INTEGRITY ASSESSMENT OF BUCKET WHEEL EXCAVATOR WELDED STRUCTURES BY USING THE SINGLE SELECTION METHOD

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Original scientific paper

In order to reduce the testing costs for structural welded joints and production losses due to excavator standstill, a new method for integrity and reliability assessment of welded joints during exploitation of bucket wheel excavators has been developed. In this paper, a part of non-destructive testing results for the butt welded joints on bucket wheel boom, counterweight boom and discharging boom is presented, prior to the repair of the collapsed bucket wheel excavator SchRs 1760×32/5. It has been in operational mode for 17 years prior to the collapse, in other words it has been subjected to aproximatelly 2 125 000 cycles of variable loading. Hypergeometric distribution has been used for calculation of probability that x welded joints, which comprise n welded joints with defects, would be selected for testing out of overall number of joints Q. The integrity assessment for welded structures of bucket wheel excavators has been performed on the basis of defect analysis and probabilistic assessment of the fatigue crack growth in welded joints. By using this method, the testing costs have been reduced by 70 % through optimized scope of the inspections and time periods between them.

Keywords: bucket wheel excavator, fatigue, integrity assessment, non-destructive tests, single selection method, welded structure

Procjena integriteta zavarenih spojeva rotornog bagera primjenom metode jednostrukog izbora

Izvorni znanstveni članak

U cilju smanjenja troškova ispitivanja zavarenih spojeva na vitalnim konstrukcijama i gubitaka u proizvodnji zbog zastoja u radu bagera, razvijena je nova metoda za procjenu integriteta i pouzdanosti zavarenih spojeva u eksploataciji rotornih bagera. U radu je prikazan dio rezultata istraživanja stanja sučeono zavarenih spojeva na konstrukcijama strijele rotora, odlagajuće strijele i strijele protutega metodama bez razaranja, prije revitalizacije havariranog rotornog bagera Sch Rs 1760×32/5. Rotorni bager je prije havarije radio oko 85 000 sati (17 godina), odnosno bio je izložen promjenjivom opterećenju tokom približno 2 125 000 ciklusa. Hipergeometrijska raspodjela je primijenjena za izračunavanje vjerovatnosti da će za ispitivanje biti izabrano x zavarenih spojeva, koji sadrže n spojeva s greškom, od ukupnog broja spojeva Q. Procjena integriteta zavarenih konstrukcija rotornog bagera izvršena je na osnovu analize grešaka i analize rezultata ispitivanja rasta zamorne prsline u zavarenim spojevima. Primjenom ove metode, troškovi ispitivanja su smanjeni za 70 %, optimizacijom opsega ispitivanja i vremenskog razdoblja između njih.

Ključne riječi: ispitivanja bez razaranja, metoda jednostrukog izbora, procjena integriteta, rotorni bager, zavarena konstrukcija, zamor

1 Introduction

All bucket wheel excavators (BWE) at Serbian coal open pit mines were manufactured by German companies "TAKRAF" and "Thyssen Krupp". They have been designed in accordance with the standard DIN 22261. The class and quality of structural welded joints, as well as type and scope of non-destructive tests (NDT) are defined by the standard DIN 22261-3, while the quality assessment of welded joints during their fabrication, as well as during exploitation of bucket-wheel excavators, is defined by the procedure DR 16.20. Procedure DR 16.20 for testing of welded structures and standard DIN 22261-3 require the following to be fulfilled: for class "B" welded joints – 100 % NDT (visual testing, magnetic particle testing, ultrasonic testing and radiographic testing), for class "C" welded joints – 20 % NDT and for class "D" welded joints – 10 % NDT. No standards, norms, recommendations or methodologies which prescribe a different method for quality assessment of welded structures of BWE were found in available references.

The plan and program of periodic testing of welded joints on vital substructures of BWE predict the inspection after 5000 hours of service. Different non-destructive tests, conducted during these inspections, are an important part of structural integrity assessment procedures. Unfortunately, bearing in mind that there are many welded joints that should be periodically tested, time required for NDT, work that needs to be carried out and losses in production due to BWE standstill, it is common practice that welded joints do not get tested at all. In practice, it is advisable to avoid both limiting situations (no testing or testing of all joints), and a possible solution is the risk based approach (RBI). Since complex structures are subject to deterioration at various locations, identification of these locations (hot spots) and failure modes becomes crucial in integrity management strategy. A detailed overview of the risk-based procedures to inspection planning is given in [1].

Due to the highly expressed dynamic character of external loading of excavators, manufacturing defects of welded joints, as well as failures in their control, can lead to significant damaging of vital parts [2 ÷ 6], and in extreme cases to a complete collapse of the machine [7 ÷ 9]. Similar problems arise with other machines exposed to periodically varying external load, such as bucket wheel stacker/reclaimers [10]. A methodology for monitoring and diagnostics of bucket wheel excavators in exploitation, with an aim to predict the potential problems, is presented in [11].

BWE SchRs 1760, Fig. 1, has been in operational mode for 85 000 hours (17 years) prior to the collapse, in other words it has been subjected to approximately 2 125 000 cycles of variable loading.

This paper deals with the analysis of NDT results obtained by examining the butt-welded joints on structures of the bucket-wheel boom (BWB) and counterweight boom (CWB), Fig. 2, as well as on the structure of the discharging bridge (DB), Fig. 3, before the repair of the collapsed BWE.
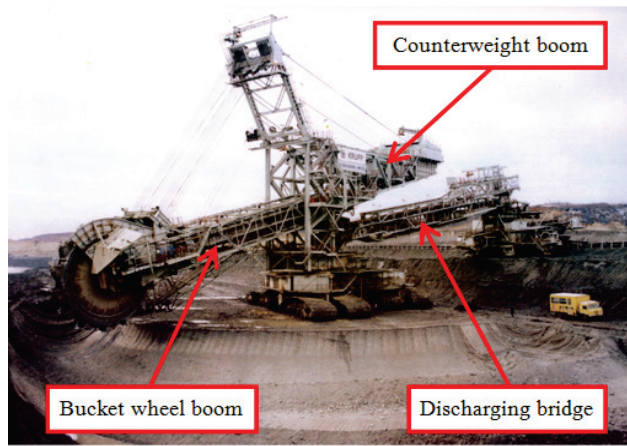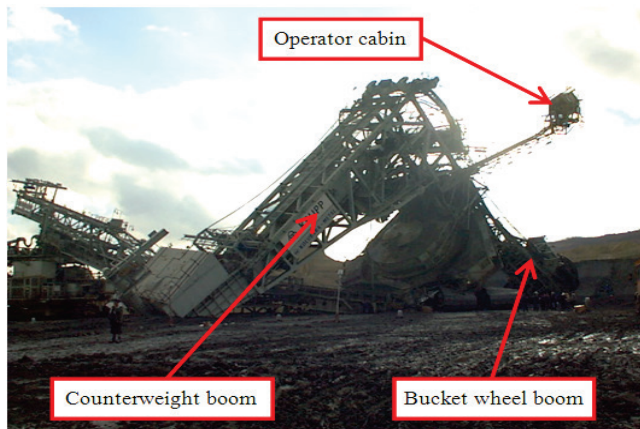
Figure 1 BWE SchRs 1760×32/5

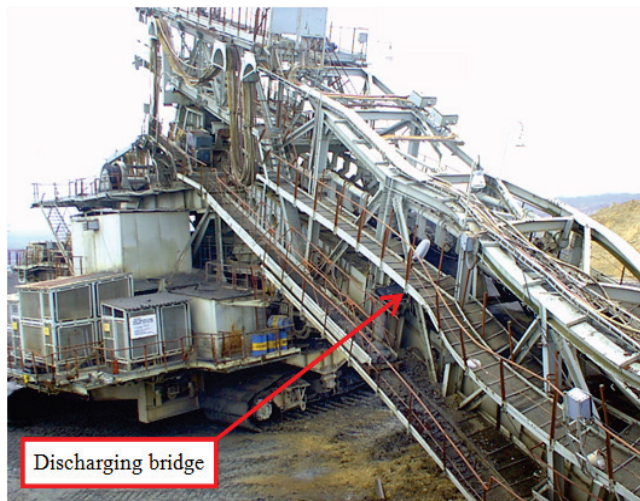
Figure 2 BWB and CWB after the collapse

Figure 3 DB after the collapse

The tests performed on welded joints on BWB and CWB proved the existence of surface and internal crack-type defects, or heterogeneities similar to cracks. In establishing "history" of their initiation and growth, which occur due to variable loading (fatigue), it is necessary to perform experimental testing in order to establish the crack growth rate.

The main aim of this work is to apply the statistical analysis (in this case, the single selection method), along with fracture mechanics procedures [12], in order to reduce the number of necessary tests without endangering the work safety. The reason for such an approach is great

complexity of the excavator structure and large number of welded joints; testing of all these joints would be very expensive and time-consuming, which is why optimization of these tests is extremely important.

2 Single selection method

A brief introduction regarding the application of the single selection method to the analysed problem is given in this chapter. The initial phase is selection of a random number of welded joints m for testing from the overall number of joints Q on the entire excavator structure ($m \leq Q$). If the number of welded joints with defects is $d(m) \leq C$, where C is the acceptance number (maximum allowed number of joints with defects), tested welded joints are acceptable, and if $d(m) > C$ they are non-acceptable. This method is characterized by two parameters: scope of testing m and the acceptance number C, Fig. 4.
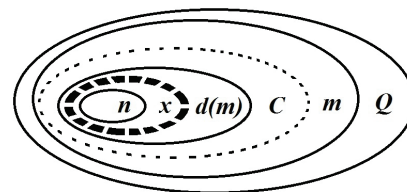

Figure 4 Scheme of the single selection method

This method is applicable for 2 groups of defects:
A – Hidden defects within the welded joints and defects which occur during the assembly,
B – Unpredicted local changes of original properties of the base material and welded joints.

On the basis of testing results, the following solutions exist:
1. To accept the rest of the welded joints without further testing,
2. To perform testing on all welded joints, eventually classifying them into acceptable or non-acceptable group,
3. To reject the rest of the welded joints without further testing.

For the group of defects listed under A, all 3 solutions could be used, while only the first 2 solutions are valid for the group of defects listed under B.

For the calculation of the probability that from the chosen number of x welded joints there will be n welded joints with defects, Fig. 4, the hyper-geometric distribution can be used [13, 14].

If the number of welded joints with defects is n, from randomly selected number of m welded joints, x welded joints with defects could be selected in C_n^x ways. Other (m-x) welded joints are acceptable and could be selected from the group of (Q-x) welded joints in Q_{Q-n}^{m-x} ways. The probability to find x welded joints with defects within the selected scope m is:

$$P(x) = \frac{C_n^x \cdot C_{Q-n}^{m-x}}{C_Q^m} , \quad C_Q^m = \binom{Q}{m} = \frac{Q!}{m!(Q-m)!} . \tag{1}$$

The crack growth rate data obtained through laboratory tests are not sufficiently reliable, because they do not take into account the realistic operating conditions, unlike the data obtained during exploitation. Defects detected during exploitation do not get repaired if their size is smaller than the critical value. Function of probability of reaching the critical size of the crack within the welded joint until the next inspection, depending on the cost of testing, is obtained taking into account the following parameters: crack growth rate, scope of testing, methods and periodicity of testing during exploitation, overall number of welded joints and damage rate of the entire welded structure in the moment of testing.

The increase of the period between the tests increases the probability that the maximum dimension of the crack will be larger than allowed. That probability, depending on crack growth rate, could be determined by processing the statistical data regarding the dimensions of cracks determined during the testing of welded joints. It is justifiable to express the period between the tests by the number of loading cycles between them (ΔN), because the dependency between the crack length a and the number of loading cycles ΔN is much more clear than the dependency between the crack length and period of time between 2 tests. The regression line in the first case has a more pronounced slope than in the other.

Number of loading cycles ΔN, at a certain moment, is not equal for all welded joints of bucket-wheel excavator structures, and that's why it is possible to oversee the testing of welded joints on some structures after the prescribed period.

On the basis of the equation for overall probability, the probability of reaching the critical crack length until the next testing could be determined:

$$P_j = \sum_{j=1}^{k} P_{\Delta Nj} \cdot P \cdot (a > a_c, \Delta N_j), \qquad (2)$$

where:

$P_{\Delta Nj}$ – probability for the number of loading cycles (ΔN_j) between 2 tests,

$\sum_{j=1}^{k} P_{\Delta Nj} = 1$

k – number of possible loading cycles (ΔN) until the next testing,

$P(a > a_c, \Delta N_j)$ – probability that after ΔN_j loading cycles maximum depth of the crack will be greater than a_c.

Probability of not finding welded joints with defects within the selected scope of testing is:

$$P_{iwj} = \frac{C_{Q-n}^m}{C_Q^m}. \qquad (3)$$

Probability that welded joints with defects will not be found (probability that the cracks will not be detected), P_{cr}, is:

$$P_{cr} = 1 - P_{de} = 1 - P_{def} \cdot (1 - P_{iwj}), \qquad (4)$$

where:

P_{de} – probability of detecting welded joints with defects (cracks)

$$P_{de} = P_{def} \cdot P_p, \qquad (5)$$

P_{def} – probability of detecting the existing cracks during defectoscopy,

P_p – probability that the welded joint with defects will be included in the scope of testing.

3   Results
3.1 Fatigue crack growth rate testing

Premature fracture or damage of BWE welded structures is caused by the simultaneous action of a large number of technological, metallurgical, structural and exploitation factors, which explains the dissipation of the tensile strength data for welded joints, taking into account various coefficients of non-symmetric loading $R = \sigma_{min}/\sigma_{max}$. Therefore, fatigue crack growth tests have been carried out through the use of the controlled force by three point bending, with the asymmetrical load $R = F_{min}/F_{max} = 0,5$. Tests have been performed on a specimen with $a = 2$ mm deep side notch. The specimen has been taken from the sample with a "K" weld, because previous tests showed that those are the most critical butt welded joints on BWE structures.

Dependency curve $a - N$ (crack length with respect to the number of loading cycles), presented in Fig. 5, shows that the propagation of the 2 mm deep initial fatigue crack, up to additional 1,5 mm (i.e. up to overall depth of the fatigue crack 3,5 mm) was slow. From this point, the crack started to propagate rapidly for a relatively low number of loading cycles.
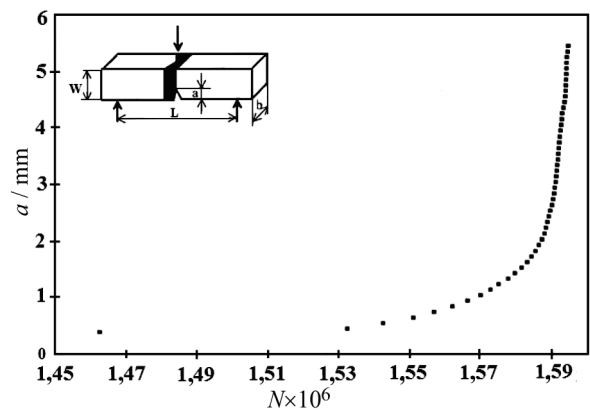

Figure 5 Experimentally obtained $a - N$ curve

Dependency $a - N$ was used as a basis for the determination of crack growth rate per loading cycle da/dN, Fig. 6. Crack growth rate per loading cycle was obtained through the use of the polynomial method, for which the computer program is presented in standard ASTM E647. For every current crack length a and crack growth rate da/dN, the suitable range of stress intensity factor ΔK was calculated, depending on specimen geometry, crack length and range of the variable force $\Delta F = F_{min} - F_{max}$.

On the basis of this calculation, values of coefficients m and C were obtained ($m = 3,516$, $C = 3,18 \times 10^{-12}$); they characterize the resistance of the material to crack growth

and define the Paris equation for the middle part of the crack growth rate curve. Obtained values for m and C correspond to those for steels with similar mechanical properties.

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot (\Delta K)^m . \qquad (6)$$

On the basis of a large number of tests, which showed that fatigue threshold occurs at low crack growth rates, in the range from $10^{-6} \div 10^{-8}$ mm/cycle, and taking into account the dependency curve $\mathrm{d}a/\mathrm{d}N - \Delta K$, Fig. 6, it can be concluded that fatigue threshold value $\Delta K_{th} = 7,24$ (MPa√m) corresponds to the crack growth rate of 10^{-8} mm/cycle. Stress intensity factor range ΔK_c, at which the maximum stress intensity factor reaches the critical value at which fracture occurs $K_{max} = K_c$ (ductile fracture), is estimated at around 40 (MPa√m). This value corresponds to the data for similar materials in the literature.
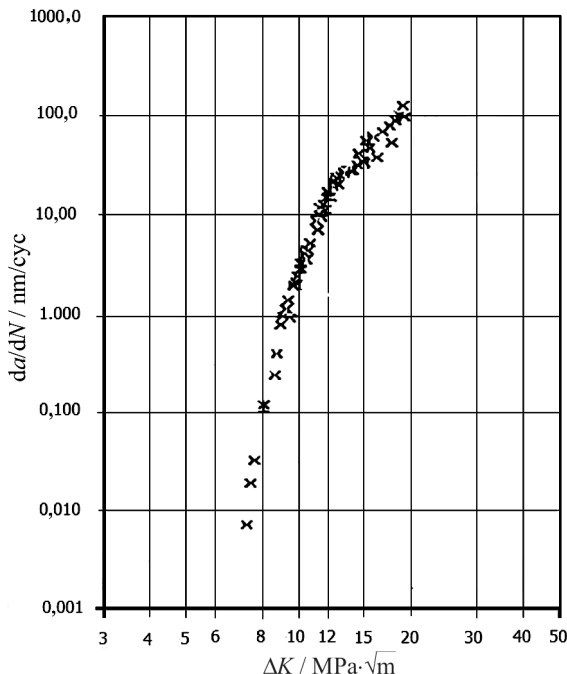

Figure 6 Dependency $\mathrm{d}a/\mathrm{d}N - \Delta K$

3.2 Application of the single selection method in testing of welded joints on the BWE SchRs 1760

As mentioned previously, single selection method was used during the NDT of welded joints on the vital structures of the BWE SchRs 1760 × 32/5. The number of tests (magnetic particle testing and ultrasonic testing) performed on welded joints of structural subsystems is as follows: 89 on the BWB, 42 on the DB and 23 on the CWB. Two cracks with length up to 1,5 mm, as well as four cracks shorter than 1 mm, were detected through the use of NDT on parts of BWB and CWB welded structures. No cracks were detected on the DB structure.

Results of tests which referred to fatigue crack growth rate in the area of the welded joint showed that it takes approximately $N = 3 \times 10^6$ loading cycles for the 2 mm long fatigue crack to be initiated (initial fatigue crack

on the specimen), while for the period of operation until the collapse of 85 000 hours (i.e. for the number of load changes of $N = 2\,125\,000$ cycles), the 1,42 mm long initial fatigue crack is to be expected.

Conditions of exploitation may change due to: 1) different excavation environment, 2) different BWE operating mode (vertical or horizontal cutting) and 3) the way of handling of BWE.

Depths of the cracks with maximum lengths, detected through NDT performed on damaged parts of the BWB and CWB welded structures, are presented in Fig. 7 and 8 (1 – regression line; 2, 3, 4 – boundaries of one-sided trust intervals for $\alpha = 95{,}97$ and $99{,}5$ %).
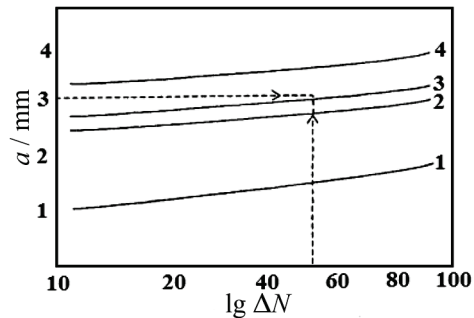

Figure 7 Test results regarding the crack lengths on damaged parts of the BWB welded structure
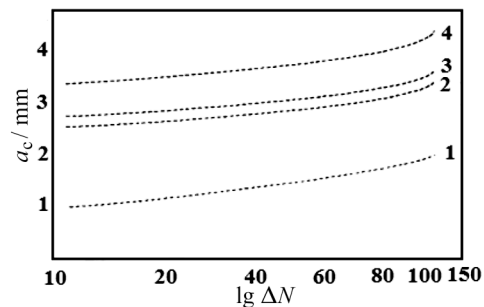

Figure 8 Test results regarding the crack lengths on damaged parts of the CWB welded structure

Figs. 9 and 10 are diagrams for determination of $P(a > a_c; \Delta N) = 1 - \alpha$, for cracks of BWB and CWB welded joints. Lines 1', 2', 3' refer to the following ranges of loading cycles $\Delta N = 2{,}125 \times 10^6$; $4{,}25 \times 10^6$ and $6{,}375 \times 10^6$, respectively.

Dispersion of points is typical for cracks in welded joints. It is conditioned by a relatively low accuracy of crack depth measurement and by the fact that, apart from the number of loading cycles, other factors in close relation to the conditions of exploitation affect the crack growth rate.
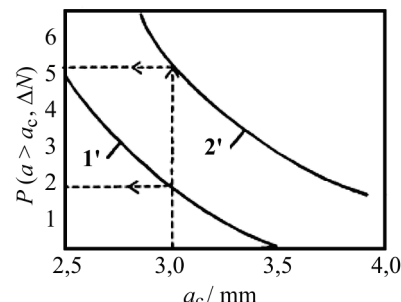

Figure 9 Graph for determination of the value of $P(a > a_c; \Delta N)$, for cracks detected on the BWB welded joints

Lowering of dispersion for values of crack depth could be accomplished on the basis of the numerical assessment regarding the influence of exploitation conditions.
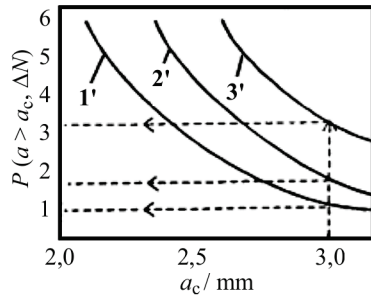

Figure 10 Graph for determination of the value of $P(a > a_c; \Delta N)$, for cracks detected on the CWB welded joints

4 Discussion

Based on the results shown in previous section, probabilities for crack occurrence until the next inspection are discussed. Determination of P value ($a > a_c; \Delta N$), for cracks on BWB welded joints, is performed on the basis of data obtained from Fig. 7. For that purpose, the graph from Fig. 9 is used for various probabilities, where vertical lines correspond to the maximum value of the loading cycle ΔN. Results are shown below:

$$P(a > 3,0; \Delta N = 2,125 \times 10^6) = 1,8\ \%, \tag{7}$$

$$P(a > 3,0; \Delta N = 4,250 \times 10^6) = 5,3\ \%. \tag{8}$$

Critical depth of the crack (obtained through the application of fracture mechanics) $a_c = 3,0$ mm, Figs. 9 and 10, is two times smaller compared to the size of the through crack which would cause the BWE collapse.

Calculation of the graph shown in Fig. 7 has been carried out with the assumption that the crack size a has a normal distribution. It has been established that a smaller number of cracks occur on the CWB welded joints than on the BWB welded joints, because the initiation and growth of cracks is accelerated due to a much higher load. That's why the regression line for the maximum depth of the crack detected on the CWB, at various intervals between tests ΔN, has a smaller slope than that of the regression line for the crack detected on the BWB (Fig. 9). Dispersion is the same for BWB welded joints as is for CWB welded joints. In that case, the following results are obtained from Fig. 10:

$$P(a > 3,0; \Delta N = 2,125 \times 10^6) = 0,8\ \%, \tag{9}$$

$$P(a > 3,0; \Delta N = 4,250 \times 10^6) = 1,5\ \%, \tag{10}$$

$$P(a > 3,0; \Delta N = 6,375 \times 10^6) = 3,0\ \%. \tag{11}$$

Probability of failure of welded joints with cracks for different numbers of joints during the testing based on the principle of random sampling on the BWB ($Q = 42$ tested welded joints) is shown in Fig. 11, while the results for the CWB ($Q = 23$ tested welded joints) are shown in Fig. 12. Lines 2, 4 and 8 refer to numbers of welded joints

with cracks, respectively. The value of P_{iwj} is obtained using Eq. (3).

Probability that there will be cracks on the BWB welded joints with depth $a > a_c$ during the next inspection changes from 5,3 % if the tests are not performed to 1,8 % if all joints are tested. For the CWB welded joints, even without regular periodic testing, that probability is 1,5 %. That's why the inspection of these welded joints could be easily prolonged. Calculation is performed through the use of results of tests performed after 6 375 $\times 10^6$ loading cycles.
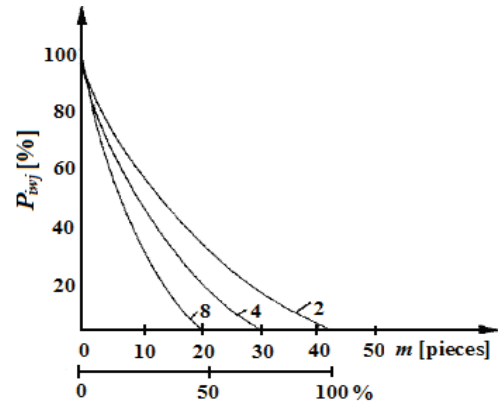

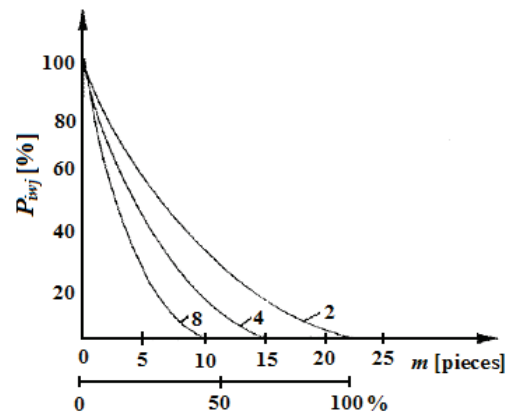**Figure 11** Probability of failure of BWB welded joints with a crack

Figure 12 Probability of failure of CWB welded joints with a crack

5 Conclusion

Calculations for various numbers of welded joints with cracks, through the use of the single selection method, confirm the possibility of an optimized approach to their inspection. In most cases it is justifiable to introduce an interval between two testing periods, twice shorter for the BWB welded joints than for the CWB welded joints and those on the DB, because welded joints on CWB and DB are subjected to lower loads. Optimal scope of NDT varies depending on the BWE structure. It is recommendable to perform the inspection on 33 % of welded joints per year on the CWB and DB structures (tests on all welded joints would be performed after a three-year period), while it is recommendable to perform tests on BWB welded joints in the scope of 50 and 100 % per year. Such scope of testing, which is not in collision with a complete inspection of welded joints (prescribed by standard DIN 22261-3), ensures reliable exploitation.

Therefore, the use of single selection method enabled an optimization of the scope of inspection, i.e. reducing the cost and duration of NDT procedures, without endangering the safe service of BWE.

It should also be noted that this method is applicable for testing of welded joints during the production and assembly of new structures, which has been confirmed during the production, delivery and assembly of another bucket-wheel excavator, SRs 2000×32/5,0, for the coal open pit mine "Drmno" (Serbia).

Acknowledgment

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