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INFLUENCE OF THE DYNAMIC/TECHNOLOGICAL FACTORS ON THE LIFE EXPECTANCY OF THE EXCAVATION EQUIPMENT IN OPEN CAST MINES

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Abstract: The paper studies the effect that the dynamic factors have on the estimation of the service life of a bucket wheel excavator. Starting from the design standards, it was found that by ignoring the dynamic factors, numerous cracks appear in the structure of the equipment. It is thus necessary to combine standards with measurements of mechanical stresses using strain gauges, both in static and dynamic mode during excavation. Based on this approach, a case study was conducted on an ERc1400-30/7 excavator, for which the specific deformations have been established in dynamic and static mode. Finally, an approximate value for the dynamic factor was obtained and the durability curves were traced, showing the influence of the dynamic factor on the S-N curve.

Keywords: *dynamic factor, life expectancy, bucket wheel excavator, strain gauge.*

1. INTRODUCTION

Excavation machines produced in Romania were designed according to standards from DIN 22261/2 [1], where the dynamic factor is defined and used in fatigue life calculations. Both the definition of this factor and its assumed values, according to that standard, do not reflect the actual operating conditions. Publications on the dynamic effect by Bahr (1965), Geldmacher (1963) and Oehmen (1968) [2] as well as static/dynamic strain gauge measurements are available.

Ignoring the dynamic factors depending on the working conditions leads to the appearance of numerous cracks (Figure 1) in the superstructure of the machine especially at the rotating platform P (Figure. 2).

The estimation of fatigue life in open cast mining machines is mainly based on the measurement of specific deformations, mechanical stresses, during operation (dynamic approach), using strain gauge (SG) measurements method with resistive electrical transducers (RET) arranged in bridges or half-bridges and thermal compensators.

Fig.1. Crack at the rotating platform after a repair

Fig.2. Rotating platform (P) of a bucket wheel excavator

By their nature, mechanical systems have large displacements in the low frequency domain, but the measurement of displacements is conducted in a relatively small number of cases. The breakdown of the vibrating signal into the basic components of the frequency is called frequency analysis [3, 4]. Measurement of working frequencies is done using piezoelectric accelerometers whose output magnitudes are proportional to the acceleration of the body to which it was attached.

Measurements with strain gauges leads to the determination of specific deformations [μm/m] which according to Hooke's laws determines the mechanical stress.

The measurement with accelerometers determines electrical signals that by simple or double integration allows the determination of speed [m/s] or displacement (amplitude) of the vibration [μm]. The location of a measuring point can be selected according to the magnitude to be determined.

2. STRUCTURAL ANALYSIS FOR THE ERC1400 BWE

As shown in papers [5-8] the determination of the service life of such machines is made based on specific deformations induced by mechanical stresses, measured in situ. These measurements are made both statically, by raising/lowering the excavator arm and moving it in different positions but also dynamically during actual material excavation.

On the other hand, the arrangement of measuring points for electro-resistive transducers or accelerometers is based on finite element analysis on a very real model of the machine.

From this point of view, it should be borne in mind that some machines are composed of laminated load-bearing elements, welded profiles or composite sections which have different behavior in the static / dynamic calculation when excavating material in the working front and in the analysis with finite element.

Thus, for ERc 1400-30/7 we created an analytical model (figure 3), which represents the flexible part of the machine and on which the vibrations and deformations produced by the cutting forces occur, the lower part being considered as a rigid part.

The transmission of the disturbance to the platform is done by the rotating bearing located on the lower part of the rotating platform.

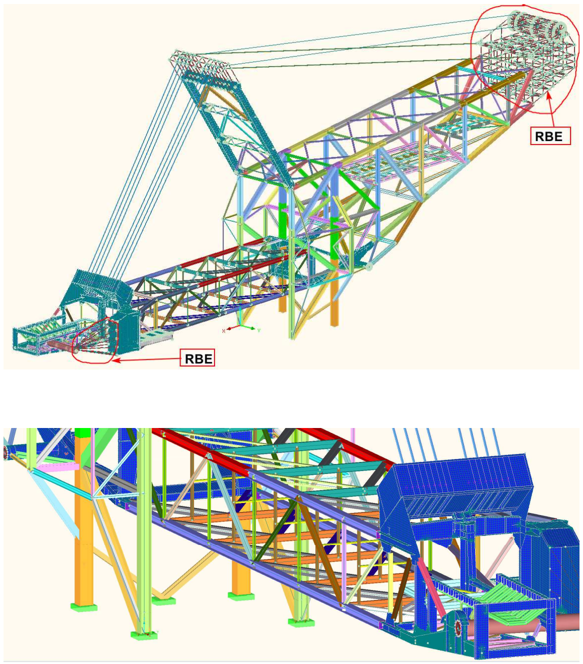

Fig.3. Analytical model of ERc 1400-30/7

In order to establish the measuring points for the strain gauges, the loads acting on the arm and the moment acting on the bucket-wheel will be imposed using load factors, for the static study as in figure 4.

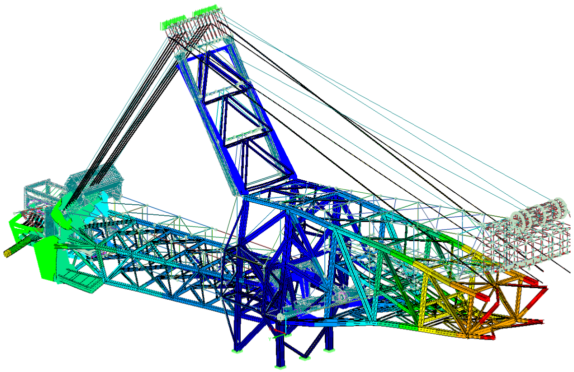

Fig.4. Displacement of superstructure of ERc-1400-30/7

From the stress analysis, three areas can be chosen for the strain gauge measuring points, as shown in figure 5, where:

- Zone Z.1 – area of the bucket wheel boom;
- Zone Z.2 – main shaft area;
- Zone Z.3 – counterweight boom.

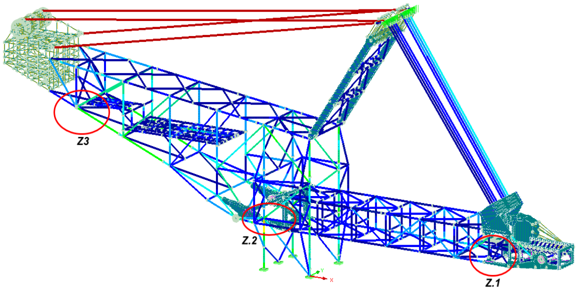

Fig.5. Areas for strain gauge measuring Z.1, Z.2, Z.3 – state of tension

The strain gauges (SG) and thermal compensators will be placed in these areas to measure the mechanical stresses during the static/dynamic regimes.

Figure 6 shows BWE drawing with the location for positioning of the strain gauges (SG) and figure 7 shows the actual positioning of these in-situ on the excavator itself.

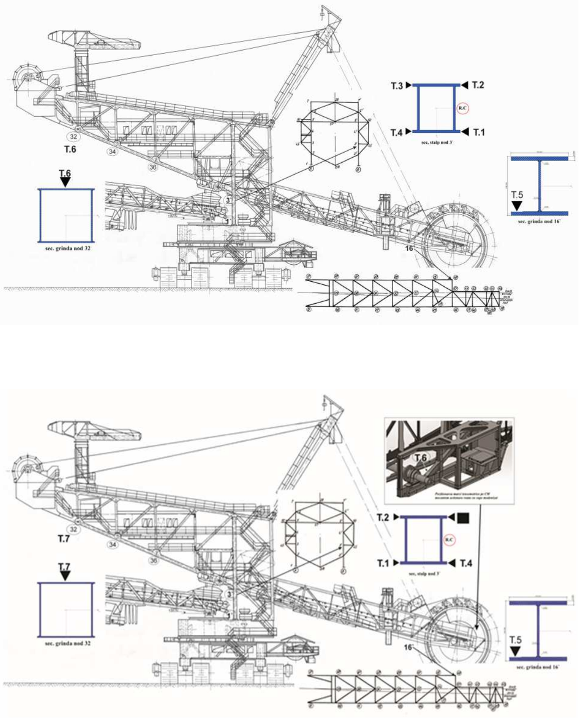

Fig.6. Locations for positioning of the SG on the excavator structure

a). SG position in Z.1 boom area

b). SG position Z.2 shaft area

c). SG Z.2 position support area

d). SG position Z.3

Fig.7. In-situ actual position of the strain gauges (SG)

3. THEORETICAL ANALYSIS OF AMPLIFICATION FACTORS

The design regulations published in Germany were setting the conditions and guidelines regarding the operation of heavy haulage bridges were also applied to excavation equipment and BWEs used in surface mining operations. New regulations for the construction and operation of large machines in surface mining were issued and the calculation procedures were defined later in accordance with DIN 22261.

Thus, the theoretical analysis of the dynamic factor leads to an analysis from the point of view of the DIN22261 standard and to its assessment from the point of view of the operation of heavy metal bridges.

3.1. Theoretical analysis based on DIN22261

The first approach is according to the design standards of the machine and based on the measurement of vibrations on the excavator.

Vibration amplitude quantification can be done in several ways:

- Peak-to-peak value (P2P) - is a value that indicates the maximum extension shape of the waveform in the body in oscillating motion;

- Root Men Square (RMS) - is the value that best characterizes the operating status of a machine. This value considers the variation in time of the vibration amplitude but also the destructive energy of the vibration.

Based on the annex to the standard, the dynamic factor ψ is defined as the ratio between the value of the measured peak-to-peak acceleration and the constant value of the gravitational acceleration [9, 11]:

$$\psi = \frac{\Delta a}{g} = \frac{a_{\max} - a_{\min}}{g} \tag{1}$$

where: a is the measured value of acceleration; g is gravitational acceleration.

The equation for *RMS* can be written [10]:

$$RMS = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (x_i)^2} \tag{2}$$

where N is the number of samples measured.

In this case, (1) can be written as:

$$\frac{1}{D} = \frac{g}{RMS} \tag{3}$$

thus, the dynamic factor ψ becomes a simple fraction multiplied by the ratio of the gravitational acceleration and the measured RMS value.

In order to simplify notations, *D* is written as *1/D*. The dynamic factor is defined separately for each machine substructure for each direction. The standard value of the factor is listed in the annex DIN 22261/2, where measurement examples can be found without any detailed instructions on how to perform such tests. The lack of this information makes it difficult to perform similar measurements and compare results with those in the norms. The approach of this dynamic factor does not show us the static-dynamic structure interaction, given by the excavation of the machine, but it does not give us any information regarding an absolute value that considers the different excavating forces that may appear. Finally, the examples given are also based on the measurement of stresses in load-bearing elements.

3.2. Theoretical analysis based on assessment of metallic bridges.

The second approach is made based on the determination of the coefficients of dynamics in the load-bearing structure of metal bridges. Looking from the point of view of the construction design is a great similarity of the achievements of load-bearing structures to mining machinery with to the heavy metal bridges. The experimental determination of the dynamic amplification coefficient is determined by comparing the size of a physical parameter of the machine determined by dynamic load with the value of the same parameter determined by loading the machine in static mode. The dynamic amplification coefficient [11-13], determined experimentally, $\psi_{meas.}$ can be described by the following general equation transposed for mining machinery:

$$\psi_{meas.} = \frac{\varepsilon_{dyn.}}{\varepsilon_{stat.}} \tag{4}$$

where:

- ε_{dyn} represents the maximum value of the monitored physical parameter, determined by the test in dynamic mode;
- $\varepsilon_{stat.}$ is the value of the same parameter determined by the static test.

Therefore, it should be borne in mind that the physical parameters that can serve to determine the dynamic amplification factor can only be specific deformations or displacements, since these can be determined experimentally in both the dynamic static tests. Accelerations, being determined strictly from dynamic test, cannot be considered in determining the amplification factor.

4. CASE STUDY, THE INFLUENCE OF FACTORS ON THE S-N CURVE

The best information on the fatigue resistance of a structure at a certain endurance limit, comes from testing real assemblies, the model at the real scale or from fatigue tests of material taken from the load-bearing structure in areas with stress concentrators.

In the case of heavy machinery, determining the fatigue resistance of the components or the load-bearing structure at real scale is difficult to achieve given their huge size and the number of cycles which they must be subjected to.

Hence an estimate of the fatigue resistance can be made based on the mechanical characteristics of the material from which the load-bearing structure of the machine is made, namely the tensile strength σ_r (S_{ut}) and the flow limit σ_c (S_y).

The endurance limit is not a property of material such as tensile strength. It is affected by factors such as: the size and the shape of the component, the surface finishing, temperature, the resistance of material to cracking and others.

The results of these tests are shown in form of a diagram called the durability, S-N, σ-N or Wohler curve.

The S-N curve is a graphical representation of the amplitude of the load (σ_{max}) about the number of cycles (N), for which the sample broke.

Two methods of plotting S-N curve can be distinguished [7, 14]:

1. The FKM method for the assessment of fatigue resistance, developed by IMA Dresden since 1994. It is based on the TGL19340 standard, and VDI Directive 2226. It is used to estimate the service life of shafts, gears, circular or rectangular section elements, casting elements with or without machining or by welding. It does not refer to structural elements of type I, U, L;

2. The North American method developed by various automotive, aeronautics, civil or mechanical construction companies, and based on the connection between fatigue resistance S_e (σ_D) and tensile strength, S_u (σ_R). It refers to both structural elements and closed, circular elements and it has a range of coefficients for both rolled, cast steels but also for cast iron or aluminum. In [15], the differences between the two methods are detailed.

The endurance limit (S_e) determined following fatigue tests on samples shall be corrected using factors that are different for each real machine part. These factors express the differences in surface finish, size, type of load, temperature and other effects which may differ from those for the laboratory test sample.

The mathematical model used for the application of these factors is proposed by J. Marin and expressed by equation [14, 16]:

$$S_e = k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f \cdot S_e^{'} \qquad (5)$$

Where
- S_e endurance limit corrected so that it can predict resistance to fatigue at a certain point in a real part;
- $S_e^{'}$ endurance limit in an R.R. Moore test;
- ka correction factor for the surface of the part;
- k_b stress gradient factor depending on the size of the part;
- k_c load factor;
- k_d temperature factor;
- k_e reliability factor considering the scattering of endurance limit fatigue data;
- k_f other technological factors.

All the k_a – k_e factors are standard and determined based on the studied part and its condition while the technological factor k_f is a defined by a combination of factors characteristic to the machine part.

For machinery operating in open cast mines, considering the working conditions, the aperiodic excavation forces, the factors used in equation (5) can be defined. So, the k_f factor can be expressed as a product of cumulative factors specific [7, 17] to the BWE, as:
- $k_{f.fi.}$ the reliability factor of the machine, depending on the number of repairs on the load-bearing structure and the safety mechanisms, the total operating hours since commissioning, the number of hours worked monthly;
- $k_{f.g.}$ the correction factor of material thicknesses;
- $k_{f.Rz.}$ the roughness factor of material cuttings for profiles made in welded construction.

Within a technical expertise conducted [18], strain gauge measurements (Fig 6) were made on a ERc1400-30/7 type excavator (BWE), for two working states:

1. Static, when the BWE is removed from the coal face and SG measurements will be made during the rotation of the upper platform and raising / lowering the bucket wheel boom;

2. Dynamic, when the BWE is in the coal face under normal excavation operation.

We will consider the case of a BWE for both states for which the dynamic coefficients are determined according to section 3.2.

Diagrams of the specific deformations for both working states are shown in Figure 9, with T.1 to T.7 (located as in Figure 6) being the chosen SG measurement points.

With the measured data plotted in fig. 9, the statistical data obtained is presented in tables 1 and 2. It results that the maximum value of the deformation appears on channel T.1 in dynamic mode, and the highest stress state is found on the pillars, area Z.2 (see figure 5) also confirmed by the FEM analysis.

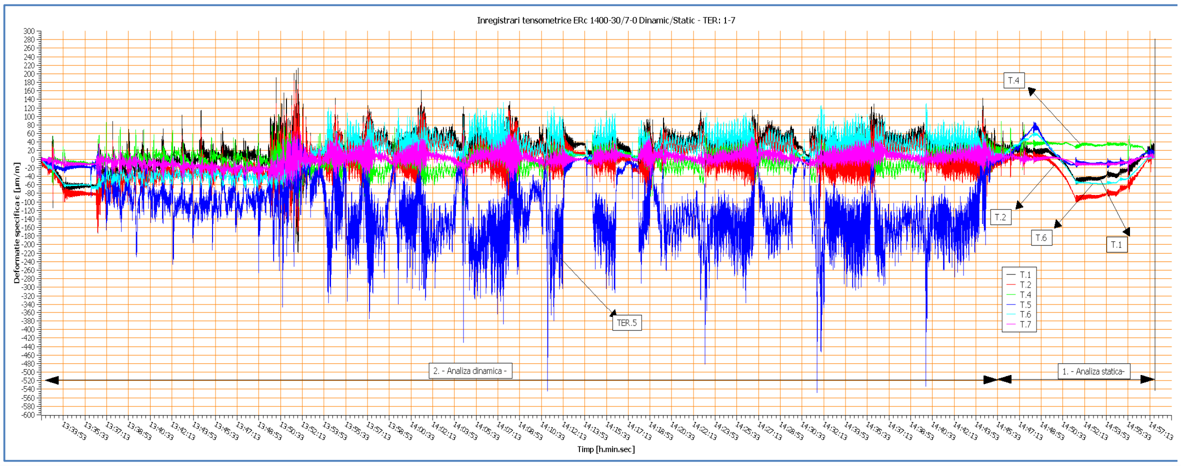

Fig. 9. Specific deformation diagrams, dynamic/static analysis

Table 1

Results of the statistical analysis from measured (static and dynamic modes) with SG positioned as in figure 6

Ch	Mean	StandardDev	Variance	Max. Spec. deformation [µm/m]	Min. Spec. deformation [µm/m]
DYNAMIC STATE MEASUREMENT					
T.1	12.28	38.38	1473.18	**213.07**	-218.03
T.2	-7.91	40.17	1613.99	184.31	-170.84
T.4	4.41	23.91	571.48	104.07	-113.36
T.5	-95.42	80.21	6433.26	86.87	-548.44
T.6	11.49	40.98	1679.33	132.68	-79.17
T.7	-0.53	14.83	219.83	66.94	-64.05
STATIC STATE MEASUREMENT					
T.1	-6.96	28.64	820.44	**85.85**	-60.02
T.2	-35.03	39.31	1544.92	65.50	-102.19
T.4	30.76	9.73	94.72	87.98	-30.94
T.5	9.82	24.92	620.81	86.87	-27.84
T.6	-9.38	39.10	1528.53	62.14	-59.68
T.7	-2.40	7.94	63.09	34.22	-29.00

The BWE under analysis has an operating life of 32 years, with 82771 effective logged hours of excavation.

The working regime is 16 hours/day and about 350 hours of work monthly [18]. The load-bearing structure material is carbon steel type OL 52.4 for the main load-bearing elements, and carbon steel type OL 37.2 for the secondary elements [19-22].

Two cases will be evaluated:

1. When no k_f factors and the dynamic factor ψ are considered, in this case the diagram of the fatigue curve S-N will look like shown in Figure 10.

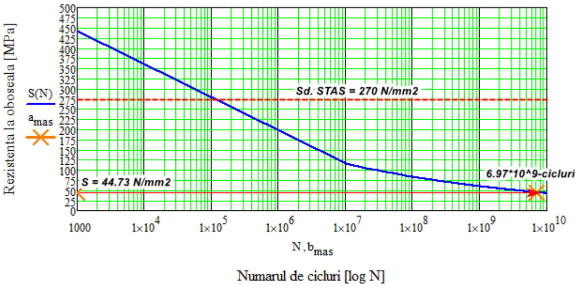

Fig. 10. S-N curve for case 1.

2. When both the k_f factors and the dynamic factor ψ are considered. The dynamic factor ψ that is included in the calculation of the total number of cycles function of the stress, is calculated for point T.1. in Table 1 (dynamic state) and for the same point T.1 in Table 1 (static state), according to section 3.2 eq. (4):

$$\psi = \frac{\varepsilon_{dyn.}}{\varepsilon_{stat.}} = \frac{213}{86} = 2.48 \tag{6}$$

In this case the diagram of the fatigue curve S-N will have the shape as in Figure 11.

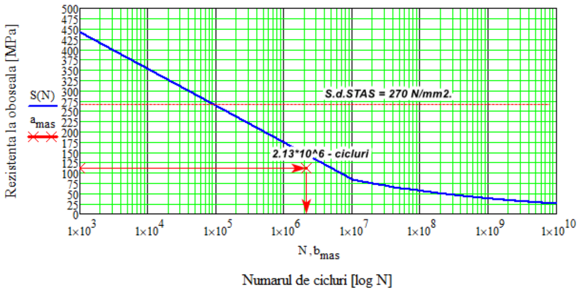

Fig. 11. S-N curve for case 2.

4. CONCLUSIONS

The dynamic factor based on the German standard DIN 22261-2 alone, cannot be used in the estimation of the life expectancy, for the type of equipment studied heretofore and the working parameters encountered during measurements. The determined factor is different, depending on the type of excavated material and other working conditions. After performing the measurements on several such BWEs [18] it was possible to determine an approximate value for the dynamic factor between (1.4 and 2.5);

The introduction of technological factors leads to a higher accuracy of the approximate determination of the service life of machines that have already a significant number of years of operation in open cast mines.

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Influența factorilor dinamici/tehnologici asupra estimării duratei de viață a utilajelor de excavare continuă

Rezumat: Lucrarea studiază efectul pe care factorul dinamic îl are asupra estimării duratei de viață a excavatoarelor cu roată port-cupe din carierele de lignit. Pornind de la standardele de proiectare s-a constatat că prin ignorarea factorilor dinamici apar numeroase fisuri în structura echipamentului. Se impune astfel combinarea standardelor cu măsurători ale tensiunilor mecanice folosind timbre tensometrice, efectuate atât în regim static cât și dinamic în timpul excavării. Pe baza abordării menționate se prezintă un studiu de caz pe un excavator ERc1400-30/7, pentru care au fost stabilite deformările specifice în regim dinamic și static. În final s-a obținut o valoare aproximativă pentru factorul dinamic și s-au determinat curbele de oboseală, arătându-se influența factorului dinamic asupra curbei S-N

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