

# Design and strength analysis of mechanical rack system

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**Abstract.** The paper deals with a construction design of the rack system which will be used for storage of metallurgical rod material in a manufacturing engineering company. To meet requirements for manual control of the pull-out mechanism it will be determined the force exerted by the worker on the hand crank required to pull in and pull out the racking system at the full load. In addition, stress analysis was conducted by means of finite element method.

**Keywords:** Rack system, functional calculation, constructional design, stress analysis

## 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 [1-3]. 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 (Fig. 1 left) 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 [4, 5]. 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 offtake. Such piles of rod material are to be stocked in racks and we recommend to seize 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 [6]. The engineering

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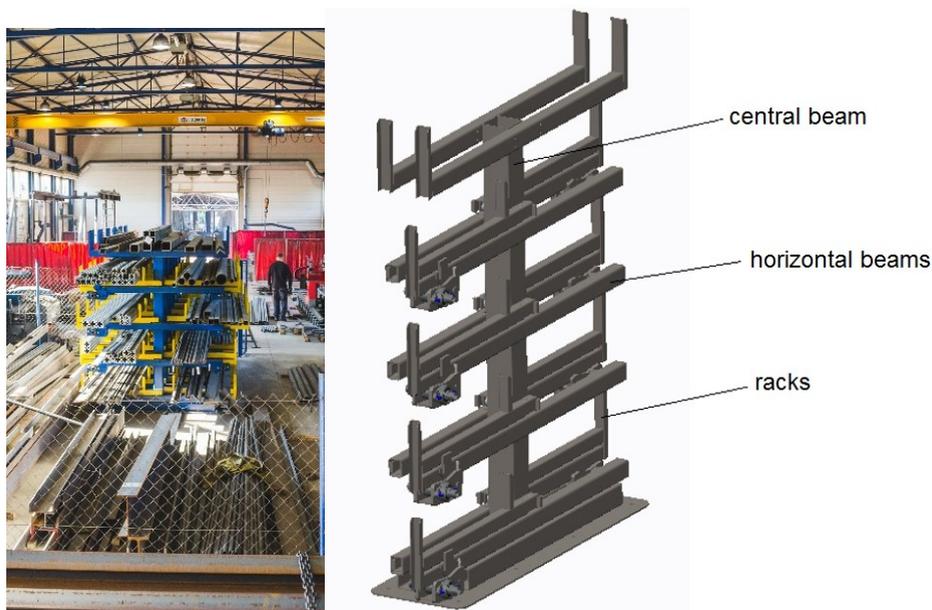
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company has to stock metallurgical material – rod material with the length of 5 meters, so for this reason it will be necessary to design the rack system with regard to customer’s requirements.

## 2 Construction design of rack system

The construction design of steel construction consists of three elements (Fig. 1 right), i.e. bearing construction of central, vertical beams and horizontal beams, into which racks are pulled in and out, are welded to this construction. The storage method ensures demanded movement possibilities, i.e. the rack movement. The material in weight of 3000 kilos 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.



**Fig. 1.** Metallurgical material warehouse within a company (left) and 1/6 model of rack system construction design (right)

Working with the 1/6 model means to save calculation because the construction is designed symmetrically from the view of geometry, fixing and loading. The construction is made from thin-walled square tubing which dimensions and materials are put in Table 1.

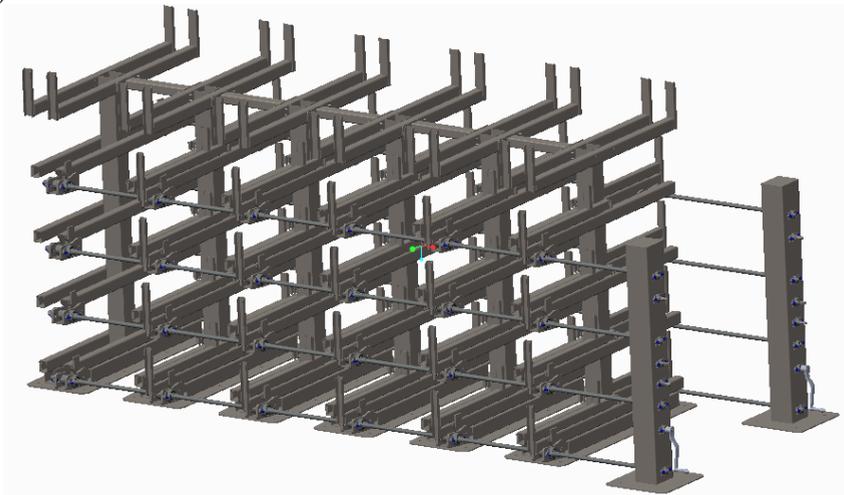
**Table 1.** Construction parts

structures	dimensions of square tubing	material
central beam	160 × 160 × 10	EN: S 235 (STN: 11 375)
horizontal beams	100 × 80 × 6	EN: S 355 (STN: 11 523)
racks	80 × 60 × 4	EN: S 355 (STN: 11 523)

Whereas the transmission of construction mechanism is driven by a crank handle, the racks will move forward at low speed, so the dynamic load of construction is not significant. We consider for material yield strength of horizontal beams and racks  $R_e = 360$  MPa and for coefficient of safety with regard to the static way of loading the construction  $k = 1.7$  (-). For

material yield strength of central beams we consider  $R_e = 240$  MPa and for coefficient of safety with regard to the static way of loading the construction  $k = 1.7$  (-). Then for allowed stress in the construction by using material S 355 we get the amount  $\sigma_{al} = 211$  MPa and for material S 235  $\sigma_{al} = 141$  MPa. In the place of weld of each construction parts 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% in the place of weld. We include this fact in the calculation by using the coefficient of the influence of welding  $c = 0,7$  (-). We get allowed amounts of stress in the place of welds for material S 355  $\sigma_{alw} = 148$  MPa and for material S 235  $\sigma_{alw} = 98$  MPa. 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 constructions because we should take into account person's performance and comfort [7-9]. 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 [10, 11]. 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 power is by a handle at circular speed of maximum  $1 \text{ m} \cdot \text{s}^{-1}$ . 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 [12-14]. Thus, the construction design of rack system is as follows (see Fig. 2).

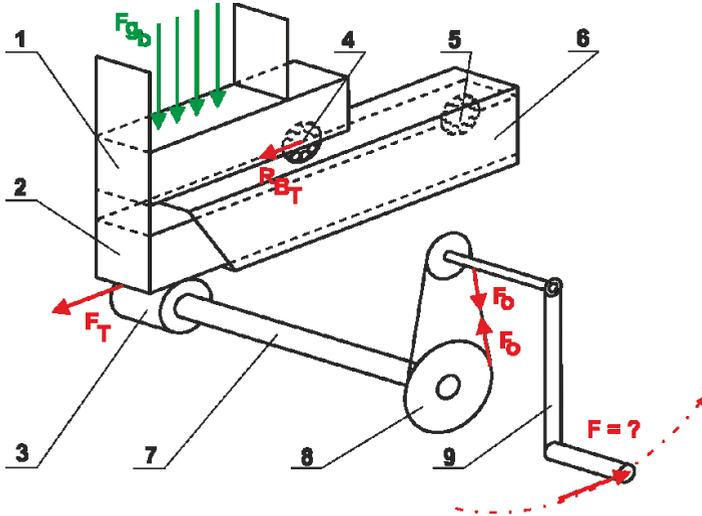


**Fig. 2.** 3D model of the designed rack system with pull-out webs

### 3 Rack pull-out mechanism operating principle

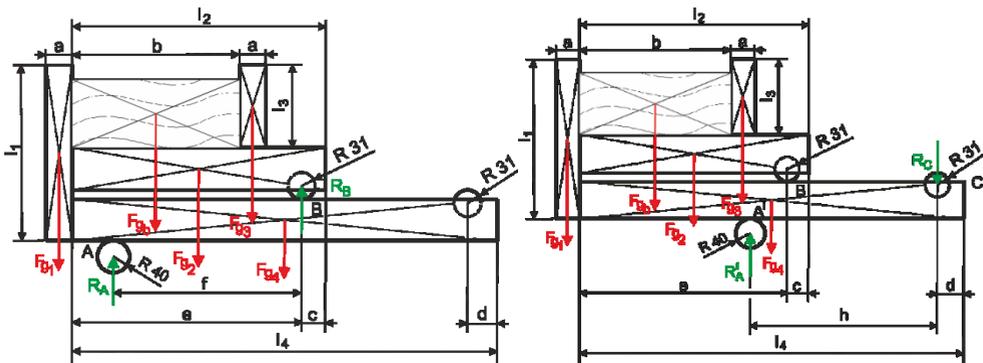
In Figure 3 we can see a scheme of a rack part with the pull-out friction mechanism. There is material put on the upper square tubing (1). This upper and as well lower square tubing (2) is pulled out by means of the friction wheel (3). The wheel (3) is firmly connected with the shaft (7) which is driven through the chain transmission (8) by means of the hand crank (9). The lower square tubing (2) is put into the larger square tubing (6). While pulling out the upper bearing (4) helps the movement and it is moving on the surface of the square tubing (6) without touching of the lower bearing (5) with the inner surface of the square tubing (6).

With pulling in of the rack the lower bearing (5) helps, it moves on the inner surface of the square tubing (6) and the upper bearing does not touch the square tubing surface (6).



**Fig. 3.** The schematic design of the rack pull-out mechanism

Supposing low working speeds and smooth motion we did not pay attention to dynamic effects while designing the mechanism, so we simplified the dynamic model and designed the static model. The mechanism is released into two positions because of having two extreme positions. One position is when the rack is pull-in and it is needed to be pulled out. In Figure 4 on the left forces and reactions are described in the beginning of pulling out the rack. We suppose that the force which releases the mechanism into motion will be greater than the force which is needed to keep it in motion, because the slide friction coefficient is greater in stillness than in motion. We also take into account the other situation when the rack is pulled in from the fully pull-out position. Then the reactions will be different, as it is seen in Figure 4 on the right.



**Fig. 4.** Releasing of the mechanism for pulling out (on the left) and pulling in (on the right)

The Table 2 presents data relating to mechanism parts and they were used during calculations.

**Table 2.** Values of the rack mechanism geometry

a	40 mm	f	958 mm
b	900 mm	$l_1$	400 mm
c	82 mm	$l_2$	1200 mm
d	103 mm	$l_3$	200 mm
e	1118 mm	$l_4$	2095 mm

After calculating on the values of load forces in the mechanism, i.e. weight forces from load and weight of the moving parts of the construction, it is possible to determine important reactions in the friction wheel and auxiliary wheel B in the pull-out position, and reactions in the friction wheel and auxiliary wheel C in the pull-in position. The values of weight forces of a rack result from linear mass density of used tubing and values of weight acceleration. The effects of forces are:  $F_{g1} = 19.29$  N,  $F_{g2} = 115.72$  N,  $F_{g3} = 9.64$  N,  $F_{g4} = 202.03$  N a  $F_{gb} = 4905$  N.

## 4 Functional calculation of the force on the hand crank

Based on simple statics equations and Fig. 4 we get:

$$R_A = 3520.86 \text{ N,}$$

$$R_B = 1730.82 \text{ N,}$$

$$R_A' = 8685.42 \text{ N,}$$

$$R_C = 3433.74 \text{ N.}$$

From the reaction on the friction wheel  $R_A$  (pulling out) and  $R_A'$  (pulling in) we count the needed tensile force  $F_T$ .

$$F_T = R_A \cdot \frac{\xi}{d_K}. \tag{1}$$

The diameter of the driven friction wheel is  $d_K = 80$  mm and the rolling resistance arm  $\xi$  in the supposed diameter of the friction wheel and material of kinematic pair (steel-steel) we choose  $\xi = 0.5$  mm. By putting the appropriate values into the equation (5) we get the amount of friction force in pulling out the mechanism  $F_{T1} = 22$  N and in pulling in the mechanism the tensile force  $F_{T2} = 54.28$  N. Not to slide the tubing on the surface of the wheel, one condition must be secured, i.e. the static condition of rolling (6):

$$F_{T1} \geq F_T, \tag{2}$$

where  $F_{T1} = R_A \cdot f$  is the tensile force supposed the sliding and  $f$  is the coefficient of slide friction, thus (7):

$$R_A \cdot f \geq R_A \cdot \frac{\xi}{d_K}. \tag{3}$$

Resulting in (8):

$$d_K \geq \frac{\xi}{f}. \tag{4}$$

After putting numeric values we get  $80 \text{ mm} > 5 \text{ mm}$  and the condition of rolling is fulfilled without sliding and increasing of needed tensile force. Then it is necessary to count the tensile force (9) on the bearing B (pulling out) and C (pulling in), which serve to facilitate movement (there is rolling resistance instead of the slide friction):

$$R_{BT} = R_B \cdot \frac{\xi}{r_L}. \tag{5}$$

When we put real values into the equation (9):  $r_L = 31$  mm the radius of the auxiliary wheel constructed as roller bearing and  $\xi = 0.005$  mm is for rolling resistance arm, so we get  $R_{BT} = 0.28$  N for the tensile force in the bearing B. We can use the same equation for the

calculation of the tensile force in the bearing C by means of appropriate values. For the tensile force in the bearing C we get  $R_{CT} = 0.55 \text{ N}$ . The total force needed for pulling out and in of the rack part will be given by the force on the bearing and by the tensile force on the driving friction wheel increased by the loss  $\eta$  in placing (10):

$$F_{Cl} = R_{BT} + \frac{F_{T1}}{\eta \cdot \eta} . \quad (6)$$

Placing is carried out by means of two rotary couplings on the roller bearings, each with the medium efficiency  $\eta = 0.98$  (-). When we put the values into the equation (10) we get the amount of total force in pulling out  $F_{Cl} = 23.19 \text{ N}$  and pulling in  $F_{C2} = 57.01 \text{ N}$ . This value needs to be increased six times because the calculation was carried out by means of the sixths model with the sixths load. Then the total force in pulling out is  $F_1 = 139.14 \text{ N}$  and in pulling in  $F_2 = 342.06 \text{ N}$ . These forces are still too great for the arms to be pulled out and in by a hand. That is why we add a chain transmission between the arms and the crank handle. The torsion moment of the friction wheel must be as great as the torsion moment of the big chain wheel (without considering the losses). When we analyse both moments and put the efficiency of the chain wheel into the calculation, in the chain of the chain transmission we get for the force  $F_{O1}$  when pulling out and  $F_{O2}$ , when pulling in (11):

$$F_{O1} = \frac{F_1 \cdot r_K}{\eta_K \cdot r_V} , \quad (7)$$

$$F_{O2} = \frac{F_2 \cdot r_K}{\eta_K \cdot r_V} . \quad (8)$$

In the equation (13)  $r_K$  is the friction wheel radius  $r_K = 40 \text{ mm}$ ,  $\eta_K$  is the efficiency of the chain wheel  $\eta_K = 0.94$ (-),  $r_V$  is the big chain wheel radius  $r_V = 60 \text{ mm}$ ,  $F_{O1}$  is the force inside the chain while pulling out,  $F_{O2}$  is the force inside the chain while pulling in. When we put the values into the equation (11), we get  $F_{O1} = 98.68 \text{ N}$  and  $F_{O2} = 242.6 \text{ N}$ . Then we also consider the moment equilibrium. The torsion moment of the small chain wheel must be equal to the torsion moment of the crank. When we analyse the moments and include all efficiency, we get the amount of force which must be used on the crank for the rack to be pulled out  $F_v$  and pulled in  $F_z$  (12):

$$F_1 = \frac{F_{O1} \cdot r_m}{\eta \cdot R} , \quad (9)$$

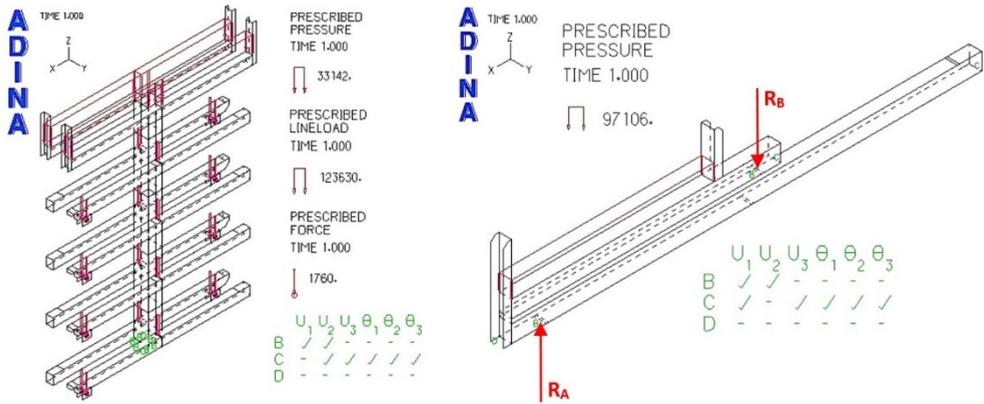
$$F_2 = \frac{F_{O2} \cdot r_m}{\eta \cdot R} . \quad (10)$$

In the equation (14)  $r_m$  is the radius of the small chain wheel:  $r_m = 30 \text{ mm}$ ,  $\eta_K$  is efficiency of the chain wheel  $\eta_K = 0.94$ (-),  $R$  is the radius of the crank and we choose  $R = 300 \text{ mm}$ ,  $F_1$  is the force needed for the crank when pulling out the rack,  $F_2$  is the force needed for the crank when pulling in the rack. Putting the values in the equation (12), we get for  $F_1 = 10.5 \text{ N}$  and for  $F_2 = 25.8 \text{ N}$ . So it is obvious that the forces  $F_1$  and  $F_2$  are low enough so that the worker is able to develop them on the crank.

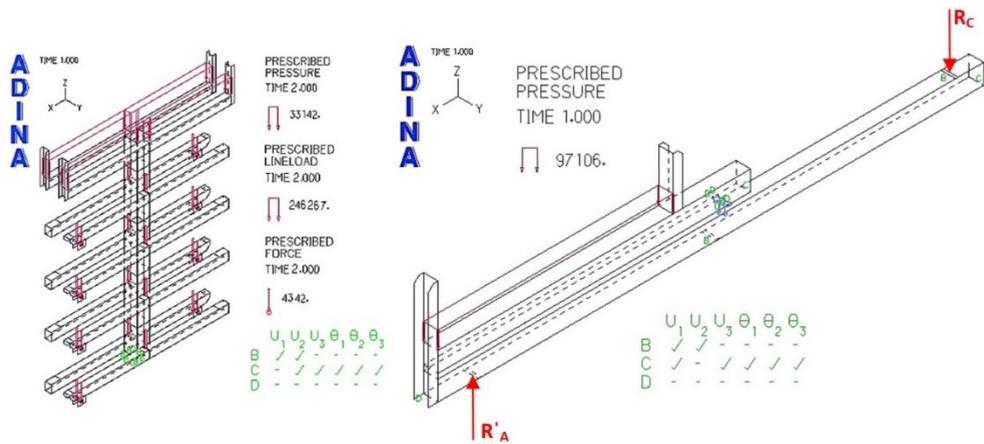
## 5 Stress analysis of the rack system

The strength analysis of the rack system will be carried out in the program ADINA by using the finite element method (FEM) [15, 16]. As the construction consists of thin-walled tubing, it is suitable for the model to be constructed from shell elements [17]. In ADINA Structures Pre-Processing we created the geometry of the shell model of the rack bearing part and the geometry of the arm shell model [18, 19].

Similarly, like dealing with the forces on the crank, we will solve it and divide it into two parts. The mechanism can be placed in two extreme positions when the rack is pulled-in (Fig. 5) or pulled-out (Fig. 6).



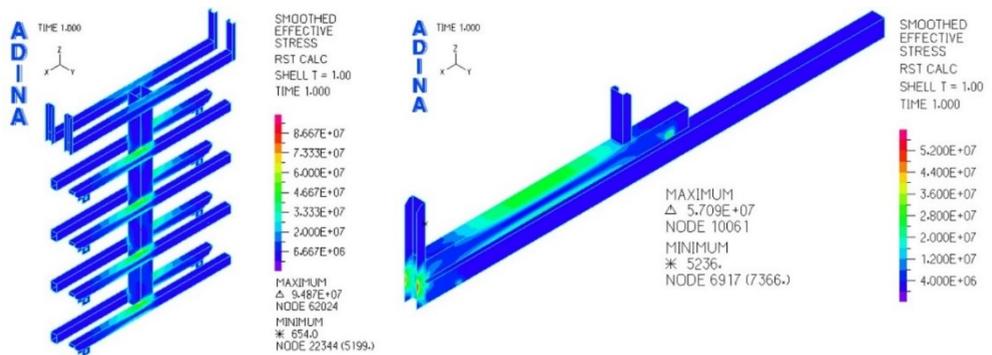
**Fig. 5.** Limits of loaded pulled-in rack system



**Fig. 6.** Limits of loaded pulled-out rack system

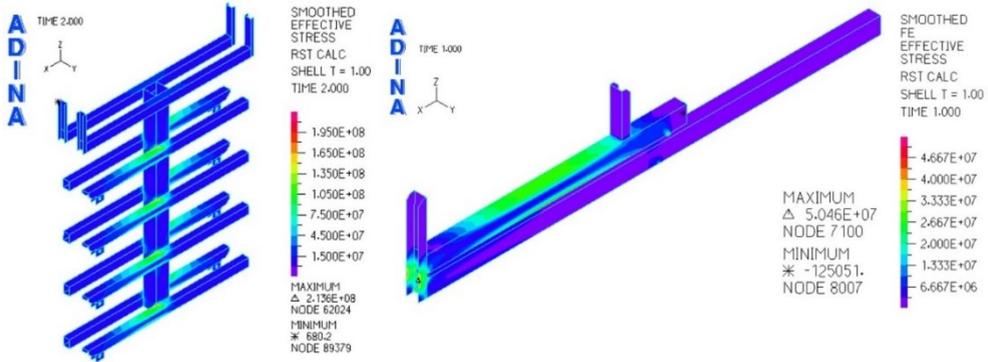
As seen in Fig. 7 on the left, in the pulled-in position of the racks the maximum smoothed stress in the load bearing construction is 86.67 MPa, except for the point of the attachment.

The simulating value is smaller than the allowed stress in the welded construction that is 98 MPa. So for the pulled-in position the rack system is set properly. As seen in Fig. 7 on the right, the maximum smoothed stress of the rack arm is 57.09 MPa.



**Fig. 7.** Smoothed stress in the rack part (on the left) and rack arms (on the right) in the pulled-in position

We will not take into account this value because the stress is at the point of applying the boundary condition. The stress according to the colour scale in the picture is important. It is 52 MPa, which in comparison with permitted stress (211 MPa) for the non-welded material (the maximum of the stress is not in the point of the weld) will prove the correctness of the construction design [20].



**Fig. 8.** Smoothed stress in the rack part (on the left) and rack arms (on the right) in the pulled-out position

In time  $t = 2$  s, i.e. in pulled-out position of racks, the bearing construction is in the stress according to Fig. 8 on the left. As it can be seen in Fig. 8 on the left, the maximum of the smoothed stress is 213.6 MPa in the point 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 permitted stress in weld (98 MPa). On the other hand we can use the strength condition for the rack arm in the pulled-out and pulled-in position. The maximum of the simulating stress (approx. 50 MPa) is suitable.

## 6 Conclusion

The aim of this article was the design and strength analysis of the rack with pull-out arms intended for using in an engineering company for steel tubes storage. We described the theoretical aspects of steel constructions, which helped to achieve the objectives. The pull-out rack analysis has proved that this part of the construction meet the safety requirements while loading the pull-out or pull-in rack positions. The analysis of the bearing construction showed significant deficiencies in strength and stability of the pulled-out rack position when the welds had the stress 213.6 MPa. Therefore, design modification has to be done in the next step of addressing this issue.

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