ENGINEERING DESIGN AND STRENGTH ANALYSES OF MAIN LOAD-BEARING PARTS OF A MECHANICAL RACK SYSTEM

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Abstract

This article presents an engineering design of a mechanical rack system along with strength analyses of its main load-bearer parts. The designed mechanical rack system is intended to be mounted in a production hall for storage of rod material with total length of 6 m. The whole structure of this equipment is welded and made of steel profiles. It consists of a main load-bearing part, which comprises a central beam and horizontal beams and four draw-out shelves on each side, which are arranged four levels. Every individual shelve is able to carry the mass of 3.0 t. As the solved rack system is not standardized but designed in compliance with specific requirements of a customer, we had to support the structure carrying capacity with strength calculations. Structural calculations were realized by means of numeric finite element method. Strength analyses were performed for the maximum load cases.

Keywords: mechanical rack system, storage of a goods, strength calculations, finite element method

1. INTRODUCTION

Storage cannot be separated from material flows in all spheres of economy. The need for storage of material of all kinds arises due to the different pace of production and consumption, the different flow in all levels of a logistic chain. Moreover, the storage forms an inevitable part of the production technology. We can deal with warehouse issues in different ways, with reference to building solutions, the organization, technical equipment and many others. From the point of view of logistic objects it is particularly suitable to pay attention to three types of warehouses, namely the warehouse of bulk material, metallurgical material and pallets. Material characteristics, material amount, and storage technology requirements in connection with other processes are essential for the right choice of warehouses. In analysing the kind of metallurgical material in a certain engineering company it was found out that only 25 % of items are material of one item in bulk with a large turnover rate of revenues and costs. The rest of material weighed less though their items formed 70 % up to 80 % of the whole items in that warehouse. That`s why it is necessary to provide with optimal conditions for storage and handling and at the same time it is simple to solve the technology of handled items off take. Such quantities of rod material are to be stocked in racks (Fig. 1) and we recommend seizing them by means of a grab bucket. Using this way of

handling we do not need to bind material and in terms of controlling it is very suitable.

Fig. 1. The mechanical rack system

2. FUNDAMENTALS OF A SOLVED PROBLEM

Generally, handling equipment consists of bearing construction, driving mechanism and other parts (various additional equipment, e.g. a cab). The steel strucutre forms a basic bearing part of any handling equipment. Mostly it means the bearing construction of all equipment working parts which transmits all external loads affecting the equipment. The shape of the steel structure defines its kind and purpose of use. Its production is carried out by joining parts into larger structures by means of either riveting (an older way), or welding (nowadays the most common way). For this reason, the designed steel structure of a rack system will be

constructed by welding. Among the most important customer`s requirements we can include the safety of the structure. The steel structure should be light and rigid enough to ensure the economy of production and operation, it should also be aesthetic and take into account the perfect arrangement of the steel structure as a whole, it should allow a safe access to all mechanisms, and it should also have an appropriate division with regard to its assembly.

In designing the steel structure we consider particularly safety and consequently, reliability (summary of characteristics and factors which affect usability, no-failure operation, and maintenance of the steel structure) [3]. The structure will be formed by means of welding and we have to ensure the welding capability of material. Welding steel without special requirements and welding conditions (due to the demand for the economy of production) cannot contain more than 0,18 % of carbon resulting in strength less than 400 MPa of the given classes of steel used for the steel structures. To increase strength we can use steel with other alloyed element, for example steel 11 523 has strength 520 MPa and is alloyed by manganese (max: 1,5 % Mn, 0,55 % Si, 0,3 % Cr, 0,3 % Ni) [1]. That`s why we have chosen steel S235 and S355 as basic material of rack system structure. In welded structures influenced statically and dynamically we use butt and fillet welds. The calculation is run on dimension principles with certain specification. To save storage area, for the company it is important that the rack, serving for material storage, provides the storage in several layers in height. To alleviate handling with material stored in the rack and to increase clarity, one kind of material is deposited together if possible. Moreover, we have to take into account the principle that if we put more kinds of material into the rack, loading and unloading of material at the bottom is time-consuming. Therefore, to increase the handling efficiency it is advisable to construct storage racks as a mechanism with a single degree of freedom, which allows to pull out the material horizontally and to grip it by means of a grab bucket.

3. DESIGN OF A RACK SYSTEM

The engineering design of steel structure consists of three elements (Fig. 2), i.e. load-bearing structure of central, vertical and horizontal beams, into which racks are pulled in and out, are welded to this structure. The storage method ensures demanded movement possibilities, i.e. the rack movement. The material in weight of 3.0 tons will be stored on eight retractable racks. Each retractable rack is divided into six parts − webs mutually connected with shafts by means of shaft coupling and they are pulled out together by a crank handle.

Working with the sixths model means to save calculation` because the structure is designed

symmetrically from the view of geometry, fixing and loading. The steel structure is made from thin-walled square tubing which dimensions and materials are put in Table 1.

Table 1. Individual parts of the designed structure

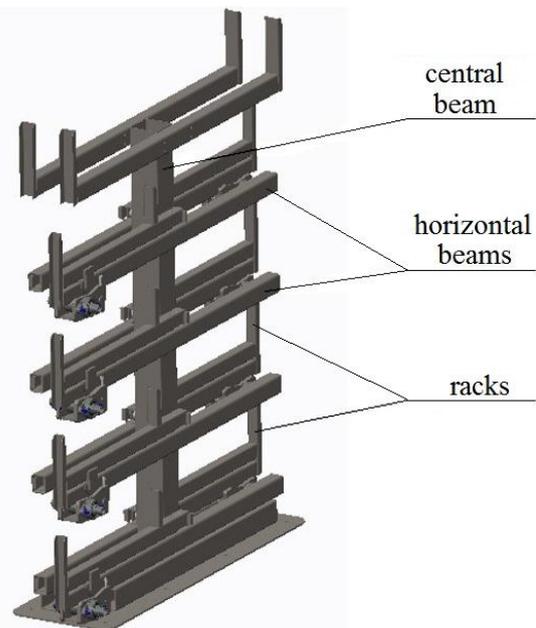| Main parts	Dimensions [mm]	Material
Centre beam	160x160x10	S235
Horizontal beam	100x80x6	S355
Shelves	80x60x4	S355

Fig. 2. Main load-bearing parts of the designed rack system

Mechanical properties of used materials whose knowledge is necessary for the structure analysis are listed in Table 2.

Table 2. Mechanical properties of used materials [1]

Steel	Yield stress [MPa]	Ultimate stress [MPa]
S235	200 – 240	340 – 420
S355	320 – 360	520 – 640

Whereas the transmission of structure mechanism is driven by a crank handle, the racks will move forward at low speed, so the dynamic stress of the structure is not significant. We count the maximum of allowed stress according to (1):

$$R_{per} = R_e \cdot \frac{1}{k} . \qquad (1)$$

We consider for material yield strength of horizontal beams and racks $R_e = 360$ MPa and safety coefficient with regard to the static way of loading the structure $k = 1.7$ (-). For material yield strength of central beams we consider $R_e = 240$ MPa and the safety coefficient with regard to the static way of loading the structure as well as in the previous case $k = 1.7$ (-). Then for allowed stress in the structure by using material S355 we get using (1) following:

$$R_{per}^{355} = R_e^{355} \cdot \frac{1}{k} = 360 \cdot \frac{1}{1.7} \doteq 211.8 MPa \qquad (2)$$

and for material S235 R_{per235} = 141 MPa:

$$R_{per}^{235} = R_e^{235} \cdot \frac{1}{k} = 240 \cdot \frac{1}{1.7} \doteq 141.2 MPa. \qquad (3)$$

In the locations of weld of each structural part it is necessary to decrease in the allowed stress of the amount which is experimentally practiced and decreases in the allowed stress of approximately 30 %. We include this fact in the calculation by using the welding coefficient c:

$$R_{perW} = R_{per} \cdot c. \qquad (4)$$

To reduce the allowed stress amount in the place of weld by recommended 30 % we choose the amount of welding coefficient $c = 0.7$ (-). By solving the equation (4) we get permissible values of stress in the location of welds for the S355 material following:

$$R_{perW}^{355} = R_{per}^{355} \cdot c = 211.8 \cdot 0.7 \doteq 148.3 MPa \qquad (5)$$

and for the S235 material:

$$R_{perW}^{235} = R_{per}^{235} \cdot c = 141.2 \cdot 0.7 \doteq 98.8 MPa. \qquad (6)$$

The realization of the mechanism for webs movement will be carried out by means of a friction wheel and we will expect low initial costs because its production technology is not really difficult. Moreover, there is no need for much maintenance because it is not necessary to lubricate, even it is not allowed. Another main advantage is a low frequency of failure rate.

Hand drive is not suitable for all mechanisms because we should take into account person`s performance and comfort. We can use it only for a small load capacity, a low lift, and low working speeds during the occasional, not permanent use. When designing the hand drive, we have to remember that the permanent performance of an average person is about 75 W. And as well, we have to take into account the ergonomic point so that a worker can use the equipment without any difficulty. The best way of transferring strength is by a handle at maximum circumferential speed of 1 m/s. During the permanent work of one worker (considering his performance) the force on the crank is set to the maximum of 100 N. It is also possible to increase the force up to 200 N during 10 minutes, of course in case of reducing the speed.

4. CALCULATION OF FORCES LOADING THE STRUCTURE

As the first step there is necessary to determine forces loading the designed structure. There act gravitational forces of individual parts and loads on arms and also reactions. Reactions depend on arm overhang. We come out from diagrams shown in Fig. 3 and Fig. 4. Every shelve is supporting on three rolling bearings marked in Figures with letters A, B and C. From the working principle of the rack system, there are two extreme loading position, i. e.

when arms are in the pulling-in (Fig. 3) and pulling-out (Fig. 4) positions. In diagrams, acting forces (red colour) and reactions (green colour) are depicted. As we can notice, in the pulling-in position reactions arise only in the A and B bearings and in the pulling-out positions, reactions arise in the A and C bearings while the B bearing is loaded no more.
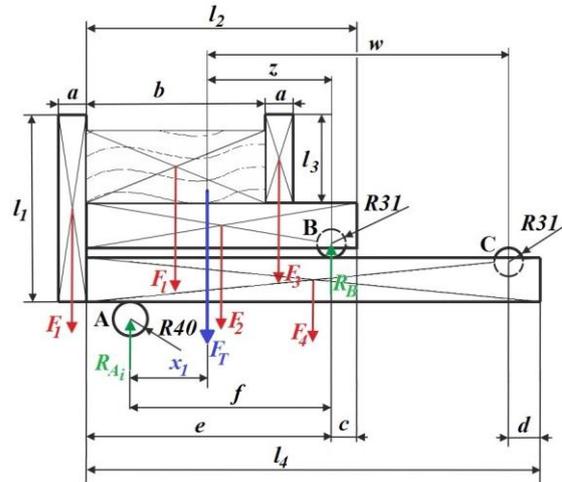

Fig. 3. Releasing diagram of the mechanism for pulling-in position of the shelve
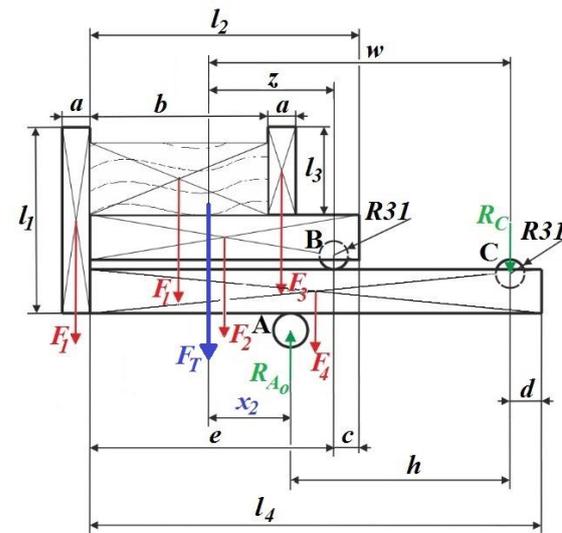

Fig. 4. Releasing diagram of the mechanism for pulling-out position of the shelve

Parameters of the mechanism dimensioning in Fig. 5 and Fig. 6 are listed in Table 3.

Table 3. Basic parameters of the mechanism

a	40 mm	l_1	400 mm
b	900 mm	l_2	1,200 mm
c	82 mm	l_3	200 mm
d	103 mm	l_4	2,095 mm
e	1,118 mm	z	643 mm
h	917 mm	w	1,517 mm
f	958 mm		

Dimensions x_1 and x_2 are variables and depend on the shelve overhanging. The dimension x_1 acquires values form the interval $\langle 0, 315.0\ mm \rangle$

and the dimension x_2 from the interval $\langle 0,\ 600.0 \text{ mm} \rangle$.

For next calculations we have to determine reactions (R_{Ai}, R_{Ao}, R_B and R_C) in supporting bearings as following. Firstly it is necessary to calculate gravitational forces of individual parts of the arm (F_1, F_2, F_3 and F_4) and of the load (F_l). We follow the familiar formula:

$$F_i = m_i \cdot g ,\qquad (7)$$

where

$$m_i = l_i \cdot m_i', \text{ for } i = 1, 2, 3, 4 \qquad (8)$$

while m_i' are masses of individual profiles per unit of length introduced in Table 4 and g is the gravitational acceleration.

Table 4. Masses of profiles per unit of length

m_1'	4.915 kg/m	m_3'	4.915 kg/m
m_2'	9.830 kg/m	m_4'	9.830 kg/m

As we consider the sixths model, also gravitational force of the load is sixths. If we take into account the gravitational acceleration of 9.81 m/s^2 and values of dimensions and masses written in Table 3 and Table 4, respectively, gravitational forces are: $F_1 = 19.29$ N, $F_2 = 115.72$ N, $F_3 = 9.64$ N, $F_4 = 202.03$ N and $F_l = 4,905.0$ N.

Now, it is relatively simple to determine value and position of the total gravitational force F_T acting on the one sixths of the arm structure. Its value is 5,251.68 N and and position is obvious from Fig. 3 and Fig. 4.

Reactions in supporting bearings we calculate using equations of equilibrium of moments in individual points. The sum of moments in the point B for the arm position according to Fig. 3 is:

$$\sum Mi_B = 0, \Rightarrow R_{Ai} \cdot (l - x_1) - F_T \cdot z = 0 ,\qquad (9)$$

From this equation we get the reaction R_A:

$$R_{Ai} = F_T \cdot \left(\frac{z}{l - x_1} \right) \qquad (10)$$

When the arm is still pulling-out, distribution of acting forces will be different and that according to Fig. 4. Then, the reaction in bearing A will be marked as R_{Ao} and it will be calculated from the different equation of moment's equilibrium. It means, that we come out form following formula:

$$\sum Mi_C = 0, \Rightarrow R_{A'} \cdot (w - x_2) = F_g \cdot w ,\qquad (9)$$

from which

$$R_{A'} = F_g \cdot \left(\frac{w}{w - x_2} \right) \qquad (10)$$

Next, we determine other reactions. For the calculation of the reaction R_B we compile the sum of moments in the point A:

$$\sum Mi_A = 0, \Rightarrow R_B \cdot (l - x_1) - F_T \cdot (l - z - x_1) = 0 ,\qquad (11)$$

thus:

$$R_B = F_T \cdot \frac{(l - z - x_1)}{(l - x_1)} \qquad (12)$$

Finally, the reaction R_C we get from the sum of moments in the point A in the pulling-out positon following:

$$\sum Mi_A = 0, \Rightarrow F_T \cdot x_2 - R_C \cdot (w - x_2) = 0 ,\qquad (13)$$

$$R_C = F_g \cdot \left(\frac{x_2}{w - x_2} \right) \qquad (14)$$

As we can see, reactions depend on dimensions x_1 and x_2. Calculated values of reactions are well-arranged listed in Table 5.

Table 5. Calculated values of reactions

	Reaction	[N]
$x_1 = 0$ mm	R_{Ai}	3,501.5
	R_B	1,715.5
$x_1 = 315$ mm	R_{Ai}	5,217.0
	R_B	0.0
$x_2 = 0$ mm	R_{Ao}	5,217.0
	R_C	0.0
$x_2 = 600$ mm	R_{Ao}	8,630.0
	R_C	3,413.5

By the above procedure we have calculated reactions, i. e. forces, which will serve as necessary input for numerical calculations of main.

5. STRENGTH ANALYSES OF MAIN LOAD-BEARING PARTS USING FEM

The strength analyses of main load-bearing parts of the rack system were carried out in the ADINA software by using known Finite Element Method [5, 10, 11]. As the structure consists of thin-walled tubing, it is suitable for the model creating to use shell elements.
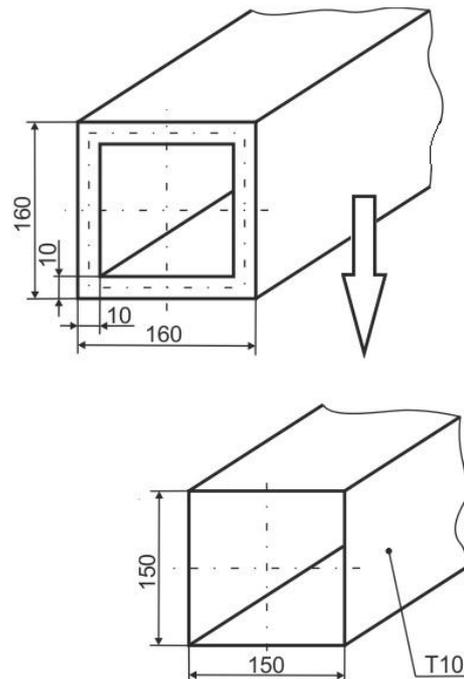

Fig. 3. Proces of shell model preparing

While modelling the shells it is necessary to prepare the geometric model with modified dimensions in advance. We have used so-called mid-surface and we have added the thickness of material (Fig. 3).

In ADINA Structures Pre-Processing [2, 4] we created the geometry of the shell model of the investigated part (Fig. 4).
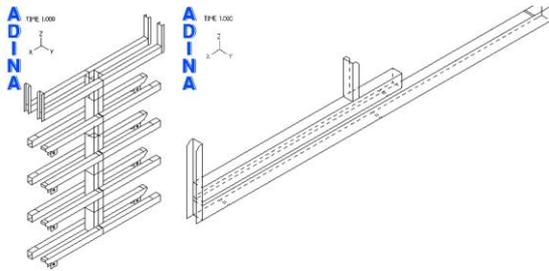

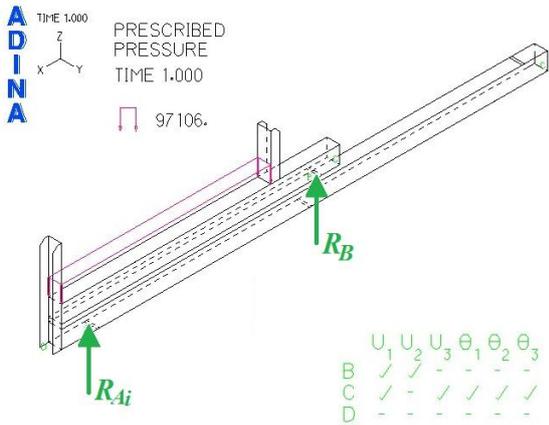Fig. 4. Geometry of the rack load-beaging part (left) and the rack arm (right)

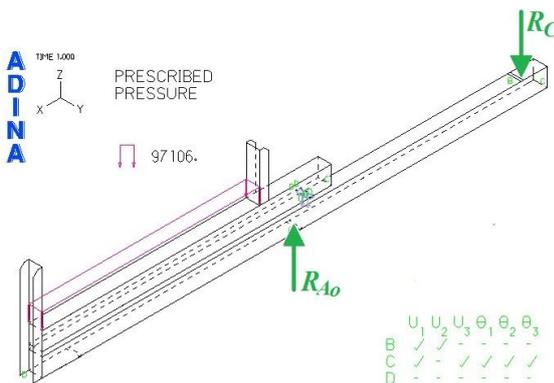Fig. 5. Load forces and boundary conditions for pulled-in position of the arm

Fig. 6. Load forces and boundary conditions for pulled-out position of the arm

The mechanism can be placed in two extreme positions when the arm is pulled-in (Fig. 5) and pulled-out position (Fig. 6), where forces F_{Ai}, F_B, F_{Ao} and F_C are forces loading the structure and they values were calculated in previous analytical calculations (Chapter 4). In numerical calculations the load is defined in the same way as in the reality,

i. continuous load (in comparison with the force vector in analytical calculations).

By reason of various loads in just mentioned two extreme positions we have analysed the structure twice. As the structure is made of steel, we choose elastic isotropic material model with corresponding mechanical properties: Young`s modulus of tensile elasticity $E = 2.1 \cdot 10^{11} Pa$, Poisson's coefficient $\mu = 0.33$ (-), density of material $\rho = 7,850$ kg/m^3.

The attachment of the model was performed by removing all degrees of freedom except of movements in *x* and *y* directions at the lower rims of the central beam by applying one edge point of the lower rim and removing one level of freedom in *x* direction at the opposing point. And we continued in forming the group of finite elements. A single group of shell elements with certain thickness was created for each part of the model with different thickness of a wall. Then it was necessary to create a group of rod elements (Fig. 7) which filled in the lifting hole in order to apply the loading forces in the middle of the lifting hole.
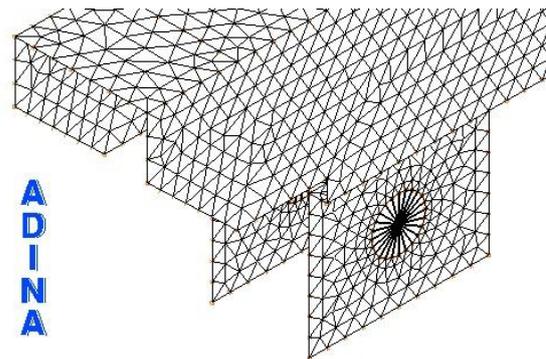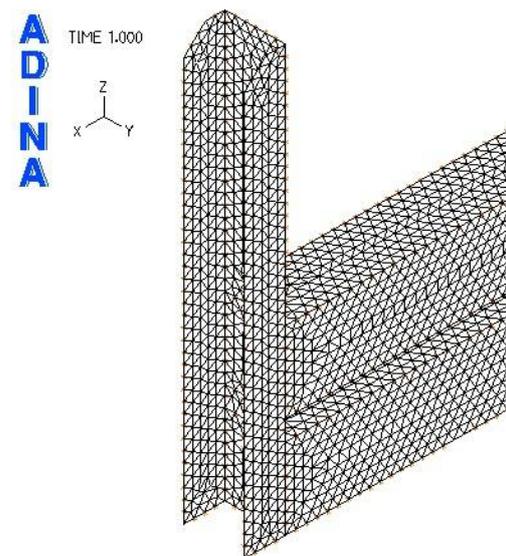

Fig. 7. Detail of FE mesh in the lifting hole

Fig. 8. Ilustration of the FE mesh of the analysed strucutre parts

Taking into account the compromise between accuracy of the calculation and needed calculation

we set the size of elements to 10 mm. Finally the model was meshed by linear tetrahedrons (Fig. 8).

After defining parameters and setting-up the FE model of the structure there is possibly to perform analyses. Then, it is necessary to switch the programme to the module Post-Processing, in which all results of analyses are presented and evaluated [5, 8].

In time $t = 1$ s, i.e. in the rack pulled-in position, stresses evaluated in compliance with the HMH hypothesis in the main-load bearing structure and in rack arms are distributed according to Fig. 9 and Fig. 10, respectively.

As we can see from these figures, in the pulled-in position of arms the maximum stress in the load-bearing structure is of 86.67 MPa except for the point of the attachment.
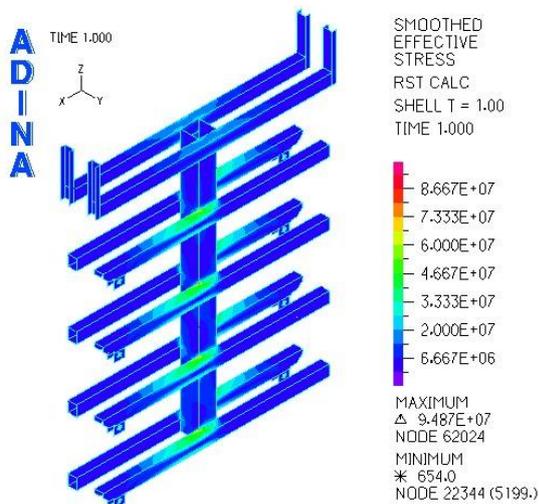

Fig. 9. Distribution of stresses in the central load-bearing part for the pulled-in position of arms
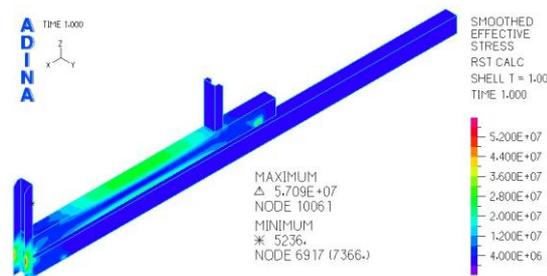

Fig. 10. Distribution of stresses in the arm for the pulled-in position of arms

The calculated value is smaller than the determined permissible stress for a welded structure (eq. 6), which is of 98.8 MPa. Thus, for the pulled-in position the central load-bearing structure of the rack system is designed properly.

Looking at the Fig. 10 we observe, that the maximum stress in the analysed rack arm is of 57.09 MPa. But, we do not take into account this value, because this stress is in the point of applying the boundary condition. Actually, the stress according to the colour scale in figure is important. It is 52 MPa. In comparison with the permissible

stress for a non-welded material (eq. 211.8 MPa) our results prove the correctness of the structure design.
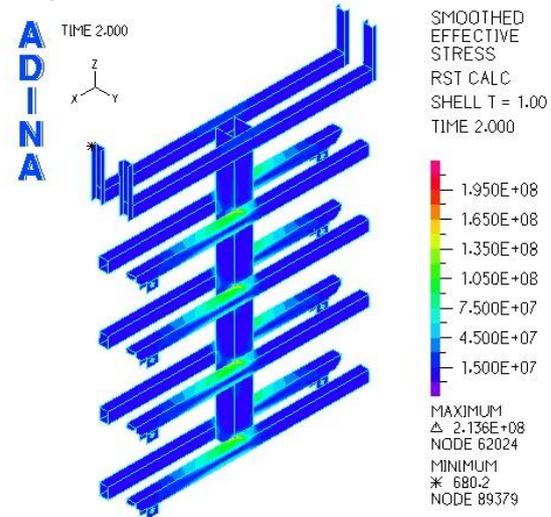

Fig. 11. Distribution of stresses in the central load-bearing part for the pulled-out position of arms
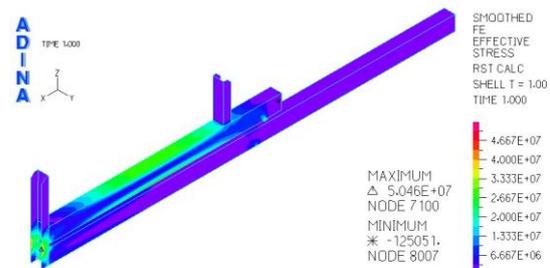

Fig. 12. Distribution of stresses in the arm for the pulled-out position of arms

In time $t = 2$ s, i.e. in pulled-out position of rack arms, the stress distribution in the central load-bearing structure and in rack arms calculated again according to the HMH hypothesis is shown in Fig. 11 and Fig. 12.

Let's a look in Fig. 11. The maximum of the calculated stress is 213.6 MPa in the location of the attachment. The stress in the weld is 195 MPa. We cannot use the strength condition, because the calculated stress (195 MPa) is bigger than the permissible values for welds (98.8 MPa, eq. 6). On the other hand we can use the strength condition for the rack arm in the pulled-out. The maximum of the calculated stress almost 50 MPa is acceptable even with sufficient allowance.

The strength analysis of the designed structure detected deficiencies of the design for the pulled-out position of racks arms. By this reason it is necessary to perform some modifications of the structure.

4. MODIFICATION OF THE CENTRAL LOAD-BEARING PART

During solution of the modification problem of the central load-bearing part structure we have found out several possibilities, how to modify this

structure. Taking into account all factors, as technological process of production, conservation of the structure simplicity, simple maintenance, production cost as well as requirements of customer, the optimal solution of this problem the complement of a supplementary sheet has turned out.

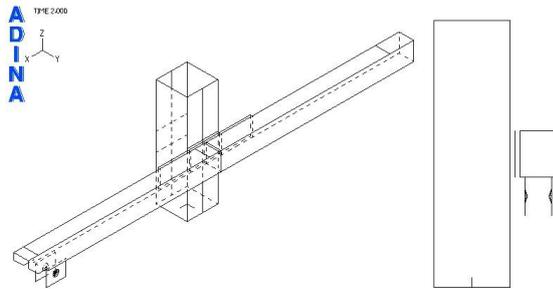Such a sheet is placed between the central beam and horizontal beams such that the thickness is increased (Fig. 13).

Fig. 13. Designed structural modification of the cetral load-bearing part

These all parts are coupled by welding. The thickness of a supplementary sheet is of 10 mm and it is made of S355 steel.

The geometry of load-bearing structure model is formed from three separated parts which are joined by means of interconnecting the displacements in each of the corresponding nodes of a mesh (Fig. 14). We have decided for this method, so that the model was more real. If only one mid-surface was modelled with the thickness of the corresponding amount of two beams and the sheet, the results would be less accurate because the sheet is welded to the beams only on the circuit and is not connected with the whole surface [4, 5].
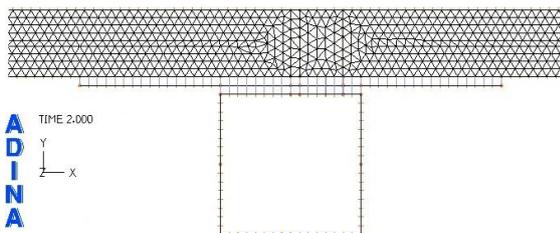

Fig. 14. Connctions of circuit nodes in the modified location

Results from reanalyses of the modified structure is shown in Fig. 15.

As we can see, designed modification of the structure results to the the stress reducing in the locations of the central beam and horizontal beams connection from 195 MPa to 118.6 MPa.
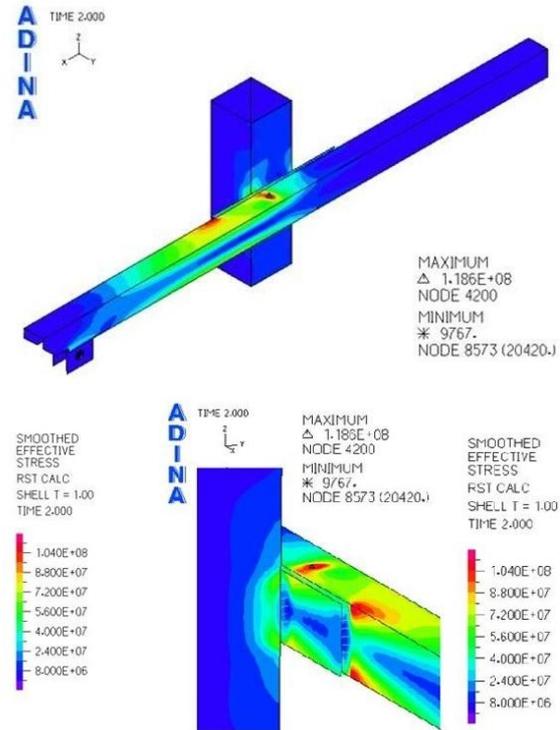

Fig. 15. Results of strength analysis of the modified central load-bearing part (above) and detail of the stress distribution in welded joint (below)

The comparison of obtained stress values with the permissible stress values for the welded material S 355 (148.3 MPa, eq. 5) we can conclude, that our designed modification of the analysed structure is proper and ensures the stress reducing in the overstrained locations to admissible values.

The maximum stress values will decrease to the safe value, and therefore the main load-bearing part of the rack system structure safely transmits required loads also during long-term operation.

In the case of necessity, further investigation of the designed rack system will be focused on setting-up so-called flexible multibody system, which means that our FE model will be imported into the MBS software, where will be possible to study dynamic effects load on the structure resulting from the long-term operation conditions [6, 7, 9].

5. CONCLUSION

This work presented technical solution of the mechanical rack system including strength analyses of its main load-bearing parts. The strength analyses were carried out in parts. The pull-out rack analysis has proved that this part of the structure does not meet the safety requirements. The analysis of the main load-bearing part of the structure showed significant deficiencies in strength and stability of the pulled-out rack position when the welds had the stress 213.6 MPa, and at the same time the arms are deformed. That is why we have designed the technical modification of the construction. This modification includes the weld

between the central beam and horizontal beams and thus increases the thickness of the structure in most loaded locations. Based on numerical calculations we have found out, that our modification ensures stresses reducing on the acceptable value of 118.6 MPa.

SOURCE OF FUNDING

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