modulus, G [MPa]			Poisson's ratio v [-]						Modulus of Rupture, MOR [MPa]
		LT	LR	LT	LR	R	T	LT	LR	RT	LR	LT	RT	TR	RL	TL	dynamic test
Pine wood	550	97	82	12809	12758	1118	584	693	1181	70	0.4	0.5	0.7	0.3	0.04	0.02	89

Moreover, for the dynamic test, the Modulus of Rupture (MOR) was also determined. The equation by use of which the MOR is determined, is important for the elastic limit range.

Based on the relationship between the MOR ratio and literature (Bergman et. al. 2010), it was assumed that the ratio of MOR to MOE of pine is about 0.007. The full characteristics of materials gathered both from experiments and literature are shown in table 1 and table 2.

Table 2. Selected properties of elastic plywood used in the tests

	Density [kg/m³]	Rigidity, Rg [MPa]		Modulus of Elasticity, MOE [MPa]		Shear modulus, G [MPa]			Poisson's ratio ν [-]					
		grains parallel	grains perpendicular	grains parallel	grains perpendicular	LT	LR	RT	LR	LT	RT	TR	RL	TL
elastic plywood 5 mm	350	-	32	124	4237	1471	2119	62	-	0.4	-	-	-	0.01
elastic plywood 8 mm	350	-	31	44	4511	1566	2256	23	-	0.4	-	-	-	0.01

Load diagrams and support

Based on the PN-EN 1725 standard and heuristic thoughts exhibiting customer's use, static diagrams were adopted as shown in figure 5.
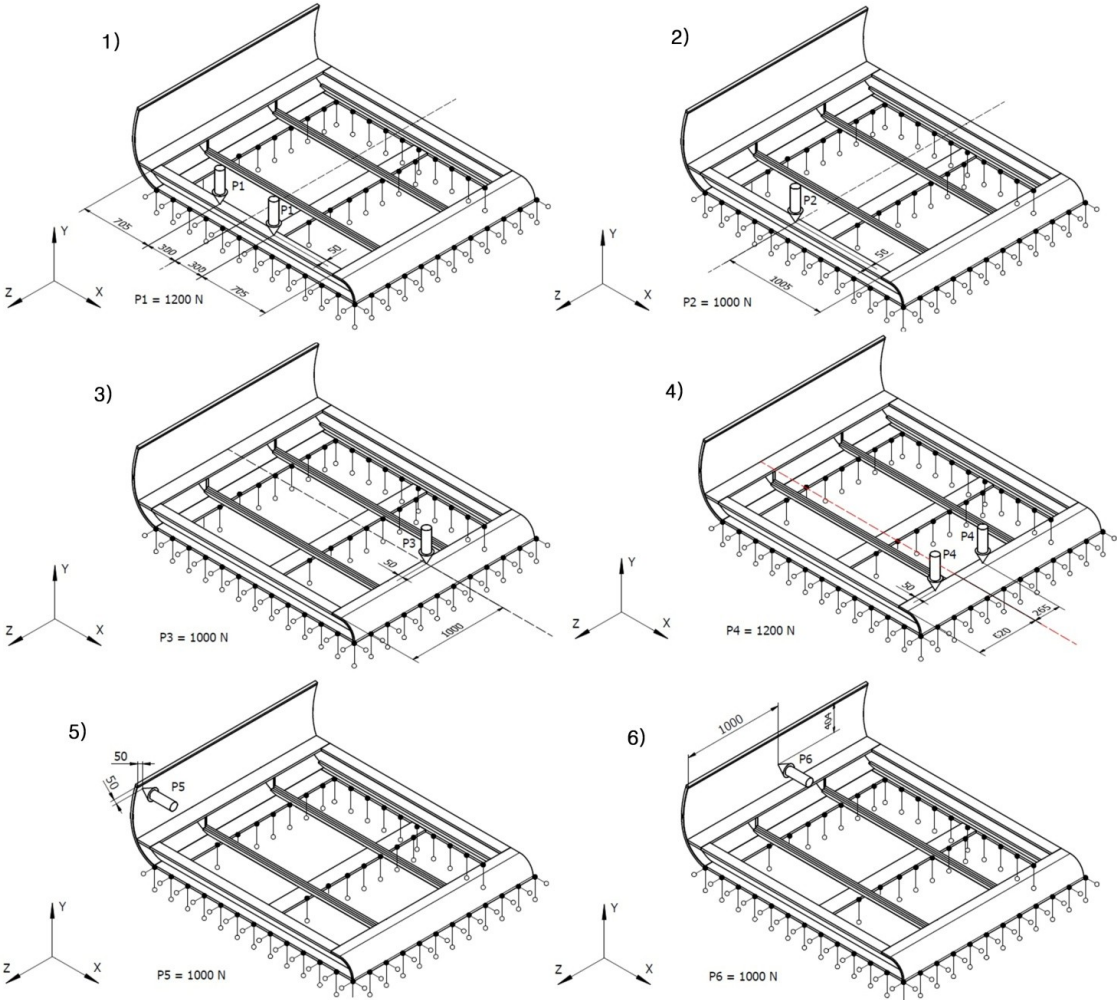

Figure 5. Static load diagrams

Loads dictated by standards were applied as force P1, P2, P3, and P4. Custom ways of usage were reflected by forces P5 (left upper corner of top is being pushed) and P6 (two persons are resting simultaneously). The dynamic experiment was simulated by dropping a steel element weighing 4.2 kg on the side of bed directly (Fig. 6).
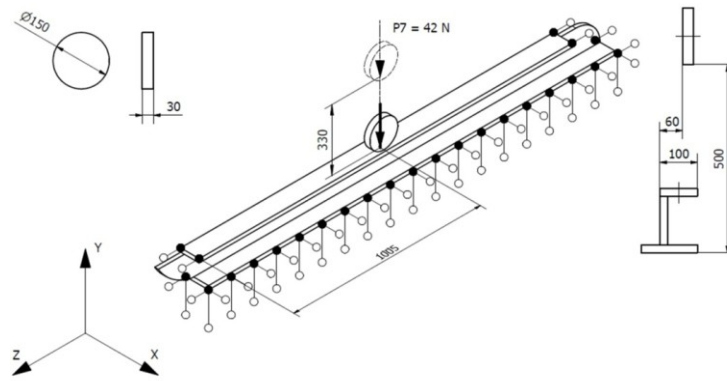
Figure 6. Dynamic load diagram

The bed frame was supported in a way to prevent its movement under the influence of the forces. In the dynamic test, the divided side of bed was supported so as to simulate the connection with the rest of construction.

Numerical models

Numerical models were prepared directly from the imported 3D bed model created in CAD software (Inventor Professional). The discretization process proceeded automatically in the CAE application (Nastran In-CAD). More attention was paid to proper attribution of material characteristics to model elements in relation to orthotropic and orthotropic axes. To do it correctly, the groups of different spatially oriented parts were separated as presented in figure 7.
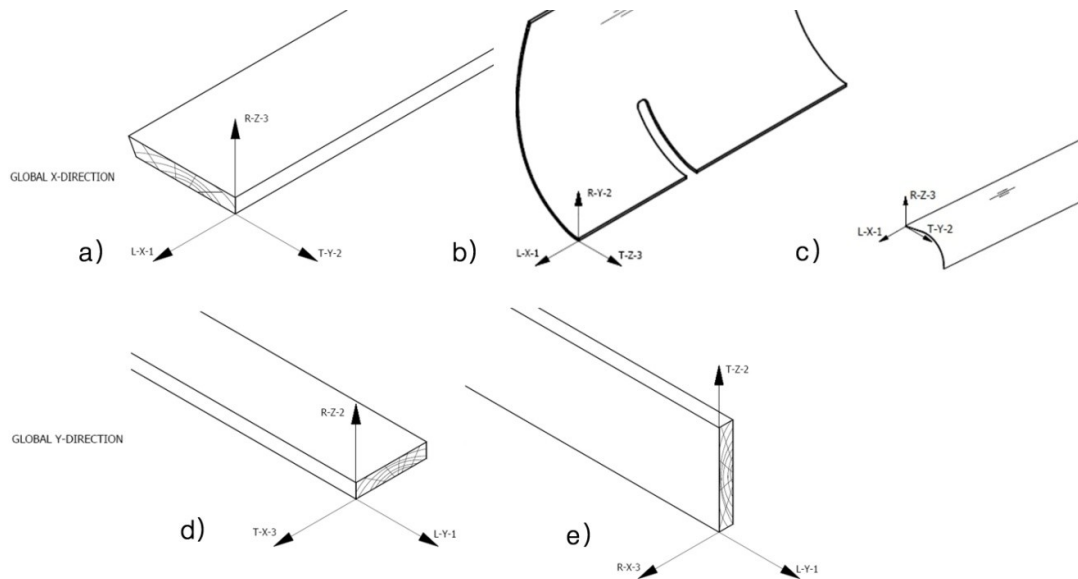

Figure 7. Major axes of orthotropy in relation to global axes of CAE software

Table 3. Orthotropy axes settings in CAE software

No.	CAE axes settings		
	Global X-direction	Global Y-direction	Global Z-direction
1	X	Y	Z
2	Y	Z	X
3	Z	X	Y

The main axes of orthotropy were attributed to the global axes (1, 2, 3) set in the CAE program (table 3). Then, the material characteristics were implemented and the bed structure was loaded and supported.

For the dynamic durability test, the contact between surfaces of the steel element and the top of bed side was defined. The gravity force was applied to the steel element. After adding support, the model was completely prepared for the dynamic test.

RESULTS AND DISCUSSION

The stiffness and durability of the bed frame were assessed on the basis of values of displacement and stress distribution in the loaded elements. The results of computer calculations were analyzed precisely and the elements with maximum stress and displacement values were indicated. In the next stage, the data obtained by numerical computation were compared to the results from previously conducted physical experiments. It led to determine whether the stress occurring in the structure results in damage or destruction of intensive elements. Figure 8 shows an example of the displacements occurred under the influence of an external load.
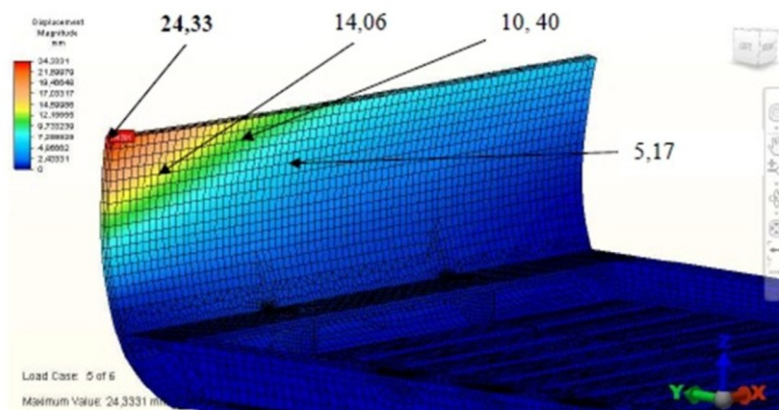

Figure 8. Displacement of bed frame under applied force

This variant presents the maximum deflection value which is remarkably higher than the effects of other forces acting. Apart from this case, based on the results (table 4) it was concluded that the bed frame remains stiff enough under the influence of other acting forces.

Table 4. Results of numerical analysis

Test	Maximum displacement [mm]	Maximum stress [MPa]	Forced element material	Max. stress in percentage of material rigidity [%]
Load diagram 1	1.03	12.29	Pine wood [LR]	14.99
Load diagram 2	0.77	7.16	Pine wood [LR]	8.73
Load diagram 3	0.66	11.32	Elastic plywood*	35.38
Load diagram 4	0.71	13.05	Elastic plywood*	40.78
Load diagram 5	24.33	15.41	Elastic plywood**	49.71
Load diagram 6	3.50	10.93	Pine wood [LT]	11.27
Dynamic test	16.16	43.70	Pine wood [LR[	53.29
* - element made of glued 5 mm elastic plywood sheets				
** - element made of glued 8 mm elastic plywood sheets				

The presented displacement values ranged from nearly 0.66 mm to 3.50 mm. They prove the satisfactory mechanical properties of the tested bed frame and contribute to attempt its suboptimization. For the dynamic test, it was determined that the steel element caused a 16.16 mm displacement while hitting the top surface of the bed side element.

The biggest value of displacement in the fifth load diagram indicated also the biggest stress result. The obtained value of 15.41 MPa corresponds to nearly 50% of the maximum rigidity of the tested 8 mm thick flexible plywood. Other stress effects in directly loaded elements did not exceed 41% of maximum rigidity of the materials that they were made of.

The calculated percentage relationships indicate that structural elements are strong and successfully carry external loads. Despite the large deflections, the top front does not show a tendency for damage or destruction under the influence of the load. This is due to the good elastic characteristics of the material from which it was made.

In dynamic tests, the calculated stress value (43.70 MPa) corresponds to 53% of the determined Modulus of Rupture. It appears that this element is strong enough. The results indicate that the impact does not cause serious deformities or damage. Moreover, the calculated stress reached values that were nearly three times higher than the results of the static tests.

CONCLUSION

In general, relatively low values of displacement and stress distribution point out that the bed structure is sufficiently rigid and stiff. The analysis of the bed frame showed that the attempts of suboptimization can be freely taken. The performed numerical calculations proved that there are possibilities of design changes to improve user safety and/or reduce production costs while ensuring sufficient mechanical properties of the furniture. Suggested solutions include:

- Reducing the number of elastic plywood sheets assembling the bed foot.
- Changing the number of supporting ribs in order to ensure better support in 1/3 of the bed head length.
- Modifying the technology of supporting ribs - these elements (made of wood) could be cut as a single MDF elements.
- Changing the material and reducing the thickness of elements in the bed sides to 18 mm.

By use of the finite element method, there is a possibility to perform multiple bed tests considering changes of the design. This can be done without any additional financial and material losses. The time devoted to this activity results in the optimal variant at the virtual modelling stage, reducing the number of prototypes produced.

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Streszczenie: *Bezpieczeństwo użytkowania mebla na wczesnym etapie projektowania.* Zgodnie z Dyrektywą 2001/95/WE Parlamentu Europejskiego i Rady z dnia 3 grudnia 2001 r. w sprawie ogólnego bezpieczeństwa produktów wymaga się, aby sposób użycia wyrobu ani on sam nie stwarzał zagrożenia dla zdrowia i życia użytkowników. Dobór materiałów na elementy mebla i sposób ich połączenia stanowią, zatem kluczowe działania w kontekście inżynierskiego projektowania mebli. Jednym z zadań wieloetapowego procesu projektowania jest kosztowne wykonywanie prototypów z materiałów docelowych. Dzięki oprogramowaniu wspierającemu projektowanie inżynierskie - CAE, można dokonać wstępnej oceny wytrzymałości konstrukcji przez numeryczne obliczenia metodą elementów skończonych. W niniejszej pracy przedstawiono wirtualne symulacje sposobu obciążenia nowej konstrukcji łóżka, podjęte już na etapie przygotowania bryły 3D. Elementy modelowano, jako wykonane z drewna sosny zwyczajnej oraz sklejki elastycznej FUMA o grubościach 5 mm i 8 mm. Wartości sił oraz punkty ich przyłożenia dobrano na podstawie odpowiednich norm. Obciążenie przykładano także do potencjalnie newralgicznych węzłów konstrukcji. Przeprowadzono ponadto symulację dynamicznego obciążenia boku łóżka. Na podstawie uzyskanych wyników ustalono, że zaproponowana konstrukcja jest bezpieczna, bowiem naprężenia w obciążanych statycznie elementach nie przekraczają 50% wytrzymałości użytego materiału. Szczyt łóżka, pomimo relatywnie dużego ugięcia, nie wykazywał tendencji do poważnych deformacji i uszkodzenia. Ostatnią część pracy poświęcono suboptymalizacji analizowanej konstrukcji łóżka.

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