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GENERAL FLAW DETECTION ISSUES

Application of Non-Destructive Testing for Condition Analysis, Repair of Damages and Integrity Assessment of Vital Steel Structures

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Abstract—Loads at vital steel structures occur during their production and assembly (residual stresses), during the execution of functional tasks in exploitation (stationary and dynamic loads) and during the disturbed process of exploitation (non-stationary dynamic loads). Considering the fact that stress concentrators, corrosion and unpredictable effects that occur during exploitation must be taken into account as well, it is clear that loading of vital structures during the design phase can not be represented with a model in which the parameters change uniformly. Therefore only experimental non-destructive tests performed at large steel structures during exploitation enable the assessment of their current condition, need for particular repairs and assessment of integrity. In that way the data necessary for determination of causes of degradation of material and welded joints at structures, for the evaluation of mutual influence of equipment parts, as well as for determination of functionality and reliability of operation of drive systems. This primarily refers to vital steel structures of bucket-wheel excavators, dredgers and cranes, as well as to vital steel structures at hydroelectric equipment, thermal power plant equipment, bridges etc. This paper presents the analysis of causes for the occurrence of damages at the support structure of the boom of the bucket-wheel excavator, which is operating at the open pit coal mine near Kostolac (Serbia), that was executed on the basis of non-destructive tests. The paper also contains the procedure for the repair of damaged structure through the application of adequate welding, performed at existing and newly produced components, and the assessment of structural integrity after the repair based on non-compliances detected during the design process, as well as during the making of the support structure of the bucket-wheel excavator boom due to inadequate radiuses defined during the processes of design and production and due to the existence of flaws on the surface and within welded joints.

Keywords: bucket-wheel excavator, welding, non-destructive tests, repair, structural integrity

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1. INTRODUCTION

Taking into account the long period of exploitation under severe operating conditions (dynamic loads with variable amplitudes), vital structures and parts of equipment of bucket-wheel excavators (BWE) have to be checked continually or periodically. This primarily refers to the areas of components at vital structures that contain stress concentrators, including the welded joints. The integrity of welded structures depends on a large number of technological, metallurgical, structural and exploitation parameters. That's the explanation for wide dispersion of values of fatigue strength for weld metal with different values of the coefficient of load asymmetry ($R = \sigma_{min}/\sigma_{max}$). Namely, due to the origination of thermal strains on parent material during the process of welding a possibility of occurrence of a large number of flaws in the welded joint arises, which can shorten the period required for the initiation of the fatigue fracture. Early failure or fracture of welded structures is basically being caused by the simultaneous effect of the above mentioned technological, metallurgical [1], structural [2] and exploitation parameters. In order to achieve reliable evaluation of the integrity of substructure or supporting structure, it is necessary to carry out the monitoring of their structural condition [8, 9], as well as monitoring of their mechanisms [10–12].

Fig. 1. Bucket-wheel excavator SchRs 800 in the open pit mine "Kostolac"—Serbia and model of the vital structure of the bucket-wheel boom (rotating platform and P frame).

(a) Damages at rotating platform and P frame structure

(b) Damages in the upper section of the P frame structure

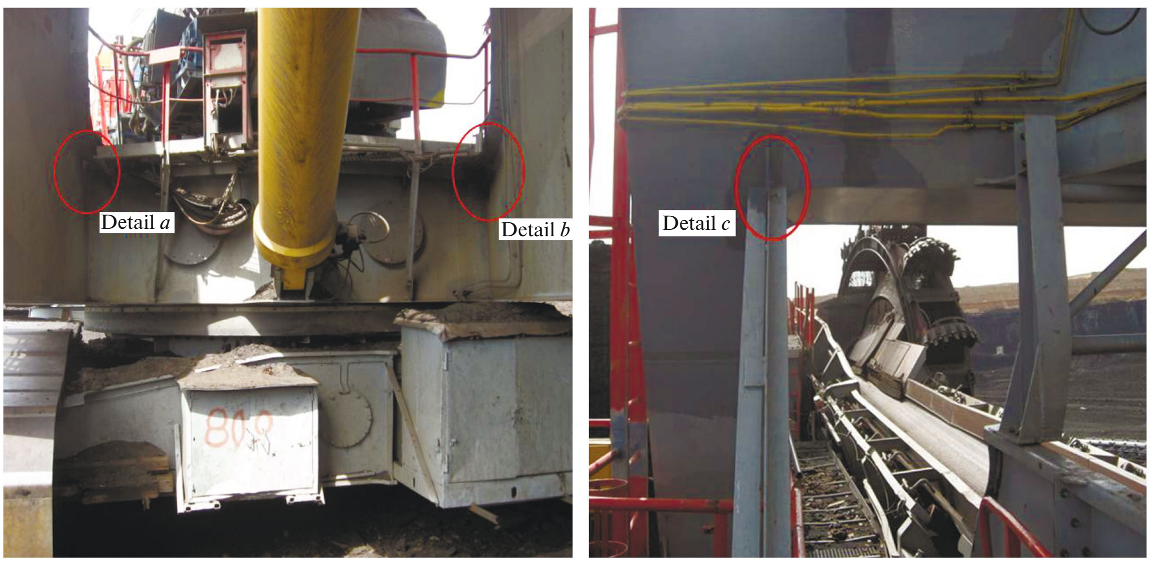

Fig. 2. Damages at the vital structure of the bucket-wheel boom.

This paper presents the results that refer to state analysis and researches performed in order to determine the causes of damage occurrence at the vital structure of the boom of the BWE SchRs 800 ("Krupp", Germany), which is operating at the open pit coal mine near Kostolac, Serbia (Fig. 1). The paper also contains the procedure for the repair of damaged structure through the application of adequate welding/surfacing performed at existing and newly produced components. The assessment of the integrity of the structure after repair was carried out as well. Vital structure of the bucket-wheel boom consists of the rotating platform and of the structure shaped as a P frame. Considered structure was made of steel S355J2G3 [13].

Areas with damages in lower and upper regions of the vital welded structure of the bucket-wheel boom were detected by visual testing [14] (Fig. 3). Appearance of damages detected through penetrant testing [15] on welded joints at the right side of the structure is presented in Fig. 4, while the appearance of damages detected on parent material and weld metal at the left side of the structure is presented in Figs. 5 and 6. The appearance of one of the damaged components of the left column of the P frame structure at which it is necessary to perform the repair through the use of newly produced components is presented in Fig. 7, while its interior is presented in Fig. 8.

Fig. 3. Cracks on the surface of column fillet welded joints—right side (crack lengths up to $L = 20$ mm).

Fig. 4. Crack on the surface of fillet welded joints, left side of the column—detail c (crack length $L = 40$ mm).

For surface flaws detection we used standard NDT testing methods (visual and penetrant testing) and after the repair it was planned to do the ultrasonic inspection of the structure also. We used existing methods for detection of possible damages since in welded joint it gives satisfying results considering size and location of defect. Ultrasonic testing was aimed to inspect structure to presence of internal small cracs which can affect the structure integrity (explained in details in Section 4).

2. PROCEDURE FOR DAMAGE REPAIR AT THE VITAL STRUCTURE OF THE BUCKET-WHEEL BOOM

Procedure for the repair of damages at the vital structure of the BWE SchRs 800 was carried out on the basis of performed non-destructive tests and recommendations of the BWE manufacturer.

Basic precondition for the execution of the repair of the bucket-wheel boom vital structure through the application of adequate technology of welding/surfacing of existing and newly produced components is to unload all objective subassemblies and do the following:

Fig. 5. Damages at parent material of the rotating platform and welded joints detected during penetrant testing.

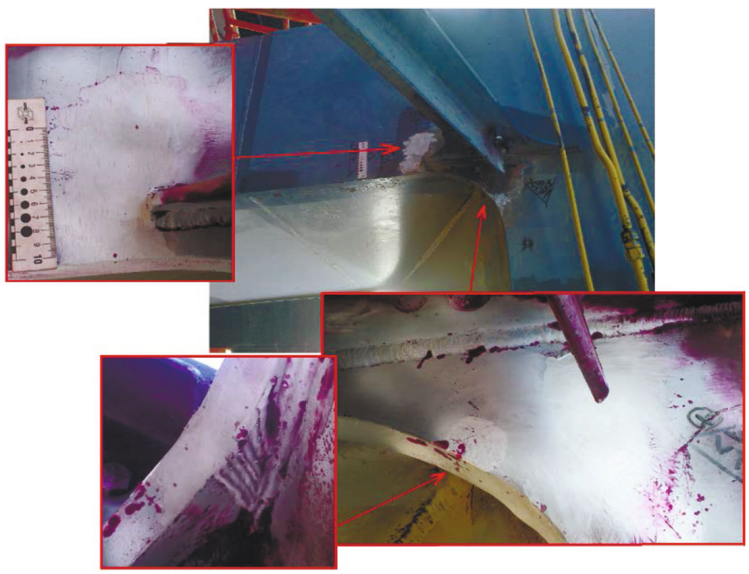

Fig. 6. Damages at parent material of the P frame and welded joints detected during penetrant testing (left side—Fig. 3, detail *c*).

— perform geometric tests regarding the mutual position of subassemblies of the vital structure of the bucket-wheel boom, rotating platform or P frame;

— carefully perform the cutting of covers at manholes within the structure of P frame columns;

— use the covers that have been cut for re-welding, as well as clean and weld the rings positioned below the root with new sheet metal;

— perform autogenic cutting of butt-welded joints and preparation of grooves for welding;

— use the stationary rectifier for currents with the intensity higher than 500 A in order to create the grooves through the application of graphite electrodes;

— carefully perform the grinding of groove ends until the metallic shine is reached;

— perform welding and careful grinding afterwards if the groove geometry is not fully realized;

— perform visual testing and magnetic particle testing at sections of welding grooves;

Fig. 7. Damages at parent material and welded joints of the P frame—left side.

Fig. 8. Grinded fillet weld at the left column of the P frame (detail A at Fig. 10).

— perform the chamfering of edges;

— perform preheating of sheet metal through the application of electric resistant heaters during welding/surfacing at temperatures of 100–120°C;

— perform the check of temperatures by optical pyrometers or thermo chalks;

— dry the electrodes at temperatures of 100–120°C;

— use the electrode quiver in order to store the electrodes at temperatures up to 1000°C;

— use the mobile ventilator/vacuum cleaner for the elimination of smoke gases from the interior of P frame columns during welding / repair welding of sheet metal;

Fig. 9. Grinded fillet weld at the right column of the P frame (detail B at Fig. 10).

Fig. 10. Grinded section at the left side of the rotating platform.

— testing of welded/repair welded joints should be carried out through the application of magnetic particles and ultrasonic device, at least 24 h after the welding has been executed;

— perform the geometric check of the mutual position of subassemblies of the vital structure of the boom, rotating platform or P frame after the completion of all welding activities.

2.1. Preparation of Components for Repair Welding

A few examples that refer to the preparation of components that belong to the vital structures of the P frame and rotating platform for repair welding are shown in Figs. 8–11.

3. TECHNOLOGY FOR REPAIR WELDING AT DAMAGED SECTIONS AND WELDING OF NEW COMPONENTS AT THE BUCKET-WHEEL BOOM

All activities that refer to repair welding that has to be executed at damaged sections and welding of new components at the vital structure of the bucket-wheel boom have been carried out in accordance with the

Fig. 11. Grinded section at the right side of the rotating platform.

following technology for welding of steels S235J2G3 and S355J2G3. Properties of structural non-alloyed steels S235J2G3 and S355J2G3 are in accordance with [13].

3.1. Weldability of Parent Material of Sheet Metal and Profiles

Weldability of material of sheet metal and profiles of metal structures could be operational, metallurgical and structural. Capacity of material to be joined by welding (technological process of joining of metals) is determined by carbon equivalent value CEV, which is being obtained on the basis of chemical composition. Formulas valid for the obtainment of CEV and HCS are given in [1].

— By use of formula for HCS it was determined that the steel is not prone to hot cracking, because the obtained value of HCS was smaller than 4.5 (limit for the hot cracks occurrence).

— For the used materials and in case of the most unfavorable content of hydrogen in weld metal (H = 6 mL/100 g) preheating at $T \geq 100°C$ needs to be carried out;

— Maximum hardness in the HAZ for given chemical compositions must not be higher than 350 HV, which means that the above mentioned materials are not prone to cold cracks;

— Critical cooling rate at which pure martensite gets formed in HAZ and causes cold cracking should be less than 32°C/s, which means there is no need to decrease the cooling rate;

— Taking into account that the tensile strength of sheet metal is lower than 700 N/mm^2, there is no danger of the occurrence of hot cracking.

3.2. Selection of the Process and Filler Material for the Execution of Surfacing at Damaged Sections and Welding of New Components

Suitability of the application of the welding process 111 was determined through the analysis of parameters on which the selection of the process of welding/surfacing depends (weldability of material, energetic possibilities of the welding process, geometric complexity of the structure, economic indicators). Due to limited possibilities of the execution of preheating and heat treatment after repair welding, the optimum solution is to use the electrode with the basic coating EVB Mo (Electrodes Jesenice), classified in accordance with standard [16].

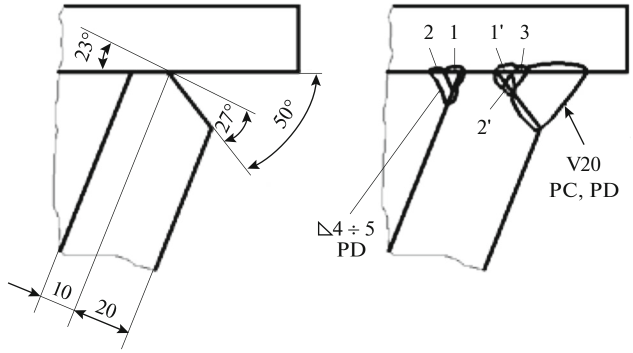

Fig. 12. Preparation for welding and sequence of passes—fillet welded joints at the support structure of the bucket-wheel boom.

3.3. Regulations That Need to Be Obeyed During the Execution of Welding/Surfacing

Regulations that need to be obeyed during the execution of welding/surfacing are presented due to the fact that no qualification of sheet metal welding technology was required;

- Allowed deviation of position of integral elements with respect to the welding axis is 1 mm;
- Allowed deviation of surface parallelism and integral elements is 1–2 mm;
- Allowed deviation of verticality of position of integral elements is 1°;
- Sides and edges of segments of integral elements have to be cleaned until they reach the metal shine immediately before welding on the outer side for 15 mm from the segment edge;
- Determination of the number of welding passes n (including the root pass) is the integral part of the welding technology specification.
- Tacking of sheet metal during welding should be executed at the length of 10 mm. Taking into account the fact that tacks remain integral parts of the root weld, they should be flawless;
- Electric arcs, used in order to create tacks, are being formed by dragging in front of the welding location on the section of the groove which needs to be welded. Formation of the arc must not be executed across the surface of parent material;
- Welded joints have to be fully penetrated all the way down to the root, as well as have smooth transition towards the parent material;
- Welding/surfacing has to be executed with the reinforcement of the weld as small as possible.

3.4. Preparation and Welding of New Components at the Left Column of the P Frame

Preparations for welding of new components for the reinforcements in the internal section of the structure of the P frame left column are presented in Figs. 12 and 13, while the preparation of the segment that needs to be replaced at the structure of the left column of the P frame is presented in Fig. 12. Non-destructive testing of welded joints was carried out during and after welding. After the finalization of all predicted works that refer to welding/surfacing the geometric check of the mutual position of subassemblies of the supporting structure of the bucket-wheel boom, or more specifically the mutual position of the rotating platform and P frame, was determined.

Ultrasonic testing was carried out in zones at the structure of the left column of the P frame where the damages have been repaired, Fig. 15 [17], while penetrant testing that was executed at the structure of the rotating platform is presented in Figs. 16–18.

4. INTEGRITY ASSESSMENT OF THE SUPPORT STRUCTURE OF THE BUCKET-WHEEL BOOM AFTER THE REPAIR

Integrity of structures is a relatively recent scientific and engineering discipline, which in a broader sense comprises the state analysis and technical diagnostics that refers to structural behaviour, revitalization of the structure and service life evaluation. Apart from the usual procedure for the evaluation of the integrity of the structure, when the flaws get detected through the application of non-destructive tests, this discipline also comprises the analysis of the stress state of the flawless structure. This procedure enables

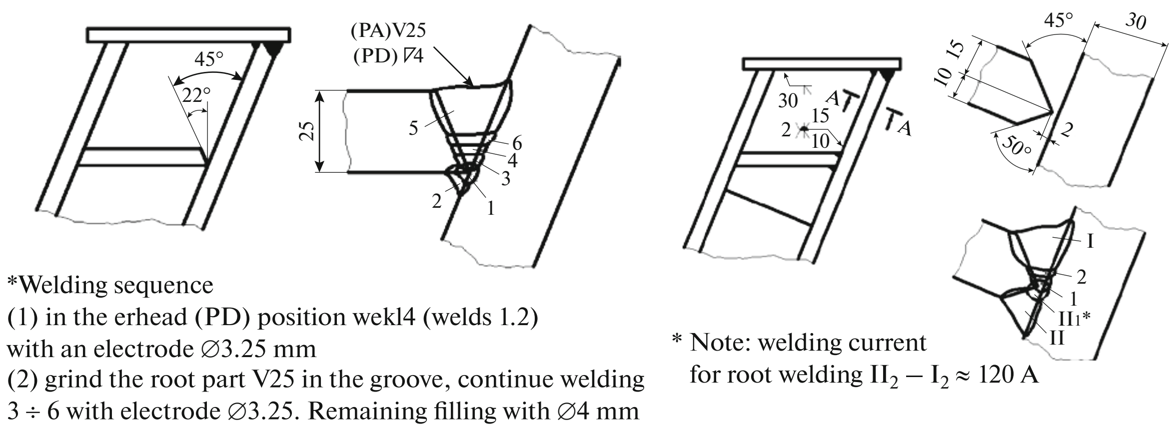

Fig. 13. Preparation for welding – fillet welded joints at reinforcements of the P frame left column.

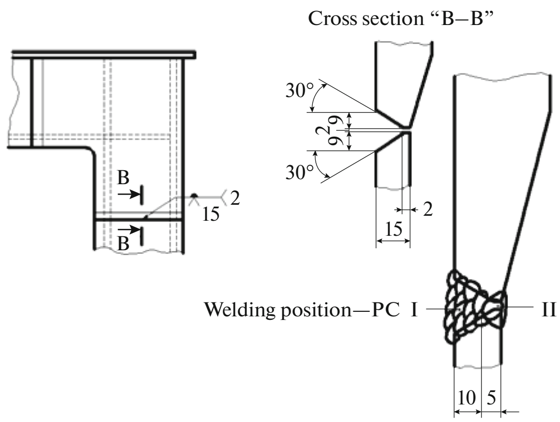

Fig. 14. Preparation for welding – butt welded joints at the structure of the P frame left column.

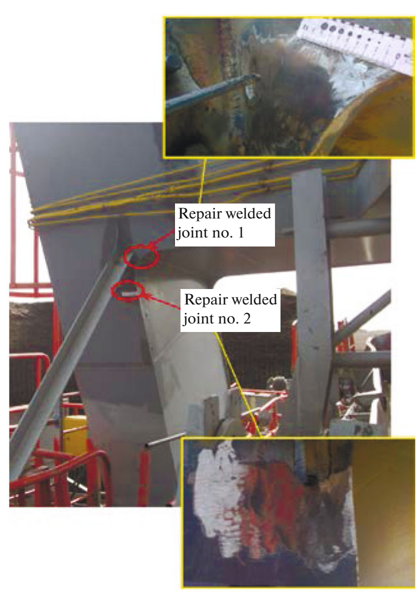

Fig. 15. Examined repair welded joint at the structure of the left column of the P frame, internally designated with nos. 1 and 2.

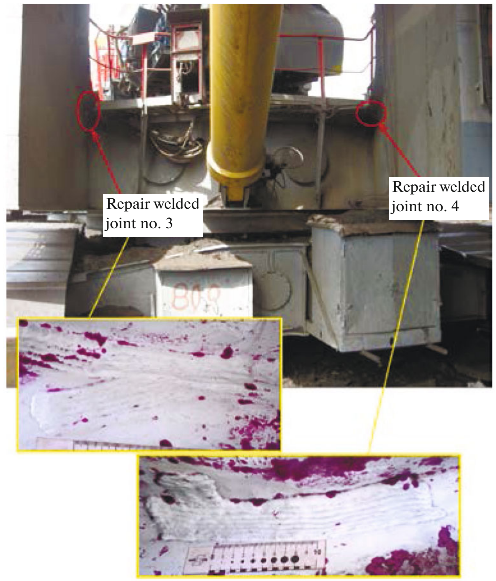

Fig. 16. Examined repair welded joint at the structure of the rotating platform, internally designated with nos. 3 and 4.

Fig. 17. Examined repair welded joint at the right side of the structure of the rotating platform.

the obtainment of the graphic of stress-strain state, which helps the identification of weak spots at analyzed components of support structures even before the flaws occur.

Assessment of the integrity of the support structure of the bucket-wheel boom (rotating platform and P frame) was carried out on the basis of the analysis of dynamic loads to which the bucket-wheel excavator is subjected during service, as well as on the basis of the influence of stress concentration on its fatigue strength.

4.1. The Effect of Dynamic Loads on the Bucket-Wheel Excavator during Service

Most of structures and components of the bucket-wheel excavator are subjected to complex dynamic loads that depend on conditions of service, in other words on digging resistance and own oscillations in stationary and non-stationary regimes of operation.

Fig. 18. Examined repair welded joint at the left side of the structure of the rotating platform.

Operating conditions can vary, depending on a large number of deterministic and random parameters. It is necessary to carry out the measurements of strain alteration and calculate the stresses in order to determine actual stress state of support structures and its alterations over a period of time. In this paper the results of tensometric measurements of strains that occur during the exploitation of the bucket-wheel excavator SchRs 800 at the support structure of the bucket-wheel boom (rotating platform and P frame) were used. Calculated stresses are presented in [20].

Allowable tensile stresses for structural steels S235 and S355, taking into account that the factor of safety S is 1.5, are $TS_{\rm all} = +157$ Pa and $TS_{\rm all} = +237$ MPa, respectively.

According to [20], maximum calculated value of equivalent stress (normal and tangential) is $ES_{\rm max}$ = 178 MPa, which is a value 11.8% higher compared to the allowable stress for steel S235 and only 25% lower than the allowable stress for steel S355. Exactly in those areas where maximum stresses were calculated initiation and propagation of initial cracks occurred (at the support structure of the bucket-wheel boom).

In [20] the stress-strain analysis at the tip of fatigue crack was performed through the use of linear-elastic fracture mechanics (LEFM) approach, for the region of stable growth of the fatigue crack defined by Paris–Erdogan Eq. (1), which is applicable for all metals and alloys [11, 18–21].

$$\frac{da}{dN} = C_p(\Delta K)^{m_p}. \tag{1}$$

Service life (n) of the support structure of the bucket-wheel boom (rotating platform and P frame) after the execution of damage repair was calculated by putting lengths of initial crack a_0 and critical crack $a_{\rm c}$ into Eq. (1). Obtained values of service life are n = 5.6 yr and n = 1.5 yr, according to the properties of sheet metal in the longitudinal and transversal direction, respectively, which proves that the design of bucket-wheel excavator should not contain only special requirements, standards and regulations, but also a completely new and contemporary approach to the entire design process.

4.2. Influence of Stress Concentration on Fatigue Strength of the Vital Structure of the Bucket-Wheel Boom

Stress concentrators, generally, appear at locations with radiuses inadequately defined during the design process (Figs. 3 and 5) and at welded structures (Figs. 2–4, 6 and 7). Welded structures depend on a large number of technological, metallurgical, structural and exploitation factors. It should also be mentioned that there is a large number of stress concentrators at fillet and butt welded joints (non-penetrated root, undercuts, cracks etc.) at actual welded structures.

$$k_t = \frac{\sigma_{max}}{\sigma_n}. \quad (2)$$

Ratio of the maximum equivalent stress ES_{max} in the smallest cross-sectional area and nominal stress S_n is the theoretical stress concentration factor k_t, which for all elements with identical shape depends on the load type and is generally the highest when tensioning occurs, a bit lower during bending and the smallest during torsioning.

$$k_t = \frac{ES_{max}}{S_n}. \quad (3)$$

When subjected to variable loading, the notch decreases the fatigue strength. Nevertheless, the decrease of fatigue strength is not as high as one might conclude taking into account the influence of k_t and it is therefore not being used for variable, but only for static loads. Fatigue notch factor k_f is being used as a property of notch influence on fatigue strength, and is equal to the ratio of fatigue strengths for the smooth specimen FS_s and for the notched specimen FS_n.

$$k_f = \frac{FS_s}{FS_n}. \quad (4)$$

Factor k_f is being obtained experimentally. Its size, when it comes to uniaxial stress state, depends on the shape of welded joint and notch dimensions, as well as on the type of material, dimensions of components and value of the variable load [20].

$$k_{kor} = \frac{\sigma_{max(-1)kor}}{\sigma_{max(-1)}}. \quad (5)$$

Values of the theoretical stress concentration factor for various shapes of components and various loading type are presented in Peterson's paper [20].

Fatigue strength in corrosive environment is defined by the following factor:

$$k_{cor} = \frac{FS_{max(-1)}}{FS_{(-1)}}, \quad (6)$$

where $FS_{max(-1)cor}$, $FS_{max(-1)}$—fatigue strengths of smooth specimens in the corrosive environment and in the air atmosphere, respectively.

Fatigue strength in the corrosive environment depends on the number of cycles, but also on the length of exposure period of elements to the corrosive environment, thus the effect of stress change frequency is significant. In relation to that, Wohler corrosion fatigue curve is a constantly descending line, therefore permanent fatigue strength practically does not exist [20].

The joint effect of corrosion and stress concentration can be expressed by the following coefficient:

$$k_{fcor} = k_f + \frac{1}{k_{cor}} - 1, \quad (7)$$

where $k_f = 1.98$—effective stress concentration factor for testing in the air atmosphere, $k_{cor} = 0.5$ (for $\sigma_{UTS} = 420–480$ MPa)—coefficient of the effect of corrosion for smooth specimens. As far as the vital structure is concerned, value of stress concentration coefficient, including the effect of corrosion, is $k_{fcor} = 2.98$.

Through the analysis of the corrosion fatigue during the asymmetric cycle it has been determined that mean tensile stress unfavorably affects, or in other words significantly decreases the dynamic durability amplitude. Mean pressure stresses favorably affect the resistance to corrosion fatigue. This effect is commonly used for the method of surface strengthening of elements that operate in the corrosive environment.

Decrease of fatigue strength of an element with respect to fatigue strength of the smooth specimen is calculated through the use of the overall fatigue strength reduction factor:

$$k_{rf} = \left(\frac{k_f}{k_3} + \frac{1}{k_{cor}} - 1\right)\frac{1}{k_{po}k_A}. \quad (8)$$

Coefficients included in the expression for the calculation of k_{rf} take into account the following effects on fatigue strength: $k_f = 1.98$—stress concentration coefficient, $k_3 = 0.6$—cross-section coefficient, $k_{ss} = 1$—coefficient that takes into account technological methods of surface strengthening, $k_A = 1$—coefficient of anisotropy for steel castings, $k_{cor} = 0.5$—corrosion coefficient. By putting values of influential coefficients into Eq. (10) we $k_{rf} = 4.3$ get for the vital structure of the P frame of the bucket-wheel boom. Factor k_{rf} determined in such a fashion can be used in formulas for determination of the factor of safety.

On the basis of determined values of the overall factor of decrease of fatigue strength (k_{rf}) it can be concluded why cracks originate and propagate in the areas with stress concentrators on the rotating platform (Figs. 6, 8) and in the areas of welded joints at the vital structure of the bucket-wheel boom (Figs. 3, 4, 7, 9).

5. CONCLUSIONS

Technical diagnostics of BWE, should be based on predefined test procedures, history of their use under service conditions, as well as on the analysis of results carried out by the team of experts with adequate experience and knowledge in areas of design, construction, service, maintenance, reliability etc. This is of special importance for welded structures due to the fact that they depend on a large number of technological, metallurgical, structural and exploitation factors. Fillet welded joints at welded structures are sources of stress concentration, while butt welded joints contain flaws that act as stress concentrators such as non-penetrated root sections, undercuts or flaws.

Presented researches show the advantage of the analysis of design of structural components and structures of bucket-wheel excavators with pronounced dynamic and cyclic load character during service. Undoubtedly, this concept demands continuous or periodic checking of potentially critical structural elements through the application of non-destructive tests on welded joints to enable the timely repair or substitution of entire segments in order to keep the integrity and the service life.

On the basis of tensometric measurements, carried out at the vital structure of the bucket-wheel boom, it was determined that the strains are the highest in the areas of transition radiuses and welded joints, where the influence of stress concentration is most highly pronounced. Maximum calculated value of equivalent stress (normal and tangential) in the areas where initiation and propagation of the initial crack occurred is $\sigma_{max} = 178$ MPa [20]. Results obtained for cracks could be applied to other stress concentrators. Paper confirms that stress concentrators generally appear due to inadequately defined radiuses during the process of design and production and in the areas where welded joints were created.

Costs of executed researches (non-destructive tests, production and installation of the new segment and components made in order to strengthen the left column of the P frame, creation of adequate welding/surfacing technology, damage repair, period of 20 days spent on specified activities) are negligible compared to the financial loss that would be generated by the exclusion of the bucket-wheel excavator from the production process (60 days, approximately). It can be concluded that through the application of this approach that comprises determination of causes of damage occurrence and repairs of damages detected on the support structure of the bucket-wheel boom at least 6000000 € were saved, without putting the safety of workers and machines at risk.

It can generally be concluded that up-to-date approach for the design of machines should not comprise only special requests, standards and regulations, but that it should be based on the experiences regarding the technical diagnostics as well. This paper presents the essence of experimental analysis, which is becoming very significant during the design process, as well as during the testing of vital structures while in service. Precision and complexity of the model are of high importance for the design of machines, and they should be confirmed and updated with models based on experimental researches, because it is the only way to accurately and fully display what is happening during their exploitation.

Methodology for state analysis, repair of damages and assessment of integrity of vital steel structures during the exploitation shown in this paper could also be in whole applied for the solvation of similar problems at mining equipment and in part for execution of state analyses that refer to cranes, hydroelectric power plants, thermal power plants, bridges, etc. The data shown in this paper should be very useful to the engineers and researchers who deal with such practical problems.

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