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Preliminary note

TYPIFIED MACHINE PARTS SERIES LOAD CAPACITY ANALYSIS FROM ASPECT OF STRUCTURAL STRENGTH

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Abstract: *Application of typisation in the process of designing mechanical sub-assemblies and assemblies is one of the ways to reduce the cost of production. Therefore, nowadays, not only roller bearings, bolts, wedges, etc. are produced as standard machine elements but, by the usage of typisation, a production of a large series of typified subassemblies and assemblies, such as electric motors, pumps, power transmissions, etc., is increasing. Increased application of typified parts, sub-assemblies and assemblies in mechanical systems requires an increase in their safety and reliability during operation. Accordingly, in this paper, the load capacity of the typified machine parts series from the aspect of their structural strength is analyzed. It has been shown that there is a scattering of calculated results of the safety factor of members of the typified series from the aspect of the structural strength. The paper presents a proposal for a calculation methodology by which the mentioned scattering of the results of load capacity of typified machine parts series can be significantly reduced.*

Key words: *load capacity analysis, typisation, structural strength.*

1. INTRODUCTION

The development of technique and technology accelerates the process of designing new and reconstructing the existing machine structures, i.e. reduces the time from the idea to the realization of the product. Modern machine construction must meet increasingly stringent criteria in terms of capacity, reliability, safety and security. In addition, the criteria from the aspect of ecological, energy and economic efficiency are more and more represented nowadays. Accordingly, new calculation procedures, materials, manufacturing technologies and design procedures are required, which will meet the above criteria. The designing, testing and machine manufacturing processes can be greatly accelerated by applying the *Cauchy's similarity criterion*. By applying Cauchy's similarity criterion, families of typified design solutions, of the same shape and material, but with different dimensions and bearing capacity are developed. According to this criterion, one designed and tested machine structure can be transformed into a family of similar machine structures, with larger or smaller dimensions and carrying capacities, without further testing and designing. In order to realize this transformation process, the physical sizes of all members of the typified series change in proportion to the changes of their dimensions, and the numerical values of these sizes belong to a set of standard numbers.
According to Cauchy's similarity criteria, the working stresses in the cross-sections of all members of the typified series have the same value. Also, according to this similarity criterion, it is stated [1-2] that all family members of the typified series have the same working capacity, that is, the same safety factor from the aspect of the structural strength, that is, their carrying capacity. It is well known that the safety factor represents the ratio of the critical and working stress, and that the critical stress depends on the size of the cross-section of the machine part [3-7]. Within a typified series of parts, the smallest, parent member of series has the smallest cross-sectional size, and the last member of the series has the largest cross-sectional size. Accordingly, machine parts of the typified series do not have the same values of critical stresses, which mean that they do not have the same safety factor value, that is, they do not have the same working ability to resist a critical condition. In order to examine the size of the dissipation field of the working ability, that is, the safety factor of the machine parts of the typified series, their working ability, from the aspect of the structural strength (dynamic fracture) in the domain of unlimited dynamic strength was analyzed. It has been shown that, depending on the typified series size, the dissipation of the working ability of the members of the typified series can be very pronounced, so that the last members of the series do not satisfy the load bearing condition from the aspect of dynamic fracture. In order to overcome this problem, the paper offers suggestions for reducing the dissipation field of the working ability of members of the typified series.

2. TYPIFICATION IN THE DESIGN PROCESS

In mechanical engineering, there is often a need for the design and production of a number of machine parts, sub-assemblies and assemblies of uniform shapes and materials used, but different in dimension and load capacity, figure 1. Typical examples of typified

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components are electric motors, gearboxes, pumps, compressors, fans, etc. One of the basic activities within the standardization is the products typification. Accordingly, typification is a form of standardization in which the product assortment is reduced to the most favorable range. It is carried out in order to increase the massiveness and quality of production while at the same time increasing the economy, profitability and productivity. Also, typification process facilitates the exploitation of mechanical systems, as well as their maintenance and supply of spare parts.

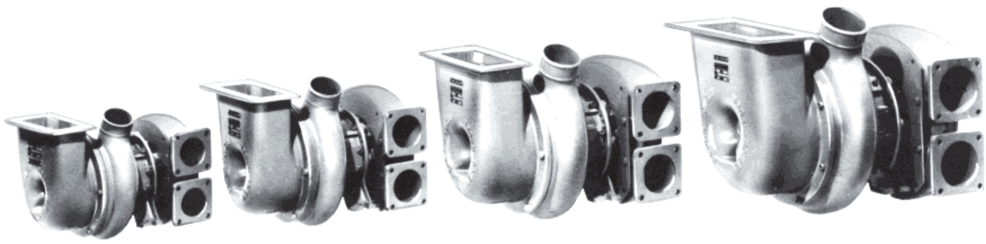
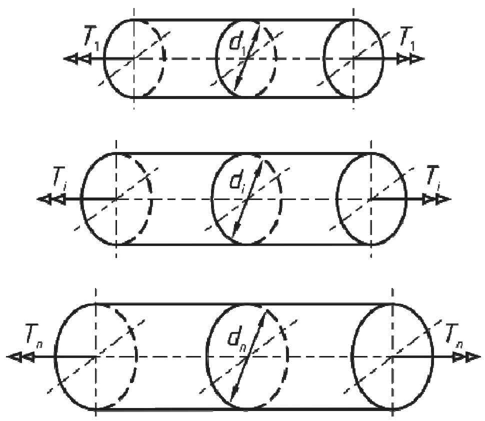


Fig.1. Application of typification process in the development of a series of turbochargers, standardized diameters of the impeller are from the order R40/3 with the growth factor φ_L = 1.18 [8]

The typification is based on the application of the criterion of geometric similarity, the Cauchy's similarity of loads criterion and a set of standard numbers [9]. Instead of designing a series of machine parts, sub-assemblies and assemblies of the same function and of different capacities, only the *parent* machine structure, most often the smallest member of the typified family, is designed. Through the phases of the designing process, the shape, dimensions, material and tolerances are defined, and, in the end, the appropriate technical documentation is generated. Then, the same, parent machine structure is produced and thoroughly examined in working conditions, in order to examine and correct possible deficiencies. Then, without the application of the designing process, but only on the basis of the results of constructing and testing the parent machine structure, the geometric quantities and the load sizes (power, flow, load, etc.) are defined for other members of the typified family. Bearing in mind the fact that the parent construction leaves all its good and bad characteristics in the heritage to its descendants, it must be a "mature construction", that is, it must be fully constructively and productively perfected.

If in the family of typified parts the *i*-th member has some length measure of the size L_i, and the member $i + 1$ has the same length measure of the size L_{1+i}, then the growth factor of the observed length measure for all members of the typified series represents the ratio of these quantities $\varphi_L = L_{1+i} / L_i$. In order to be able to express the growth factors for other physical quantities (surfaces, volumes, axial moments, loads, mass, etc.) in the function of the growth factor of the length measure, it is necessary that all length dimensions (length, width, height, diameter, etc.) with the observed typified parts have the same growth factor. Consider a family of *n* typified machine parts stressed to torsion. If the moment of torsion T_1 applies on the first member of the family, then, by applying the series of standard numbers or geometric progression, the moment of torsion can be determined for all members of the observed family.

$$\begin{aligned} &T_1, \\ &T_2 = \varphi_T \cdot T_1, \\ &T_3 = \varphi_T^2 \cdot T_1, \\ &\vdots \\ &T_{\mathrm{i}} = \varphi_T^{i-1} \cdot T_1, \\ &\vdots \\ &T_{\mathrm{n}} = \varphi_T^{n-1} \cdot T_1. \end{aligned}$$



Based on the last expression, the growth factor for the moment of torsion follows:

$$\varphi_T = \left(\frac{T_{\mathrm{n}}}{T_1}\right)^{1/(\mathrm{n}-1)}.$$

For members of the typified series, with the increase of the transverse dimensions, the amount of acting load increases in the same cross-sections. Therefore, according to Cauchy's similarity criteria, the working stresses in the cross-sections of all members of the typified series are the same by intensity:

$$\tau_1 = \tau_2 = \cdots = \tau_{\mathrm{i}} = \cdots = \tau_{\mathrm{n}}. \quad (1)$$

Also, the working stresses of all members of the typified series must have the same law of change over time, that is, they must have the same stress asymmetry factor:

$R_{\tau 1} = R_{\tau 2} = \cdots = R_{\tau \mathrm{i}} = \cdots = R_{\tau \mathrm{n}}$.

The equation (1) can be written in the form:

$$\frac{T_1}{d_1^3 \cdot \pi \cdot 16^{-1}} = \frac{T_2}{d_2^3 \cdot \pi \cdot 16^{-1}} = \cdots$$
$$= \frac{T_\mathrm{i}}{d_\mathrm{i}^3 \cdot \pi \cdot 16^{-1}} = \cdots = \frac{T_\mathrm{n}}{d_\mathrm{n}^3 \cdot \pi \cdot 16^{-1}}.$$

By observing any two consecutive members of the family, the following equality can be written:

$$\frac{T_{1+\mathrm{i}}}{T_\mathrm{i}} = \left(\frac{d_{1+\mathrm{i}}}{d_\mathrm{i}}\right)^3.$$

On the basis of this equation, a relationship can be established between the growth factors of the load i.e. the moment of torsion and the growth factors of the increase in length measures:

$$\varphi_T = \varphi_L^3.$$

According to Cauchy's similarity criterion, all members of the typified series perform their elementary or partial function with the same safety factor against different types of structural and/or surface destruction. Therefore, the following equality can be written:

$$S_1 = S_2 = \cdots = S_\mathrm{i} = \cdots = S_\mathrm{n}. \quad (2)$$

The same equation can be written in the form:

$$\frac{[\tau]_1}{\tau_1} = \frac{[\tau]_2}{\tau_2} = \cdots = \frac{[\tau]_\mathrm{i}}{\tau_\mathrm{i}} = \cdots = \frac{[\tau]_\mathrm{n}}{\tau_\mathrm{n}}.$$

On the basis of equations (1) and (2) it follows that the critical stresses for all members of the typified series are the same:

$$[\tau]_1 = [\tau]_2 = \cdots = [\tau]_\mathrm{i} = \cdots = [\tau]_\mathrm{n}. \quad (3)$$

That is, the critical stresses growth factor is equal to one:

$$\varphi_{[\tau]} = 1.$$

3. ANALYSIS OF THE WORKING ABILITY OF MACHINE PARTS OF THE TYPIFIED SERIES FROM THE ASPECT OF STRUCTURE STRENGTH

In this paper the working ability of machine parts of the typified series from the aspect of dynamic fracture, in the domain of unlimited dynamic strength is considered, in conditions when the stress asymmetry factor is R_τ = -1 (alternating torsion). In order to analyze the working ability of machine parts it is necessary to know their working (*Ws*) and critical state (*Cs*). These two states depend on the character of the change in the working stresses over time, that is, the stress asymmetry factor, and the intensity of the working and critical stresses. The positions of the working (Ws_1), and the critical (Cs_1). states of the parent machine part of the typified series in Smith's diagram are shown in figure 2a, in accordance with the change in the working stress shown in figure 2b.

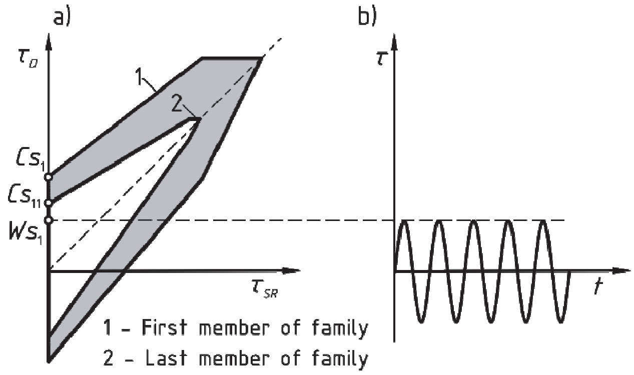


Fig.2. Smith's diagram for material EN295 in the case of torsion; b) Change in working stress over time

For the working ability analysis of the members of the typified series from the aspect of dynamic fracture in the domain of unlimited dynamic strength, a family of lightweight shafts, loaded only with torsion, of 11 members was observed. Unnotched shafts were considered, without a source of stress concentration. The smallest member of the family is exposed to the moment of torsion whose intensity is T_1 = 12.50Nm, and the largest family member to the moment of torsion whose intensity is T_{11} = 12500Nm. The material of the shaft is EN295 (Č0545), and the safety factor against the dynamic fracture of the shaft series is 2.00.

Dimensioning, i.e. determining the transverse dimensions of the shaft without stress concentration, was carried out with the first - parent member of the observed shaft family based on its working and critical state, Figure 2. The dimensions of the cross-section, the values of the moment of torsion and the working stresses of other members of the typified shaft series were determined on the basis of the criteria of geometric similarity and the Cauchy's similarity criteria. The results of the conducted analysis are shown in Table 1.

Table 1: Results of the analysis of the safety factor of members of the typified series

	Typified family member										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
d [mm]	10	12,50	16	20	25	31,50	40	50	63	80	100
Wp [mm^3]	196	383	804	1570	3067	6137	12566	24543	49096	100531	196350
T [Nm]	12,50	25	50	100	200	400	800	1600	3150	6300	12500
τ [N/mm^2]	63,6	65,2	62,1	63,6	65,2	65,1	63,6	65,2	64,1	62,6	63,6
ξ_1	1,00	0,96	0,93	0,89	0,85	0,82	0,78	0,75	0,73	0,72	0,71
τ_{DM} [N/mm^2]	130	124,8	120,9	115,7	110,5	106,6	101,4	97,5	94,9	93,6	92,3
S	2,00	1,91	1,94	1,81	1,69	1,63	1,59	1,49	1,47	1,49	1,44

In order to analyze the working ability of all members of the typified shaft series, it is necessary to define their working and critical states in Smith's diagram. Based on the equation (1) and the results shown in table 1, it can be noted that the dissipation of the working stresses of the members of the typified series of shafts are within the limits acceptable to the technical-engineering practice. Accordingly, the operating conditions of all members of the typified shaft series coincide with the working state of the parent member - shaft, $Ws_1 = Ws_i$, figure 2a. It is known that the critical stresses, that is, the critical condition of the shaft, from the aspect of dynamic fracture, depends on the size of the cross-section [3-7]. Because of this fact, the members of the shaft typified series will not have the same critical stresses values, τ_{DM} in table 1, and the positions of their critical states will not coincide with the critical state of the parent structure $Cs_1 \neq Cs_i$, figure 2a. Accordingly, the equality of critical stresses (3) and equality of safety factor (2), according to Cauchy's similarity criterion, can't be achieved with all members of the typified series. Based on the working and critical stresses, the values of the safety factors against dynamic fracture are determined for all members of the typified shaft series, table 1. The dependence of the safety factor and the transverse dimensions of the typified shaft series is shown in Figure 3.

It is known that the minimum value of safety factor for the shafts, from the aspect of the dynamic fracture, should minimally be 1.50. According to that, based on the diagram in figure 3, it can be concluded that the proposed family of shafts with 11 members can't exist with all its members in the domain of unlimited dynamic strength, from the aspect of dynamic fracture. Only the members of family from 1 to 7 have satisfactory working ability from the aspect of the dynamic facture of the shaft. Other members (from 8 to 11) do not satisfy the condition of working ability from the aspect of dynamic fracture. The results of the scattering of the working and critical stresses and the safety factor of the shafts of the observed typified series in relation to the values of the same sizes of the parent shaft (which is labelled 1) are shown in the diagrams in Figure 4.

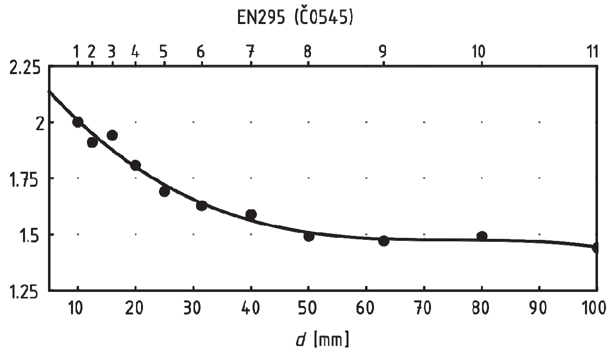


Fig.3. Dissipation field of the safety factor for the members of the typified shaft series

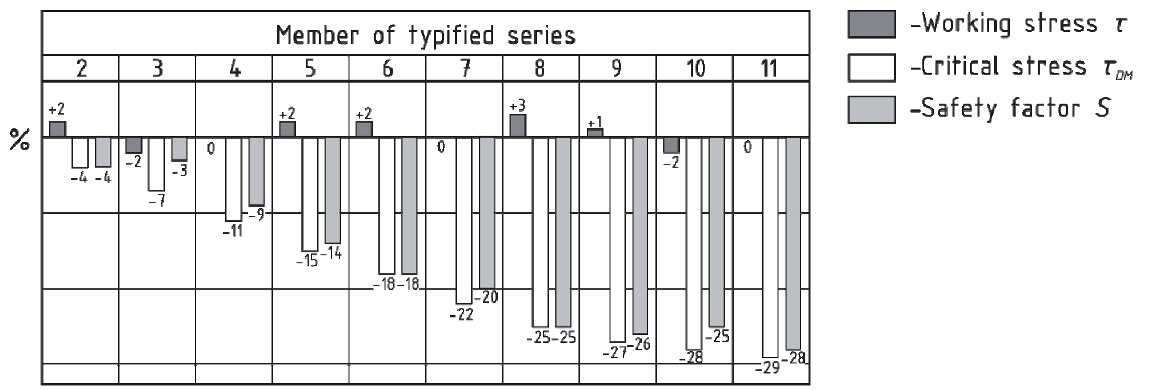


Fig.4. The percentage difference between the working and the critical stresses and the safety factor of the members of the typified series in relation to the parent member

The dispersion of working stresses among members of the typified shaft series in relation to the working stress of the parent shaft is within the limits acceptable in technical practice and amounts to 3%, the diagram in figure 4. However, deviations in the critical stresses and safety factors in individual members of the typified shaft series relative to the parent shaft are drastically higher than the acceptable-allowed in technical practice. The biggest deviations of the critical stresses and safety factor, in the amount of 29% and 28% respectively, are generated with the largest members of the typified shaft series. Acceptable deviations in technical practice are in the range of 5% to 10%. Bearing this in mind, and according to the results given in figure 4, the acceptable number of members of the considered typified shaft series is in the interval from 3 to 4. The question arises as to whether such large-scale scattering of the critical stresses and safety factors of the shafts of the observed typified series can be reduced. In the continuation of this work, the variant solutions for reducing the dissipation of the working ability of members of the typified shaft series will be considered.

4. VARIANT SOLUTIONS TO REDUCE THE DISSIPATION OF THE WORKING ABILITY OF MEMBERS OF THE TYPIFIED SERIES

In the case of a family of typified parts, it is customary to adopt the smallest family member as a parent member, due to the lower cost of production and testing. This economic criterion for the selection of the parent member of the typified series limits the number of members of the series from the aspect of working ability, the diagram in Figure 3.

In order to overcome this problem, in the considered typified shaft series, the solution of the dismantling of a large family into two smaller families, subfamilies *a* and *b* was analyzed. The first subfamily consists of seven members and the other one of four members. The results of the analysis of the working ability of the members of these subfamilies are shown in the diagram in figure 5. With this variant solution, all members of the considered subfamilies have a satisfactory working ability in terms of dynamic fracture, that is, for all members the safety factor is greater than a minimum value (1.50). The results of the dissipation of working and critical stresses and safety factors are shown in the diagram in Figure 6.

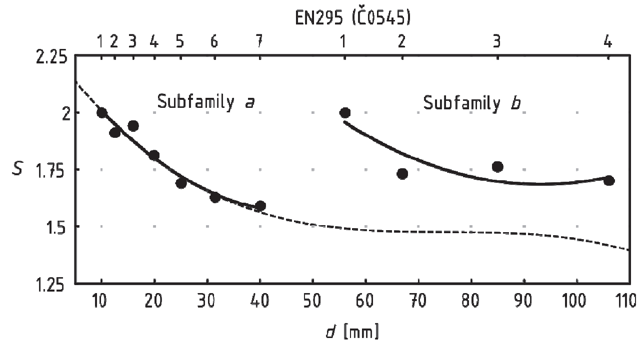


Fig.5. Reduction of the dissipation of the safety factor values of the initial family (dashed line) by dividing the typified series into two subfamilies

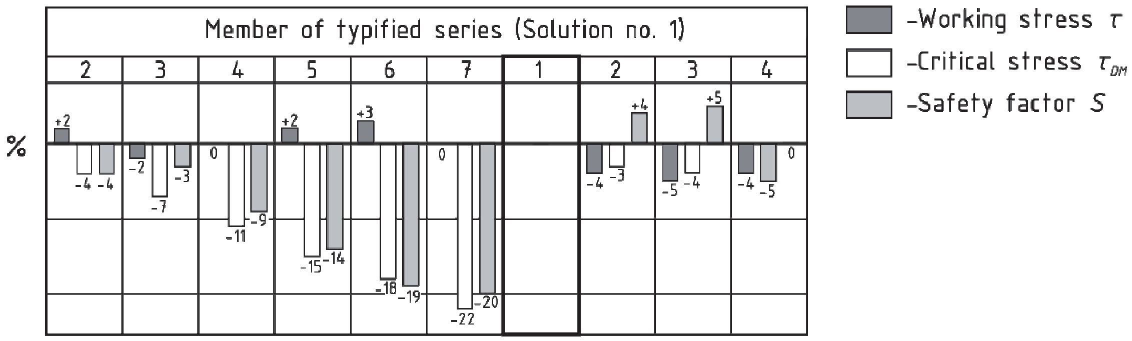


Fig.6. Percentual change in the working and critical stresses and safety factor of the members of the typified series in relation to the parent members in the method of dividing the typified series into two subfamilies

In the second variant solution in the considered typified shaft series of 11 members a middle member of the family was adopted for the parent shaft. This variant solution also ensures that all members of the typified shaft series have the required working ability from the aspect of the dynamic fracture, the diagram in figure 7. The members of the typified series of the larger cross section have less dissipation of working capacity, observed in relation to the parent member, compared to the members of the smaller cross section, the diagram in Figure 8.

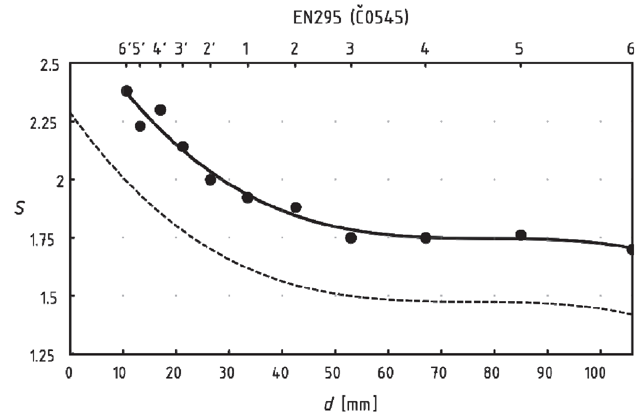


Fig.7. Reduction of the dissipation of the safety factor values by the method of adopting a middle member as a parent

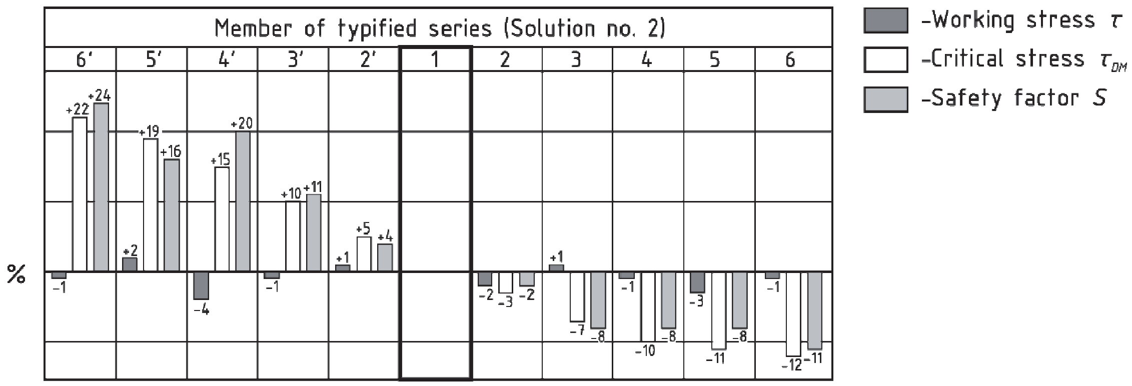


Fig.8. Percentual change in the working and critical stresses and safety factor of the members of the typified series in relation to the parent member in the method of adopting a middle member as a parent

5. CONCLUSION

In the new generations of mechanical constructions, there are ever more stringent criteria from the techno-economical aspect. Therefore, the processes of designing, constructing and manufacturing mechanical structures are more and more based on the application of typification, that is, on generating a typified series of machine parts, sub-assemblies and assemblies. Accordingly, in this paper we tried to illuminate the assumptions on which the process of designing the typified series of products is based. It has been shown that the assumption of equality of working ability from the aspect of the load capacity of all members of the typified product series is not valid. It is true that the working stresses in the cross-sections of all the members of the typified series are approximately the same, i.e. that their deviations are within the limits acceptable in the technical practice. However, the assumption of the critical stresses equality among the members of the typified series can't be accepted due to the fact that these stresses are a pronounced function of the size of the cross-section of the machine part. It has been shown that there is a great dissipation of the critical stresses and safety factors among the members of the typified series in relation to the parent structure. It has also been shown that for typified series with a large number of members, the working ability of the members of the largest dimensions may be insufficient in terms of load capacity or it is at a minimum load capacity limit.

In order to reduce the dissipation of working ability among members of the typified series, appropriate variant solutions have been proposed. The first solution relates to the application of subfamilies, or the dismantling of large families to a smaller number of partial families. In the second solution, it is suggested that, in the case of large families, a middle member of the family should be selected as a parent member, and not the smallest member of the family, which is a common practice.

Bearing in mind the significance of typification in the design and construction of modern systems, the results and suggested proposals in this paper should stimulate a greater number of papers in this field, in which until now, there are almost no scientific papers.

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