

STATIC ANALYSIS OF AN OFFICE DESK CONSTRUCTION

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Abstract

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The objective of the paper is a static analysis of a desk construction and the determination of its probable mechanical behaviour using Finite Element Method. The construction was modelled and numerically analysed in Autocad Inventor 2011 and the stability of the entire desk was calculated with the size and placement of the loading force based on the standards and cited literature. Possible locations and directions of the deformation were analysed and a solution for its prevention was proposed and the stability of the desk as well as the extreme position of the stand were calculated. The verification of the obtained results in an accredited furniture testing lab is planned using a prototype of the office desk.

an office desk, construction, steel, numerical simulation, stability

A construction of an office desk stand made of steel plate, which enters the production as a large-scale material, has several advantages over commonly used semi-finished products. Steel profiles and tubes used in the furniture industry are usually over-dimensioned for the purposes of furniture production as they are primarily designed for engineering or civil engineering. On the other hand, production of castings is usually very expensive and connected with the production of large batches. However, the use of up-to-date CNC processing methods for metals provides furniture producers with a lot of freedom to create their own construction with original design and the optimum use of material properties. In this way, a required combination of attractive design, suitable mechanical properties (construction rigidity, strength, stability, etc.) and lower costs can be obtained when producing small or medium volume of products.

The analysed desk construction (Fig. 3 and Fig. 4) was produced as a prototype using CNC laser cutting, precise CNC press braking (metal parts – stand) and typical furniture production CNC

processing (wooden composite materials – desk top).

The aim of the study was to establish the probable mechanical behaviour of the office desk, especially the stand, in consequence of the defined static loading based on the standards dealing with the testing methods for stability and mechanical resistance of office desk constructions. The study focuses on the analysis of the extreme response (maximum tension) points and the probable breakage points by means of static numerical analysis. These points will be evaluated and based on that we will propose a solution for the achievement of the optimum results. The study further deals with the numerical establishment of the office desk stability and as a consequence provides other possible shape modifications.

Similar issues related to analyses of furniture construction and numerical simulation of specific types of constructions were in the past dealt with by e.g. Eckelman (2003), Koňas (2006), Smardzewski and Prekrat (2009), Joščák (1999) or Nicholls and Crisan (2002).

MATERIAL AND METHODS

Numerical simulation

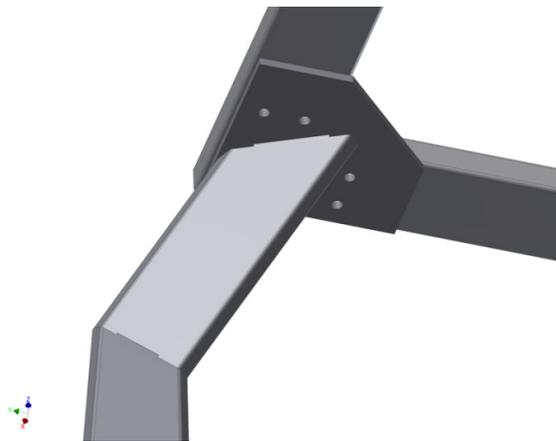
The model of the analysed construction was created in the modelling environment of the CAD software Autodesk Inventor 2011 using the tools for the creation of 3D models. The three-dimensional model was fully parametric so its geometry could be modified anytime during its processing. The process of model creation started with individual parts of the construction, which were then put together into subsets. Thus the subset desk legs and the subset apron were created and these were then again put together into the resulting set – stand (Fig. 4) which was used for the numerical analysis of strength.

The strength numerical analysis was carried out in the module Strength Analysis of the Autodesk Inventor 2011 application by means of the finite element method (FEM). A mesh of connected parts of the construction with a finite number of elements was created. The mesh of the model was composed of elements of quadratic tetrahedron of SOLID type with the maximum ratio of sides 1:7 (Autodesk, 2011) and consisted of 107 393 elements and 220 845 nodes. The mesh was made finer at the points of higher exposure due to higher tension and more complicated geometry (Fig. 1 and Fig. 2). The nodes were then the points where the resulting parameters were measured. Further, boundary conditions of the construction model were established – material properties of individual parts, contacts, bonds, type and direction of loading, degrees of freedom. The model is nonlinear (inhomogeneous) in its

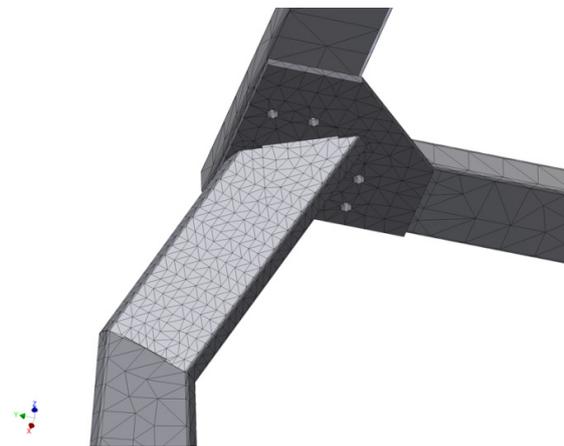
geometry and it is made of three different materials. All components were allotted with the appropriate material and the material properties: physical and mechanical properties and constants such as density, Young's modulus of elasticity, Poisson constant, yield points and rupture points in tension (Tab. I) were established based on literary sources and standards. Metal parts of the construction (stand, aprons) were treated as made of steel, class 11 373 (ČSN 41 1373, 1994, respectively EN 10025-94), welds (G3Si1 type) were specified according to Czech standard ČSN EN ISO 14341 and the plastic adjusting screw was made of polyamide PA 66 (Nylon) (www.polymerweb.com).

Due to the character of the desk legs and their connection with the aprons, it was important to identify the contacts on contact surfaces of the individual parts correctly. The contacts of surfaces between the material and welds were set as fixed – the contact areas are bound tightly together. I. e. no movement was allowed between these contact areas. Also the bonds in the point of screw connection of the desk leg and the apron were set as fixed for a simplification of the calculation. For the areas which came into contact but could separate and move in different directions against each other, the type of contact was set as "separation".

The important boundary conditions included the location of a fixed bond on the lower surface of a selected adjusting screw. This surface was thus deprived of all degrees of freedom and it played a role of the basic fixed point. The lower surfaces of the remaining adjusting screws were equipped with



1: A detail of leg and apron geometry



2: A detail of a finite-element model of the leg and the apron

I: Mechanical properties of used materials

	Density ρ (kg/m ³)	Young's modulus E (GPa)	Poisson constant μ	Yield point in tension R_e (Mpa)	Breaking strength in tension R_m (Mpa)
Steel ČSN 11373	7 850	210	0,3	207	345
Weld steel ČSN EN ISO 14341: G3Si1	7 850	210	0,31	min. 460	530–680
Screw steel	7 850	210	0,3	Min. 340	Min. 420
Polyamide (PA 66)	1 130	2.93	0.35	82.75	82.68

'an ideal bond' (Autodesk, 2011). This prevented the movement of the surface in a perpendicular direction and only made the stand able to move horizontally. Thus the behaviour of the construction at the points of contact with the floor was defined.

The process of ascertaining the size of the affecting force was based on the Czech standard (ČSN EN 527-3) which deals with the methods for the construction stability and mechanical strength establishment. Based on paragraph 5.2 of the standard – Vertical loading test – two points where a loading force of 1 000 N was applied on the construction were selected. The first was the centre of a long apron; the second point was a corner of an apron.

The construction of the desk stand was analysed with emphasis on the upper part of the leg. The leg is made of an open profile, therefore, we expected that it will be the most sensitive to loading. We also made details of this part.

Stability calculation

Testing of stability of office desks is defined in Czech standard ČSN EN 527-3 Office Furniture – Working Desks and Tops – Part 3: Methods for Testing Construction Stability and Mechanical Strength. The standard defines that testing stability is performed by applying a vertical loading of 750 N on a point 50 mm far from a desk top edge. The stability calculation was carried out in compliance with literature – Joščák (1999). We established the heeling moments (M_k) and stability moments (M_s). Their subsequent comparison revealed whether the desk will turn over or not. To be able to calculate the stability we need the following input values (Fig. 3):

- $m = 47,4 \text{ kg}$
- $F_g = 474 \text{ N}$
- $F_v = 750 \text{ N}$
- $F_h = 0.1 \times 750 \text{ N} = 75 \text{ N}$,

where m is the weight of the desk (kg), F_g is the affecting force of gravity (N), F_v is the affecting

vertical force (N) and F_h is the affecting horizontal force (N).

The moment of stability was calculated using equation /1/:

$$M_s = F_g \times \frac{d}{2} \quad (\text{Nm}), \quad /1/$$

where d is the shortest perpendicular distance between the desk centre of gravity and the turning axis (in Fig. 3 shown as an anchor), or the distance between the desk edges (mm) divided by two.

The heeling moment was calculated using equation /2/:

$$M_k = F_v \times (d_1 - d_{F_v}) + F_h \times h \quad (\text{Nm}), \quad /2/$$

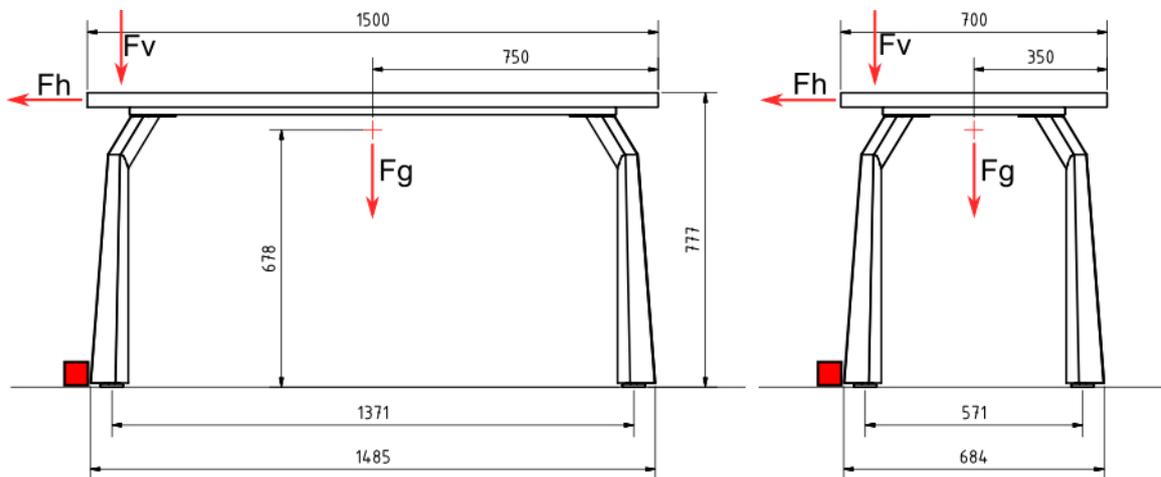
where d_1 is the shortest perpendicular distance between the turning axis (in Fig. 3 shown as an anchor) and the side of the desk top (mm), d_{F_v} is the distance of the application point of F_v from the side of the desk top (mm) and h is the shortest perpendicular distance between the turning axis and force F_h , i.e. the desk height (mm).

RESULTS

Numerical simulation

The results of the numerical simulations are presented in a graphical form as pictures showing the progress of the measured quantity by means of colour spectra. The resulting images represent von Mises stress (Figs. 4 and 6) and the coefficient of safety (Figs. 5, 7 and 8).

The desk top was excluded from the simulation as in the final prototype this is made of anisotropic or generally orthotropic material – laminated chipboard, which would unnecessarily prolong the calculating time. With respect to the focus of the study on the analysis of the stand and the critical points in the upper part of the leg, an inclusion of a desk top would be inefficient. Therefore, when



3: The diagram for stability calculation: along the length (left) and along the width of the desk (right). All dimensions are in millimetres.

assessing the results of the analysis, we have to take into account that the loading force applied to the desk apron at the given point would be more homogeneously distributed over the entire construction – thanks to the desk top.

The simulations we obtained show clearly that the loading was transmitted over the apron into the entire desk construction. As regards the desk legs, an important role was played by the edges created by CNC bending technology. They strengthened the construction of the leg and they were the means of transmitting the loading from the upper part of the desk into the stand. The expected critical points were the upper parts of desk legs (Fig. 8), which were not made from closed profiles (due to production technology). The risk of leg damage was thus brought not only by the strength of the used material but also the construction of the element itself, which may not ensure sufficient rigidity in the upper part of the leg. That is why these points were devoted most attention when assessing the results.

Von Mises stress reached the highest values at the points where the loading force was applied and at the critical points of the construction (Figs. 4 and 6). In respect of the above mentioned expected critical points in the upper parts of the desk legs, the range of the colour scale was revised (adapted). The new scale gave more distinction to the colour presentation of the tension equivalent in the points of the upper parts of desk legs. When assessing the critical and extreme values, we had to consider the location and geometry of the element where they appeared. In some cases, some points (e.g. weld beads) were analysed as critical although these would in fact have a completely different geometry and no damage would probably occur to them. Due to the size of the affecting force and desk construction geometry, the significant extremes of tension equivalent were present when the loading force was applied to the apron corner (Fig. 6). This however did not necessarily mean that damage would occur at these points.

In this respect, the coefficient of safety k (dimensionless quantity) has a higher information capacity. Coefficient of safety is based on the theory of allowable stress. This theory states that the construction under static loading should not strain to the limit of strength and dynamic loading forces should not reach its limit of fatigue. Condition of safety is met, if these assumptions are fulfilled. Therefore, the coefficient of safety $k > 1$ is established. Allowable stress σ_d is calculated using equation /3/:

$$\sigma_d = \frac{\sigma_{kt}}{k}, \quad /3/$$

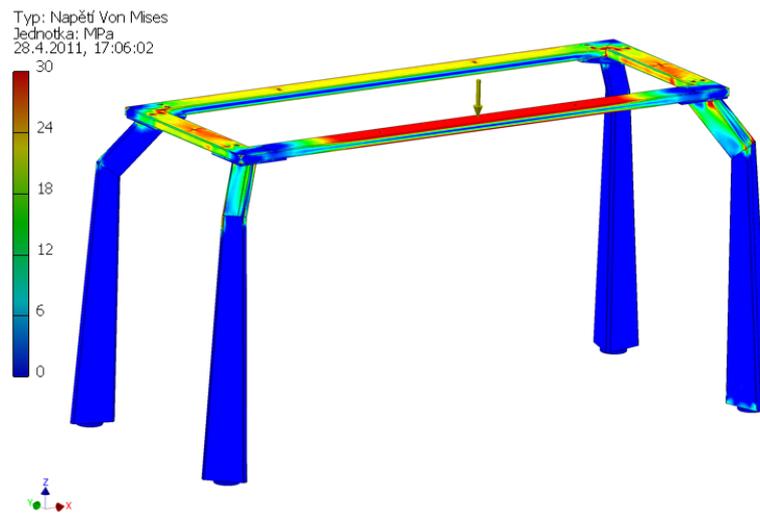
where k is the coefficient of safety and σ_{kt} is yield stress (R_c). The equation /4/ is based on numerical simulations and is derived from equation /3/ while the aim is to determine the coefficient of safety.

Therefore is the allowable stress σ_d replaced with equivalent tension (von Mises) ($R_{ekv(von\ Mises)}$), which represents the current value of tension at a given point of construction:

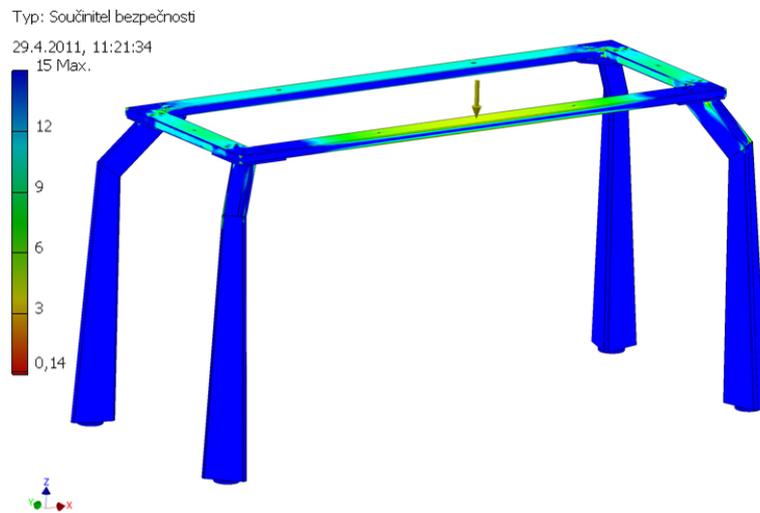
$$k = \frac{R_c}{R_{ekv(von\ Mises)}}, \quad /4/$$

and where R_c is yield stress (the lowest tension at which the plastic (permanent) material deformations occur (Hluchý, 2007)), which sets the maximum allowable tension (Autodesk, 2011).

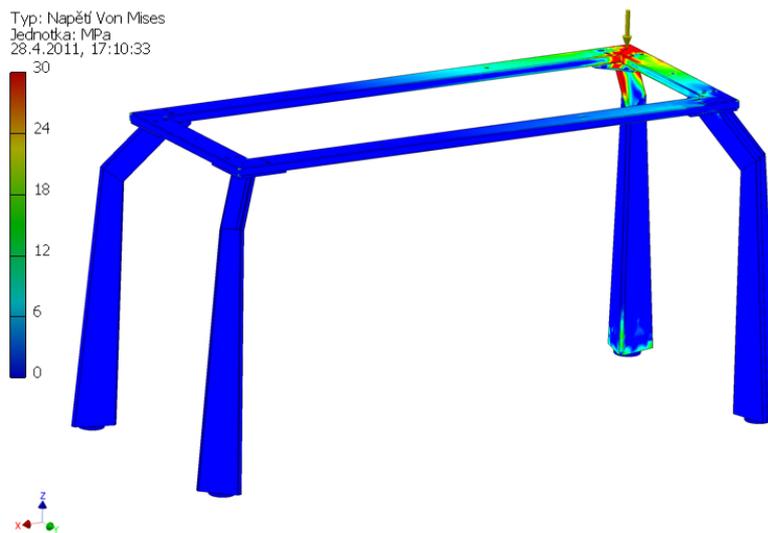
According to the analysis, the expected deformations and damage would occur at the points where the upper part of the desk leg is connected to the plate (which ensures the dismantling connection of the desk leg to the apron), specifically at the points of contact between the plate and the edges. Because of the symmetry in the leg geometry and the symmetrical progress of tension in this geometry, the leg was divided by a vertical plane in the axis of symmetry and further we will only concentrate on the results of one half of the model. In Fig. 8 we can see the lowest coefficient of safety of 0.41 in bending inside the open profile. This value says that the equivalent tension at this point is 504.88 MPa, which is approximately 2.5 times higher than the yield point of steel (R_c 207 MPa). According to the numerical analysis, a permanent deformation of the material would appear at this point. Moreover, the equivalent tension exceeded the rupture point (R_m 345 MPa) would be exceeded and the material would also break at this point – ultimate strength 0.68 – the ratio between the breaking strength in tension and the equivalent tension (von Mises) (Autodesk, 2011). At the same point but the outside of the profile is the value of safety coefficient is 2.63, which corresponds to the value of equivalent tension of 78.71 MPa. This is approximately 2.5 times lower than the yield point of steel (R_c 207 MPa), i.e., at this point no permanent damage or breakage should appear. However, the difference of the maximum values of the equivalent tension between the internal and the external side at the point of bending is 426.17 MPa. This indicates that the deformation (shift) at the extreme point should develop outwards from the open profile. This was caused by the enormous loading applied to these edges (bends) which, as hypothesized, worked as transmitters of the affecting forces in the entire construction of the desk leg (see Fig. 8). The other places with decreased values of safety coefficient are not so significant as they did not exceed the critical value of 1, at which permanent deformations would occur. However, there is still the risk of repeated loading, which in areas with value of safety near 1, could eventually lead to material fatigue and possible deformations (Autodesk, 2011). Therefore, it is important to achieve a coefficient of safety of 2 and more at each point of the construction.



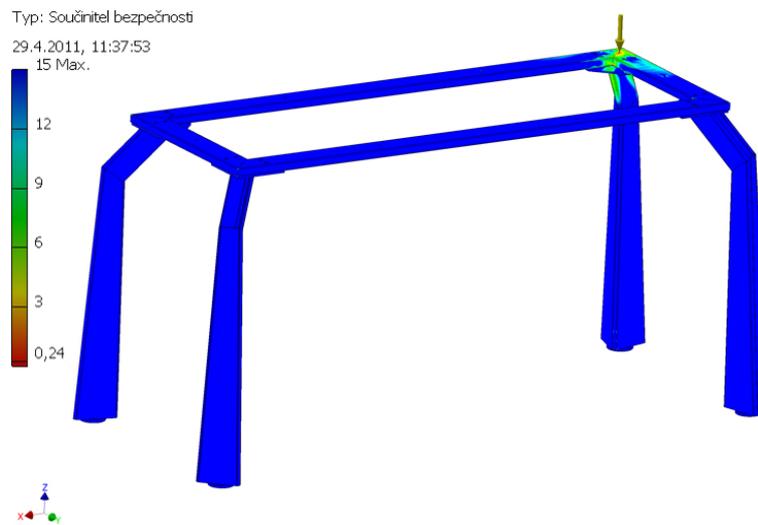
4: Equivalent tension (von Mises) when the centre of the long apron is loaded



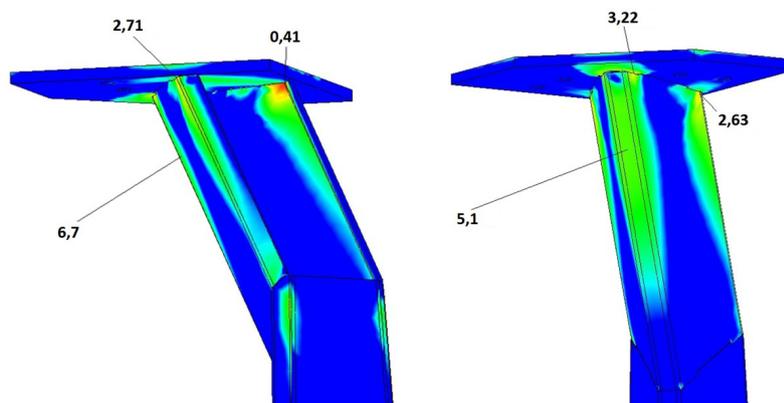
5: Coefficient of safety when the centre of the long apron is loaded



6: Equivalent tension (von Mises) when the apron is loaded in the corner



7: Coefficient of safety when the apron is loaded in the corner



8: Coefficient of safety – detail of the upper part of desk leg

Numerical stability analysis

Using equation /1/, we obtained the numerical value of the moment of stability along the desk length:

$$Ms = 474 \times \frac{1.485}{2}$$

$$Ms = 351.945 \text{ Nm.}$$

Using equation /2/ we obtained the numerical value of the heeling moment:

$$Mk = 750 \times (0.008 - 0.05) + 75 \times 0.777$$

$$Mk = 26.775 \text{ Nm.}$$

By comparing the values of the moment of stability and the heeling moment we found out that according to the theoretical calculation the desk will not turn over in the direction of its length because the value of the moment of stability is considerably higher than the value of the heeling moment.

In the same way, the value of the moment of stability was calculated for the direction along the desk width using equation /1/:

$$Ms = 474 \times \frac{0.684}{2}$$

$$Ms = 162.108 \text{ Nm.}$$

The heeling moment was calculated using equation /2/:

$$Mk = 750 \times (0 - 0.05) + 75 \times 0.777$$

$$Mk = 20.775 \text{ Nm.}$$

Again, it was proved that the desk would not turn over in the direction along its width as the moment of stability is considerably higher than the value of the heeling moment.

When the moment of stability was equalled to the heeling moment /5/, we ascertained the distances determining the extreme position of the stand in which no stability loss would occur. These represented the distances by which either

the desk top or the space between the desk top sides and stand edges could be enlarged. However, an enlargement of the desk top would lead to the increase in its weight. On one hand, that would contribute to its stability, on the other hand, it would load the desk stands inadequately (the desk top enlarged by the calculated values would weigh 60 kg in contrast to the original 24.6 kg).

Therefore, according to the above mentioned assumption, we created this relationship:

$$Ms = Mk.$$

After placing the variables to equations /1/ and /2/, the biggest distances between the axes of turning and desk tops sides at which no stability loss would occur were calculated:

$$351.945 = 750 \times (d_1 - 0.05) + 75 \times 0.777$$

$$d_1 \cong 0.442 \text{ m,}$$

$$162.108 = 750 \times (d_2 - 0.05) + 75 \times 0.777$$

$$d_2 \cong 0.188 \text{ m.}$$

Based on these results, we established how the dimensions of the desk top or the aprons could be modified. It means that during the prototype production their sizes could be changed to a certain extent without any effect on the stability. For a clearer picture, the dimensions were converted to the centre of the adjusting screw (Fig. 9).

DISCUSSION AND CONCLUSION

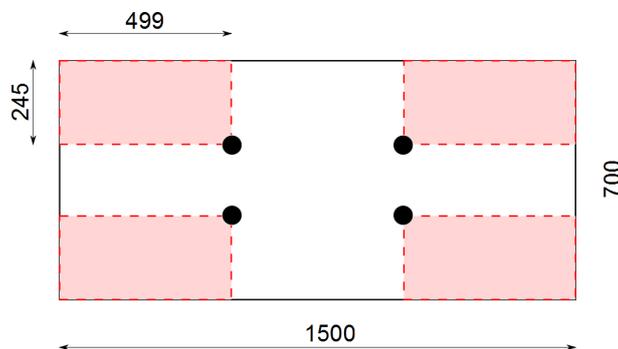
The results of the numerical simulation carried out by means of FEM analysis showed the probable propagation of tension in a construction of an office desk and located the possible areas of extreme tension leading to permanent deformations or potentially material breakage. Based on the

numerical calculations, tests will be conducted in the Furniture Testing Lab (Department of Furniture, Design and Habitation), Mendel University in Brno. The numerical analysis allows for an easier and reliable determination of possible areas of deformation or breakage, which could otherwise remain undiscovered due to the rather complicated construction of desk legs and aprons.

Another step will be an optimization of the geometry of separate elements of the construction. That will demand a more powerful and more advanced solver (e.g. ANSYS Workbench). We can assume that the geometry of the upper part of the desk leg will be modified by inserting and welding on a steel plate and closing the open profile. This should ensure a sufficient strength of the leg-apron contact and also sufficient rigidity of the entire desk construction. All these modifications should aim for a value of safety coefficient from 1.5 to 3.5 at each point of the construction. This should ensure that the construction will be able to resist even higher loads; but still, these modifications should not result in a considerable increase in the construction weight.

The calculation of stability will be tested in the above mentioned Furniture Testing Lab as well so that the desk complies with valid Czech standards (ČSN EN). It could be used as a basis for a number of dimension-related versions of the apron and corresponding dimensions of desk tops.

The study deals with the possibilities of employing computational methods in the practice of designing more complicated furniture constructions. Thanks to the advanced methods it is now possible to find not only various strength and stability problems but also indications of their optimization and possible solutions. These methods are highly interesting for the practice mainly because the time and costs are not high in contrast to the production and testing of prototypes of individual versions.



9: The areas of possible placement of the adjusting screw centre in relation to the desk top area. All dimensions are in millimetres.

SUMMARY

The aim of our study, which focused on a static analysis of a desk construction, is the determination of a probable mechanical behaviour of an office desk construction, especially its stand, in consequence of a defined static loading based on the standards of the testing methods for stability and mechanical resistance of office desk constructions. The conducted numerical analysis focused on the most exposed points; subsequently, the stability of the entire desk was calculated. The construction was modelled and numerically analysed in Autocad Inventor 2011. The size and placement of force loading and the material properties of the individual elements of the construction were based on valid standards and cited literature. The results of the construction loading by force loading in its various parts (selected based on standards) were assessed and used for the analysis of the points where deformation or breakage is the most probable. The simulation confirmed that the points with high probability of breakage are located in the upper part of the desk leg. Moreover, possible directions of the deformation progress in this area were analysed and a solution for its prevention was proposed. The stability calculation was based on valid standards and was used for the solution of dimension modifications of the stand and the desk top. The stability of the desk was calculated as well as the extreme position of the stand in relation to the desk top. As the next step, we are planning the verification of the obtained results in an accredited furniture testing lab using a prototype of the office desk construction and an optimization of the construction by means of more advanced numerical solvers.

Acknowledgement

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REFERENCES

- AUTODESK, 2011: Autodesk Inventor Professional 2011 – User's Guide. [online] cited on May 4, 2011. Retrieved from: http://wikihelp.autodesk.com/Inventor/enu/2011/Help/User%27s_Guide.
- ČSN 41 1373, 1994: *Ocel 11 373 (Steel: class 11 373)*. Český normalizační institut, Praha, 24 p.
- ČSN EN ISO 14341 (05 5311), 2009: *Svařovací materiály (Materials for Welding Technology) – Dráty pro obloukové svařování nelegovaných a jemnozrných ocelí v ochranném plynu a jejich svarové kovy – Klasifikace*. Český normalizační institut, Praha, 16 p.
- ČSN EN 527-3 (911105), 2005: *Kancelářský nábytek – Pracovní stoly (Office Furniture – Working Tables) Část 3: Metody zkoušení pro stanovení stability a mechanické pevnosti konstrukce*. Český normalizační institut, Praha, 16 p.
- ECKELMAN, C., 2003: *Product Engineering and Strength Design of Furniture*. Purdue University, West Lafayette, Indiana, 204 p.
- HALLIDAY, D., RESNICK, R., WALKER, J., 2003: *Fyzika: vysokoškolská učebnice obecné fyziky (Physics textbook)*. VUTIUM, Brno, 1198 p. ISBN 80-214-1869-9.
- HLUCHÝ, M. a kol., 2007: *Strojírenská technologie 1 – 1. díl Nauka o materiálu (Mechanical Engineering Technology – part 1 Materials)*. Scientia, Praha, 266 p. ISBN 80-86960-26-5.
- JOŠČÁK, P., 1999: *Pevnostné navrhovanie nábytku (Strength Design of Furniture)*. DF, TU vo Zvolene, 246 p.
- KOŇAS, P., 2006: *Finite element model of the bed*. Acta univ. agric. et silvic. Mendel. Brun., LIV, No. 2, pp. 67–72.
- NICHOLLS, T., CRISAN, R., 2002: *Study of the Stress-Strain State in Corner Joints and Box-Type Furniture Using Finite Element Analysis (FEA)*. Holz als Roh- und Werkstoff, v. 60, pp. 66–71.
- SMARDZEWSKI, J., PREKRAD, S., 2009: *Optimisation of Sofa Frame in the Integrated CAD-CAE Environment*. cited on February 4, 2011. Retrieved from: http://www.ejpau.media.pl/author_177.html.
- ŠIMEK, M., KOŇAS, P., 2009: *Bending stress modeling of dismountable furniture joints applied with a use of finite element method*. Acta univ. agric. et silvic. Mendel. Brun., LVII, No. 1, pp. 137–146.

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