Designing Chairs For Users With High Body Weight

Miloš Hitka,[a] Milan Naď,[b] Nadežda Langová,[c] Miloš Gejdoš,[d,]* Denisa Lizoňová,[e] and Maciej Sydor [f]

The relationship between the functional dimensions of the furniture and a user’s anthropometric dimensions is crucial for safety and functionality. The weight and dimensions of the user's body significantly affect the functional dimensions of the furniture, especially for overweight users. This paper is focused on the concept of chair structural design, which is suitable for bariatric users, including the application of additional reinforcing structural components. Such components are expected to improve the stiffness and strength properties of the chair structure, and it provides the possibilities to a chair design with improved ergonomic parameters. To increase rigidity and reinforce the frame structure of a chair for obese users, the side stretchers, middle braces inserted under seat and armrests are used. The main goal of the different structural designs of chair frames is to minimize internal forces acting in the structural components of the chair. The finite element method (FEM) was used to determine the internal forces and stress-strain state in the structural elements of the chair, starting with the standard design of the chair frame and comparing different design variants. A synergistic effect is obtained, making the bariatric chair durable and ergonomic, without stigmatizing its users.

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Contact information: a: Department of Economics, Management and Business, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia; b: Institute of Applied Informatics, Automation and Mechatronics, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu 2744/24, 917 24 Trnava, Slovakia; c: Department of Furniture and Wood Products, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia; d: Department of Forest Harvesting, Logistics and Ameliorations, Faculty of Forestry, Technical University in Zvolen, T.G. Masaryka 24, 960 01 Zvolen, Slovakia; e: Department of Mathematics and Descriptive Geometry, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia; [f]:Department of Woodworking and Fundamentals of Machine Design, Faculty of Forestry and Wood Technology, Poznań University of Life Sciences, Poznań 60-637 Poland;
**Corresponding author: gejdos@tuzvo.sk*

INTRODUCTION

Obesity was declared a primary public health issue by the World Health Organization in 1997. Over 1.9 billion adults aged 18 and older are overweight, and over 650 million are considered obese. The prevalence of obesity has increased dramatically in the last four decades, and if this trend continues, most of the world's adult population will be either overweight or obese by 2030. Obesity is caused by the interaction of genetic, metabolic, behavioral, and environmental factors, and it is a significant contributor to the global burden of chronic disease and disability, affecting people of all ages and socioeconomic groups (Haththotuwa *et al*. 2020). Respecting patient dignity and delivering optimum clinical care are primary issues, as are establishing procedures for safeguarding these patients' and their caregivers' health and well-being. The design of furniture is an essential tool for improved long-term clinical outcomes for bariatric patients. Success mandates a three-prong approach to the design process: appropriate facilities and space, proper equipment and furnishings, and training and standardized care protocols. Furnishings for spaces that are often overlooked, but are vitally important, are the lobby and waiting areas. Obese patients and visitors are often reluctant to sit for fear of not fitting in standard-sized furniture (Wignall 2008). Consequently, in some countries, there is a regulation of up to 15 to 20% of reception and family waiting room seating to accommodate obese individuals.

One of the many areas of bariatric care to consider is the appropriate selection of furniture, such as chairs, armchairs, and beds for bariatric users (Bakewell 2007). When selecting furniture for bariatric users, it is essential to consider factors such as weight capacity, size, stability, and comfort, which requires thorough evidence-based design research to fully understand the role these items play in meeting the needs of their users.

The methodical principles of product design guide designers toward making appropriate decisions (Asimow 1962). These principles in furniture design support the fulfillment of all groups of requirements for contemporary furniture:

Aesthetics: The design should be visually appealing and should complement the environment in which it is placed.

Ergonomics: furniture design prioritizes users' comfort and safety by considering the human body's natural posture and movements. The risk of accidents and injuries should be minimized, especially for vulnerable groups of humans. Furniture should be designed to fulfill its intended purpose effectively.

Durability: The furniture should be designed to last a long time, withstand everyday wear, and offer a reasonable reserve of endurance in unexpected situations during usage.

Sustainability: Eco-friendly materials and production processes that minimize waste should be prioritized.

Cost-effectiveness: The furniture design should consider the production costs and the market price to ensure that it is affordable and accessible to the target users.

Considering these principles, furniture designers can create products that are aesthetically pleasing, safe, functional, durable, sustainable, and cost-effective (Eckelman 2003; Smardzewski 2015; Jong *et al*. 2017). Evaluation of chairs on the domestic and global markets depends primarily on their quality, defined for specific user groups.

The functionality of seating furniture is influenced by the basic positions of the human body when it is supported, *i.e*., the active and passive positions of the human body when upheld. An active position is upright sitting and full contact of the feet with the floor, while a passive position is a reclined seat and the contact of the feet with the floor is light. These positions must be taken into account when designing bariatric chairs so that standing up and sitting down are especially comfortable for the user. The basic requirements for seating furniture result from the interaction between the user and the supporting surfaces, *i.e*., seat and backrest. For the magnitude and distribution of internal forces in the chair components, the vertical force acting on the front rail and the horizontal force acting on the backrest are crucial (Hajdarevic *et al*. 2023). Several studies also confirmed this by testing products under real-use conditions (Jeršić and Sinković 1978; Prekrat *et al*. 2012). Due to the material and time requirements for manufacturing chair prototypes, computer modeling methods are used to study the characteristics of the chair or the critical points with the greatest values of internal forces or deformation (Smardzewski and Papuga 2004; Hitka *et* *al*. 2018; Kasal *et al*. 2020).

In many cases, structures designed at a high artistic level do not meet the strength point of view, which would not fulfill the purpose they are supposed to serve. To avoid these shortcomings, it is necessary to know the size and nature of the distribution of internal forces in the structural components of chairs. Understanding the regularity of the distribution of internal forces in chair frame constructions is of fundamental importance when combining aesthetics and structural statics. The more perfectly the designer combines both aspects, the more elegant and functional the construction. Collaboration between designers and engineers in the early stages of design should be able to reduce structural integrity issues during the design phase itself. Efforts should focus on supporting such a collaborative design process.

Furniture used by bariatric users must meet all of the above criteria. Bariatric chair design requirements must take into account a wide variety of body types. These types of chairs must have dimensionally appropriate components on the seat that are sized correctly and are able to distribute weight greater than 200 kg. Bariatric furniture, or furniture for overweight, and equipment are not just larger objects. Bariatric furniture must combine the load limit, the relevant dimensions, and the aesthetics of the form, which is combined with an environment in which both the comfort and safety of the sitting persons and also the carer are ensured. Of the above-mentioned furniture requirements, special attention must be paid to the fulfillment of ergonomic requirements of individual furniture items (Martin and Hanington 2012). Bariatric furniture must also meet general safety requirements and increased strength resulting from its intended use. To ensure the comfort and safety of bariatric users, *e.g.*, introduction of electromechanical seating furniture positioning systems has great potential (Maňák 2014). Designing safe products must respect the requirements for primary prevention and health protection.

The main goal presented in the paper is the specification of a suitable construction concept of a wooden chair, which is based on selected types of components and their mutual configuration. The selection and evaluation of the suitability of the wooden chair construction concept involves determining the distribution of internal forces and reducing their values, which arise as a result of the chair's load with the user's weight is over 200 kg. Internal forces were determined using computer simulations relevant loads acting on virtual models of wooden chairs. The Finite Element Method (FEM) and the ANSYS software were used to perform the simulations. Due to the long-term sustainability and greening of production from renewable materials and the shape and strength stability of the wooden material, the study focused on chairs made of solid beech wood. Though the strength of joints connecting pieces of wooden furniture is often a point of failure, the topic of joint strength and joint design were not considered in the present work.

EXPERIMENTAL

Specifying the Load Based on Anthropometric Data

The necessary anthropometric data were collected directly in medical facilities in the years 2020-2023 in the Slovak Republic, while the anonymity of all respondents was guaranteed. The respondent's body weight, body height, and seat width are considered basic anthropometric characteristics for designing the basic geometric dimensions of the chair. The BMI coefficient of the respondents was calculated from the obtained data and a person with a BMI value higher than 40 is already considered a bariatric respondent. The results of statistical processing of indicators obtained by measuring bariatric respondents are shown in Table 1.

Chair Construction Design

A bariatric chair has to carry much weight, which results in the need to increase the seating area compared to conventional seating furniture. The recommended height is 46 cm. If the chair is height adjustable, its height is within the range of 44 to 59 cm. It is very important to adjust the chair to the right height. If the chair is too high for the user, the feet will lift off the ground, making it difficult to get seated in the chair. The user will have trouble getting up if the chair is too low. At the same time, sitting must prevent unwanted compression of the popliteal vessels. A shallow seat with a depth of 43 cm is more suitable for bariatric chairs. A shallower seat will make it easier for an overweight person to get up from a chair.

Table 1. Descriptive Statistics of Bariatric Respondents

	Body Weight (kg)	Stature Height (cm)	BMI
N	240	240	240
Mean	143.45	171.12	48.96
Median	139.00	170.00	47.53
Minimum	93.00	150.00	35.49
Maximum	242.00	199.00	89.75
Percentiles			
1th	97.00	150.00	36.36
5th	103.50	156.00	38.95
50th	139.00	170.00	47.53
95th	191.00	187.00	61.03
99th	233.00	197.00	76.38
Standard deviation	27.47	9.21	7.89

The width of the seat needs to be larger than a standard chair. Most bariatric chairs have a seat width of 61 to 76 cm in order to be properly adapted to the user. Bariatric chairs should include armrests to ensure a more comfortable process of getting up. The armrests need to be wider and higher than in standard seating furniture. The armrests should have a round shape of the surfaces that will allow painless support of the palms of the hands when sitting and getting up. On the upholstered surfaces of seating furniture, there must be no protruding elements of the structure that, if seated for a long time, would cause pain, hematoma, or even injury. It is also ideal to be able to slide feet under the seat when getting up. Chairs or armchairs on legs are therefore suitable. This will also allow sanitary cleaning of the floor under the chair.

Based on experience, it is important to note that from the point of view of the conceptual design of the chair structure, the greatest internal load accumulates in the joint of the side rail and the rear leg. The reduction of internal forces values in these joints can be achieved by applying other components in the chair construction, namely the side stretchers and armrests. The different concepts of construction frames of wooden chairs (Fig.1), which are assembled from different components, are presented in this paper.

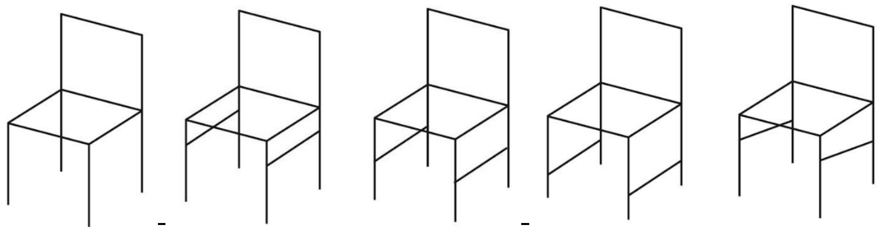


Fig. 1. Construction diagrams of frame chairs with the possibility of reducing the stress on the back joint

The chairs design is based on the user's anthropometric parameters and ergonomic requirements for seating furniture.

These parameters and requirements are applied in the creation of finite element models of chairs, which are created in accordance with the conceptual designs of the chairs (Fig. 1). The loads, corresponding to the person with overweight, are applied to a virtual počítačový model (FEM) of wooden chairs. By performing computer simulations, the values and distribution of internal force effects arising in structural chair components are obtained.

It follows that the size and distribution of internal forces in particular depend on the shape and dimensions of the structure, the mutual position, and shape of structural components. The properties of the material from which the chair is made are other parameters on which the fulfillment of the required strength criteria depends. Designing structures according to specified strength aspects should enable strength optimization of the proposed structures.

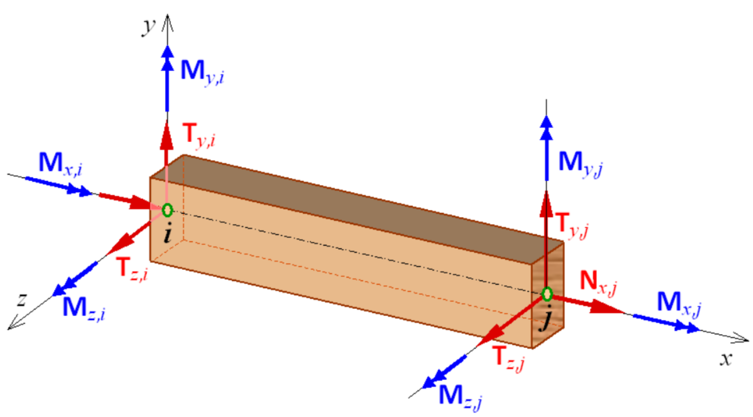


Fig. 2. Components of internal force effects in the cross-sections of the structural element. (force vectors - with one arrow; moment vectors - with two arrows)

A specific problem that must be solved in the detail design of the structure of wooden chairs is the mutual connections of the elements. The design, method and type of connection of the chair components depend on the magnitude of the internal forces that arise in the joints of specific elements. There are many construction methods for making suitable joints between chair components, but this is not the main purpose of this paper. When the structure is loaded, each structural element is stressed by force effects, which are represented by components of forces and moments concerning three mutually perpendicular axes. In general, three moment components act in each cross-section of a structural element, *i.e.*, two bending moments (vectors $\mathbf{M}_y$ and $\mathbf{M}_z$) and one torque (vector

$\mathbf{M}_x$). In addition to the moment components, three internal force components also act in each cross-section, *i.e*., two transverse forces (vectors $\mathbf{T}_y$ and $\mathbf{T}_z$) acting perpendicular to the x-axis and one normal force (vector $\mathbf{N}_x$) acting in the x-axis direction of the structural element. Thus, six components of internal forces act in each cross-section of the structural element, which is shown in Fig. 2.

The stress-strain states that arise in the components and joints of the chair structure depend on the method of loading and the magnitude of the forces. The loading method must reliably describe the typical load to which the structure is exposed during proper functional use. The sizes and the method of loading seating furniture are defined in EN 12520:(2015), EN 15317 (2007), and EN 1728:(2012) standards. The vertical and horizontal force loads specified in these standards correspond to a person's weight of 110 kg.

The size of the load of chairs for bariatric users was based on the requirements of the standards for mechanical tests of seating furniture EN 12520 and EN 1728. In the mentioned standards, a user weight of 110 kg is considered, while currently, European standards do not consider users who are significantly overweight. From the mentioned standards, it follows that in the case of a user weighing 110 kg, the force F_1 acting on the seat is 1300 N, and the force acting on the backrest F_2 is 450 N. The general structural model of the chair with geometrical dimensions and applied loads are shown in Fig. 3. The magnitudes of the forces caused by a user weighing 210 kg were calculated by linear extrapolation from load forces with a user weight of 110 kg. The force F_1 acting on the seat is 2482 N, and the force acting on the backrest F_2 is 860 N.

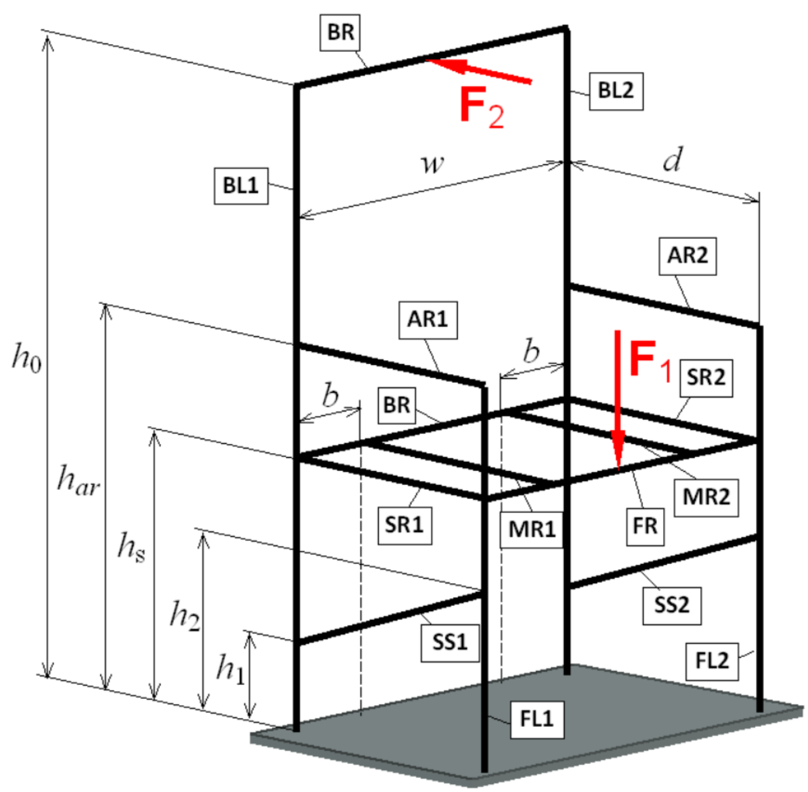


Fig. 3. General structural model and geometrical dimensions of the chair frame.
(RL - rear leg, FL - front leg, FR - front rail, RR - rear rail, SR - side rail, AR - armrest, SS - side stretcher, MB - middle bar, TR - top rail)

Table 2. Basic Geometric Dimensions of the Chair Frame Structure

Basic Dimensions of Chair Frames			A-01	A-02	A-03	A-04	B-01	B-02	B-03	B-04
Chair height h_0		(mm)	1150							
Width of the seat w		(mm)	680							
Depth of the seat d		(mm)	470							
Seat height h_s		(mm)	490							
Height of armrests h_{ar}		(mm)	- - -				690			
Position of brace under the seat b		(mm)	- - -	- - -	170	170	- - -	- - -	170	170
Height of the stretchers fixation	back leg h_1	(mm)	- - -	160	- - -	160	- - -	160	- - -	160
	front leg h_2	(mm)	- - -	160	- - -	320	- - -	160	- - -	320

The recommended geometric dimensions of the chairs concerning the different arrangements of the structural elements of the chair frames are listed in Table 2. The cross-sections of structural components that are used in the design of the concepts of the chair structure are shown in Table 3. Beechwood has been selected as the material for all elements of the chair frames to determine their strength properties and assess the degree of deformation and shape stability. The basic mechanical properties of beech wood, which are used in computational simulations of the load of the considered types of chair frames, are listed in Table 4.

Table 3. Cross-sections of Individual Elements of the Chair Frames Structure

Structural Element	Cross-section Dimensions (mm)		Structural Element	Cross-section Dimensions (mm)	
front and rear legs	25×42 (b×h)		top rail	18×70 (b×h)	
armrests			front, rear, side rail		
side stretchers			middle bar under the seat		

Table 4. Mechanical Properties of Beech Wood

Mechanical Properties of Beech Wood (at moisture content MC = 12%)				
Density ρ	(kg/m^3)	720		
Modulus of elasticity	(GPa)	E_L	E_R	E_T
		16.67	1.13	0.63
Shear modulus	(GPa)	G_{LR}	G_{RT}	G_{LT}
		1.2	0.19	0.93
Poisson's ratios	(-)	μ_{LR}	μ_{RT}	μ_{LT}
		0.044	0.33	0.027
Ultimate bending strength σ_{MOR}	(MPa)	104.0		

Notations: The fiber directions of the beech wood: L - longitudinal (the longitudinal direction of the chair component), R - radial (b dimension of cross-section), and T - tangential (h dimension of of cross-section). (data source: (Novák 2013))

When choosing the chair's dimensions, described in Table 3, the guidelines contained in the literature describing the design of chairs for obese people were followed (Hitka *et al*. 2022b). Standards have also been taken into account, such as ANSI/BIFMA X5.41-2021, Large Occupant Public and Lounge Seating (2021) and ANSI/BIFMA X5.11-2015 (R2020) Large Occupant Office Chair (2015). Considering the described guidelines, the seat height h_s was increased from 460 mm to 490 mm, and the seat width was 680 mm.

Typical chair designs with the arrangement of structural components used for chair frames are shown in Fig. 4. In accordance with the required geometric dimensions of the chairs, a computational finite element model was created in the ANSYS program (release 18.2). Finite element BEAM188 was used to model the chair components. The joints of the chair components were modeled as rigid. At the contact points of the front and rear legs of the chair with the floor, all translational degrees of freedom are removed.

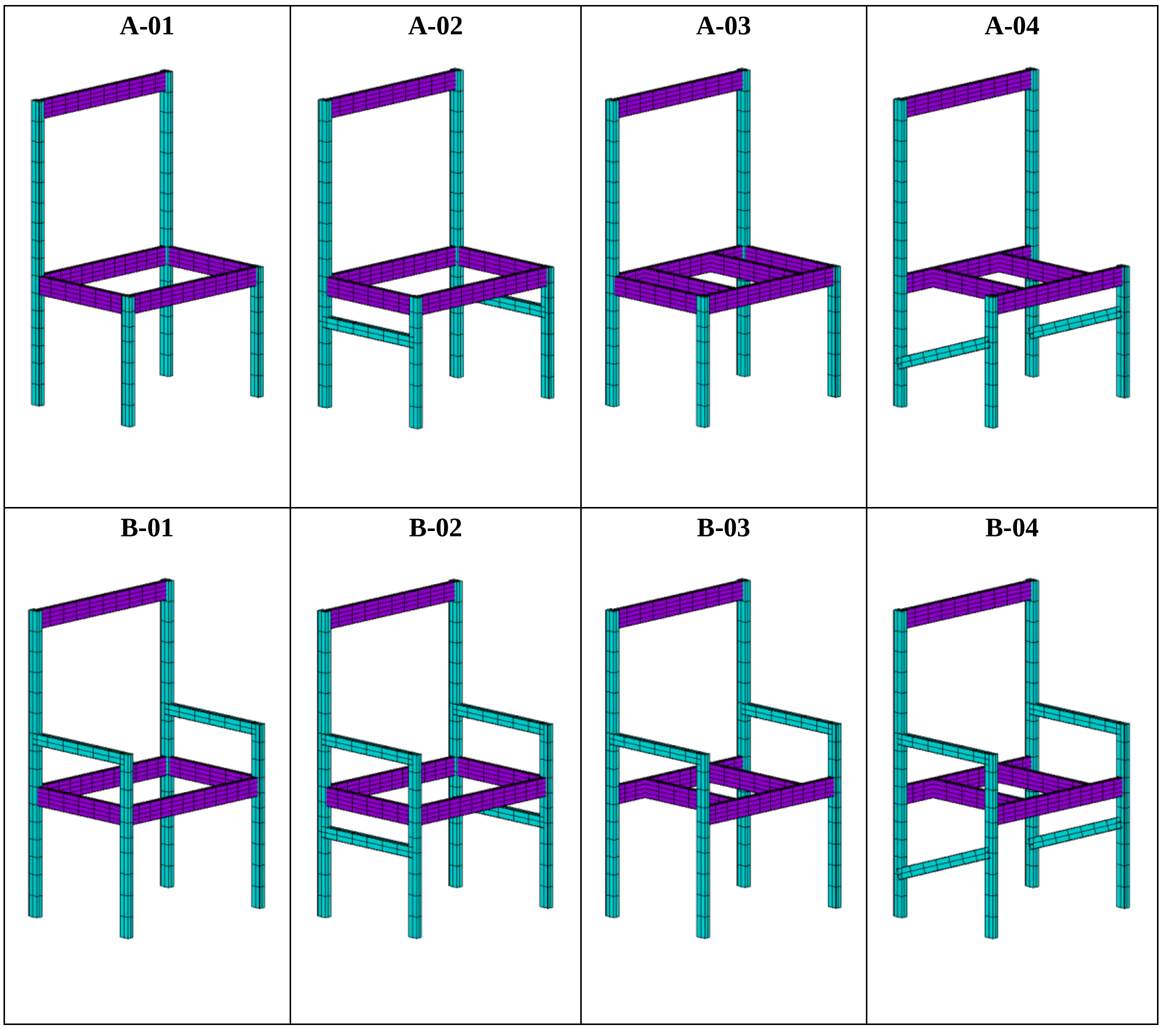


Fig. 4. Overview of typical constructions used for chair frames

RESULTS AND DISCUSSION

Given that the designed chairs are frame constructions, the following condition must be met when analyzing and assessing the breaking limit state of the structural element:

$$S_d \leq R_d \quad (1)$$

where S_d is the design value of the internal force and R_d is the design value of the allowable internal force. Given that the elements of the chair frame structure are beam elements with dominant bending stress, they are used to assess the limit state of the chair structure according to Eq. 1 for the value $S_d = \sigma_{b,max}$ and for the value $R_d = \sigma_{\mathrm{MOR}}$. The stress $\sigma_{b,max}$ is the stress that arises in the extreme fibers of the cross-section of the beam element as a result of its bending.

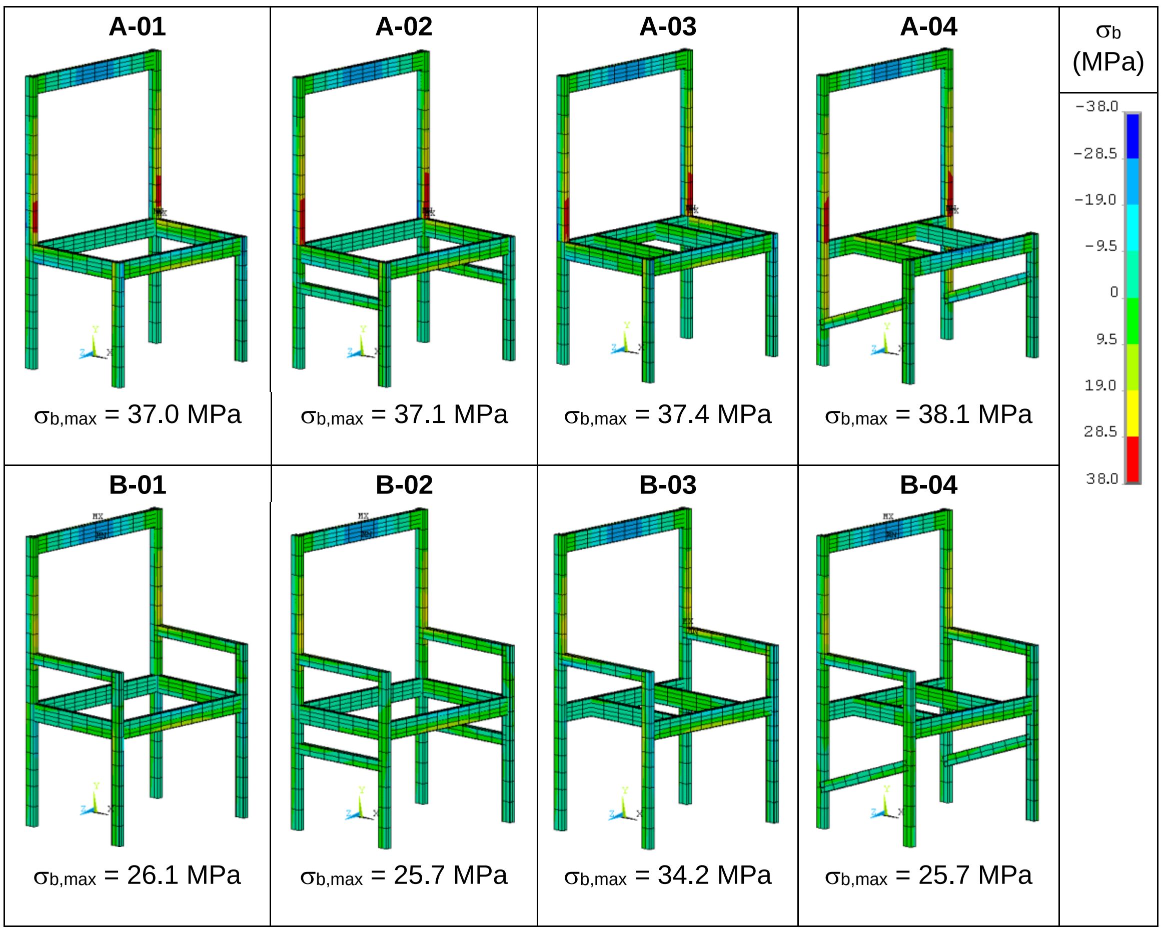


Fig. 5. Bending stress in elements of chair frames

Given the tension arising in the elements of the chair (Fig. 5), it is clear that due to the bending of the individual elements of the chairs, the greatest bending stresses arise in the chair's back legs. The total deformations of chairs under increased (for overweight persom) load are shown in Fig. 6.

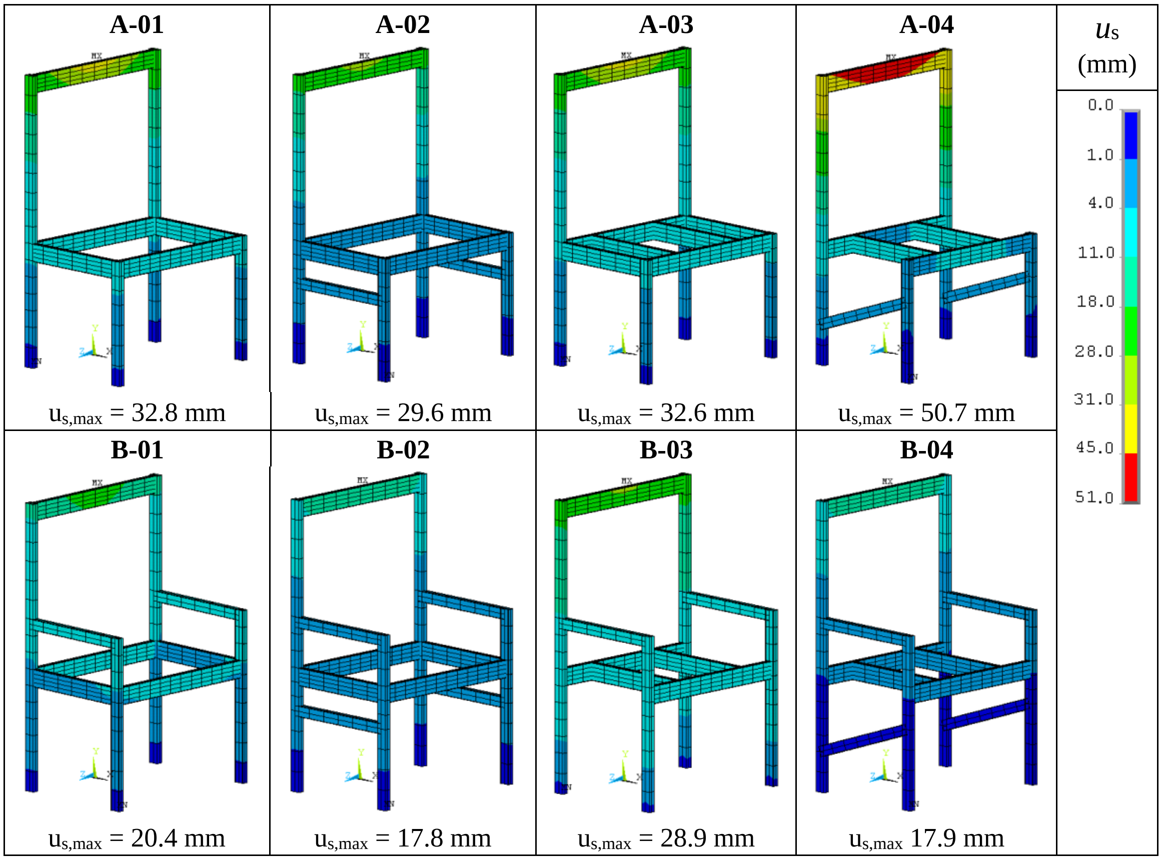
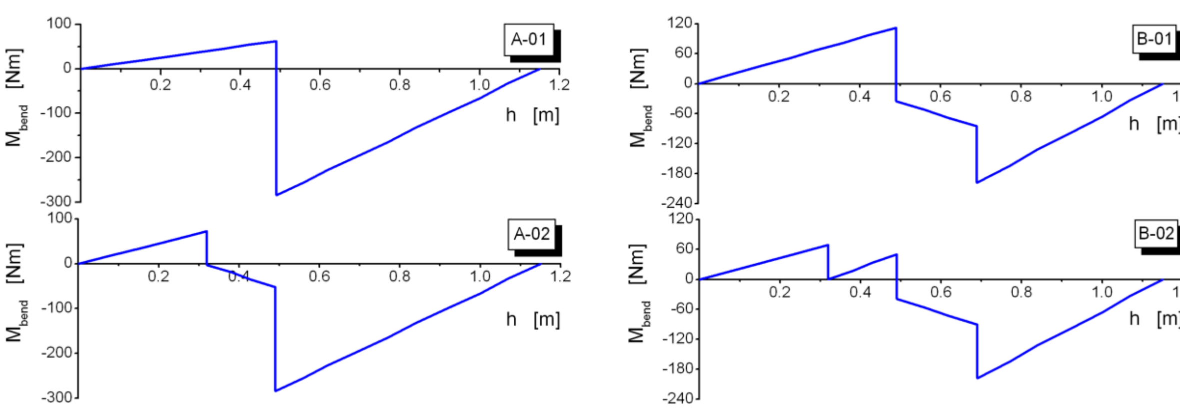


Fig. 6. Total deformation of the chair frames

The values and distribution of internal forces in the chair's components depend mainly on the geometric shape of the chair and on the position and mutual configuration of the components in the chair's frame. The stiffness and strength of the chair frame are significantly influenced by the fact of what components are used to connect the front legs and rear legs. To the mutual connection of the front and rear legs, the side rails, side stretchers, and armrests in various combinations (Fig. 4) are used. The results of the distribution of bending moments in selected elements of the investigated chair structures are presented in the following graphs - rear legs (Fig.7), side rails (Fig.8), side stretchers (Fig. 9), and armrests (Fig. 10).



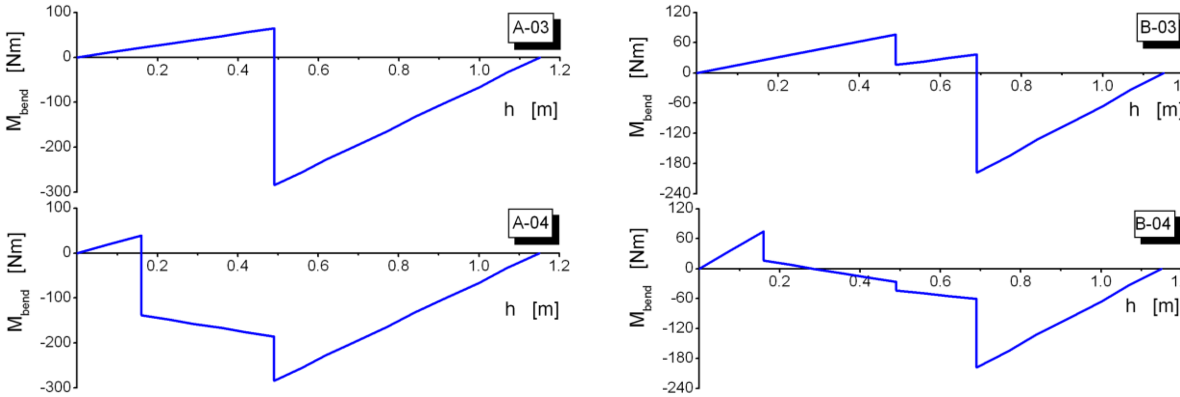


Fig. 7. Bending moments about z-axis in the rear legs (RL) of chair frames

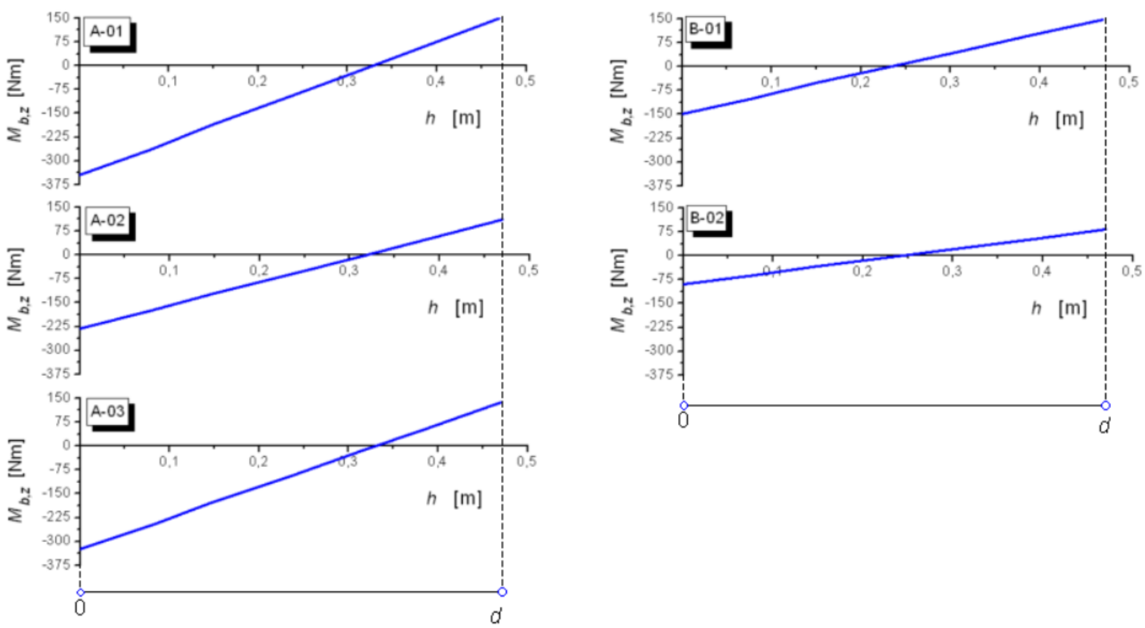


Fig. 8. Bending moments about *z*-axis acting in the side rails (SR) of chair frames

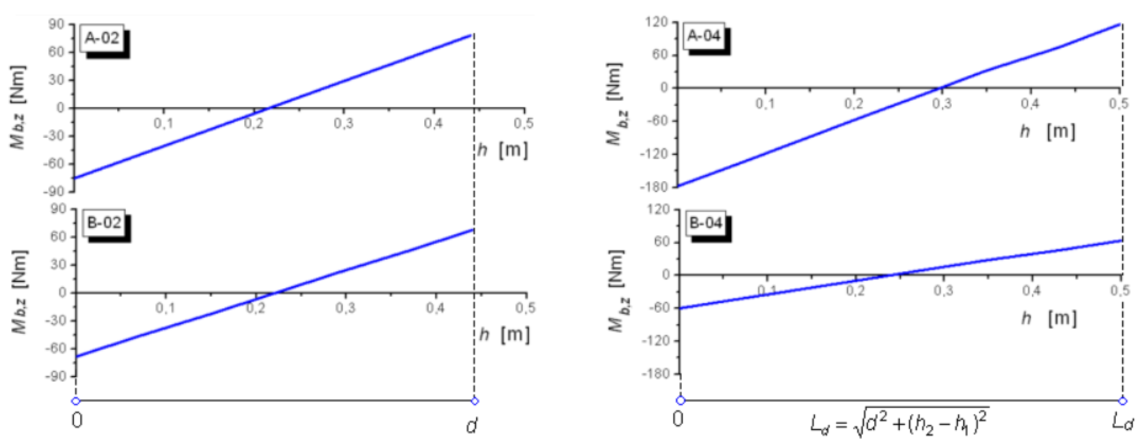


Fig. 9. Bending moments about *z*-axis acting in the side stretchers (SS) of chair frames

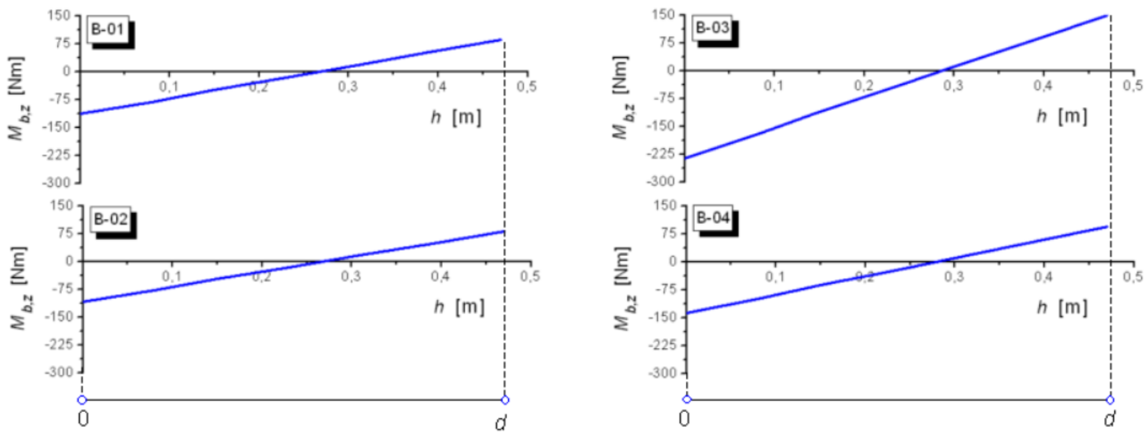


Fig. 10. Bending moments about *z*-axis acting in the armrests (AR) of chair frames

From a construction point of view, it turns out that there is a significant influence on the stiffness and strength of the chair, *i.e.* on the deformation values and the stress values arising in the chair components. Such chair structures include built-in armrests, side rails, and other reinforcing structural elements (stretchers) connecting the front and rear legs (B-01, B-02, and B-04).

Based on the frame structures of chairs analysis results, it is possible to evaluate whether the designed frame meets the usage requirements and whether strength parameters of the chair structure, *i.e.*, deformation, stress and internal forces values are within permissible limits. These parameters depend on the basic chair components arrangement, their dimensions, cross-sectional shapes, joint types, and the materials from which the structure members are made (Hajdarević and Busuladžić 2015). Using computer simulations on computational models of the chair structure, the so-called virtual prototypes, wide possibilities for an effective process of designing a chair structure or its modification in terms of meeting normative requirements are provided (Ceylan *et al.* 2021).

The above calculations give designers and constructors a vision of the distribution of internal forces, deformations, and stresses from the load of the bariatric user. Based on these calculations, it is possible to adjust and optimize the chair's shape, the dimensions, and position of the structural components. The results of the values and distribution of the bending moments generated in the chairs components are important in further design process. Then component connections can be structurally designed in such a way that they will meet the loads that were calculated for the chair structures (see Fig. 3). The strength and durability of seating furniture structures can be then evaluated by experimental testing to ensure that no element, connection, or part is broken. In addition, tests can confirm that rigid joints remain secure and in place and that the furniture continues properly functioning while meeting strength and stability requirements. These requirements include the ability to withstand load when sitting on the front edge of the seat, leaning against the backrest, sides, armrests, and stretchers without tipping over (EN 12520; EN 15373). It is crucially important to ensure that seating furniture meets these requirements for users' safety and comfort and preventing damage to the furniture. It is ideal if, after implementation of computer simulations results, the product prototype is tested in natural conditions. However, in the environment of the European Union, there are no defined standards for furniture in non-residential spaces, which would consider the increased weight of users (Hitka *et al.* 2022a).

As mentioned, the seat height has increased from 460 mm to 490 mm. Galli *et al*. investigated the sit-to-stand movement pattern in obese subjects compared to normal-weight subjects. The authors concluded that the sit-to-stand movement pattern in obese subjects significantly differs from that in normal-weight subjects and is related to biomechanical and muscular factors (Galli *et al*. 2000). In this case, even a slight increase in the seat's height significantly increases the comfort of getting up from the chair (Sydor and Hitka 2023). However, it is worth noting that a too-high seat remarkably reduces the comfort of sitting on the chair, so its height should not be excessive.

Specific chairs design requirements for obese have been studied in scientific literature. Hitka *et al*. (2018) investigated the load-carrying capacity and joint size of wooden chairs designed for users with higher body weight. The load-carrying capacity of chair joints designed for normal-weight individuals was insufficient for users with higher body weights. Particularly the joint size and geometry of chairs designed for normal-weight individuals were inadequate for users with higher body weight. The authors concluded that chairs designed for users with higher body weight require different joint sizes and geometry than chairs designed for normal-weight individuals.

Langová *et al*. (2019) confirmed the potential of using laminated wood to design seating furniture with increased load capacity. The wood-based lamella was found to have a higher load-carrying capacity than solid wood, and its properties can be adjusted to meet specific design requirements and obtain the durability and safety of the furniture for users with higher body weight.

The results presented in this article confirm the usefulness of beech wood for the design of bariatric chairs. It is worth emphasizing that the finite element method enables the verification of many variants of the designed product. This makes it possible to identify the most loaded parts of the structure and to reinforce them with elements that can affect also increase level ergonomics for an overweight person. Reinforcing the seat with ribs and adding an inclined stretcher. Adding armrests can also reduce stress on critical areas of the chair frame structures.

CONCLUSIONS

1. Using the assumption that chairs for obese users are based on the design of standard chairs, the most suitable construction is the addition of an stretcher and side ribs that reinforce the seat. The addition of armrests also significantly reduces stress on critical components and joints of the chair frame structures. When using armrests and side stretchers, the results of internal forces confirm a decrease in the value of the moments in the critical joint rear leg *vs.* side rail. In the case of the comparable chair design A-01 and B-01, there is a decrease in the value of the moment in this joint more than 55%. In the case of structural design A-02 and B-02, the moment drop is over 60%. These results show that the way to meet the strength limits is not only by increasing the cross-sections of the components and creating stronger connections of the components. By rationally using appropriate chairs components and their structural arrangement, it is possible to meet the strength limits for the required dimensional parameters and for the increased load of the chair for bariatric patients.
2. Moving the ribs under the seat creates space for fitting additional chair parts, such as folding tables, pockets, or other holders.

3. It is necessary to think about the design of chairs that would provide comfort to all users, especially in public spaces, so that bariatric users do not feel uncomfortable when sitting on chairs that are reserved only for them.
4. Much of today's bariatric seating represents larger versions of standard products. However, new offerings will consider the psychosocial needs and physical requirements of obese individuals as well as the interests of interior designers in achieving a consistent look public interior.

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