Bucket Wheel Excavator Reliability Improvement by Use of Probabilistic Approach and Fault-Tree Analysis

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Abstract. Welded joints' reliability in responsible welded structures is of the utmost importance. If such a structure, for example, a bucket wheel excavator, suffers damage or failure, the financial losses are two-folded – the machine does not deliver the required quantity of coal, while, due to that, the power plant does not deliver sufficient electricity to the industry and households. This paper presents a method, based on the probabilistic and semi-probabilistic approaches to express the coefficient of validity and welded joints weakening, defining reliability as a measure of the quality of installed vital welded structures on the bucket wheel excavators in service. The "fault-tree" analysis was applied to enable a quantitative and qualitative analysis of the welded structure failure causes, diagnostics of behavior, and structural degradation, to evaluate the integrity and estimate the service life of the vital welded structures that have a flaw in the welded joint. The database was created, as well, by which the reliability of the bucket wheel excavators can be increased. The proposed method enables to efficiently test the welded joints during all the phases, from manufacturing, via acceptance to assembling of various welded structures, e.g. machines, like excavators or cranes, or the constructions like bridges, etc.

Keywords: Bucket wheel excavator · Welded structure · Fault-tree analysis · Welded joint reliability

1 Introduction

Bucket-wheel excavators represent extremely complex machines that perform very responsible and demanding tasks. All this imposes the need for all the elements of the assembly to be operational for a long period of time. Excavator consumables are most often replaced through preventive (periodic) maintenance, although certain, most

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responsible positions can be monitored with measuring instruments, as well, to be able to react as soon as possible in the case of noticed irregularities. This especially applies to elements that are made by welding. Another way of monitoring the working conditions of such constructions is the fault-tree analysis, through which one is able to identify potential causes of failure and analyze their impact on the integrity and reliability of the construction as a whole.

The objective of this paper was to show/introduce a new method, based on the probabilistic and semi-probabilistic approaches, which predicts that based on possible/potential errors that may occur in the welded joints on the excavator, their impact on the excavator as a whole can be predicted. In addition, the method implies the introduction of the coefficient of validity and welded joints weakening, which defines reliability as a measure of the quality of installed vital welded structures on the bucket wheel excavators in service.

Taking into account all the potential causes of failures and applying the proposed method, it is possible to monitor the condition of the structure during exploitation and to assess its reliability and integrity in operation, as well as to carry out more efficient maintenance of the equipment, which can lead to prevention or delay of accidents and prevention of material (monetary) losses due to replacement of parts or downtime of a machine.

2 Cracks as Causes of Failure of the Bucket-Wheel Excavators and a Role of the Non-destructive Testing in Assemblies State Diagnostics

The stress state in a bucket wheel excavator is complex due to residual stresses after manufacturing and assembling, stationary and dynamic loadings in operation non-stationary dynamic loadings caused by unexpected events. The most critical areas in this respect are welded joints since crack-like defects are always likely to be present. Figure 1 shows the schematic of the bucket wheel excavator complex stress state.

Considering that the bucket wheel excavators have a long service period in very harsh exploitation conditions, their vital welded joints have to be controlled both continuously and periodically since their integrity depends on a large number of technological-metallurgical [1, 2], structural [3, 4] and exploitation factors [5–7]. This explains a wide range of welded joints' fatigue strength values, at different values of the asymmetry coefficient of loading ($R = \sigma_{\min}/\sigma_{\max}$) [8]. Therefore, it is necessary not only to monitor their structural condition [9–15], but to monitor possible defects that can lead to damage of the structure [16–19], as well. One possible way is shown in Fig. 2.

The reason for monitoring this type of equipment is that failures on such complex systems can occur due to improper maintenance or by accident. Accidental failures of the bucket-wheel excavator were considered by authors in [9], which found that by careful analysis of failures, the expected time of proper operation of the excavator, for each year, can be obtained. That is an important factor when considering the maintenance, as well as periodic controls and repairs of parts of the bucket-wheel excavators and mining equipment, in general. In addition, the contribution is that plans for that machine operations, i.e. its expected productivity, can be made. In the case that such machines

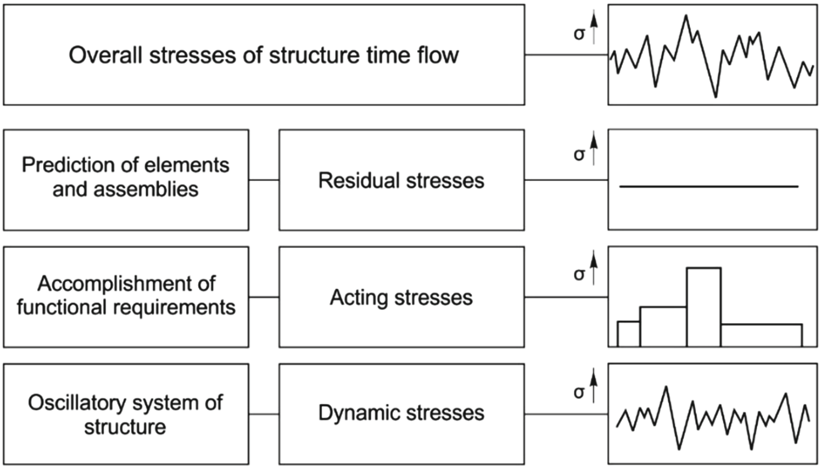

Fig. 1. Presentation of the total stress as divided according to the stress origin.

were loaded more than they should be, i.e. to be exposed to prolonged work in difficult working conditions, failure can occur very easily. The initiator of such a failure can be even a small error, as analyzed by the authors in [10]. They determined that failure of larger excavator components can occur due to fatigue and accelerated/sudden failure. By analyzing the failure of an excavator, they reached the conclusion that even very small errors during the welding, which are most often ignored, can lead to a chain reaction and the failure of a more responsible and expensive working part. The authors of the paper [11] went a step further and conducted research into the causes of damage and an assessment of the integrity of the welded grid structure of the boom of the bucket-wheel excavator's dumper, before and after the repair of vital parts of the structure. The analysis of the results obtained after the non-destructive testing, measurement of the stress state and numerical analysis, determined that there was no danger to the integrity of the grid structure of the boom of the bucket-wheel excavator after repair, if it was executed correctly and if the procedures in working conditions were followed. Similar research was carried out in papers [12–15], where the influence of cracks on various working elements on the integrity of the entire structure was mainly considered. Excavator wheels and tracks [12, 13], bridge conveyor [14] and mine hoist rope attachment elements [15] were analyzed. All the analyses have shown that the impact of cracks on the integrity of the structure is very strong, whether it was already generated in an element during its manufacture or created by welding the entire structure or during the machine's operation. The author's recommendation is that with such complex constructions, in the places that are considered the most critical, constant monitoring of their condition during exploitation, especially when working in very difficult conditions (modes), must be performed.

Classes and quality of the welded joints are defined by the DIN 22261–3 standard [20]; ultrasonic testing of the welded joints is being conducted according to the standard

Fig. 2. Placement of the strain gauges on the welded structure of the bucket wheel boom [6].

SRPS EN ISO 17640 [21]; control of the quality of the welded structures in manufacturing and exploitation of the bucket wheel excavators is done according to standard SRPS EN ISO 5817 [22].

For the non-destructive testing (NDT) of the welded structures the following tests are prescribed by the standard: for the welded joint of the quality class "B" – 100% of joints must be subjected to NDT (visual test – VT, magnetic particles test – MT, ultrasonic test – UT and radiographic test RT); for the quality class "C" – 20% of joints and for the quality class D – 10% of joints must be tested [22]. Performing those tests requires certain labor costs and significant losses in production productivity due to the excavator's downtime during the tests. No standards, norms, recommendations, or methodology exist in the available literature, which would require some other type of control of the welded structures of the bucket wheel excavators, so these methods can be considered reliable enough [23].

Welded structures of the bucket wheel excavators are made of structural steels S235 and S355 [24]. The plan and program of tests of the welded joints on the bucket wheel excavator predict the tests to be conducted after every 5000 h of exploitation (approximately a period of one year of excavator's operation). In order to reduce the costs of welded joints' tests and losses in production due to the excavator's downtime, a new method was developed, based on the fault-tree analysis, which decreases the testing costs by 70% and the excavator's downtime by 50%.

Crack-like defects are frequent phenomena during the manufacturing, assembling process and exploitation of the complex welded structures, due to flaws in the production technology, insufficient forming, structural stress concentrators and conditions of the structure realization (Fig. 3).

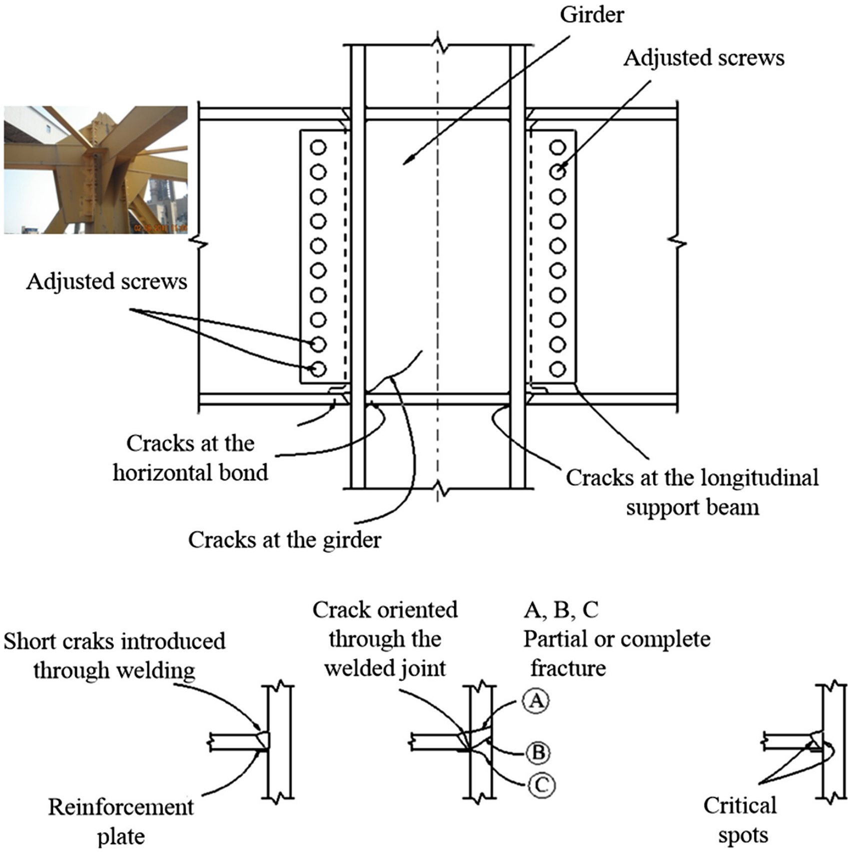

Fig. 3. Locations at which fatigue cracks mainly occur [6].

The characterization of fracture as a multiphase process of crack initiation and growth also includes different starting stages, on which depend the possibilities for further crack growth. The crack can, generally, be stable, subcritical and unstable and possibilities for the crack growth can be along different paths (Fig. 4, paths 1–8). This is especially characteristic of the welded joints and welded structures.

All the bucket wheel excavators at open-pit mines in Serbia are produced by German companies “TAKRAF” and “Thysen Krupp”, while the excavators on the coal deposits are produced by “Ameco” from France. They are designed according to the DIN 18800 standard.

There are examples of fault-tree analysis application for nuclear power plants, airplanes, communication systems and some other industrial processes, but there are no cases of its application in manufacturing and exploitation of the vital welded structures of the bucket wheel excavators.

Numerical indicators (validity coefficient of the welded joint and weakening coefficient of the welded joint and reliability) for quantitative, as well as qualitative analysis and evaluation of the failure causes of the welded joints in vital welded structures of

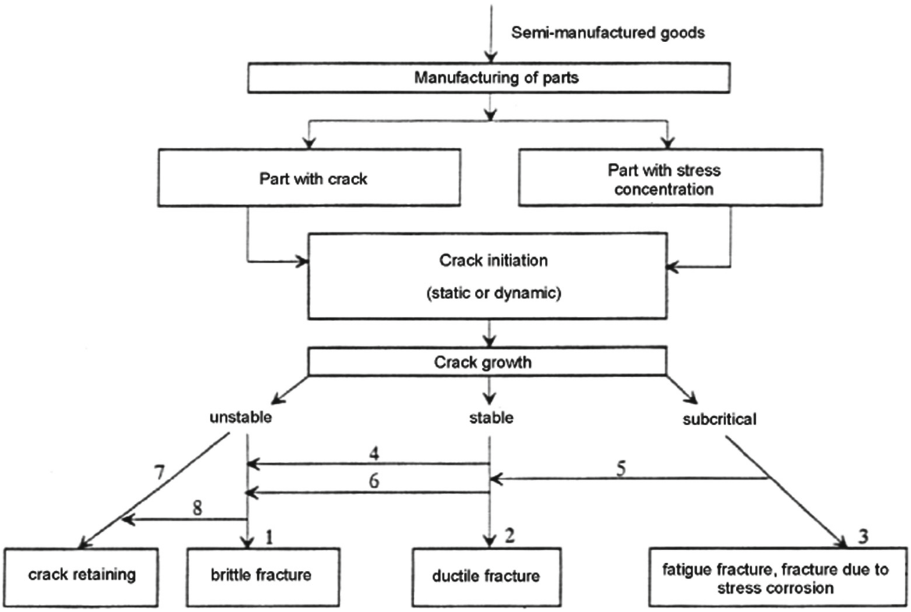

Fig. 4. Options for crack propagation.

the bucket wheel excavators, which appeared as a consequence of manufacturing and/or exploitation, are described in this paper. By analyzing the individual failure cases, one comes up with a conclusion about what their causes were, like wrong material and/or welding technology selection, wrong calculation or the forming method, or deviation from the predicted exploitation conditions.

3 Materials and Methods

The failure analysis is a process where a failed product is investigated in order to find out what caused the failure. Different methods can be used to detect the cause of failure, like the Ishikawa fishbone (cause-and-effect) diagrams, failure modes and effects analysis (FMEA) and fault-tree analysis (FTA).

The basic concept of the Fault-Tree Analysis is the translation of the failure behavior of a physical system into a visual diagram and a logic model. The FTA is an analytical technique, where the undesired state of the system is specified and the system is analyzed to find all the realistic ways why and/or how the undesired event occurred or could occur. The FTA analysis uses the bottom-to-top approach and the undesired event (failure) is the so-called top event.

In the FTA, the diagram presents a visual model that shows system relationships and the root cause paths. The logic segment provides a mechanism for qualitative and/or quantitative evaluation. Events, analyzed as faults by the FTA, can be associated with hardware failure, human or software errors, or any event, which has led to the undesired one. Thus, a fault tree presents the logical interrelationships of basic events that led to the top event of the fault tree. The FTA is based on reliability theory, Boolean algebra and probability theory and uses a very simple set of rules and symbols to provide a mechanism for the analysis of very complex systems, as well as complex relationships between hardware, software and humans [25, 26].

The FTA is a deductive method, which by analyzing the individual influences, enables a conclusion on causes and individual contributions to failure [27]. The main advantages of the FT method are:

- Simple graphical presentation of the logic of failure,
- Failure logic can be followed gradually,
- Possibility of both qualitative and quantitative analysis by application of the Boolean algebra,
- When the quantitative input data are available both quantitative and qualitative analyses can be performed, in the opposite case only the qualitative analysis is being conducted,
- The computer programs are developed for the fault tree analysis, as well as for its graphical presentation,
- The fault tree analysis can include various influences, unlike some other methods,
- No special training or knowledge is necessary for the application of the fault tree method.

Results of the fault tree analysis are used for failure prevention, analysis of failure causes, namely influences on reliability, clearly defining and quantifying those individual influences, and ensuring conditions that would give good reliability.

Application of the FTA in manufacturing of a welding structure of the bucket wheel excavator, taking into account chemical composition (CC) of the base metal and filler metal (FM), base metal quality, welding parameters, shielding gas and heat treatment, as well as the heterogeneity of welded joints (base metal, BM, weld metal, WM, heat-affected-zone, HAZ), is presented in details in [28]. It was shown that the cooling rate significantly influences the structure of the WM and HAZ, diffused hydrogen and residual stresses.

Application of the FTA during the welding structures of the bucket wheel excavator exploitation is also presented in detail in [29]. It was shown that the undetected flaws have an important effect on the reliability and safety of the bucket wheel excavators since they are frequently causing fractures and sometimes failures. It was also shown that the fatigue crack growth, defined by the Paris Law [30].

$$\frac{da}{dN} = C \cdot (\Delta K)^m, \tag{1}$$

where a is the crack length, N is the number of loading cycles, C and m are the material constants and ΔK is the stress intensity gradient, which presents one of the major problems, if undetected before the crack reached the critical value (a_c).

One should also keep in mind that corrosion plays a significant role in the fatigue process, so special focus should be given to the failure due to corrosion fatigue, as shown in Fig. 5 and explained in [28]. Notation in Fig. 5 is as follows:

T – Fracture due to the corrosion fatigue (T = F = 1–R);

E1 – Flaw was not detected through NDT;

E2 – Crack propagates due to fatigue until reaching the critical length ($a = a_c$);
E3 – Flaw was not detected through the NDT;
E4 – Flaw was not detected through the NDT immediately after the occurrence;
E5 – Flaw was not detected through the NDT in the later phase of inspections;
A – Conditions for the crack propagation;
B – test device did not detect the flaw;
C – The operator did not detect the flaw, which could have been detected by the device.

Derivative of the fault tree in Fig. 5 is then:

$T = E1 \times E2 = E2(B1 + C1) = A(B1 + C1) = A(E4 + E5)(B1 + C1) = A(B2 + C2 + C3)(B1 + C1)$.

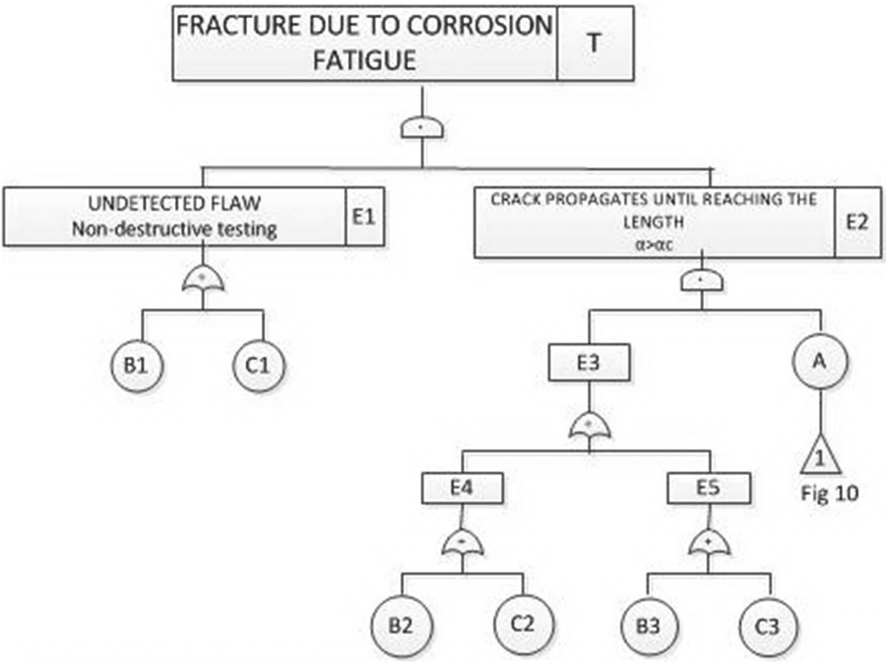

Fig. 5. Appearance of the fault tree due to the corrosion fatigue [27].

For the case when the crack reaches length $a > a_c$ (event A in Fig. 5), the fault tree is shown in Fig. 6.

4 Results

Using the fixed values for calculating the validity and weakening coefficient and the degree of safety of the welded joints is the usual deterministic calculation method. However, the probability of failure can vary from very small to unacceptably large values, for the same values of calculation coefficients and factors, taking into account

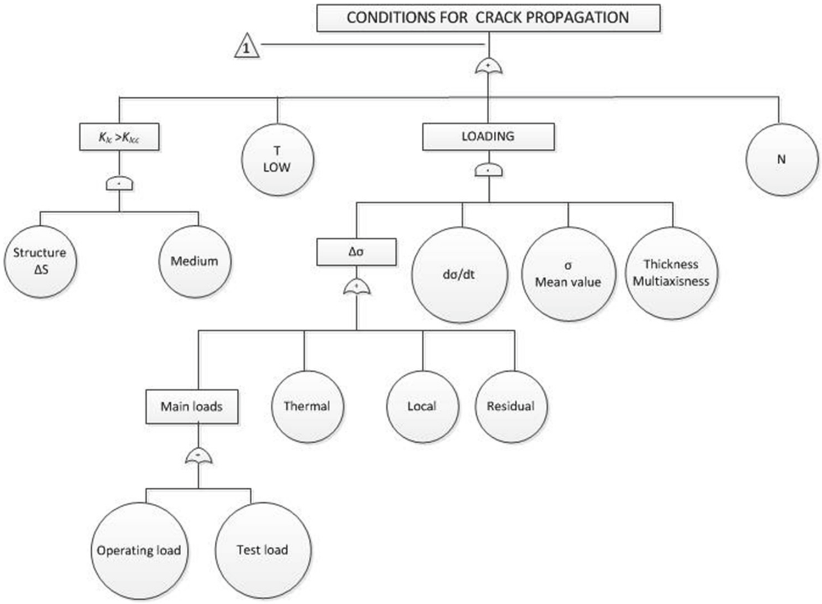

Fig. 6. The fault tree for the crack length $a > a_c$ (event A in Fig. 5)

the smaller or greater possible variability of stress, strength, cross-sections, welded joint flaws and the like.

Since the properties of the welded joint and the base metal, as well as the exploitation conditions, are variable, the more realistic and efficient for the evaluation of various quantities and analysis of the joint's properties and phenomena is the probabilistic approach [27].

The reliability of the welded joints is a numerical probability, with given confidence limits, that the welded joint will execute the set function within the predicted conditions and exploitation time. The probabilistic expression of the welded joint's reliability is more realistic than the reliability factors, which represent a pair of random values.

The bucket wheel excavator design defines the categories (classes) of welded joints that correspond to the predicted reliability of welded joints or welded structures.

Reliability of the welded joint or the welded structure can be calculated by application of the probabilistic model "welded joint yield stress (WJYS) – base metal yield stress (BMYS)" Fig. 7, for the case of the normal distribution by application of Eq. (2), which for the mean distribution value $m = 1$ and when the dissipation of the mean value – the standard deviation is $s = 1$, obtains the form of Eq. (3):

$$R = \int_{\infty}^{t} f(t)dt = \frac{1}{\sigma\sqrt{2\pi}} \int_{\infty}^{t} e^{-\frac{(t-m)^2}{2\sigma^2}} dt, \tag{2}$$

$$R = \int_{\infty}^{m} f(t)dt = \frac{1}{\sqrt{2\pi}} \int_{\infty}^{m} e^{-\frac{t^2}{2}} dt = \Phi(m_1), \tag{3}$$

with

$$m_1 = -\frac{\overline{WJYS} - \overline{BMYS}}{\left(\sigma_{WJYS}^2 + \sigma_{BMYS}^2\right)^{\frac{1}{2}}}, \quad (4)$$

where: $\overline{WJYS}$ is the mean value of the welded joint yield stress, $\overline{BMYS}$ is the mean value of the base metal yield stress, σ_{WJYS}^2 is the variance (average value of the square of deviation of the random variable welded joint yield stress), σ_{BMYS}^2 is the variance (average value of the square of deviation of the random variable base metal yield stress).

Equation (2) is valid with the assumption that there is no correlation between the WJ and BMYS properties. The reliability calculated as

$$R_{50\%} = R\left(\overline{WJYS}, \sigma_{WJYS}, \overline{BMYS}, \sigma_{BMYS}\right), \quad (5)$$

is an average value for 50% of the reliability estimate and for a single way of failure, only.

The lower limit for reliability R_L, with introducing the number of samples n and confidence limit $h\gamma$, is calculated according to the following expressions:

$$R_L = \Phi\left(m_1^/\right), \quad (6)$$

$$m_1^/ = m_1 + \frac{h_\gamma}{n^{1/2}}\left(1 + \frac{m_1^2}{2}\right)^{1/2}, \quad (7)$$

$$R_L = R_L\left(\overline{WJYS}, \sigma_{WJYS}, \overline{BMYS}, \sigma_{BMYS}, h_\gamma, n\right). \quad (8)$$

Figure 7 presents the schematics of distribution of the base metal yield stress, weld metal fatigue strength and base metal fatigue strength. Based on schematics in Fig. 7, the welded joint properties weakening, reliability and weldability can be quantified.

5 The Welded Joint Validity Coefficient

Every test of a certain welded joint (WJ) property – resistance to some failure and comparison to the corresponding base metal (BM) property, is a part of the weldability investigation.

If the individual fixed values are being compared, one obtains indicators of the welded joint validity or exploitation of the base metal properties. The lower the weakening, namely the bigger the welded joint validity coefficient, the weldability is better:

$$\nu = \frac{\text{Properties of the welded joint}}{\text{Properties of the base metal}} = \frac{WJ}{BM}. \quad (9)$$

Considering that the WJ and BM are the random variables, distributed according to a certain distribution law (Fig. 13), the validity coefficient (ν) is a random variable, as

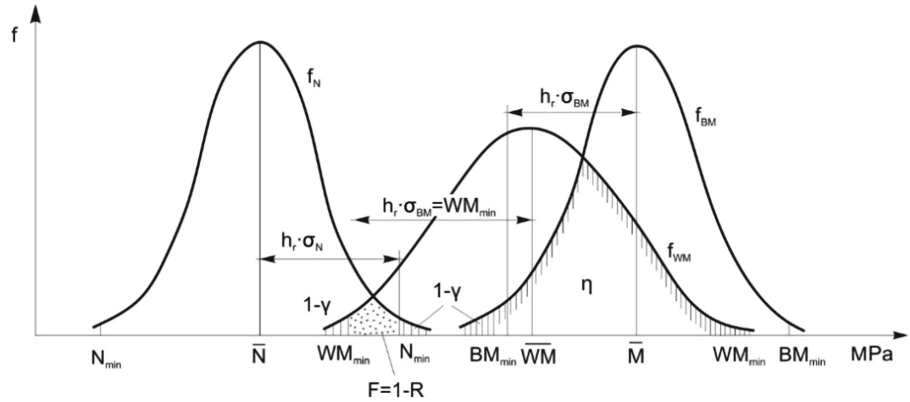

Fig. 7. Schematics of the base metal yield stress distribution ($\overline{BMYS}$, σ_{BMYS}), weld metal fatigue strength ($\overline{WJ}$, σ_{WJ}) and fatigue strength of the base metal ($\overline{BM}$, σ_{BM}).

well. It is usually defined with certain confidence limits and assumption of the normal distribution for a single failure:

$$\nu = \frac{WJ_{min}}{BM_{min} = \frac{WJ_y}{BM_y} = \frac{\overline{WJ} - h_\gamma \cdot \sigma_{WJ}}{\overline{BM} - h_\gamma \cdot \sigma_{BM}}}. \tag{10}$$

Values σ_{WJ} and σ_{BM} are estimates of the standard deviations of the basic sets of welded joint and base metal properties. Values of the h_γ coefficient depend on the required estimate of reliability. For the standardized normal distribution, they are given in Table 1.

Table 1. Recommended values of reliability h_γ in terms of welded joint quality [26]

Reliability estimate γ (%)	h_γ	Welded joint quality level
99.86	3.0	"B"
99.0	2.33	"C"
95.0	1.65	"D"
90.0	1.28	Engineering practice

The validity coefficient ν can be calculated for some other characteristic pairs of properties, like the average values of the WJ and BM properties, or WJ minimal and maximal properties and yield stress (WJYS).

$$\overline{\nu} = \frac{\overline{WJ}}{\overline{BM}}; \nu \frac{WJ_{min}}{BMYS_{max\ min}}; \nu \frac{WJ_{max}}{BMYS_{min\ max}}. \tag{11}$$

In a similar manner, one can define the calculated safety degree for the welded joint S_{WJ} and the base metal S_{BM}:

$$S_{WJS} = \frac{WJ_{min}}{BMYS_{max}}; S_{BM} = \frac{BM_{min}}{BMYS_{max}}. \tag{12}$$

In the design of the bucket wheel excavators, one usually uses the safety degree and the weakening coefficients of the welded joints and thus of the welded structures, as well and their experimental verification is usually not required.

Example: Evaluation of the welded joint strength on the bucket wheel excavator SRs 2000 20/5 after 10 years of exploitation

Evaluation of the WJ strength can be equated with the reliability estimate, given here for the bucket wheel excavator SRs 2000 20/5 (manufactured by "Thyssen Krupp" of Germany) (Fig. 8). Based on the test results of the BM and WJ mechanical properties, as well as analysis of flaws discovered by the non-destructive tests in the weld metal of joints made by welding process 111 (SMAW), on the vital constructions of the bucket wheel excavators made of the S235 and S335 steels, the probabilistic model of the reliability calculation, based on the WJ properties, is presented.

By applying Eq. (3), the following relationship between the mean value of the welded joint yields stress $\overline{WJYS}$ and the standard deviation $\sigma_{WJYS} = f\left(\overline{WJYS}\right)$ can be established. Results of the ($\overline{WJ}$, σ_{WJ}) properties investigations are entered into the diagram in Fig. 15 and the level of reliability, namely the level of quality, to which they correspond is being determined. Categories of vital welded structures are denoted by the Roman numerals I through IV (the rest belong to "engineering practice") and classes of the WJ validity are denoted by the Arabic numbers 1 to 7 (Fig. 9).

Three sets of welded joints are being depicted, which belong to the validity classes "B" (1–3), "C" (4–5) and "D" (6–7). Belonging of a point to a higher level of reliability (the smaller value of the weld weakening coefficient), expressed by the reliability coefficient of reliability m_2, corresponds to the higher validity coefficient of the welded joint v.

The welded joint weakening coefficient η can be expressed as a numerical probability, with given confidence limits that the WJ properties would be equal to or better than the BM properties. As it is possible to use the numerical probability for reliability R, one can also use the numerical probability for the welded joint weakening coefficient η instead of the welded joint validity coefficient, for a certain way of failure.

When the WJ and BM properties are given by the normal distribution law, analytical expression for value of the weakening coefficient can be obtained in the usual way:

$$\eta = \int_{m_2}^{\infty} f(t)dt = \frac{1}{\sqrt{2\pi}} \int_{m_2}^{\infty} e^{-\frac{t^2}{2}} dt = \Phi(m_2) \tag{13}$$

$$m_2 = -\frac{\overline{WJ} - \overline{BM}}{\left(\sigma_{WJ}^2 + \sigma_{BM}^2 - 2 \cdot \rho \cdot \sigma_{WJ} \cdot \sigma_{BM}\right)^{1/2}} \tag{14}$$

$$\sigma_{WJ} = \frac{\left(\overline{WJ}^2 - 2\overline{BMYS \cdot WJ} + \overline{BMYS}^2 - m^2 \cdot \sigma_{YS}^2\right)^{1/2}}{m^2} = f\left(\overline{WJ}\right), \tag{15}$$

Fig. 8. The bucket wheel excavator SRs 2000 20/5 in exploitation, Kostolac (Serbia)

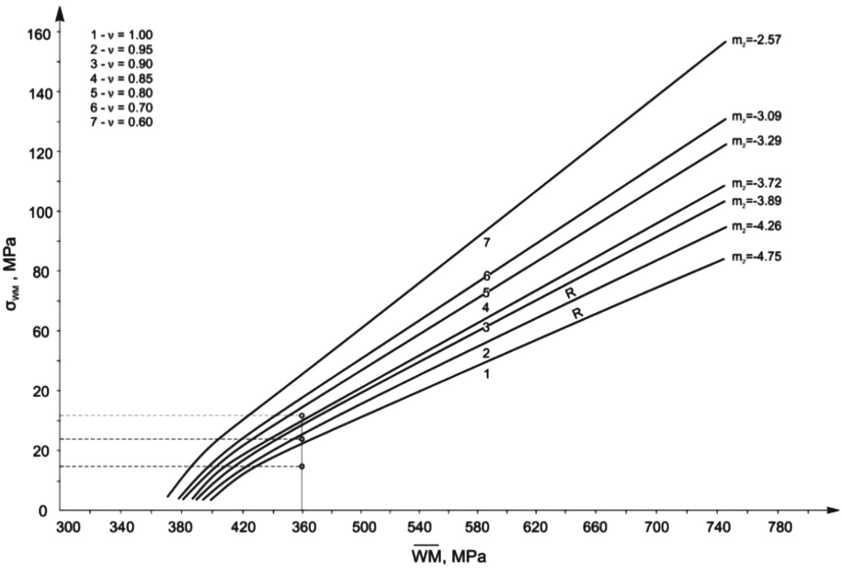

Fig. 9. Influence of the WJ properties on reliability $R(m_2)$, according to Eq. (3)

with ρ being the correlation coefficient between the WJ and BM properties,

$$\eta 50\% = \eta\left(\overline{WJ}, \sigma_{WJ}, \overline{BM}, \sigma_{BM}, \rho\right). \tag{16}$$

It is also possible to calculate the lower limit of the welded joint weakening, introducing the confidence limits $m_2^{/}$ and the minimal number of samples n for the WJ and BM properties.

$$\eta_L = \Phi\left(m_2^{/}\right) \tag{17}$$

$$m_2^{/} = m_2 + \frac{h_\gamma}{n^{1/2}}\left(1 + \frac{m_2^2}{2}\right)^{1/2} \tag{18}$$

$$\eta_L = \eta_L\left(\overline{WJ}, s_{WJ}, \overline{BM} s_{BM}, \rho, n, \gamma\right). \tag{19}$$

Based on laboratory investigations of the workshop and in-situ executed WJ and their comparison to the initial or the current BM properties, the weldability indicators can be obtained.

If the BM properties are known $\left(\overline{BM}, \sigma_{BM}\right)$, the weakening coefficient of the welded joint η would then numerically represent the WJ weakening. Values of η will be 0.5 when the properties of the WJ and BM are equal ($\overline{WJ} = \overline{BM}$), thus the value for η can be expected within limits 0–0.5 [31]. The equality $WJ\overline{WJ}_{\gamma_{\min}}$ should be additionally checked.

Example: Evaluation of the welded joint strength on the bucket wheel excavator SCh Rs 1400 28/3 during the assembly

The tensile strengths of the BM and WJ, executed by the welding procedure 111 of structures made of the S235 and S335 steels, can be considered according to the normal or Weibull distribution [27], as presented for the bucket wheel excavator SCh Rs 1400 28/3 (produced by "Thyssen Krupp" of Germany) (Fig. 10).

Fig. 10. Bucket wheel excavator Sch Rs 1400 - 28/3 during the assembly, Kostolac (Serbia)

Reliability of the welded joint *R*, expressed by the weakening coefficient η, or by the reliability coefficient m_2, for the case of the strong correlation between the tensile strengths of the WJ and BM, namely for the correlation coefficient $\rho = 1$ (though experimental results have shown that the correlation depends on the welding parameters and is within limits from $\rho = 0.75$ to $\rho = 0.85$ [32]) and for medium values of the BM and WJ tensile strengths, smaller than $\overline{R}_{mbm} = 600$ MPa and $\overline{R}_{mwj} = 590$ MPa for their standard deviations $\sigma_{BM} = 26$ MPa and $\sigma_{WJ} = 33$ MPa, will amount to:

$$m_2 = -\frac{\overline{R}_{mWJ} - \overline{R}_{mBM}}{\left(\sigma_{WJ}^2 + \sigma_{BM}^2 - 2 \cdot \rho \cdot \sigma_{WJ} \cdot \sigma_{BM}\right)^{\frac{1}{2}}} = -\frac{590 - 600}{\left(32^2 + 26^2 - 2 \cdot 1 \cdot 32 \cdot 26\right)^{\frac{1}{2}}} = 0.20, \quad (20)$$

with $\eta_{50\%}$ (m_2) = $\eta_{50\%}$ (0.20) = 0.42 from the tables of standardized normal distribution.

By establishing changes of mechanical properties of the base metal and the welded joints of structures during the exploitation, by varying the large numbers of influential factors and reducing the undesirable effects to the acceptable values, one can realize the favorable design solution of a bucket wheel excavator as a whole. This paper represents a good basis for creating such a database, a structure of which is presented in Fig. 11.

Application of the presented method also enables efficient reparation and revitalization of the bucket wheel excavator, with savings in the invested labor and reducing the production losses due to shortening the excavator's downtime. The efficient investigation of the welded joints, during the manufacturing, acceptance tests and mounting of the new welded structures, are enabled, as well. In that way, the structure can be monitored during all of the exploitation periods with satisfactory reliability.

6 Conclusions

The method presented in this paper is an efficient and reliable tool to evaluate and improve the safety of vital welded structures of the bucket-wheel excavators, as well as to determine the causes of their failure during the exploitation. The probabilistic and semi-probabilistic approaches are defined for expressing the validity coefficient (v), weakening coefficient (η) and reliability (R), as measures of reliability in the exploitation of the welded structures, mounted to the bucket wheel excavators. The applied fault tree method enabled qualitative and quantitative analysis of the causes of the welded joint failures and the creation of the corresponding database, which contributes to increasing the bucket wheel excavators' reliability. If still the damage occurs, the data from the proposed database (Fig. 11) can be used to do the reparation of the structure with minimal costs and losses.

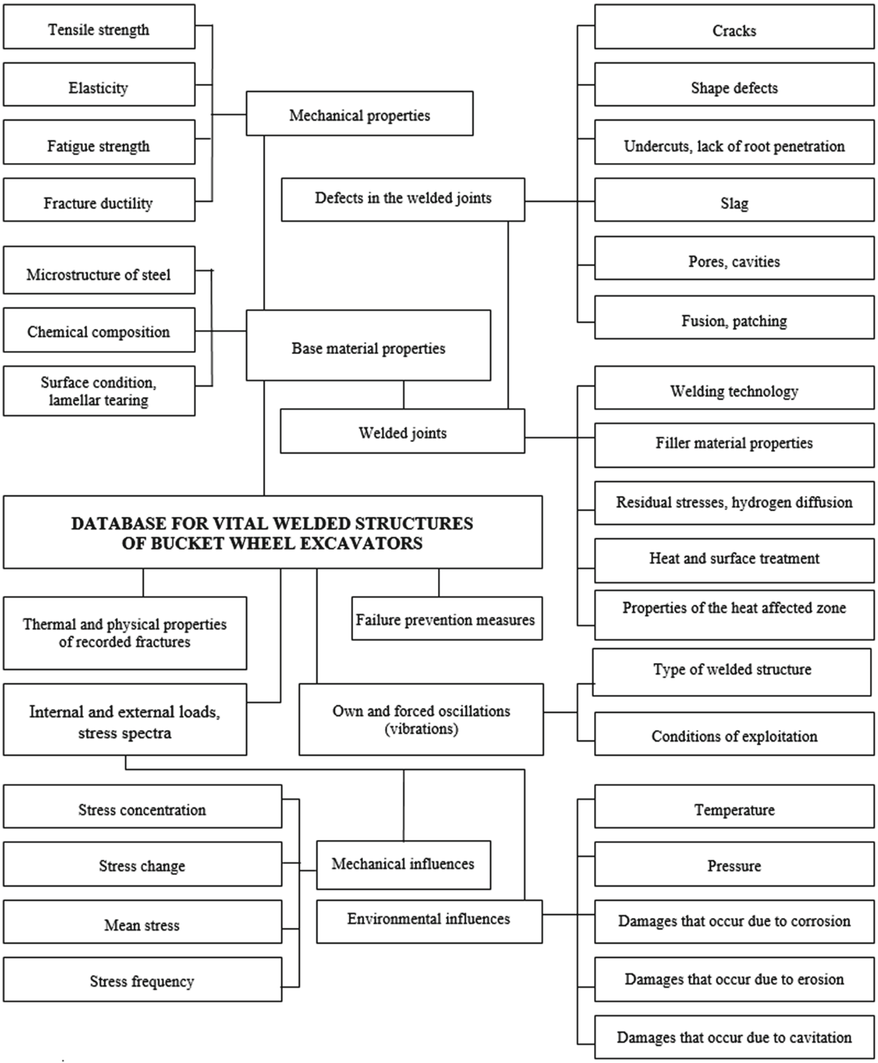

Fig. 11. Database structure for vital welded structures of the bucket wheel excavators

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