Fatigue Life Estimation in Bucket-Wheel Excavators Maintenance

J. Alenowicz and W. Huss

It is obvious, that designing process of bucket-wheel excavators includes not only static resistance, but also fatigue life. Carrying out measurements on machines at being operation, estimating fatigue life and comparing them with mining conditions, gives new information about the way of a structure effort. This builds the machine user knowledge about possibilities of its farther safe operation and also it helps the designer of every next machine.

This paper outlines main technical issues, experienced by the authors, that appear during the whole process of estimating fatigue life of a structure.

1 Measurement of Stress for Fatigue Life Estimation

Because estimation of fatigue durability is based mainly on strains, strain gauges are the best choice for field conditions measurements. A measuring point can be selected in two ways—for estimating fatigue life of a location, where the sensor is mounted directly [1] or—when it is going to be a reference point for a structure notch [2]. According to this, a kind of strain gauge is chosen.

When a maximum resistance to changes in temperature and a very precise compensation of lateral strains is needed, a full-bridge rosette is applied (Fig. 1a). In situation, when a direction of vibration is set, a single strain gauge with temperature auto-compensation (Constantan and Karma alloys) can be chosen. If the

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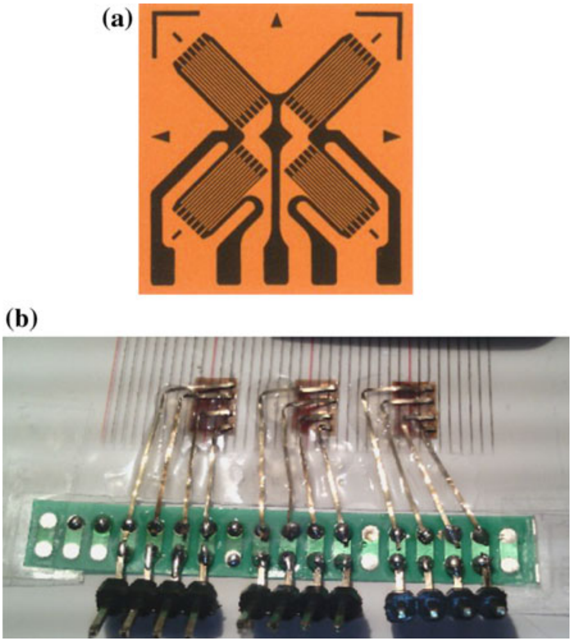
Fig. 1 Strain gauge rosettes applied to measurements accompanying fatigue life estimation [3, 4], **a** a full-bridge rosette, **b** dedicated rosette for measurement at welded joints



aim of the measurement is the estimation of fatigue in the bottom of a weld notch, due to [2] an individually adjusted rosette must be used (Fig. 1b).

In both cases, selection of locations for measurements is made with significant help of FEM analysis. Using an excavator's FEM model and knowing forces affecting its structure, locations and structure joints with higher effort can be found. Sometimes due to technical causes, a direct measurement right in the place isn't possible. Then, using an application of FEM analysis or an analytical method [2] a relation between stress in the desired place and the location of strain gauge can be found. When modelling the analysed joint, a particular attention should be paid to accurate reproduce the geometry and to the skilful usage of FEM tools to model the nature of the joint in a right way (Fig. 2).

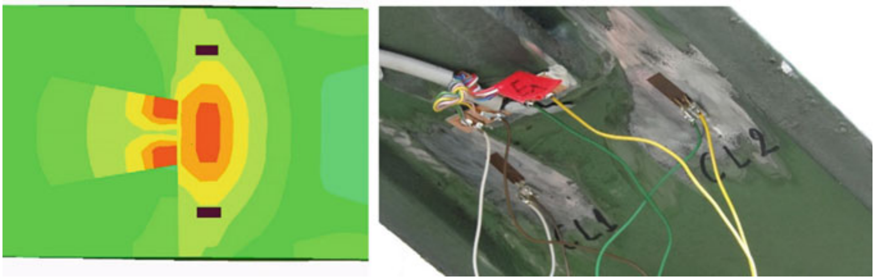


Fig. 2 An example of selecting measurement points due to FEM model results [5]

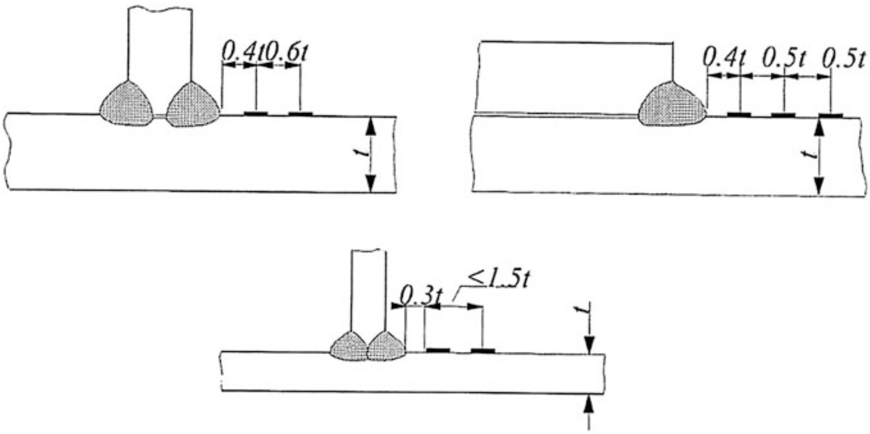


Fig. 3 Distribution of strain gauges for stress gradient measurement in front of weld edge on plate girders in the "hot spot" method [2]

In the case when the examination concerns a welded joint, a knowledge of a stress gradient in front of the weld edge is needed. It can be calculated with a support of FEM model [6] or analytically on the basis of strain gauge rosette (Fig. 1b, [2, 3]). Gauges in such rosette are placed according to the kind of joint and to the thickness of the sheet (Fig. 3). Measurements obtained this way are then corrected using stress accumulation factor. This finally gives a strain value in the bottom of the weld notch, as a place of potential fatigue crack.

2 Estimation of Internal Stress (Hole-Drilling Method)

Calculation of durability in a structure part (beside welded joints, for which a notch factor is assumed) requires knowing a value of internal stress in it. This stress isn't caused by active influence of any external force. It cumulates in elements of a structure due to making most of material processing, they result from deadweight and assembly processes. Knowledge of its value in locations for which fatigue life is being estimated is necessary, because they add to every dynamic influence. This sum, corrected by appropriate safety factor, not only isn't allowed to exceed elastic limit, but also gives information about fatigue durability. Assuming same range of operational vibrations, the higher internal stress, the lower is the fatigue life of requested location.

The simplest method used for estimating internal stress is hole-drilling with strain gauges. It works opposite to usual strain gauge measurements. Instead of measuring an increase of strain as a result of external force, it measures shrinkage due to relaxation of stress existing in the material. The method uses specially selected strain gauge rosette, which consists of three to six sensors laid concentrically (Fig. 4). Such rosette is glued to the structure so its centre is placed in examined location. A signal from gauges logged in this situation is a reference to the relieving change, which appears during drilling a hole in aforementioned centre of the rosette.

Drilling a blind hole of a depth equal to 40% of rosette diameter [7] ensures maximal relief of surface stress. Then, calculation using adequate equations in relation to every gauge [2, 8] enables estimating of values and directions of principal stress (Fig. 5). As comes from research conducted on many bucket-wheel excavators, static loadings exceed dynamic loadings several times (Table 1).

Measurement of internal stress using hole-drilling method is generally treated as non-destructive testing. A small, blind hole doesn't spoil a structure or load capacity of examined element in a significant way. Particularly, in the case of open-cast mine machines it isn't much of a problem, because thickness of the most responsible parts usually exceeds 15 mm.

The hole-drilling method is currently one of the few and also the most mobile method of determining internal stress in structures. Yet, this should be noted that careful conduction of the measurement significantly determines reliability of the result.

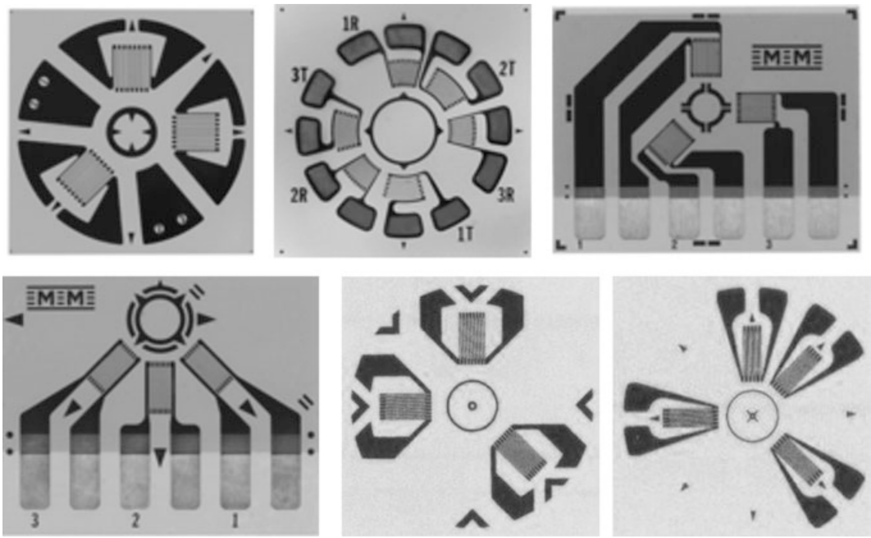
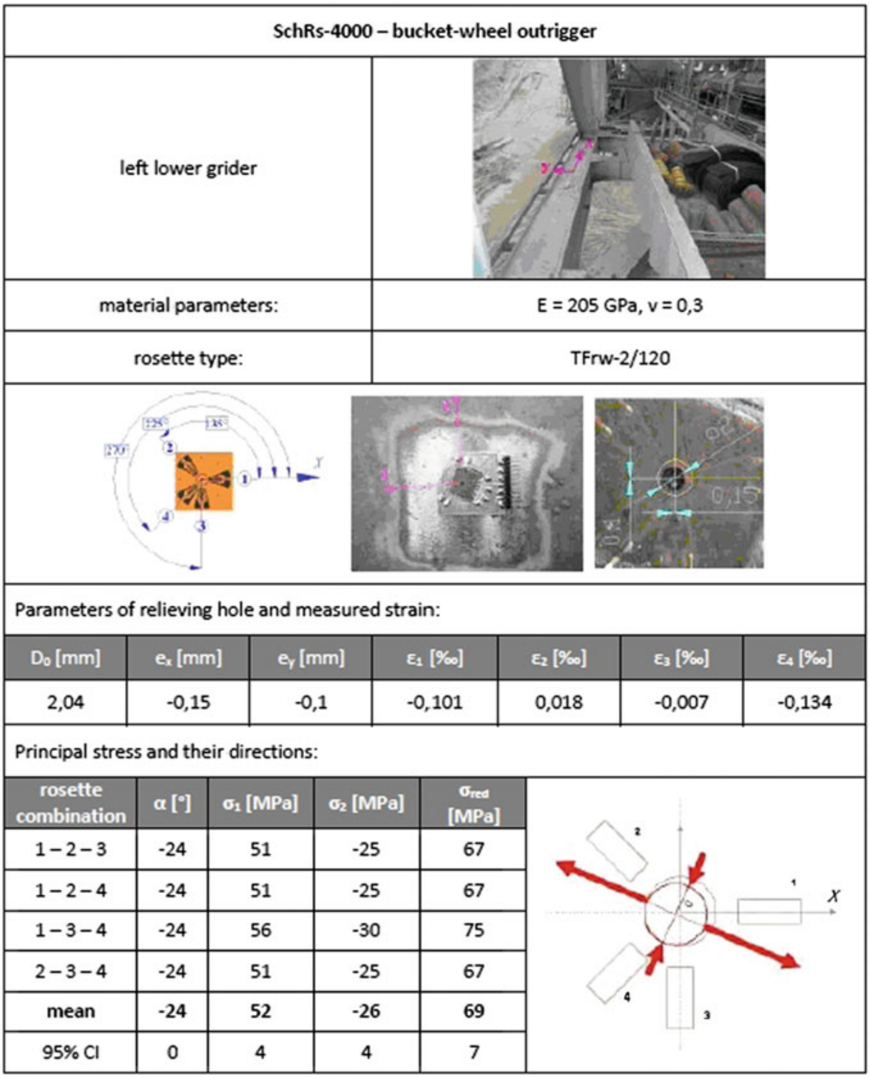


Fig. 4 Examples of commercial strain gauge rosettes dedicated to the hole-drilling method [4, 7]



SchRs-4000 – bucket-wheel outrigger	
left lower grider	
material parameters:	E = 205 GPa, v = 0,3
rosette type:	TFrw-2/120

Parameters of relieving hole and measured strain:

D_0 [mm]	e_x [mm]	e_y [mm]	ε_1 [‰]	ε_2 [‰]	ε_3 [‰]	ε_4 [‰]
2,04	-0,15	-0,1	-0,101	0,018	-0,007	-0,134

Principal stress and their directions:

rosette combination	α [°]	σ_1 [MPa]	σ_2 [MPa]	σ_{red} [MPa]
1–2–3	-24	51	-25	67
1–2–4	-24	51	-25	67
1–3–4	-24	56	-30	75
2–3–4	-24	51	-25	67
mean	-24	52	-26	69
95% CI	0	4	4	7

Fig. 5 An example of report concerning internal stress measurement using hole-drilling method (bucket-wheel excavator SchRs400, *left bottom* girder of wheel outrigger) [1]

Table 1 A comparison of internal and dynamic stress in exemplary measuring points

Excavator	Internal stress (MPa)	Dynamic stress (MPa)
SchRs-900	143	56
KWK-1200M	78	8
SchRs-4600/30	173	28.8

3 Rainflow and Fatigue Life Estimation

Rainflow is a popular, simple and robust method of fatigue cycle counting. Thanks to publishing it in form of standard (ASTM E 1049-85. (2005). "Standard practices for cycle counting in fatigue analysis". ASTM International, TGL 33787/01. Gruppe 921020, "Ermüdungsfestigkeit. Regellose Beanspruchungsfunktionen. Statistische Auswertung im Amplitudenbereich", DDR 1984), it was included in a set of standard tools useful for engineers. It enables not only a usage of Miner's rule of damage cumulation, but is also compatibile to some other hypotheses (Haibach, Serensen-Kogayev, Corten-Dolan).

The core of the method is cycle counting between some maxima and minima from a time series of stress. The calculation is conducted twice—according to time flow and opposite. During one iteration, half-cycles are counted. Half-cycles are found, when a maximums envelope started at a local minimum (Fig. 6):

- ends at the end of a time series,
- encounters other envelope, which started earlier from other minimum,
- encounters other envelope, which started from minimum of higher absolute value.

Two half-cycles create one full cycle when they have the same length but opposite sign (resulting from this algorithm conducted opposite to time flow).

Finally, cycles are presented in the form of histograms (spectrums). According to the place of interest, mean stress value is important—for uniform structure element, or not—for welded joints the notch factor is used. Thereby the histogram is three-dimensional (Fig. 7a) or two-dimensional (Fig. 7b).

In the course of further proceedings, an appropriate hypothesis of damage accumulation is chosen. Also the number of hours in so far operation is taken into account and an assumption is made, that working conditions were the same during

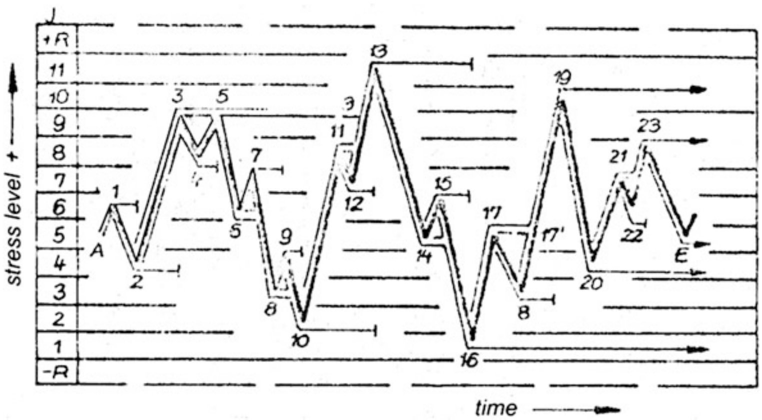


Fig. 6 A fragment of time series as an example for Rainflow algorithm in [9] standard

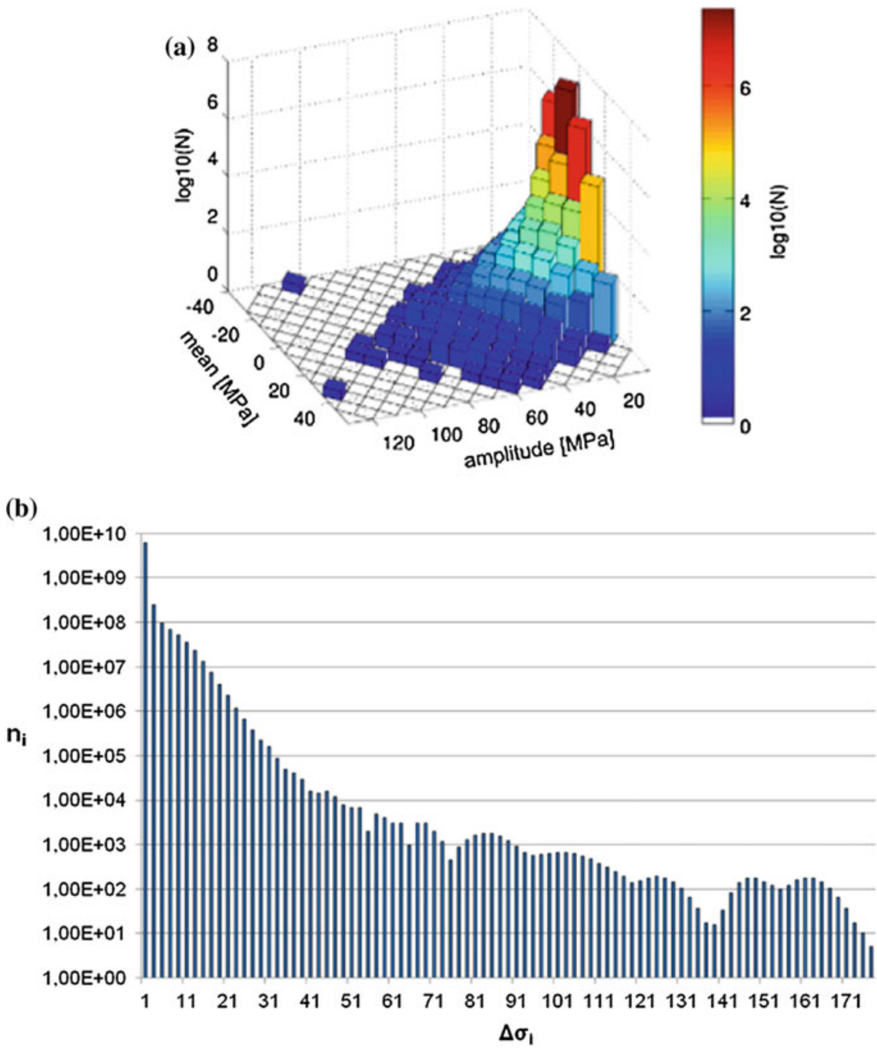


Fig. 7 Exemplary Rainflow histograms (spectrums) of fatigue cycles: **a** three-dimensional with mean value of cycles [1], **b** two-dimensional for welded joints [3]

that time as during the measurement. On this basis, a histogram of partial damage is calculated for cycles in every histogram bin (Fig. 8). The remaining fatigue life until assumed degree of total damage is estimated (in cycles, hours).

It can be seen than Rainflow is a complex tool for estimating fatigue life of any structures, not only open-cast machines. Yet, one must keep in mind, that obtaining reliable information needs the longest time series possible. It is particularly visible in case of cycles of the highest stress range. They appear rather seldom, and because

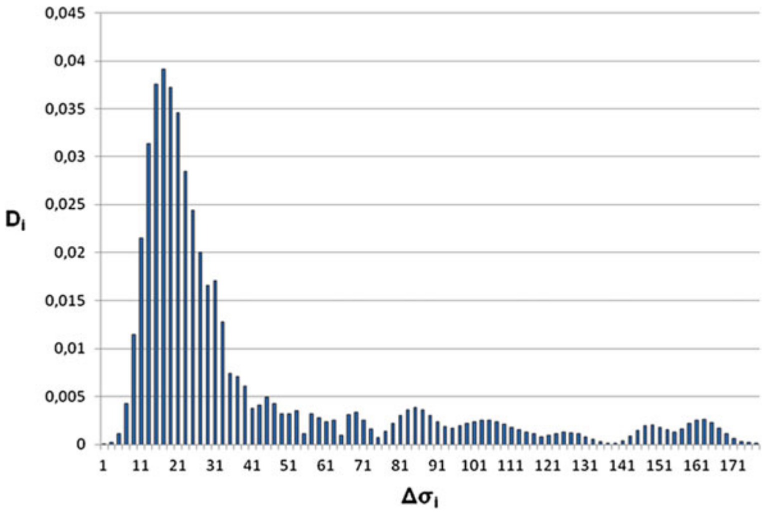


Fig. 8 An example of partial damage histogram [3]

of this they might not appear during short-term measurement or appear just as isolated cases. This makes estimation of fatigue difficult and doesn't give the full information about structure loadings (Fig. 9).

In case of bucket-wheel excavators, from measurement practice [3] comes, that the period of gathering the stress time series shouldn't be shorter that ca. 170 operating hours. During this time one should bear in mind that working conditions shouldn't be drastically changed (i.e. shifting a machine to another place in a pit). Of course gathering Rainflow spectrums from different working conditions is very advantageous, yet for every each of them logging period should last as long as possible.

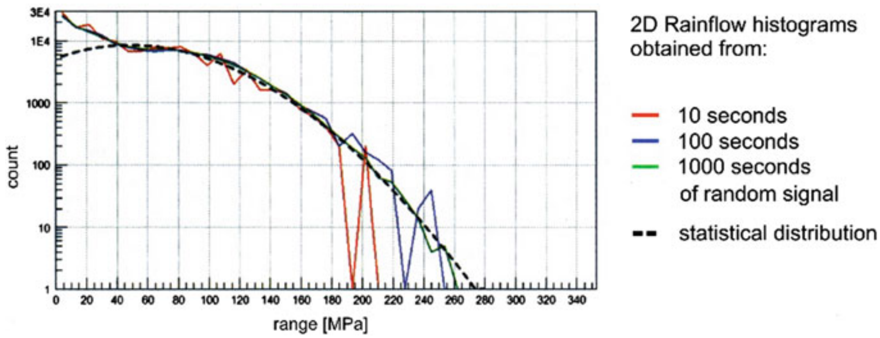


Fig. 9 Rainflow spectrums calculated from synthetic time series with different lengths and their comparison to statistical distribution from which they were generated [10]

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