Assessment of remnant life duration for bucket wheel excavators in lignite quarries

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Abstract. In Romania, as well as worldwide, lignite for the production of electrical energy is mainly extracted in quarry conditions. At the present time and for the near future at least, extracting lignite will be done with the help of continuous action excavators, especially with rotary headed excavators with radial digging, that undertake the cutting and the evacuation of the rocks from the baric step and of the lignite. On the mechanized operation lines, the excavator is the leading equipment. The growth in work efficiency of the excavator is conditioned by choosing it according to the concrete conditions of exploitation and in correlation with the other equipments on the operation lines for extracting lignite and mine waste from the coating of the lignite strata, rational intensive and extensive exploitation, adopting a modern and efficient system for doing maintenance, as well as undergoing rehabilitation and modernization processes for maintaining their technical condition at a suitable level. Estimating the duration of safe functioning of an equipment that has a certain degree of risk is a requirement of current legislation. This paper undertakes to present one of the calculus methods that is at the basis of the objective estimation of the remnant life duration of an excavator.

1. Introduction

In order to exploit lignite deposits in Oltenia in quarries and coal deposits, a technology of continuous operation with bucket wheel excavators, dumping machines and high capacity depositing machines is applied [1], [4], [8]. When normal operation life ends, or in case machinery is updated, an analysis of lifting structure is required to determine the real state of mechanical tensions in view of establishing remnant life and conditions for the further safe operation. German standard DIN 22261-1 provides inspection and expertise periods for these machines with a long operation life. Manipulation and excavation of coal have a specific dynamic regime, supporting both atmospheric influence and exterior and interior tensions generated by cutting forces [2].

2. General aspects

During the excavation process, Figure 1, buckets cuts in point A, then AB circular trajectory follows, falling over BC area, over the cover of the wheel with buckets, in the bunker of belt I take over. The impact generated by flowing of the excavated material over BC area generates tensions in the arm of the bucket holder wheel, tensions transmitted to the rest of the lifting structure.
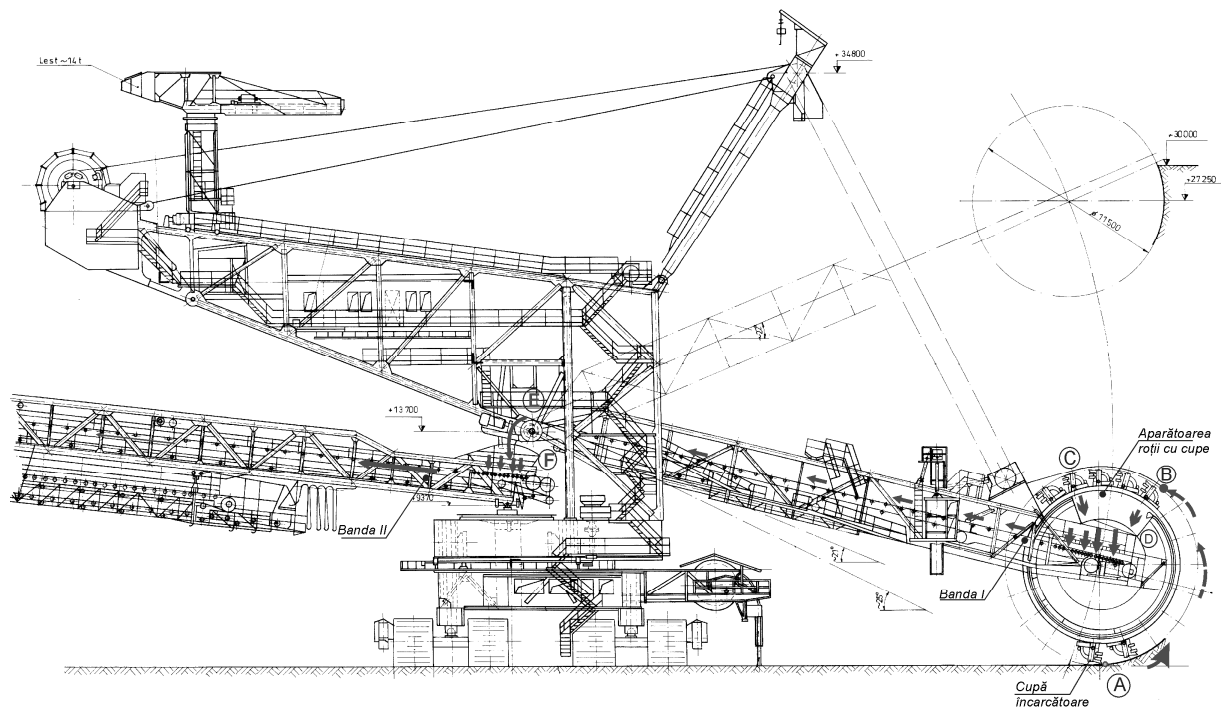
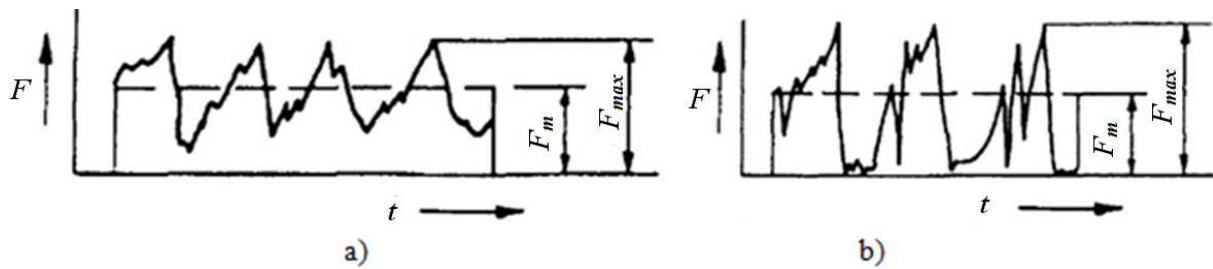**Figure 1.** Track of the excavated material.

There are three stages of AC track, Figure 2 [8], stages in which the arm of the bucket holder takes over the tensions generated by the displacement of the material to be excavated, stage AB, and tensions produced by the flowing of the material in the takeover belt I.
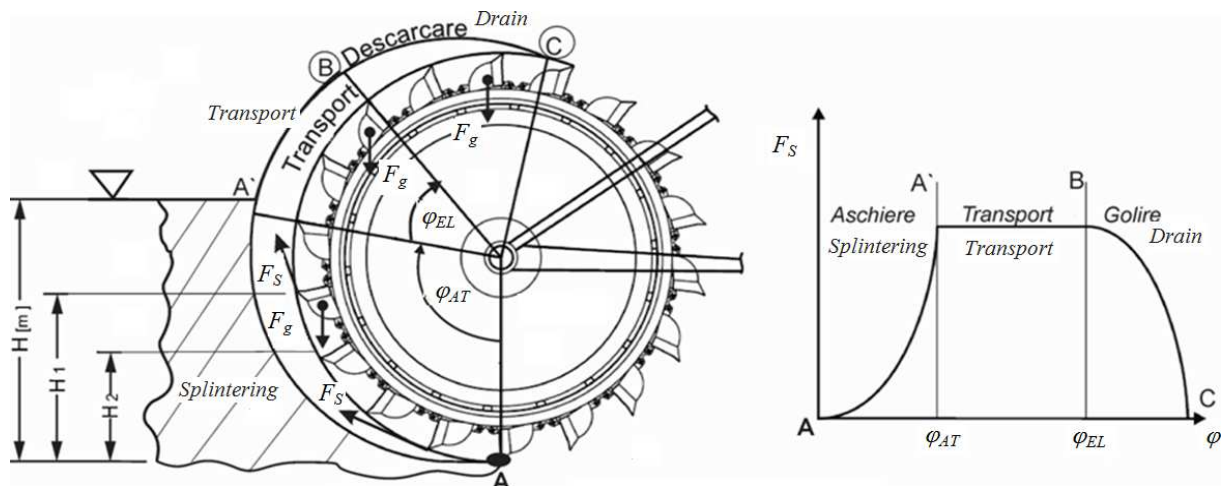
Figure 2. Stages of excavation force actions.

The Since cutting is not done in homogeneous and isotropic material, the excavated material having different composition and mechanical features, the intensity of the cutting forces is valid depending on time and excavated material, Figure 3, resulting various forms of the cutting forces diagrams.

Thus, approximated forms for diagrams for: compacted sand, gravel, medium resistant clay, clay, marl, illustrated in Figure 3.a, and for compacted clay, sandstone, limestone, hard coal Figure 3, b [8].

Figure 3. Form of force diagram function of the nature of the excavated material.

The best pieces of information regarding resistance to fatigue of a certain structure to a specific fatigue limit come from testing real assemblies, the real scale model or from fatigue trials of the material taken from the lifting structure in the areas with tension concentrators.

In the case of heavy machinery, it is difficult to determine the resistance to fatigue of component parts or lifting structures at real scale, considering the functional size of those, and the number of cycles to which they should be submitted, and the size of the cutting forces. In the absence of these data, an estimation of the fatigue resistance can be made based on the mechanical characteristics of the material of which the lifting structure of the machinery is made, namely tensile strength. σ_r (S_{ut}), flow limit σ_c (S_y) and magnitude of mechanical tensions on specific lifting elements determined by strain gauges measurements.

The results of these tests are graphically presented by a fatigue curve, marked in literature S-N, σ-N or Wohler curve, which is the graphic representation of the tension amplitude σ_{max}, compared to the number of cycles (N), for which the sample broke.

Generally, a curve S-N can be made as a continuous line on the elastic region, [5], [6], [8], made up of two distinct linear regimes and graphically represented in log-log coordinates. S-N curve, for a component made from steel, illustrated in Figure 4, is made up of an inclined linear segment for HCF regime, and a horizontal, asymptotic one for the fatigue limit.
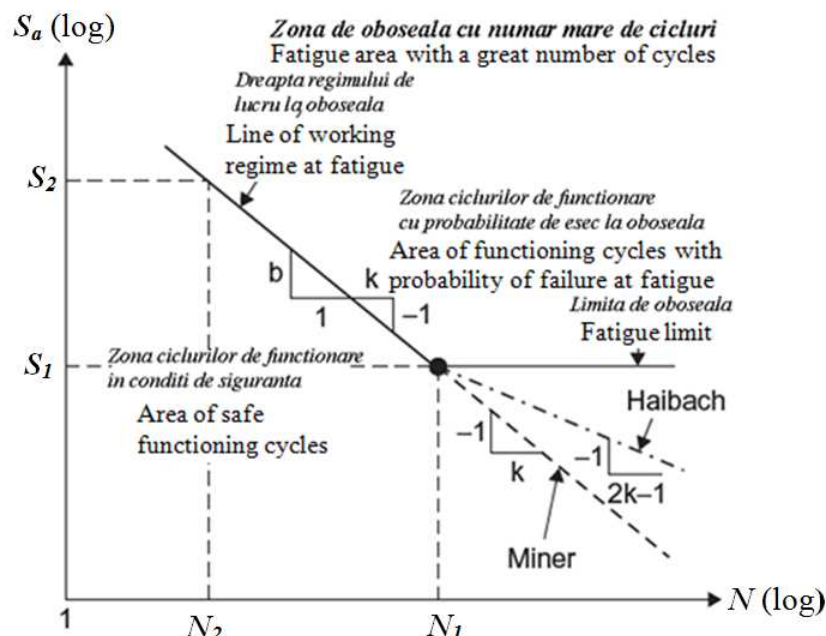
Figure 4. Constant amplitude S-N schematic curve of a steel made part.

Similarly, two areas are noticed, function of the number of cycles determined: an area of safe functioning cycles, the area where the probability of breaking is high.

3. Procedure of drawing *S-N* diagram for extraction and dumping machinery
From the technical literature studied, two methods of drawing Wohler diagrams are noticed, methods that might be used in the calculation of the component parts in the excavation machinery [5], [6], [7]:

   a) FKM method- to assess the resistance to fatigue, developed at IMA Dresden, "Forschungskuratoriums Maschinenbau E.V." (FKM), in the year 1994. It is based on Este TGL 19340 Standard, previous to Directive VDI 2226. It is used to assess the life duration of shafts, gears, parts of circular or rectangular section, of cast parts with or without processing or welding. No reference is made to I, U, L type structural elements.

   b) North American Method – developed by various firms in the field of automobiles, aeronautical, civil or mechanical building, it is based on the relationship between resistance to fatigue S_e (σ_D) and resistance to tear S_u (σ_R). It refers both to structural elements and to closed, circular elements.

In order to examine the approximate remnant life duration of machinery in quarries, we shall present the North American Method of drawing the Wohler curve, which can assess the I, U type structural elements as well, elements used in the lifting structures of machinery with bucket wheels.

To explicit the method, ERC 1400-30/7 type bucket wheel excavator is considered, Figure 5 and the identification data of the machinery in Table 1, for which strain gauges analysis for the tensions in dynamic regime per working cycles had been done, in order to establish the remnant life duration for this machinery.

**Figure 5.** ERC 1400-30/7 type bucket wheel excavator.

Table 1. Identification / technical data of the machinery.

| Name of the machinery	ERC 1400-30/7-0 Bucket wheel excavator (with bucket holder wheel
Manufacturer	CIUMMR Timisoara, Romania
Commissioning date	08.1990
Number of hours of operation	65923
Nature of excavated material	Sterile + lignite
Age of the machinery (years)	26, measurements have been done in the year 2016
Material, lifting structure of resistance	OL 52.4/ STAS 500-76, St52 –DIN 17100 equivalent
Rotation of bucket wheel, rpm	5,11
Number of discharge	46

Working procedure for drawing diagram:

Measurement of mechanical tensions on lifting elements with high degree of load, which can be established by finite element method by technical expertise by observing excessively, tensioned areas.
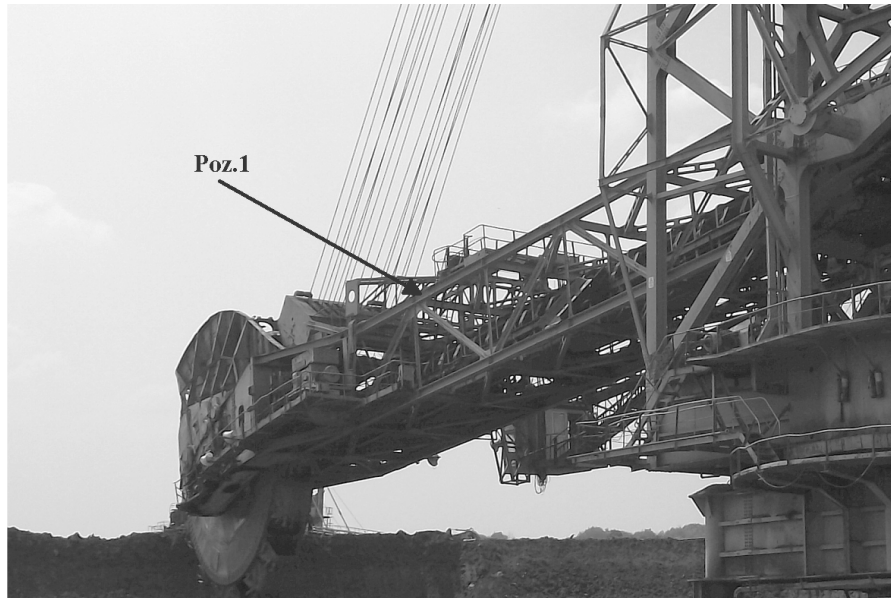

Figure 6. Arm of the bucket holder wheel.

For the machinery considered, measurements have been made on the arm of the bucket holder wheel, Figure 6, and in Figure 7 the placement of strain gauges (TER) on the wheel arm are shown.


Figure 7. Place of electro resistive transducers (TER) on the arm of the bucket holder wheel.
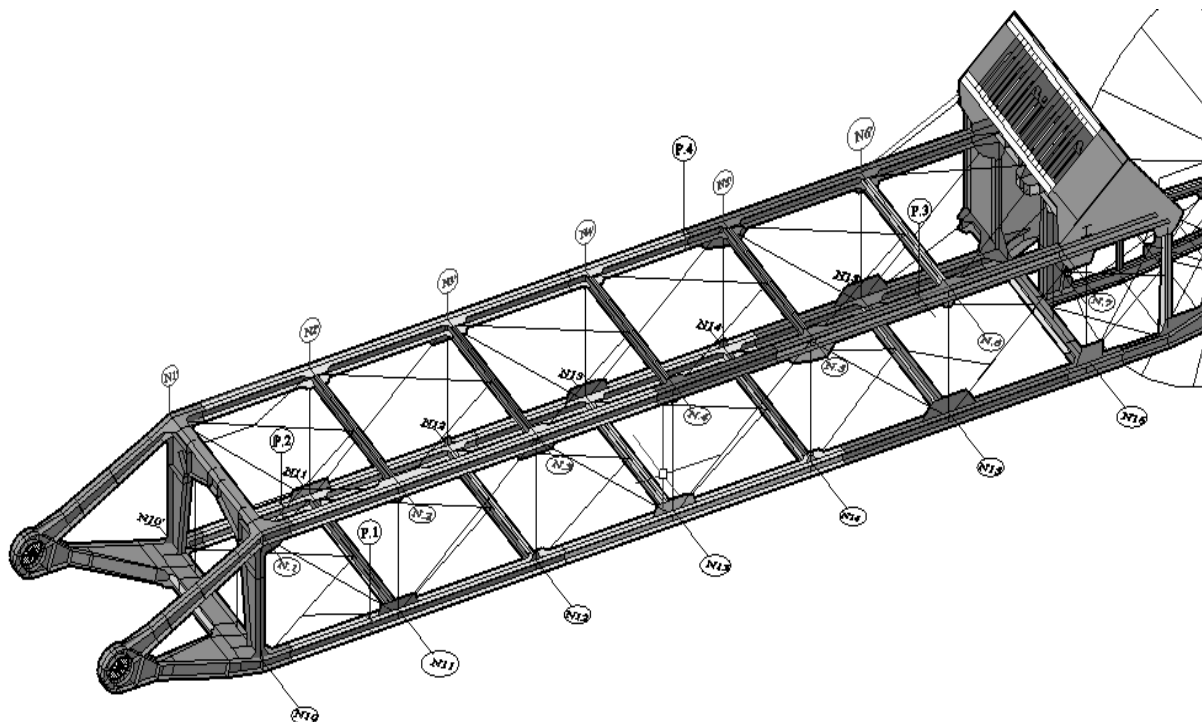
For sections that do not deplane(circular, annular section and T and L shaped sections), three TER for each will be applied as close as possible to the corners of the section, at T and L sections, and at equal distances to periphery, at circular and annular sections. If for T profile the thickness of the core is small and does not allow a TER to be placed on the edge, 4 TER will be applied instead of three, Figure 8, a;
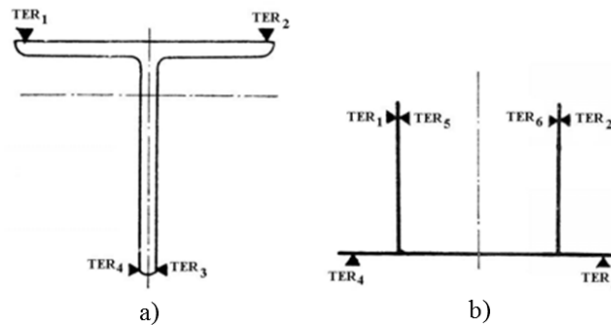
Figure 8. Place of TER function of the profile type.

For the sections that deplane, simple or compound sections with continuous link of the principal elements(I, U, II sections) , four TER for each will be applied, as close as possible to the corners of the sections and symmetrically placed to the symmetry axis of the section. At sections II, if the thickness of the cores is small, two TER for each will be applied, so that there will be six TER in all Figure 8, b; For the sections of the lifting beams (I in welded construction) TER will be applied as it follows, Figure. 9 [7]:
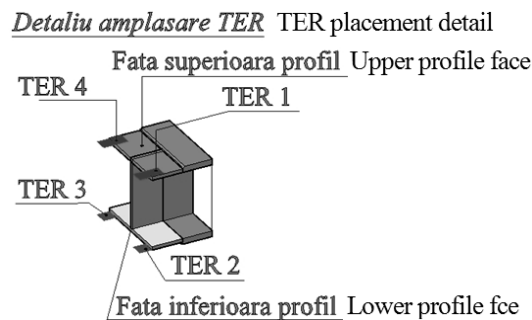
Figure 9. Place of TER of the lifting beam.

After TER being placed, their cabling has been done to the measuring devices, type SPIDER 8, and measurements per cutting cycles have been done, shown in Figure 10. Considering the above, on the arm of the wheel strain gauges have been placed, thus:

Figure 10. Cabling and tension-metric measurement on the arm of the bucket holder wheel.

Table 2. Place of tension-metric marks.

The tension-metric point according to Figures 7	Upper face	Lower face
P1	Foto P1.1_43	Foto P1.3_2
P2	Foto P2.1_4	Foto P2.3_2
P3	Foto P3.1_4	Foto P3.2_3
P4	Foto P4.1_4	Foto P4.2_3

After the measurements, it has been establish that strain gauges P4 recorded the highest value in the left-right cutting regime, namely a tension: $\sigma_{P4.TER2}$ = 11,4 N/mm^2 on TER2, inside, Table 2, photo P4.1_4.

Calculation of the number of cycles $n_{1.PIF}$ [cycles]- number of cycles since commissioning (PIF), is established function of: T_{PIF} – exploitation time from commissioning [hours]; n_{rc} – bucket wheel rotation [cpm]; f_{desc} – number of discharges in the takeover bunker, with the formula:

$$n_{1.PIF} = 60n_{rc}T_{PIF}f_{desc} \text{, [cycles]} \tag{1}$$

Drawing diagram with number of cycles N function of nominal tension measured by strain gauges measurement, $\sigma_{P4.TER2}$, stage including:

Establishing resistance to breaking: S_{ut} [N/mm^2] of the material used: S_{ut} = 510 [N/mm^2] – STAS 500-80.

Resistance to uncorrected fatigue is estimated: $S`_e$ (or $S`_f$) function of the resistance to breaking of the material S_{ut} [7], [8]: $S_e = 0,5 \, S_{ut}$.

Loading factor C_{Load} is established function of the loading time:

Shape factor, size C_D – is established function of the size and shape of the required profile. In the case of lifting beam on which measurements have been done, P4 strain gauges, is a I 300 profile in welded construction, with a $C_D = 0,698$ shape factor.

Correction factor for C_{Surf} - surface that takes account of the surface imperfections of a real part compared to the surface of a sample.

Temperature factor – C_T – is taken into account for temperatures higher than 500^{0}C, for temperatures lower than 450^{0}C, $C_T = 1$.

Reliability factor- C_R – When fatigue tests data of a component are not available, a statistic analysis cannot be done to take into account the random nature of the life duration to fatigue. Haugen and Wirsching [7] show that standard deviations of the points of resistance to fatigue of steels are rarely higher than 8% of their average values.

Limit calculus of corrected resistance S_e for a material with an inflection on S-N curve and S_f represents resistance to fatigue corrected for a given number of cycles N for a material that has no inflection function of the correction factors can be written:

$$S_e = C_L C_D C_S C_T C_R S_{e`} \text{,} \tag{2}$$

The resistance of material to fatigue for 10^3 cycles applying the formula:

$$S_m = 0,9 S_{ut} \text{,} \tag{3}$$

Exponents of lines are calculated from formula:

$$S(N) = aN^b \text{,} \tag{4}$$

$$b = -\frac{1}{3}log\left(\frac{S_m}{S_e}\right) \text{,} \tag{5}$$

$$log(a) = log(S_m) - 3b \Rightarrow a \text{,} \tag{6}$$

Estimation of remnant life duration for which the machinery would operate, in the conditions in which nominal tensions in the structure are those that have been measured.

Calculus of number of cycles N_{TER}- for a measured tension, S_{masuN1},- $S_{TER} = \psi$ x $_{STER\_measured}$, ψ = 1.4- conformable DIN 22261/2 – partial factor for resistance to fatigue,

Using a calculus program, for example MathCAD, the line graphic for fatigue is drawn, illustrated in Figure 11 for measured tensions, resulting maximum cycle number for this tension.

Knowing the number of cycles for measured tension, the remnant life duration (DVR) can be estimated, determining the number of functioning cycles characteristic to the number of cycles specifically determined nominal measured tensions, according to Miner- Palmgren criterion:
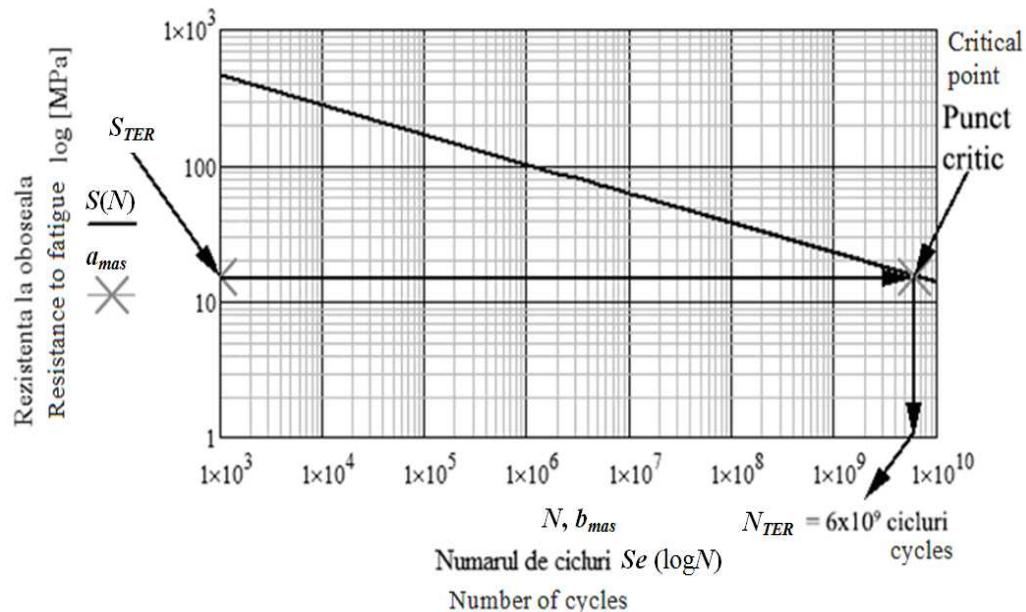
Figure 11. *S-N* curve for joint beam 4`-5` bucket holder arm.

$$D = \frac{n_{1.PIF}}{N} + \frac{n_{2.DVR}}{N} = 1,$$ (7)

$$n_{2.DVR} = N_{TER} - n_{1.PIF} \text{ , [cycles]}$$ (8)

Remnant life duration T_{DVR} in years, for which the machinery will operate, is

$$T_{DVR} = \frac{n_{2.DVR}}{n_{an}} \text{ , [years]}$$ (9)

n_{an} – approximate number of hours per year of the machinery for the analysed machinery a functioning period has been determined.

4. Conclusion
The method presented is easily approachable and can be applied to heavy duty machinery, but in order to have a greater certitude regarding life duration and implicitly drawing the line for fatigue, tension-metric measuring points on the machinery will be extended. Establishing nominal tensions can be done only tension-metrically for longer duration measurements on the same machinery but in different excavation conditions.

Acknowledgments

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