Problems derivation and functionality enhancement of a double girder overhead crane for billet transmission: case study

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Abstract

Double girder cranes are mostly used for heavy loads. The steel structure or some specific parts of this crane go under extra load during the crane operation. The crane condition depends on many variables that change over time randomly. The current standards of Europe have not solved the effects of the forces on the fatigue damage. In this paper, reasons for the skewing of the crane from the main path, and wear of the wheels and rails of it, and the effect of the lateral and thermal forces on the double girder crane are presented. Experimental measurements and computer simulations are used for the analysis. The existence of symmetry in the crane design and operation period is very important. The carriage location influences the amount of force. The results show that for preventing movement difficulties in the rail and crane, it is recommended to cover the structure with the heat shield and insulation materials, especially those parts in exposure to the hot billet. Creating the expansion gap in rails of the crane needs to be obeyed according to the standards. Also, using the rail guide is very good to reduce the skewing of the crane. Furthermore, heat treatment and hardening of the wheels must be completely obeyed.

Keywords: Double girder overhead crane, Rail wear, Wheel wear, Fatigue, Crane skewing.

1. Introduction

A view of the billet transport span in the South Kaveh Steel (SKS) company is shown in Fig. 1. The produced billets from the casting unit are placed on the walking beam employing the billet transfer car. These billets are hot and lose their redness at the end of the path on the pusher. The 30tone- double girder overhead crane removes the billets on the pusher and stores them at the end of the salon for transport and loading. This crane has encountered various problems in the last four years. Wear of the rail and crane, skewing of the crane to one side, and exiting from the rail have led to the production stop and high repair and maintenance costs.

This paper investigates the reasons behind these problems and presents technical and practical advice for enhancing crane functionality.

The skewing of the crane is revealed in different consequences including the destruction of the vertical and horizontal wheels, structure elements, and crane. The lateral forces formed due to the skewing can cause the frequency fatigue, runway destruction, and plastic deformation of moving parts of the crane and even departure of its structure [1,2]. Fig. 2. shows the crane structure in the billet transport shed of the SKS Company. When the hoist of the crane lifts the hot billets and moves in longitudinal and lateral directions causes movement and vibration of the crane in these directions on the rail. The crane of this company is more likely to skew towards the west rail. The walking beam and pusher are placed in one-third of the span's west direction. Some of the beams and columns of the

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crane structure in the west direction are affected by the temperature of hot billets. There is a temperature difference of 60°C between the hot and cold parts of the shed. Therefore, thermal stresses are formed in the structure and the crane.

Fig. 3a. shows the wear on the wheel surface.

Fig. 3b. indicates that the crane does not use the total width of the wheel. The wear is due to the longitudinal and lateral slippage of the wheel. Continuous contact between the wheel's flange and rail's head, the crane moves in a straight line and in a long period this leads to the wear of one edge of the rail and flange of the corresponding wheel. Wear of the wheel's flange, which tends to move on the rail, is more than the inner surface of the wheel. If regular repair and maintenance of the wheel are not performed, then according to Fig. 3c. the thickness of the wheel's edge is decreased, leading to the failure of the flanged edge of the wheel.

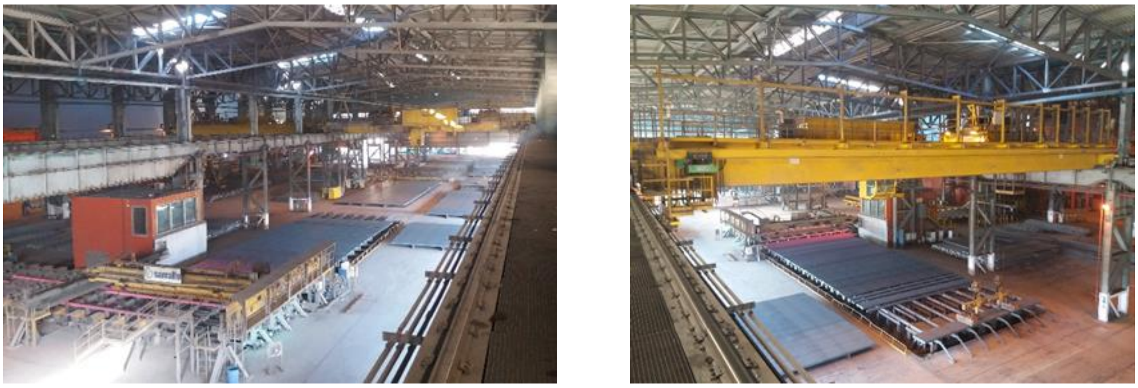

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Fig. 1. The billet transport span in the SKS company a) South view b) North view.

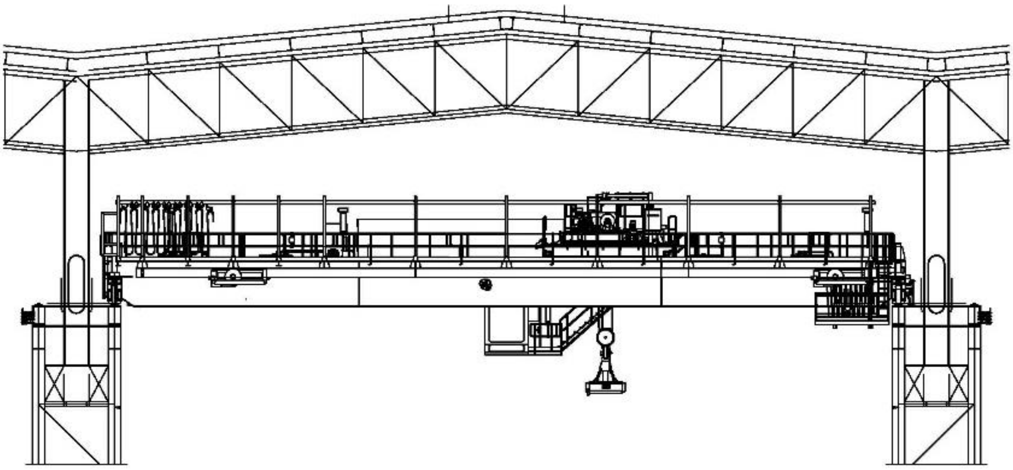

Fig. 2. The crane structure in the billet transport span of the SKS company.

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Fig. 3. The wear on the wheel of crane.

The most common harms to the crane rails are shown in Fig. 4. The lateral loads often cause the deformation of the rail in specific parts. The wear occurs in both of the wheel flange and head of the rail due to the increased pressure at the contact place of them. When the crane skewing becomes above the allowed values, some problems occur during its movement. The vertical error is typically the result of the mistakes in the time of the structure and crane installation. Movement of the wheel on this path creates extra loads with high pressure and vibration of the crane structure. The lateral loads even can open rail connections. In the case of the crane skewing, the flange of the wheel tends to move on the head of the rail due to the contact of the wheel edge with the rail, which is very dangerous and can damage the crane wheel remarkably. The keen edge of the flange causes mechanical damages to the head of the rail, and even danger of the crane fall is likely to happen. The rail deformations due to the vertical and horizontal loads are readily observed during the operation of double girder overhead cranes as the workplace temperature increases, such as in the casting and rolling sheds.

A few works are investigating the current topic in the literature. In recent decades some research works are conducted on the double girder overhead cranes in steel sheds. Alkin et al. [3] studied the way for selecting the double girder cranes, determining the working class, and needed the safety of the cranes. In another research [4], the effect of the span opening length on the behavior, overstrength, deformability, and reduction factors is investigated. The results of this research showed that the behavior factor of the span is increased with the span opening length. Furthermore, a relation for determining the variation of this factor with the span length was proposed. Evaluation of the effects of changing the crane capacity on seismic parameters of the steel bending frame spans is conducted by Jiang et al. [5]. In this research, the seismic behavior of the steel spans is studied using the non-linear static overload method utilizing the Sap2000 software. Models were evaluated for 5 and 10 tones loads. The results showed that changing the crane load does not have a considerable effect on the deformability and overstrength factors. However, the behavior factor is decreased by increasing the columns of the span frames. El-Tourkey et al. investigated the dynamic instability behavior of industrial space structures, in the span form, under the impact loads of the apparatus [6]. The design parameters of a crane with a length of 32 m and a capacity of 150 tones were evaluated, and the optimized values were obtained in their work. The optimum geometrical parameters of the structure in the considered stress, deformation, and buckling limits were evaluated using the 3D finite element analysis. There are some works related to designing the single girder crane with different capacity and opening length using the finite element method. Designing a double girder overhead crane using the finite element method was performed by Zhao [7]. The selected case study in their work was a crane with a capacity of 35 tones and a length of 13 meters. In the initial stage of this research, the typical design was performed using the Federal and DIN standards to evaluate different stress and skewing levels. Then, the design conducted using the tetrahedral element with four nodes in solid and shell forms, and it was found that the shell element better models the structure. Rettenmeier et al. achieved some accomplishments in controlling the double girder crane and preventing its oscillation. Using the phase controller, the crane reaches the destination uniformly, in a short time, with a small oscillation angle and almost with no error [8]. In another research, the natural frequency and vibration of the beam system, on which the rail of the crane is placed, was evaluated considering the crane is fixed, and the frequency equation, a numerical sample of spectrum cover, and transport speed were presented. It was found that the maximum beam skewing when carrying the load by the crane is dependent on the carriage speed [9]. In another research, according to the needed high precision, location, short transport time, high safety and small oscillation angle of a crane and because infiltrating the crane system is very hard, therefore, a non-linear behavior was invented by coupling with the adaptation mechanism which minimizes effects of the system oscillation such that its error becomes zero. The results were simulated for two systems, and the tests were shown [10].

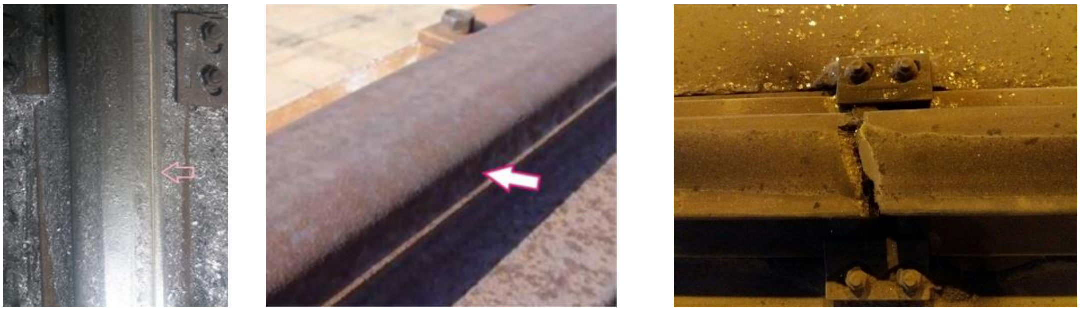

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Fig. 4. The most common harms to the crane rails. a) wear of rail surface b) wear of the rail's head c) fracture of rail.

In this research, designing of a double girder overhead crane with a width of 31 m, which commutes on two rails installed on the girders placed on the shed columns, is conducted, all problems of the crane are evaluated, and the crane is compared with the real one in the SKS Company. This crane has the ability to move in x, y, and z directions. The y-direction is along the span width, and the movement is by the carriage. The x-direction is along with the span length and the movement is performed by the wheel on the rail. The z-direction is along with the height and the movement is carried out by the lifter. In the mentioned real structure, the crane has movement difficulties in the longitudinal direction. This problem is revealed as extreme wear of the wheel and rail that causes the distance between one side of the wheel and the rail becomes more than the standard value sometimes. This problem can happen for some reason. The casting hot billets are in this shed that is entered from the west edge of the shed and exists from its north edge after some time. The temperature of the billets is reduced with time such that the billets in the exit part of the span have a lower temperature. This temperature difference in the crane structure reaches up to 60°C, which causes extreme expansion and contraction in the structure. Another reason for the problem can be insufficient strength of the structure versus the applied forces. In this research, the evaluation and control of the acceptance criteria are performed according to the acceptance criteria of the 360 issue. Furthermore, the span is modeled based on the Iranian Standard No. 2800 (the building design bylaw, 1384). Modeling of the crane structure is performed using the SAP software. The use of welding innovation from an economic point of view, to repair the crane wheel was investigated in this research. Heat treatment, the metallography analysis and measuring of the hardness of the crane wheels are also important.

2. Methodology

In most standards for cranes such as the sixth subject of the national building rules [11] and international instructions like the early versions [12], a simple method is presented for calculating the lateral forces and forces perpendicular to the crane movement. According to the requirements of these standards, the skewing loads are not considered in the stress calculations caused by different loads that can cause the fatigue of materials. According to the traditional methods, calculations of the axial friction force applied to the vertical wheel and the skewing force are still conducted by a simple static model. However, the results of some analytical and extensive experimental [13] work to verify that the effects of dynamic loads need to be considered. The overall diagram of the vertical, longitudinal, and lateral forces is shown in Fig. 5.

According to the 3-9-5-6 section of the sixth subject, the effect of the vertical impact or vibration load for the cranes with motorized rails has to be increased by %25. The total weight of the crane including the girders, bogies, pulleys, electrical motor, carriage, and load equals 90 tones. Therefore, the vertical force in the most critical condition, which is when the load and carriage are at the nearest distance from the wheel, is 40 tones. Therefore, the vertical force applied to the wheel, considering the effect of the dynamic factors, equals:

$$F_Z = 1.25 * 400kN = 500kN \quad \text{Eq.(1)}$$

According to the 5-9-5-6 section of the sixth subject, the longitudinal force applied to the crane needs to be considered %10 of the maximum load applied to the crane wheel:

$$F_x = 0.1 * 500kN = 50kN \quad \text{Eq.(2)}$$

According to the 4-9-5-6 section of the sixth subject, the lateral force applied to the crane rail with electrical carriage needs to be equal to %20 of summation of the weighted crane load and the carriage weight:

$$F_y = 0.2 * \big((300 * 1.25) + 150\big) = 105kN \quad \text{Eq.(3)}$$

Because of the temperature difference, beam deflection more than the standard limit, the crane is placed on the beam, and impact loads create movement problems for the crane, the following steps are conducted:

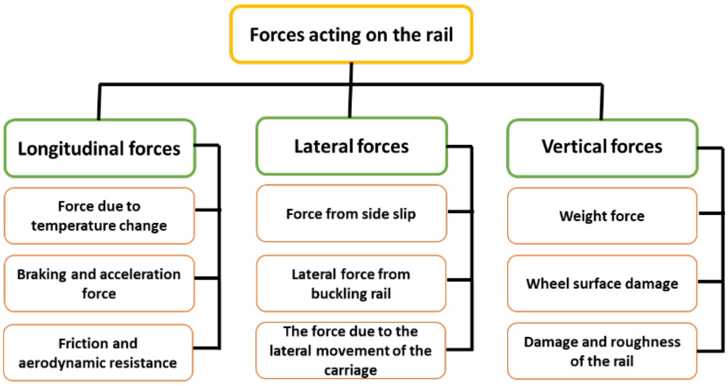

Fig. 5.The overall diagram of the vertical, longitudinal, and lateral forces.

First, the span, without loads of the crane, is modeled using SAP2000 software based on the Iranian 2800 standard, see Fig. 6. Because the structure has a double girder overhead crane, the seismic analysis needs to be conducted for selecting a good behavior factor. The seismic force is dominant in the design. Therefore, the span was modeled with the crane load, seismic behavior, and temperature difference. Then the structure was modeled under the applied forces such as the earthquake, wind, thermal stresses, and impact loads. One of the reasons for the crane structure problems can be a lack of correct implementation of the structure, i.e., lack of consistency between the structure plans and its construction in the real world, which is evaluated and compared in the continue.

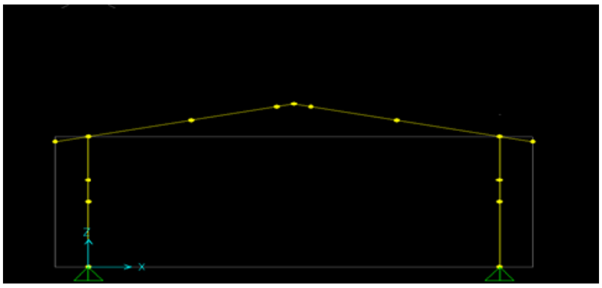

Fig. 6. The span, without loads of the crane, is modeled using SAP2000 software.

Generally, the crane forces are classified in the range of the occasional forces and the fatigue phenomenon. This important factor is typically ignored in the cranes' design [14-16]. The fatigue analysis of the crane parts cannot be carried out without the knowledge of the time period of the crane operation. Identifying the fatigue effects and exact information from the value of different loads during the lifetime of the designed crane is necessary for forming the stress load or spectrum, and further calculations including the collected damage and remained fatigue lifetime [17].

The applied forces between the wheel and rail and the resultant velocity are shown in Fig. 7. The movement direction of the vertical wheel is indicated by the skewing angle α_W, measured from the rail direction. The driver wheel i moves on the rail j with the vertical force of $F_{Z(ij)}$, torque of $T_{W(ij)}$ and tangential velocity of $V_0=(D_W/2)\,\omega_{W(ij)}$, in which D_W is the wheel diameter and $\omega_{W(ij)}$ is angular velocity of the wheel. Two 30KW electrical motors, rotating with the speed of 45rpm, transmit their power to two driver wheels of the crane, with a diameter of 71cm. The slip velocity in the rail direction and perpendicular to the rail equal V_x and V_y, respectively. The latter velocity, V_y, is prevented when the wheel edge contacts the rail head. The velocity in the rail direction, V, is the summation of V0, V_x and V_y. The corresponding longitudinal and lateral forces are $F_{x(ij)}$ and $F_{y(ij)}$, respectively. $F_{S(ij)}$ is the skewing force applied at the contact place of the wheel edge and rail head. The driven wheel is under the tension force $F_{W(ij)}$. The driven wheel has no slippage in the rail direction and thus $F_{x(ij)}$ is not applied to it.

The crane skewing, wheel and rail wear, and exiting of the crane from the rail are unique in different industries. The skewing forces in the bridge and gantry cranes are dependent on the load dynamics and structure fatigue. The crane stability and skewing are highly dependent on the crane opening. Important factors including the frequency of occurrence, domain values, and history of the skewing force are effective on the crane movement, stability, and dynamic behavior [18]. The required information for conducting current research was extracted from valid Iranian and foreign published papers, and also from the SKS Company. Other information obtained using the exact mapping with the mapping camera is compared with the software information. Furthermore, the structure temperature caused by the hot billets is measured with the thermometer to be entered into the software. After conducting the modeling using SAP software, the results are analyzed and discussed. Heat treatment, the metallography analysis and measuring of the hardness of the crane wheels are important. The use of welding technology to repair the crane wheel was investigated from an economic point of view in this research.

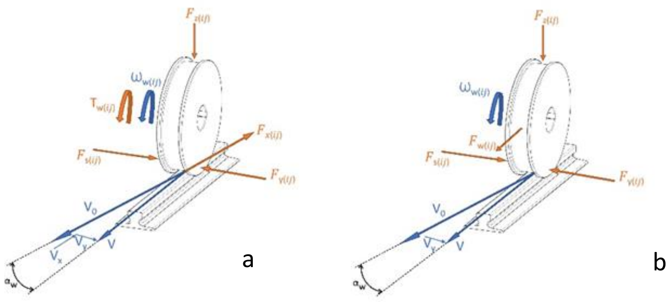

Fig. 7. The applied forces between the wheel and rail and the resultant velocity a) driver wheel b) driven wheel.

3. Results and discussion

High thermal stresses are applied to the rail when its temperature and temperature gradient is very high. The fatigue phenomenon and failure occur in the rail due to the repetition of this process. The displacements vs. temperature are shown in Fig. 8. diagrams. The longitudinal displacement is more than the other two directions. In the z-direction, the displacement in place of the hot billets is upwards and downwards at the span end. Furthermore, the difference between the displacements of the span middle and entrance regions is very considerable such that the displacement in the span entrance has reached 10 mm in the y-direction. These results agree with those obtained from the mapping of the structure.

As shown in Fig. 9. the west columns of the structure, have a lower height than the east ones and thus the crane tends to skew towards the west. The height difference is between 1 to 2 cm. The hot billets are in the west part of the structure, where the crane time of operation is almost twice the one in the east part. This is because of a lack of symmetry in the plan design of the line, walking beam, and pusher in the billet transport span. According to Fig. 1. the walking beam and pusher are not designed in the middle of the span and are near the columns and west beams of the crane girder. It is also possible that the difference in the height of the eastern and western columns is due to errors in the installation time of the structure parts and assembly of the structure.

Due to the existence of the thermal stresses in this shed, which are created due to the temperature gradient or different thermal expansion factors, there is non-homogeneous expansion or contraction in the structure leading to the failure of the rail. In a homogeneous material, the average thermal stress due to the temperature gradient is calculated by $\sigma = \frac{E\alpha\Delta T}{1-\vartheta}$, considering a rail with length L, cross-area of A, Young's module of E, thermal expansion factor of α is under the temperature gradient of ΔT. The change in rail length equals $\Delta L = \pm L\alpha\Delta T$. The resulting normal strain is equal to $\epsilon = \frac{\Delta L}{L} = \pm\alpha\Delta T$. If the rail has a free space for the contraction or expansion, then no stress is applied to it. If the rail is constrained as shown in Fig. 10a. and cannot expand or contract, the tensile or compression force P is applied to it, Fig. 10b. which is equal to $P = \pm EA\alpha\Delta T$. The corresponding stress is the rail is $\sigma = \pm E\alpha\Delta T$. Due to the heat changes of the rails during the time, fatigue also occurs in them. According to Fig. 10c. in a fixed end beam under the temperature difference $+\Delta T$, buckling, or failure happens (Also see Fig. 4c.).

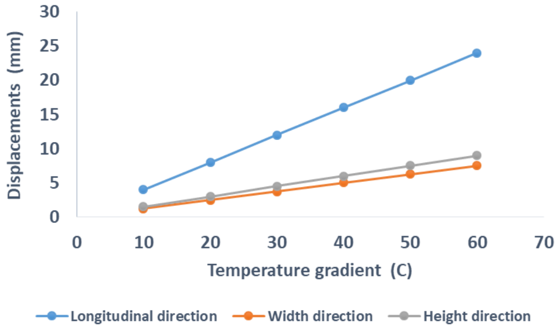

Fig. 8. The displacements vs. temperature.

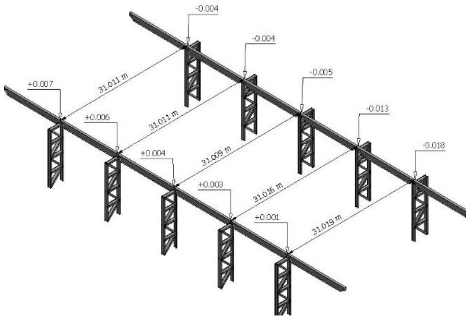
Fig. 9. Structure mapping results.

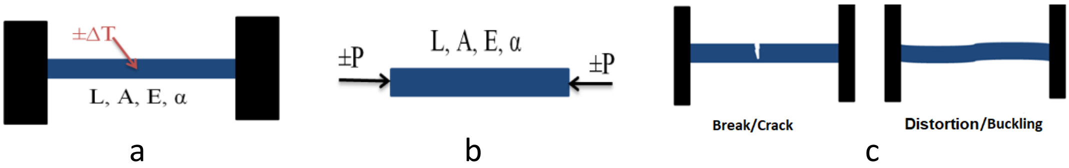

Fig. 10. Rail under thermal stress.

For solving the thermal stress that cause buckling and cracking, using the rail patch and expansion gap can be proposed. The longitudinal and expansion/compression forces are compensated using the rail gap in the crane paths. A sample of the rail gap attachment which is designed and installed in the crane rail of the SKS Company is shown in Fig. 11. The way of designing the gap between two rails, in millimeters, is shown in table 1.

The heat shield and splash thermal insulation called the anti-fire covers, based on the rock wool, need to be used on the crane beam and columns at the hot billets location. These insulations are resistant to wear and corrosion. In the design without the thermal insulations, the temperature at the middle and the entrance of the span was 100°C and 40°C, respectively and thus the temperature difference reached 60°C, which definitely interferes with the crane movement due to the rail expansion and contraction. In the designing with the heat shield and thermal insulation, these temperature difference is reduced significantly. Fig. 12a. and 12b show a kind of thermal insulation and heat shield, respectively. With a simple simulation and industrial trials, the temperature difference reduced from 60°C to 30°C which has a considerable effect on the displacement as illustrated in Fig. 8.

Fig. 11. A sample of the rail gap attachment which is designed and installed in the crane rail of the SKS Company.

Table 1. The way of designing the gap between two rails, in millimeters [19].

Railing temperature (C)	maximum rail temperature at the installation site (C)			
	50	**60**	**70**	**80**
more than 40	3	3	4	5
30 to 40	3	4	5	6
20 to 30	4	5	6	7
6 to 20	6	7	8	9
-6 to 6	8	9	10	11
-20 to -6	10	11	12	12
less than -20	11	12	13	14

a b

Fig. 12. a) Thermal insulation b) Heat shield.

The experimental measurements in the crane runway verify that high crane skewing occurs if the crane is loaded asymmetrically [20,21]. The skewing causes extreme fatigue of the runway and wheel edges of the crane. For such a high crane skewing amount, horizontal rollers rail guides are needed to be installed on the crane. In other words, keeping the correct geometry of the crane runway and structure is necessary. Furthermore, some instructions need to be declared to the operators for keeping the crane load to be symmetric during its movement in the runway. If a horizontal guide wheel is designed for the vertical wheel, then according to Fig. 13 the skewing force $F_{S(ij)}$ of is transferred to the guide wheel from the edge of the flanged wheel. The wear on the horizontal guide rollers is less than the flange edge of the vertical wheel and the repair and maintenance cost of these rollers is also much lower than the vertical wheel.

To reduce the crane skewing, the crane operation condition needs to be changed to symmetric loading. This fact was verified by the experimental measurement results. However, the double girder overhead crane of the billet transmission shed cannot always work symmetrically. Therefore, other proper actions need to be employed for removing the crane skewing. Nowadays, there are various systems for removing the crane skewing [22,23]. If justified technically and economically, a technical solution for inspecting the lateral loads can be used in more complex systems for inspecting the crane condition during its use. Simultaneous measurement of the lateral forces and vertical wheels' vibrations is necessary for forming the load spectrums of the crane structure [24]. Other effective factors of the crane skewing, based on empirical and field research, are shown in table 2.

According to the mentioned various reasons, designing the rail guide was performed by the engineering group of the SKS company to decrease the contact between the existent wheel's edge and rail, and wear of them and also to provide easy and fast installation and repair. Fig. 14. shows the designed rail guide by the engineering, research, and technology group of the SKS Company. Fig. 15. shows the way of assembling the rail guide below the crane bogie.

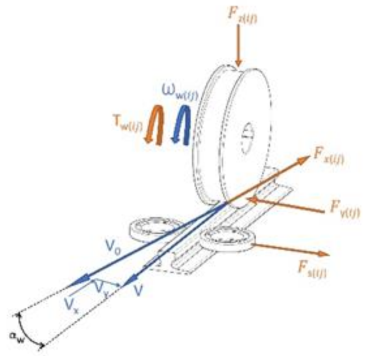

Fig. 13. The skewing force of the vertical wheel and horizontal guide rollers.

Table 2. Effective factors of the crane skewing.

Before the time of operation	During operation time
• Deviations that are formed in the installation time of the structure parts. • Geometrical error in the manufacturing and installing time of the crane rails. • Errors in the crane design, manufacturing, or assembly due to lack of information about the crane skewing problems. • Geometrical defects and deviations formed during manufacturing and installing the vertical wheels of the crane. • Incorrect location of the horizontal guide rollers, geometrical defects, and installation errors of their parts.	• Factors dependent on the crane set up, operational conditions, and environmental conditions, which cannot be changed with technical measures. • Unequal angular velocity of the driver and driven wheels. • Irregular and inconsistent maintenance of the crane and its railway.

Fig. 14. The designed rail guide by the engineering, research, and technology group of the SKS company.

Fig. 15. The way of assembling the rail guide below the crane bogie.

Although the wear observed on the crane wheel was initially attributed to the incorrect rail balance, the metallography analysis and measuring of the hardness shows that incorrect heat treatment of the crane wheels is also important [25]. Little details are discovered about the flame hardening procedure utilized for the wheels in SKS Company. However, there is a possibility of rotating the wheel as a fixed flame is applied to the surface. Microstructure observations show that uniform heat treatment is not applied to the wheel surface. The complete hardness is just obtained at the surface center while the outer edges of the wheel surface almost remain in the normal condition. Continuous contact between the wheels and rail leads to the plastic deformation of smoother edges, stretching of the seed structure towards the center of the wheel surface indicates this fact. Local deformation and periodic nature of the applied stresses lead to the surface scattering and microstructure transmission. Both local plastic deformation and wear of the internal surfaces of the flange have contributed to the sedimentation of waste materials in the surface center.

Repairing the crane wheel is under analysis in terms of economics and technological methods. The method of crane wheel repairing, selection of the welding method, proper filler, and testing mechanical properties on the coated wheel is necessary. Using the welding technology discussed by Tanaskovic et al. [26] leads to the repair of the utilized wheels by creating a new contact layer having martensitic microstructure and hardness of 42 HRC. It has been proven that the operating life of a repaired wheel with submerged arc welding is equal to the new one while its repair cost is one-third of a new wheel cost. The repair method can be carried out in less than 48 hours, compared to several weeks required for making a new wheel which can have a considerable effect on delaying the production procedure. It should be mentioned that one wheel cannot be repaired frequently. Results show that the wheel can be repaired 3 to 4 times and further repairs lead to their damage in the welding stage.

4. Conclusions

This paper investigates the wear of the crane wheel and rail due to its skewing. The following conclusions are achieved by studying and modeling:

- Creating the expansion gap in crane rails needs to be carried out according to the standards.
- It is recommended to cover the structure with the heat shield and thermal insulation materials, especially those parts in the exposure to the hot billets.
- Using rail guide is very good for reducing the crane skewing.
- The effect of the carriage location on the amount of force is important. Symmetry is very important in crane design and operation.
- It is recommended to evaluate or reconsider the flame hardening procedure for every surface that is likely to have a contact with the rail during the service.
- Repairing the damaged wheels using the submerged arc welding is much more economical than manufacturing a new wheel.

Acknowledgments

This research was accomplished by support of SKS.

Special thanks to the generous helps of R&D and the steel making unit of SKS; the authors would like to gratefully appreciate H. Soltani, M. Farsi and S. Lak for their help to this study.

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