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Determination of Residual Fatigue Life of Welded Structures at Bucket-Wheel Excavators through the Use of Fracture Mechanics

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Abstract

This paper presents a methodological approach for the assessment of service life of vital welded structures of a bucket-wheel excavator Sch Rs 650/5x24 ('Thyssen Krupp', Germany) boom, subjected to cyclic loading with a variable amplitude through the use of experimental tests carried out in order to determine operational strength and growth of a fatigue crack. Realized researches and results presented in this paper offer great possibilities for the analyses of behaviour of vital welded structures of the bucket-wheel boom. By the application of the measurement device with 8 channels for registration and processing of electric signals HBM Spider 8 and measurement tapes HBM 6/350xXY31 deformations were measured at vital welded structures of the boom in the area of the bucket-wheel, made of steels St 37.2 and St 52.3 in accordance with standard DIN 17100, or steels S235J2G3 and S355J2G3 in accordance with standard EN 10025-2. The objective of the test is to determine if there is a possibility of occurrence of plastic deformations or initial cracks due to fatigue at vital welded structures. Tests that refer to the growth of the fatigue crack located at the welded joint have been carried out by bending at three points with asymmetric load R = 0.5 ($R = \sigma_{min} / \sigma_{max}$) at the specimen with a single edge notch. Tests were performed through the use of controlled force, ranging between F_{max} and F_{min} at the high-frequency pulsator 'Cracktronic', while obtainment of data regarding the crack growth was carried out through the use of measurement gauge ARM A-10.

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Keywords: bucket-wheel excavator, stress condition, crack, service life

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1. Introduction

Vital welded structure of the boom of the bucket-wheel excavator Sch Rs 650/5x24 (‘Thyssen Krupp’, Germany), presented in figure 1, is subjected to stresses that occur during the fabrication of components and assembling of equipment (residual stresses), during the process of performing functional tasks (stationary and dynamic stresses), as well as during the disturbed process of exploitation (non-stationary dynamic loads). Therefore, loads that occur at components and elements of a bucket-wheel excavator structure can’t be presented in the form of a simple mathematical function, i.e. they can’t be completely presented by a model in which variables or parameters evenly change under operating conditions.

Tests performed on components and elements of structures of bucket-wheel excavators under operating conditions enable the complete assessment of their condition, obtainment of necessary data for quality comparison and evaluation of machines and structures, for the evaluation of load-carrying capacity of certain components and elements as well as for determination of characteristics of conjoint operation of drive units and structures [1, 2, 3, 4, 5, 6, 7]. Basic technical and technological properties of the bucket-wheel excavator Sch Rs 650/5x24, which operates at the largest Kosovo open pit mine 'Dobro Selo', are as follows:

- design (theoretical) capacity	Qt = 4212 [m3/h]
- volume of the bucket, taking into account the empty space	Wbuc = 650 [l]
- maximum cut depth	L = 5 [m]
- maximum cut height	H = 24 [m]
- bucket-wheel drive power [2x450 kW]	N = 900 [kW]
- bucket-wheel diameter	Dbw = 10.2 [m]
- number of buckets at the bucket-wheel	z = 21
- number of bucket unloads	ns = 36 [min-1]
- specific resistance to digging, taking into account blade length	kL = 109.6 [kN/m]
- overall drive utilization factor	η = 0.935
- cutting speed	Vr = 2.78 [m/s]

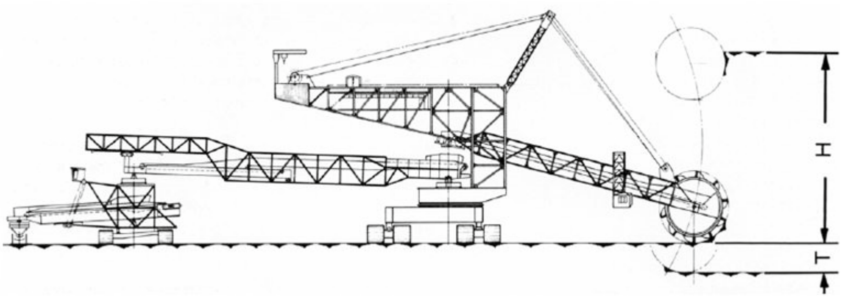

Figure 1: Schematic appearance of the bucket-wheel excavator Sch Rs 650/5x24

2. Dynamic loads at the bucket-wheel excavator during service

Most components and elements of vital structures of bucket-wheel excavators are subjected to complex dynamic loads, which depend on conditions of exploitation (resistance to digging and own oscillations) in the stationary and non-stationary operational regimes of bucket-wheel excavator drive systems during service. By studying the behaviour of parent material and welded joints of vital structures subjected to variable loading it was determined that nodes are critical locations, because 80% of fatigue cracks occur there, figure 2.

Measuring tapes were applied in order to determine deformations and calculate the stresses at the elements of the vital welded structures of the boom in the bucket-wheel area, made of steels St 37.2 and St 52.3 in accordance with standard DIN 17100, or to put it differently made of steels S235J2G3 and S355J2G3, in accordance with standard DIN EN 10025-2 [8]. The objective of the stress condition check is to determine whether there is a possibility of occurrence of plastic deformations or initial cracks due to fatigue. Properties of structural non-alloyed steels S235J2G3 and S355J2G3 of which metal sheets and profiles were made are presented in tables 1 and 2.

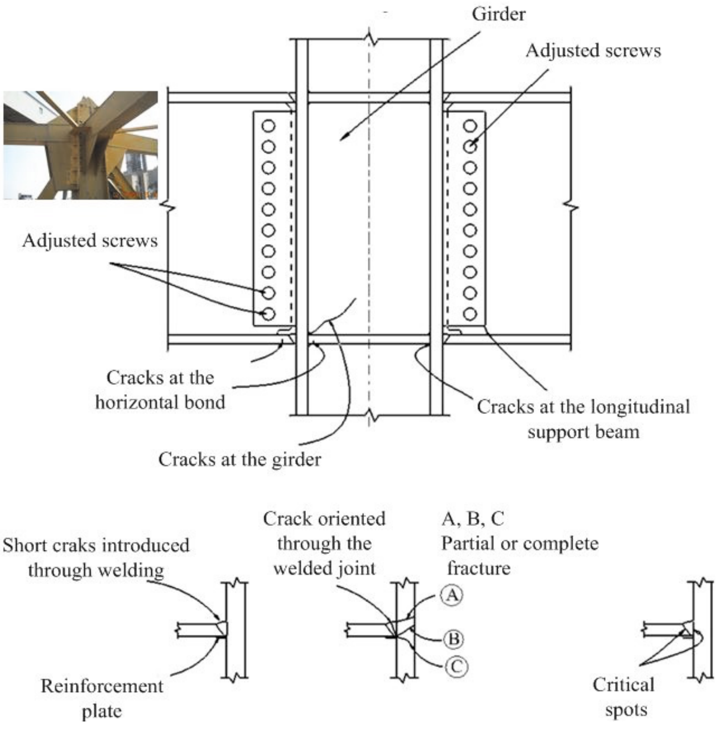

Figure 2. Appearance of a node at the welded structure and locations at which fatigue cracks mainly occur

Table 1. Chemical composition, mass percentage [8]

Steel	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cu[%]
S235J2G3	≤ 0,19	-	≤ 1,50	≤ 0,045	≤ 0,045	≤ 0.60
S355J2G3	≤ 0,23	≤ 0,60	≤ 1.70	≤ 0.045	≤ 0.045	≤ 0.60

Table 2. Mechanical properties [8]

Steel	Yield strength YS [N/mm2]	Tensile strength TS [N/mm2]	Elongation A5 [%]
S235J2G3	235	360 - 510	24
S355J2G3	355	470 - 630	22

Measurements of strains at elements of the vital welded structures in the bucket-wheel area have been performed by 12 measurement tapes HBM 6/350xXY31. Structure of measurement equipment for registration and processing of electric signals (HBM Spider 8 – measurement device with 8 channels) is shown in figure 3.

In figure 4 locations where gauges for measurement of strains at the elements of vital welded structures of the boom in the bucket-wheel area subjected to various conditions of coal mining (dynamic loading) are shown.

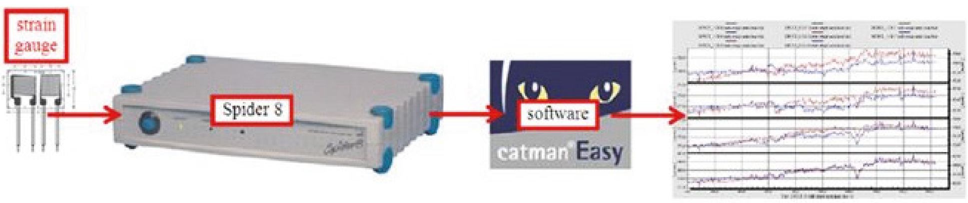

Figure 3. Appearance of the measurement equipment for registration and processing of electric signals (HBM Spider 8 – measurement device)

Figure 4. Welded structure of the bucket-wheel boom and spots where strain gauges were located

Locations where deformations were measured at vertical girders (M1–M4), horizontal girders (M5–M8) and diagonals (M9–M12) were selected on the basis of design and technical documentation, in order to enable insight in stress condition at characteristic locations of the welded structure of the boom in the area of the bucket-wheel.

On the basis of calculated stresses at the elements of the vital welded structure of the boom in the area of the bucket-wheel (figure 4), presented in tables 3 and 4, it can be concluded that stresses are in linear elastic area and that they are 50% lower than yield stress for steels S235J2G3 and S355J2G3. Highest values of stress were determined for diagonals.

Table 3. Calculated stresses at vertical and horizontal girders of the boom structure in the bucket-wheel area, σ_1 [MPa]

Operational mode of the bucket-wheel excavator	Measurement locations							
	M1	M2	M3	M4	M5	M6	M7	M8
Average load during the digging of loose overburden	54.8	58.2	54.2	46.4	45.7	47.1	45.3	42.8
Full cut load during the digging of loose overburden	57.3	62.8	57.3	50.6	48.6	50.9	48.1	44.3
Average load during the digging of compact grey clay	67.6	70.1	59.9	53.2	55.1	57.4	54.2	48.8
Full cut load during the digging of compact grey clay	73.9	73.9	67.3	58.6	59.3	62.1	60.7	54.3

Table 4. Calculated stresses at diagonals of the boom structure in the bucket-wheel area, σ_1 [MPa]

Operational mode of the bucket-wheel excavator	Measurement locations			
	M9	M10	M11	M12
Average load during the digging of loose overburden	65.5	59.3	60.5	54.2
Full cut load during the digging of loose overburden	97.7	63.9	67.7	57.6
Average load during the digging of compact grey clay	114.9	75.6	69.2	62.7
Full cut load during the digging of compact grey clay	145.5	108.4	102.8	93.1

Taking into account the fact that tests by which the stress condition of elements of the vital welded structure of the bucket-wheel boom was determined did not comprise boundary loads which occur during the digging of petrified rock masses, when due to impact loads bucket-wheel halts, the limit of useful load can't be determined.

3. Determination of fracture mechanics parameters

Curve a – N (crack length vs number of load cycles), figure 5, shows that growth of initial crack from 2 mm to 3.58 mm starts slowly, and rapidly progresses afterwards.

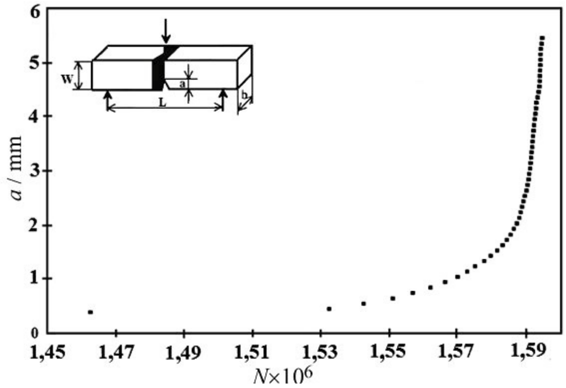

Figure 5. An experimentally obtained a – N curve

Values of measured and calculated parameters of fracture mechanics for the highest possible value of the stress range $\Delta\sigma$ = 145.5 MPa (the mean value of fatigue crack growth rate for 4 specimens) are as follows:

Y(a/W) = 2.32 – parameter which depends on specimen geometry and crack shape,

$\Delta\sigma$ = 145.5 MPa – highest possible value of the stress range,

$C_p = 1.58\cdot10^{-14}$ - Paris-Erdogan equation constant,

m_p = 3.55 - Paris-Erdogan equation constant,

K_{Ic} = 126.5 MPa√m - critical value of stress intensity,

a_o = 2 mm – length of initial crack that existed at tested specimens,

a_{cr} = 44.65 mm – critical length of edge crack calculated by [9]:

$$a_{cr} = \frac{1}{3.14}\cdot\left(\frac{4000}{145.5\cdot 2.32}\right)^2 = 44.65 = 0.004455m \tag{1}$$

For the above mentioned welded structure the remaining number of load cycles for the bucket-wheel excavator is obtained as follows:

$$\frac{da}{dN} = C_p \cdot (\Delta K)^{m_P} \tag{2}$$

$$\begin{aligned} Na_0 - Na_{ck} = N &= \frac{1}{\left(\frac{m_p-2}{2}\right)\cdot C\cdot f^{m_p}\cdot \pi^{\frac{m_p}{2}}\cdot \Delta\sigma^{m_p}}\left[\frac{1}{a_0^{\frac{m_p-2}{2}}} - \frac{1}{a_{cr}^{\frac{m_p-2}{2}}}\right] = \\ &= \frac{1\cdot 10^{14}}{\left(\frac{3.55-2}{2}\right)\cdot 1.55\cdot 2.32^{3.55}\cdot 3.14^{\frac{3.55}{2}}\cdot 145.5^{3.55}}\left[\frac{1}{0.002^{\frac{3.55-2}{2}}} - \frac{1}{0.04455^{\frac{3.55-2}{2}}}\right] = 1.182\cdot 10^7 \ cycles \end{aligned} \tag{3}$$

For the average number of operating hours per year Ty = 4250 h, the overall number of stress variation cycles is:

$$Ny = 60\cdot Ty \cdot n_{BW}\cdot n_B = 60\cdot 4250\cdot 4.86\cdot 21 = 2.6\cdot 10^6 \ cycles\,/\,year \tag{4}$$

where:
$Ty = 4250$ h – average number of operating hours of the bucket-wheel excavator per year,
$n_{BW} = 4.86$ rpm – number of revolutions of the bucket-wheel,
n_B - number of buckets.

On the basis of determined parameters of fracture mechanics, the service life of the carrying welded structure in the area of the bucket-wheel at maximum expected load after the repair of the existing damage in case of initiation of a new edge crack in the longitudinal direction of sheet metal is being obtained from:

$$n = \frac{N}{N_U} = \frac{1.182 \cdot 10^7}{2.6 \cdot 10^6} = 4.55\, years \tag{5}$$

4. Conclusion

Results presented in this paper offer possibilities to designers of bucket-wheel excavators to carry out analysis for vital welded structure of the boom in the bucket-wheel area. Such analysis enables determination of modifications of mechanical properties of welded joint materials due to variation of a large number of influential factors because of the heterogeneity of their structure (parent material, heat affected zone, weld metal), in order to get safer structures or reduce undesirable effects to bearable values, i.e. to realize the favorable structural solution of the bucket-wheel excavator as a whole.

Taking into account the fact that tests, by which the stress condition of elements of the vital welded structure of the bucket-wheel boom was determined, did not comprise boundary loads which occur during the digging of petrified rock masses, when due to impact loads bucket-wheel halts, the limit of useful load can't be determined.

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