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Probabilistic approach and fault-tree analysis for increased bucket wheel excavator welded joints reliability

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Abstract

The main part of this paper is consisted of presentation of a new method for determination of reliability of the structures. Presented method provides more knowledge and confidence when evaluating the construction of vital welded structures and determining the cause of their failure in service. The probabilistic and semi-probabilistic approaches have been defined for expressing the coefficient of validity (ν) and the coefficient of the welded joint weakening (η), while reliability (R) has been defined as a measure of quality of installed vital welded structures on bucket wheel excavators in service. The applied "fault-tree" analysis enables quantitative and qualitative analysis of the failure causes, diagnostics of behavior and structural degradation, evaluation of integrity and estimate of the service life of the vital welded structures that have a flaw in the welded joint, as well as creating a data base, by which the reliability of the bucket wheel excavators can be increased. The method also makes possible to efficiently test the welded joints, during the manufacturing, acceptance and assembling the new welded structures of the bucket wheel excavators, cranes or bridges.

Keywords: bucket wheel excavator; welded structure; fault-tree analysis

1. Introduction

Straining in the vital welded structures of the bucket wheel excavators appear during their manufacturing and assembling (residual stresses), during the execution of the functional requirements in exploitation (stationary and dynamic loadings) and during the disturbed exploitation process (non-stationary dynamic loadings). When the

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unexpected influences during the exploitation are added, it is clear that straining of the vital welded structures cannot be completely represented by a model in which the parameters are uniformly varying in the exploitation conditions. This is the reason why only the experimental investigations during the excavator's exploitation enable estimate of its status and integrity. In that way one can obtain the data necessary for determination of conditions and causes of degradation of material and welded joints of the vital welded structures and for determination of the excavator's functionality and operational reliability and for estimate of the mutual influences of spatial operation of structures as a whole. The time course of the excavator's complex stressing is shown in Figure 1, with all the stress components classified according to causes of their appearance.

Considering that the bucket wheel excavators have a long service period in the very hard exploitation conditions, their vital welded structures have to be controlled both continuously and periodically. This is specifically true for welded joints, since the integrity of the welded structures depend on their behaviour [1-8]. This explains a wide spread of welded joints fatigue strength values, at different values of the asymmetry coefficient of loading ($R = \sigma_{min}/\sigma_{max}$). To enable the reliable integrity assessment and remaining service life of the vital welded structures of the bucket wheel excavator, it is necessary not only to monitor their structural condition [9-11], but to monitor their mechanisms, as well [12-13]. The reason for that is that during the exploitation majority of parts and elements of those structures are exposed to complex dynamic loadings, which are dependent on exploitation conditions, namely the digging resistance and their own vibrations, in the stationary and non-stationary modes of operation of the excavator drive system. One possible way of monitoring the strain and stress state of the vital welded structures by strain gauges, [14]. In this paper the fault tree method is developed for failed welded structure, with focus on different zones of welded joints.

2. The fault tree method

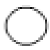
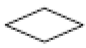
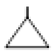
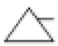
The failure analysis is a process where a failed product is investigated in order to find out what caused the failure. Different methods can be used to detect the cause of failure, like the Ishikawa fishbone (cause-and-effect) diagrams, failure modes and effects analysis (FMEA) and the fault-tree analysis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

2.1. Application of the FTA in manufacturing the welding structures of the bucket wheel excavator

Individual parameters are considered here, affecting manufacturing of the welded structures: chemical composition (CC) of the base metal (BM) and filler metal (FM), base metal quality, welding parameters, shielding gas and heat treatment. Especially important is influence of the BM CC and FM CC on introducing some elements in the welded joint and on homogeneity of joining the BM and FM into the weld metal (WM). Legend of symbols used in further Figures on application of the Fault Tree Analysis is shown in Table 1.

Table 1. Legend of symbols presented in Figures on FTA.

Symbol	Meaning
	Elementary event, initial defect
	Intermediate event or on top (I)
	Undeveloped event due to a lack of information
	AND gate: a defect on the output side occurs if all defects on the input side occur
	OR gate: a defect on the output side occurs if one defect on the input side exists
	Further development of the fault tree on the other figure
	Entrance of the part of the fault tree from the other figure

Influence of the steel's chemical composition during the manufacturing of the welded structures of the bucket wheel excavator can be analysed according to constituent elements and according to equivalent carbon (C_{eq}). The significant influence on quality of the welded structures is imposed by the quality of the base metal in the as delivered state and prior to welding. The cooling rate and/or time of keeping the welded joint (WJ) structure within the certain temperature range significantly influence the structure of the WM, as well – Figure 1 and Heat Affected Zone (HAZ) – Figure 2, appearance of the diffused hydrogen – Figure 3 and residual stresses – Figure 4.

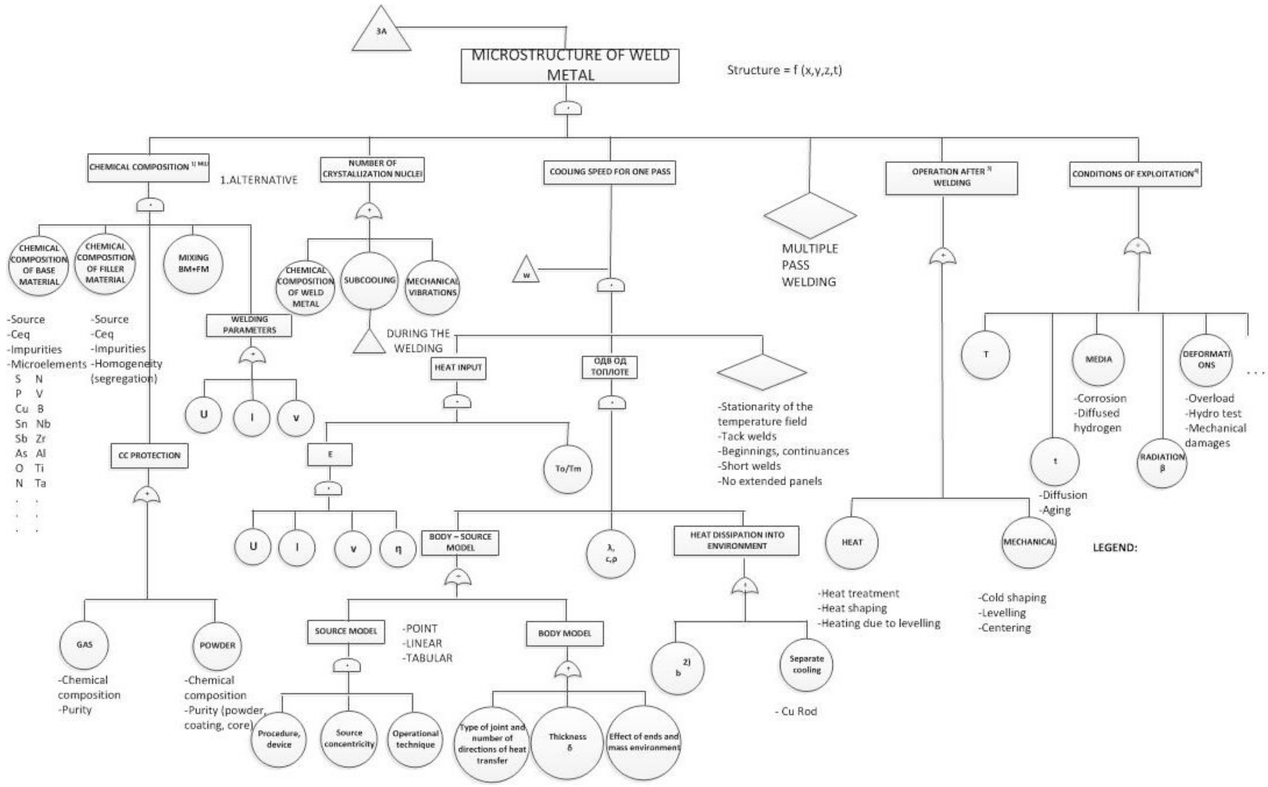


Fig. 1. Scheme of influences on microstructure of the weld metal.

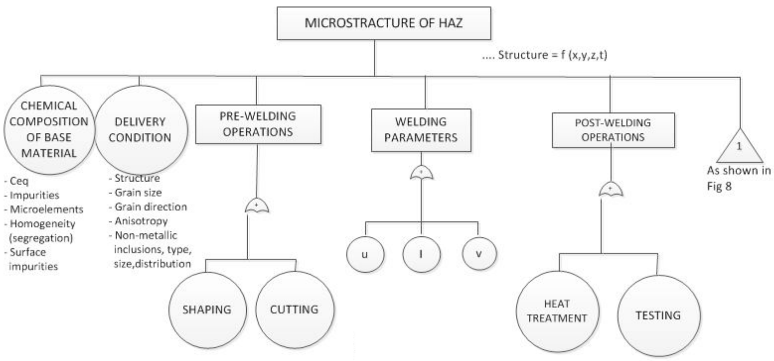


Fig. 2. Scheme of influences on microstructure of the heat affected zone (HAZ).

Numbers on the Fig. 1 represents: 1) Chemical composition; 2) Coefficient b that takes into account dropping of the body temperature due to the heat transfer into the environment; 3) Occurrence of cold cracks is significantly influenced by operations performed within the first 100 hours after the welding; 4) Exploitation conditions influence on occurrence of cold cracks if the reparatory welding is being carried out, as well as the cold cracks growth during the fabrication.

For diagram in Fig. 4, the numbers represent as follows: 1) If being carried out within the first 100 hours after the welding contributes to initiation of the cold cracks; 2) Influence of the weld metal ΔT and the HAZ ΔT on values of the residual stresses in the WM and HAZ for the high strength steels; 3) Residual stresses.

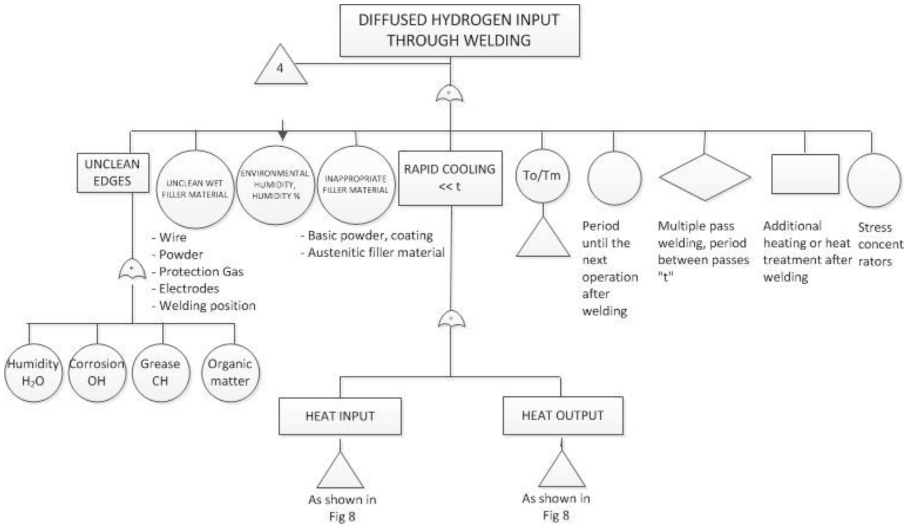


Fig. 3. Scheme of influences on appearance of the diffused hydrogen through welding.

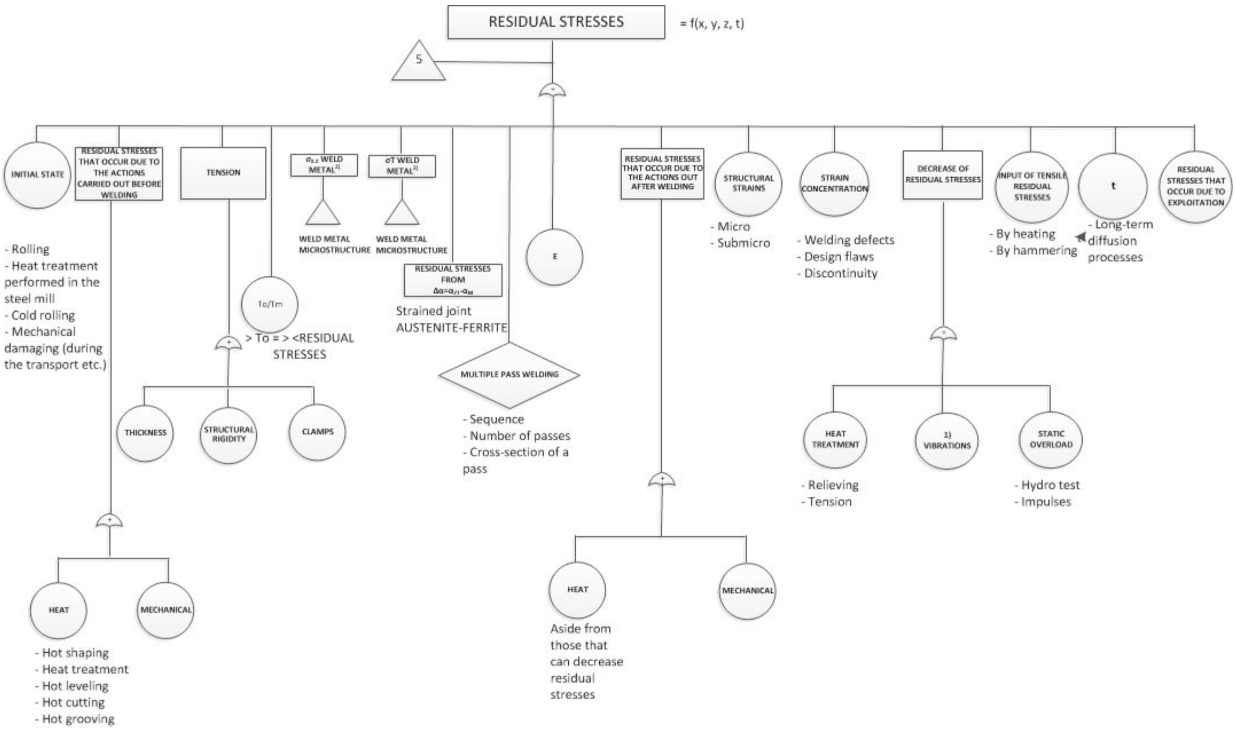


Fig. 4. Scheme of influences on initiation of residual stresses.

Development of the non-destructive testing methods (NDT) has increased the possibility for establishing the inhomogeneity or discontinuity (interior or surface flaw), namely for determination of the extended volume of the quality characteristics. However, it is not a rare phenomenon that despite the conducted investigations of the welded joints, some structures with flaws in welded joints are released to operations – Figure 5.

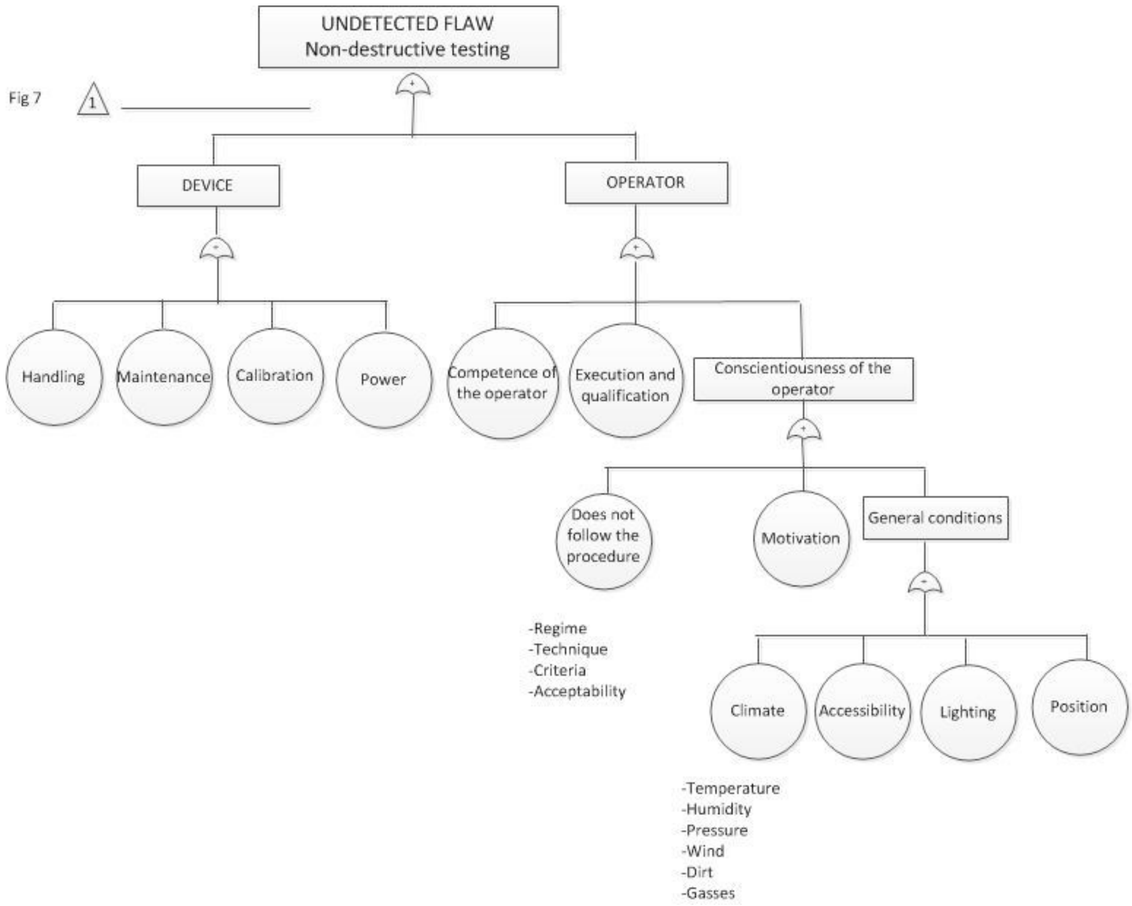


Fig. 5. Sequence of events when the flaw goes undetected during the non-destructive testing.

2.2. Application of the FTA during the welding structures of the bucket wheel excavator exploitation

The undetected flaws due to the manufacturing (Fig. 6) or due to corrosion fatigue – Fig. 7, have important effect on reliability and safety of the welded structures of the bucket wheel excavators, since they are causing fractures or failures of structures.

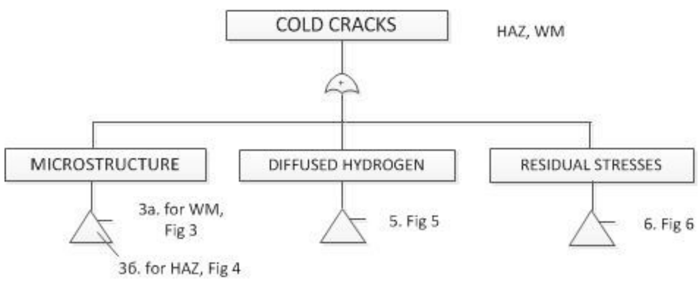


Fig. 6. Fault tree for cold cracks which originate during the manufacturing or exploitation process

Fractures of those structures have also the large negative financial impact due to costs and time needed for manufacturing the new structures, what is in direct relation to losses in the electrical power that should have been produced during that period. In exploitation, degradation of the welded joints and fractures of the welded structures most frequently occur due to fatigue – Figure 8.

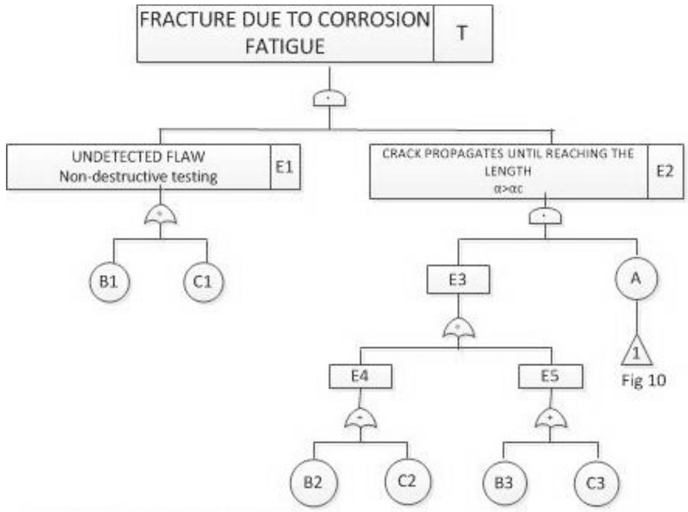


Figure 7. Appearance of the fault tree due to the corrosion fatigue.

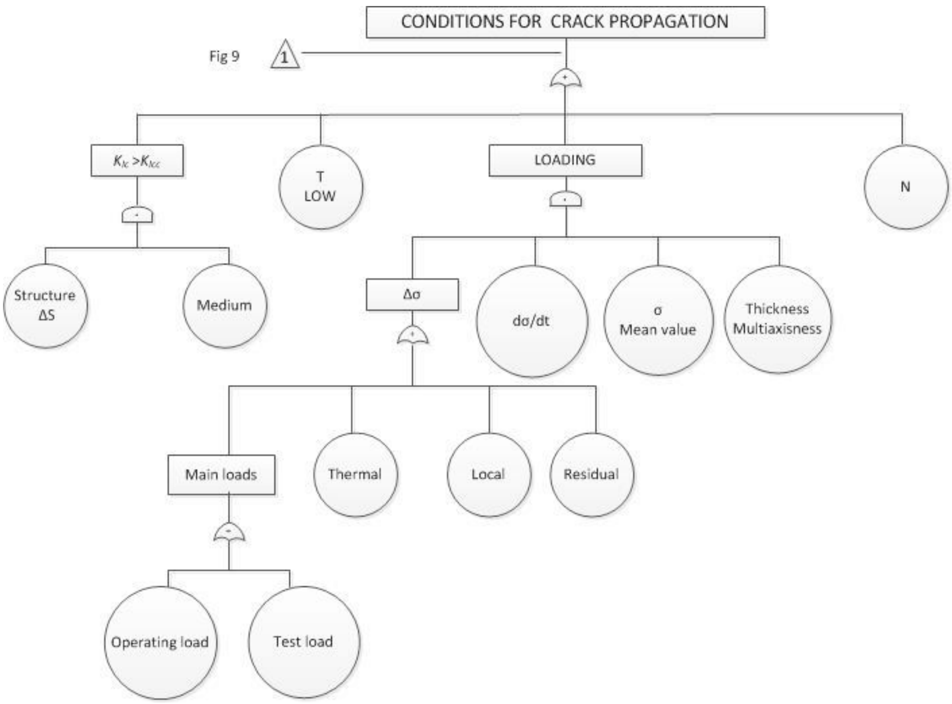


Figure 8. Appearance of the fault tree when the crack reaches length $a > a_c$ (event A in Figure 7)

Propagation of fracture of the welded structure due to fatigue occurs in three phases [6]:

- Existence of the undetected flaw during the manufacturing or initiation of the crack in exploitation;
- Gradual stable crack growth according to Paris law [6]:

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

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;

- Unstable crack growth until the critical length (ac) and appearance of fracture.

For diagram in Fig. 7, the numbers/symbols represents 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 NDT; E4 – Flaw was not detected through NDT immediately after occurrence; E5 – Flaw was not detected through NDT in the later phase of inspections; A – Conditions for the crack propagation; B – test device did not detect the flaw; C – Operator did not detect the flaw, which could have been detected by the device.

Derivative of the fault tree in Fig. 7 is:

$$T = E1*E2 = E2*(B1+C1) = A*(B1+C1) = A*(E4+E5)\ (B1+C1) = A*(B2+C2+C3)\ (B1+C1) \tag{2}$$

3. Conclusions

The method, presented in this paper provides more knowledge and safety for evaluation of manufacturing the vital welded structures of the bucket wheel excavators and for determination of causes of their failure during the exploitation. The probabilistic and semi-probabilistic approaches are defined for expressing the validity coefficient (ν), weakening coefficient (η) and reliability (R), as measures of reliability in exploitation of the welded structures, mounted to the bucket wheel excavators. The applied fault tree method enabled qualitative and quantitative analysis of causes of the welded joints failures and creation of the corresponding data base, what contributes to increasing the bucket wheel excavators' reliability.

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