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Fatigue lifetime correction of structural joints of opencast mining machinery

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Highlights

- The novel comprehensive approach to fatigue design of welded superstructures was presented.
- Functionality of the method has been developed and verified on the real object remaining in operation.
- Fatigue lifetime correction results for long-time operated object was provided.
- The procedure improves fatigue lifetime assessments credibility and helps to provide requested lifetime.
- The method aids maintenance of superstructure providing information about its technical condition.

Abstract

Opencast mining machinery represents a group of large-scale individually manufactured technical objects operated with long-life requests. Since their manufacturers are obliged to provide product that will reach declared time of life, fatigue strength and durability conditions have to be taken into account for superstructures to meet the requirements. The paper highlights main problems occurring while assessing fatigue lifetime during design. Firstly, the short survey of current state of the art regarding the approach to this problem is presented. Secondly, the most important reasons of unsatisfactory accuracy of the assessments are discussed. As a main objective of the study, the authors introduce the unique method of continuous fatigue lifetime correction for the welded superstructures during the machine lifecycle, as a remedy for this group of machinery. Furthermore, results and experience from adapting the approach in real object are presented, including fatigue lifetime correction due to the real intensity of loading acquired from a bucket-wheel excavator during its long-lasting operation. It is expected that proposed procedure can help to improve credibility of fatigue lifetime assessment of heavy earthmoving machinery.

Keywords

fatigue life, lifetime assessment, supporting structure, welded joints, opencast mining machinery.

1. Introduction

1.1. Background of the problem

Opencast mining machines (wheel-bucket excavators, spreaders, etc. – Fig. 1) that are commonly used for earthmoving work such as surface mining, transportation and dumping of material, are one of the largest and heaviest machines ever produced and their operational efficiency is also beyond any comparison – these affects their design and the way of operating. To provide economical efficiency, life cycle of this kind of objects has to be very specific and they should normally operate with long-life requests [37].

Conditions in which every individual machine is operated are unique – they strictly depend on geological structure, which is almost an individual feature of each mine, or may even differ a lot on various areas of the same mine. This is one of the most important reasons why the analyzed group of machines is manufactured in one-off or semi-one-off production scale – it results in their quite unique design, as well as in the operational characteristics (lifting capacity, efficiency, etc.)

The essential components of these objects are supporting structures, which technical condition and durability determines not only the total lifetime of the whole machine, but usually also decides about safety and operating costs of the machinery.

At the same time, structural components usually undergo intensive, cyclic loading at variable courses. The load intensity and its high variation during machine lifecycle causes that the load may be difficult to determine at the design stage. The problem becomes more visible when the requested lifetime is very long – reaching dozens of years.

Welding techniques that are applied to join structural components together make the structure very sensitive to the fatigue degradation process [36], which is often intensified by corrosion [1, 55], nearly always occurring in such a long time of usage. As a result, the fatigue lifetime of the structure is limited mainly by progress of fatigue degradation of welded structural joints [53]. The observable general rule in design is that these machines get more and more stressed, because of reducing cross-sections and using materials which, admittedly, have increasingly greater tensile strength, but its permissible fatigue stress range remains the same or grows slightly, which in addition, worsens work conditions (greater strains, vibratory sensitivity, etc.). All of

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Fig. 1. Spreader A_2RsB 15400 – typical example of opencast mining machinery (photo. P. Grabowski)

these factors put together result in the situation that the hazard of fatigue degradation for the structural joints becomes the main problem in achieving forseen fatigue lifetime of the object.

On the other hand, at this scale of an object, it is not a rare situation when a supporting structures failure leads to a catastrophe [5, 41] – the effects of such failures may be huge [29] and their reasons are often in the fatigue degradation of structural joints (it holds true as well for the surface mining equipment [8, 24], as for many different types of large-scale objects superstructures [34, 54]).

The whole spectrum of the aforementioned problems reveals the necessity to determine the technical risk of using an object, corresponding to its operational reliability. For the process of fatigue degradation, it may be expressed with Fatigue Lifetime (FL) – this parameter allows to assess the time of life of structural components, in the meaning of the timespan remaining to the moment when critical fatigue damage occurs.

The trend to determine the FL, as early as at the design stage of machinery, is observed – determination and provision of this condition become obligatory. It follows either from valid or drafted directives (Machine Directive [13] in this case), harmonized standards, and many other sources of national and international law – it imposes a statutory duty for a manufacturer (designer) to include calculations on the stages of fatigue degradation and brittle fracture into the design process.

At the stage of service life, to ensure reliable and safe operation, repair intervals are scheduled according to results of inspection and maintenance experience [56]. Nevertheless, it is quite common nowadays to determine the remaining fatigue life of large-scale machines and other technical structures like roadway [15] and railway bridges [16, 48], wind turbines [31], railroad components [58] or existing steel structures under cyclic loading in general [27].

The aim of fatigue dimensioning is to prove that structural components are able to reach preliminary defined fatigue life (its value is determined in the technical-economical brief foredesign). The process is usually carried out in compliance with applicable standards – e.g. EN 13001-3-1 [14] and ISO 20332 [20] for cranes or several standards devoted to the surface mining machinery: AS 4324.1 [3], DIN 22261 [11] (and its Polish equivalent PN-G-47000-2 [38] which origins are in the first edition of the DIN standard) – just to point out those to have the greatest impact on design process of such equipment [33], [40]. These standards usually allow either for the traditional approach – the permissible stress proof or the limit state approach, which is rather preferable nowadays. Typical methodology conducted in accordance with requirements and recommendations of these standards while designing welded structural joints, shares the general idea [50] highlighted in Fig. 2.

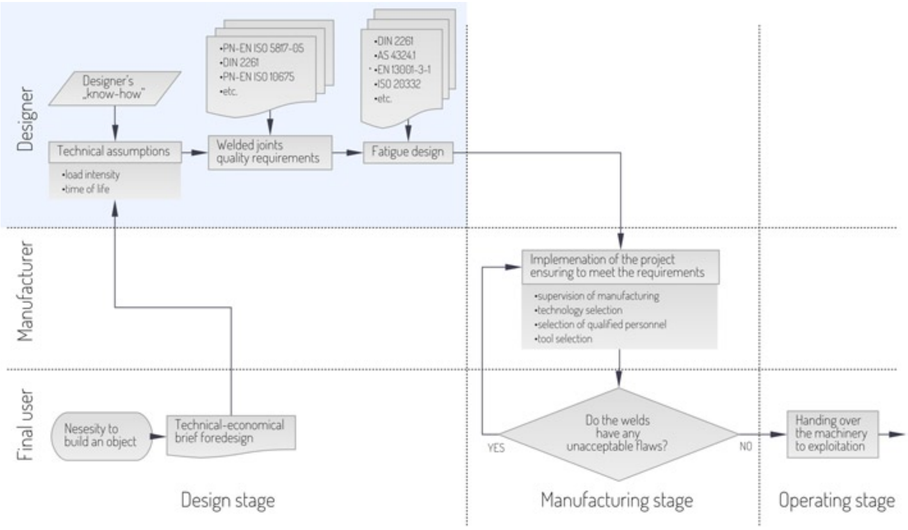


Fig. 2. Schematic methodology of design following the standardized approach (the shaded upper left corner), on the background of object development stages of lifecycle (vertical divisions in diagram refer to consecutive phases of object early stage of lifecycle, while the horizontal ones point out the main executor of the process)

Basing on the general static analysis (e.g. using FEM), some joints are classified as the most exposed to fatigue. The classification is basing on foreseen operating load characteristics, joint importance for the integrity of the whole structure, and joints shape and geometry. The latter one involves existence of notches in these structural joints, caused by local variability of cross-sections in the transient zone between welded elements. The next step is to evaluate load intensity in these notches, which commonly is the process of choosing the most similar notch type from the enclosed list to obtain the fatigue parameters that should fit best a real element. The types of welded joints and process engineering factors are taken into account at this step. Next, the notch class is evaluated, and, as a result, the comparison between the limit and real values of stress is made, which answers the question whether the condition is fulfilled (usually using high-cycle fatigue approach).

It should be pointed out, that the proof of fatigue durability executed in accordance with the presented procedure has some important shortcomings, which has not been comprehensively resolved yet and the available literature offers little information on methods, which could improve it. Pietrusiak [37] proposes to make calculative models of the dynamic effects instead of applying the predefined standard values of dynamic effects factor, and includes its latter experimental verification to the design process. In another paper [25], it is suggested to control the assumed values of the factor, by correcting the settings of the machinery protection systems in the real time during its operation. Therefore, those studies introduce concept of extending some steps of design process onto the further phases of the lifecycle. Such an approach has also been postulated by Jakubczak et al, in their studies [21]. In contrary to the considered group of machinery, elements of that approach are used to maintain the other group of fatigue loaded structures with a limited design service life – the civil engineering infrastructure, especially railway and roadway bridges [28], which in a way of design, operating and maintenance are quite comparable with superstructures of open-pit mining machinery. In this paper authors try to adapt and generalize a similar approach, by introducing the procedure of continuous fatigue lifetime correction, which is expected to be a helpful tool while designing load-bearing structures of large-scale individually manufactured machinery.

The proposed methodology requires the use of structural health monitoring system, which involves periodic read-outs of continuously recorded information from a net of sensors located on structural components of the supervised object. The acquired data are, in turn, interpreted respectively to the structure technical condition. The data sent to and stored in the central unit enables a remote observation of an object technical condition [17]. The role of structural health monitoring recently becomes more and more popular in the diagnostics of engineering structures. In the literature one can find many publications about real time diagnostics applied to identify the technical condition of machinery bearing structures. For example, Sikora et al. [47] describes a system for monitoring and diagnosing a gantry, which is capable to acquire, visualize and monitor vibration levels of the gantry crucial structural components. The system equipped with a computing and analytical module enables the predictive maintenance due to the obtained vibration level assessment. Similar approach is presented by Rusiński et al. [43] to evaluate dynamic loads corresponding to certain operational loading of surface mining equipment and, in turn, to carry out the modal analysis of the superstructure. Another paper [34] presents results of long-term load tests of bucket wheel excavator. The load carrying structure of the machinery is equipped with the monitoring system in order to determine the real stress values in selected welded joints, to enable prediction of the structure health. In work [51] authors present an identification method of technical condition of complex geometry large-size objects taking into consideration the power line supporting structure. The presented technique is based on testing the correlation between the change of stress in the system and the change of modal parameters caused by damage.

1.2. Fatigue life assessments of welded joints in the machinery structural components – difficulties and limitations of standardized procedures

In practice, design engineer has to face with many diverse difficulties making the actual fatigue lifetime of an object substantially different from the requested one. A number of papers manifests the problem of the impact of the external environment [52, 35], ageing [53, 55] and wear processes [36] or their combinations [10] on the technical system functioning. The problems, discussed in this section, are especially noticeable while considering the group of long-lasting large-scale one-off manufactured machinery [9, 39].

Significant doubts occur just when conditions of operating have to be assessed. Those remain almost unknown for the designer. Service conditions collected in the past represented in the form of various loading spectra may sometimes be available in manufacturer's database for some similar objects, but in most cases they are not directly applicable, so the service conditions could only be assumed according to his engineering experience with similar objects, and drawing on the results of consultations with a final user, about how the user plans to operate and maintain the machinery. Bearing in mind the size of the equipment and the unique nature of the operating conditions in surface mining, there is little to no knowledge of the operating stresses at critical details [50].

Alternatively, for some groups of machines, this information may come from applicable standard recommendations. This is quite often situation for calculating the classification group of cranes [59]. Nevertheless, such kind of "statistical truth" in many cases remains inapplicable for the group of individually manufactured machinery, where the designer's knowledge about working conditions of similar objects from the present generation is very limited.

For machinery with foreseen lifetime reaching 40-50 years (common situation in the considered group), the real operating conditions may not reflect designer's expectations [44, 45]. Furthermore, service conditions may also significantly change over time [7], so even if the characteristic is accurate for the initial stage of machine's lifecycle, the conditions may change a lot in the future. As far as opencast machines are concerned, the significant change of conditions may be just a result of different geological parameters of the successive layers of mined material.

The fact is that for some groups of machines the attempts to assess external loads occurring during object lifecycle may give satisfactory results. This approach is applied to cranes by calculating their classification group. However, an accurate determination of external load does not guarantee proper evaluation of its effects – it is almost impossible to determine results of these loads in individual structural joints (stresses in considered cross-sections). Moreover, foreseen number of load cycles usually may be assessed very approximately – in real conditions there may incidentally appear stresses of great amplitude or frequency, which completely change the character of operating (vibrations, resonance, etc.). Further complication of the problem is caused by gradual degradation of machines components (increasing clearances of knuckle joints, which tends to alternate the structure's response to external impulses). Such a missed load spectrum, substantially increases the differences between designed and real fatigue lifetime consumption ratio (the time necessary to obtain a critical damage).

Improper maintenance, usage prolongation beyond the designed lifetime of an object and variable degree of technical culture of an operator, as well as of a technical service, are another factors with random character, which influence onto machine structure fatigue lifetime in long time horizon is hard to determine. Working conditions of open-pit machines can be even more unpredictable, if some non-technical factors are considered – e.g. strictly political decisions. Great affect onto the whole branch will surely have the introduction of "green order", which can cause sufficient alternation of costs structure in coal mines for maintenance of machinery, which will seem to be "abandoned" in future. Reducing subventions for repairs and modernizations, while their growing necessity (because of objects increasing age), may be very important problem that technical services will have to face with in near future.

Another important difficulty, but of a different kind, is the right selection of fatigue resistance S-N curve of welded joints in order to evaluate its fatigue strength. Its value is significantly influenced by such factors as shape and local dimensions of a joint (quality of type), but also quality of conformance [14, 18] involving e.g. residual stresses which stems from the manufacturing process [46]. The last one is difficult to determine unambiguously for the purpose of preparing fatigue assessment [4]. It is also problematic to obtain the form of welded joints determined by the designer, which may differ (sometimes considerably) in the real object (i.e. shape, manufacturing quality, or post-welding treatment). Stress of the structural joints or their material stress-life (S-N) curve may also be changed by major repairs or modernizations which are common processes in long-life operated machinery.

At last, durability condition itself – defined with usage of stress instead of operating time – may be inadequate for the purpose, becoming another source of problems during the design of the FL of structural components. According to the aforementioned standard recommendations, stress in a welded joint has to be lower than the permissible stress range (or should not exceed the value corresponding to the limit state in case where this approach is regarded) for such joint. It means that fatigue lifetime is expressed indirectly, using only a stress criterion (it is so for the foreseen load, as well as for permissible values). The problem is that FL cannot be defined only by stress. The information about number of load cycles (converted into time unit) is also required. The FL expressed in units of time is exactly the parameter which will later be important for a machinery user. Converting the stress criterion into lifetime is possible using traditional damage accumulation hypotheses (e.g. Palmgren-Miner), but in the same time it is very prone to input changes [19], since it results from strongly exponential shape of stress-life curve. It means that slight variation of stress values highly alternates FL assessment, therefore the evaluation of the design quality of the component turns out to be difficult.

The described approach is justified by the procedures recommended by applicable standards. They are, in the considered case, harmonized with Machinery Directive [13], which requires designer to evaluate fatigue lifetime. In this case, the only possible solution is to predict FL, according to the manufacturer's experience referring to operating similar objects of previous generations and bearing in mind economical factors, which usually are just expectations. It makes the FL evaluation a very difficult stage of machinery design. In most cases, it is possible to assess it only roughly and this also is often recognized as highly inaccurate – the results of such analyses are very unreliable for the considered group of machinery.

2. Fatigue Lifetime Correction – the methodology of through-life design

In order to reduce the problem of analyzing fatigue lifetime of structural components of heavy construction equipment, it seems to be reasonable to correct the pre-designed lifetime at the stage of machinery operating.

While analyzing factors presented in the previous chapter, one may notice two ways which could help to increase level of reliability of FL assessment through its correction:

- verifying whether a joint is produced in compliance with its documentation and selection of its stress-life curve strictly for the real local geometry and for provided manufacturing quality, instead of using original characteristic taken from the closed list of standard joints (notch classes),
- involving reliable load spectrum, e.g. acquired by continuous registration of load in real time and, in the next step, correction of foreseen FL according to acquired data.

The methodology presented in this chapter includes both of them, so that the two most important problems might be obeyed. First, it enables to evaluate local stress at notches, with respect to their real geometry (weld toe angle, bead transition radius). On the other hand, making correction after the initial stage of machinery operating, taking into account the acquired real load history, allows the designer to find out what the real service conditions of the machine are.

Fatigue Lifetime Correction (FLC) provided at the stage of service life becomes then a tool included into the extended design process, helping the designer to face with typical engineering problems which occur in the real machine lifecycle in comparison to the assumptions made earlier. The designer gets then an answer about how does the Fatigue Lifetime (pre-designed in accordance with defined materials, notch classes and manufacturing quality of welded joints, foreseen loads, etc.) reflects the real service conditions (with account for provided quality of welded joints). This means that for the considered group of machinery the design stage should not finish after putting an object into operation, but it should be continued, incorporating the stage of manufacturing, as well as the service life. As a result, FLC becomes an integral part of the design process, and the process is extended onto the whole lifetime of an object. This is, what is meant here as a "through-life design", which general idea has been introduced in [21]. In order to avoid misunderstanding, fatigue design completed on the design stage of life (as it is commonly understood), is mainly called the original design (or pre-design) in the latter part of the paper, and the one being performed periodically during service life – the corrected fatigue design.

2.1. Idea of an approach

The algorithm of the proposed FLC method is depicted in Fig. 3, to locate it on the life cycle background of an object.

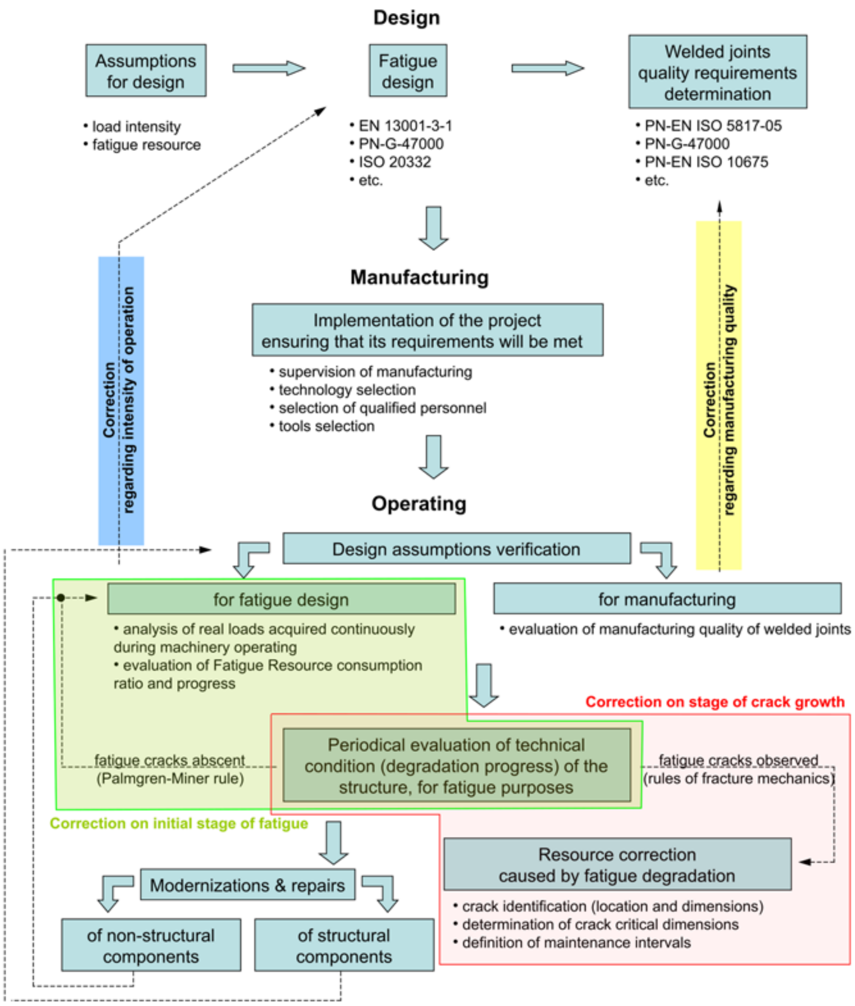


Fig. 3. Diagram of Fatigue Lifetime Correction of structural welded joints of opencast mining machinery

In this approach, the design stage is carried out in the same manner as in current engineering practice – at the beginning, expectations and assumptions are formulated (including requested FL of an object) basing on consultations with a final user, then the original fatigue design (pre-design) is made, with respect to procedures required by applicable standards (e.g. [14]). This step includes the determination of joints potentially prone for fatigue degradation – they will be supervised later by acquisition of their stress histories. A joint can be qualified as potentially weak with account for stress level, its variability, or its high importance for the integrity of the structure. After formulating requirements about limit fatigue stress of such joints, FL is assessed through commonly known high-cycle methods [30], [36].

In view of current requirements, this is where the formal fatigue design procedure has already been finished. In order to make FLC, the next steps should be taken at the subsequent stages of the machinery lifecycle.

The aim of the manufacturing stage is to satisfy all requirements defined in the previous stage, especially by manufacturing welded joints at acceptable quality level. After this stage, machinery is handed over to the final user – this is when the first FLC should be executed. It is expected to be carried out only once and includes the evaluation of manufactured welded joints, which quality significantly affects the total lifetime [49]. FL is revised with respect to this evaluation, and it results in the verification of designed notch classes of structural components, according to their real parameters and weld quality. So the real S-N curve is applied instead of the one expected by a designer.

The next part of the procedure, including corrections at the operating stage, is more complex. It requires continuous load (stress) data acquisition in joints that have been selected as potentially prone for fatigue. Hence, the machinery has to be equipped with the data acquisition system capable to collect data in real time. The load history of the initial period of the machinery usage is especially important, since the first correction caused by the intensity of operating allows a designer to analyze the real service conditions of the object, so that he is able to evaluate how do they reflect the expected ones. This gives feedback between particular phases of the object lifecycle and integrates activities of a designer, manufacturer and operator.

The periodical evaluation of the structure FL consumption rate (degradation progress) should be provided with respect to actual working conditions, since they strongly affect the design [33], and it should be followed by the inspection [12] regarding evaluation of structure's technical condition with the applicable methods [42]. The next step depends on the results of the evaluation. If fatigue cracks have not been observed yet, the next correction is made, as shown in the green loop (Fig. 3) – the high-cycle method analysis (according to Palmgren-Miner's rule [32]) is applied to calculate damage. It allows to assess FL, taking into account the successive load history data.

In the case when some fatigue cracks had been spotted in any of the supervised joints, further action is taken according to the red loop in Figure 3, where different method of FL assessment calculations is chosen – based on the rules of fracture mechanics. It should be emphasized, that for the considered group of machinery, because of their specific features described at the beginning of this paper, it is allowed and economically justified to use a machine also after cracks occurrence, although their supervision is required. So, at this stage there is another important diagnostic symptom – crack dimensions. After identifying the location and actual size of cracks, it is necessary to define their critical dimensions, after reaching which the brittle fracture becomes really hazardous.

The difference between these stages of degradation, followed by the different character of corrected lifetime results should be noticed. At the initial stage, the rate of FL consumption from previous periods is being analyzed. The obtained results of total joint FL may either be greater or lower than designed. In turn, the fatigue growth stage (the red loop), concerns the observation of a real physical crack which increases during further service life. Continuous monitoring of the structural health of heavy earthmoving machinery to predict remaining service life is generally suggested [57]. The crucial parameter at this phase is the remaining lifetime – the time which allows to operate machinery safely while the crack growth is stable (from the time when the correction was executed to the time when it reaches the critical dimensions). It is obvious, that the time defined this way will be decreasing, so FL will be gradually consumed. While the FL is consumed, the assessment of actual technical condition of the joint should be more careful. It means that at the stage of crack growth, the FLC method reveals its another important value – it allows to define the recommendation for service, regarding the maintenance intervals for supporting structure.

Another problem is FLC after modernizations and repair activities (either due to damage or "technological type" failures [9]) which may cause total change of fatigue characteristics of structural joints, and / or load intensity. That is why after such activities, the revision of design assumptions is necessary, taking into account the already known load history (also including local stresses in notches). Another analysis and selection of joints potentially prone to fatigue (e.g. using FEM methods) and correcting location of sensors in these joints may also be recognized as necessary.

The procedure presented above is versatile enough to be applied not only in open-pit mining machinery, but also in the group of other objects of a similar scale and design. It seems to be quite simple, as the methodology does not affect the phase of pre-design. The designer still uses in his project the indexes and parameters, specific to designed group of objects – e.g. dynamic effects factor for the surface mining machinery or stress history parameter and, in turn, division of cranes into load classes, etc. Hence, the pre-design remains in compliance with the applicable standards and the FLC method can be considered as a kind of a supplement to it.

It can be also noticed, that diagnostic symptoms used to detect the failure – fatigue damage accumulation rate and the rate of crack growth – are universal and common to various structures (independently from the type of machinery under analysis), which in turn simplifies the whole procedure.

2.2. Gathered experience and results of FLC for the wheel-bucket excavator

The approach proposed above is under development and tests basing on the experience from operating the wheel-bucket excavator, KWK 910, which is in service in the Turów brown-coal mine (Poland) for more than 10 years now. In this part of the paper some practical aspects of adapting the methodology in this type of object and recent results concerning corrected fatigue lifetime are presented. The machinery is the first realization of an excavator completely designed and manufactured in Poland, which is dedicated for operating in hard and very hard rocks [2]. Tough service conditions, existing in Turów's deposit, which is characterized by irregular geological structure and variable mineability, have significant influence on the design of machinery and its structure [5]. While designing the structure, there were 12 joints selected as potentially vulnerable to fatigue degradation, and these joints were equipped with diagnostic hardware for continuous load acquisition, in order to evaluate stress state within them. These joints are located as shown in Fig. 4. Components of data acquisition system, the method of data acquisition and its processing have been described in [25].

Processing of collected data includes converting the recorded stress history into a form applicable for the FL assessment calculation – the stress spectrum, defined by a stress range $\Delta\sigma_i$ and number of cycles n_i for corresponding stress levels, or into stress matrices, including additionally mean stress level σ_m. The obtained load (stress) spectra for some exemplary structural joints are depicted in Fig. 5 – each series in the chart shows the spectrum ($\Delta\sigma_i$ – n_i plot) collected during the particular time period.

The revision of data is carried out each 500-2,000 hours of operating. Due to a gathered experience, such intervals seem to be reasonable, since they are long enough to notice some characteristic trends in service conditions, whereas in case of any problems with monitoring system they can be found out soon, so that the resulting gaps in data are not crucial to overall results. The time spans are also appropriate for the supervision requirements of the structure. Keeping these intervals ideally equal to each other is not necessary for the method workability, as further analysis uses intensive (time-independent) indexes. Data acquired thus far contain information on working conditions in-

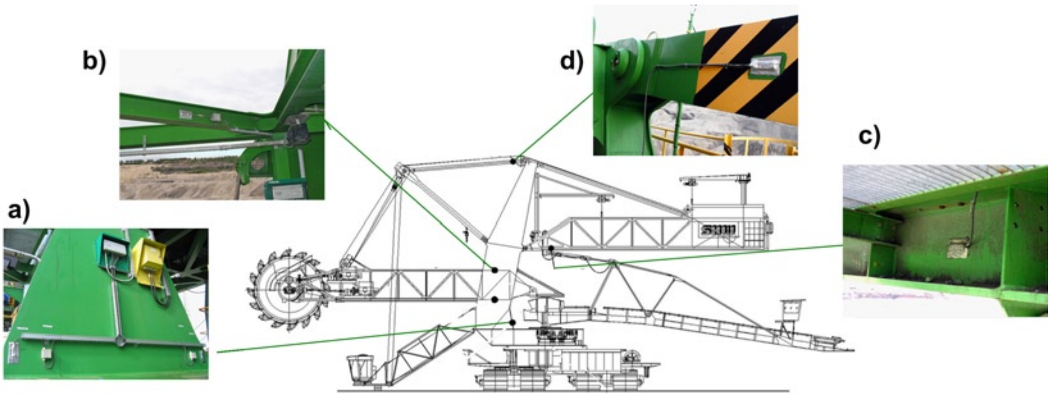


Fig. 4. Location of supervised structural joints on KWK-910 excavator: a) notches #1-4, b) notches #5-8, c) notches #9-10, d) notches #11-12

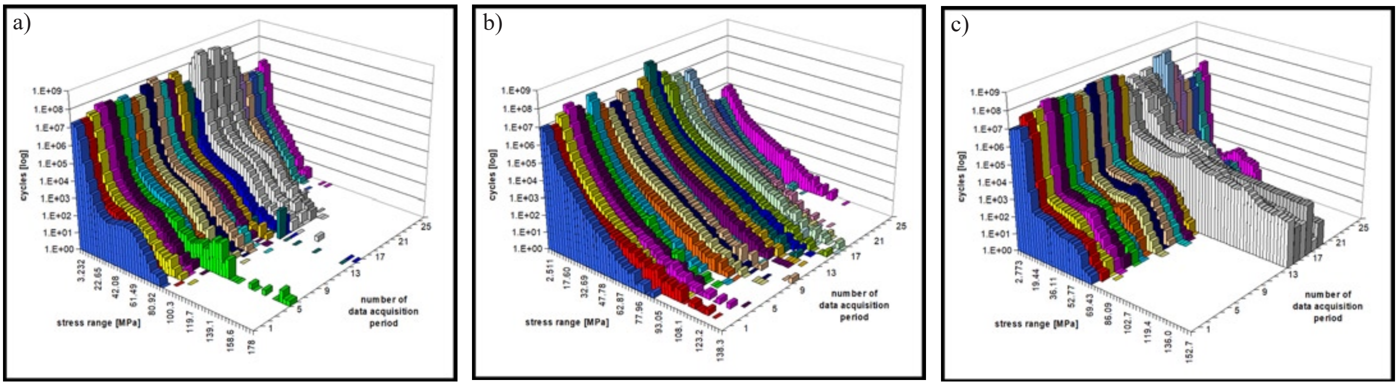


Fig. 5. Sample operating load spectra: a) notch #1; b) notch #8; c) notch #10

cluding ca. 25,000 [h] from the beginning of the machinery service life. The rate of damage accumulation on the initial stage of fatigue is assessed in turn, basing on the collected data. It should be pointed out that no fatigue cracks have been observed yet in any notch, so the results described later in this paper cover only the initial stage of fatigue degradation. In the next step, FL is calculated using the Palmgren-Miner's rule of damage accumulation [32] with respect to notch classes and their Stress-life (S-N) curves (according to standard [20] regulations). The principle of damage calculation is depicted graphically in Fig. 6. Each block in the diagram shows the number (N) of stress cycles at the corresponding range value ($\Delta\sigma$), caused in particular structural joint by operational loading during the considered time period. On the other hand, the line in this chart shows the standardized [20] S-N curve for the notch, which is the reference for fatigue damage value calculations. The fatigue stress-life curves used (in a log-log plot), are composed of straight lines and are described by 3 characteristic points [26]:

- $\Delta\sigma_C$ (at N=2×10^6 cycles) designate a notch class of the structural joint. It is understood that 97,7% of all specimens under this stress range ($\Delta\sigma_C$) survive N=2×10^6 cycles.
- $\Delta\sigma_D$ (at N=5×10^6 cycles) is established as the fatigue limit at constant stress range (below this value, for constant stress ranges, it is assumed that fatigue damage does not occur). The slope of the curve below $\Delta\sigma_D$ changes from 1:3 to 1:5.
- $\Delta\sigma_L$ (at N=1×10^8 cycles) is the stress range below which any (even under variable stress ranges) fatigue damage may be neglected. This level is a cut-off limit, but in calculations often the fatigue strength curve is extended to low stress ranges without limit (in considered calculations to zero level). In described method that approach is also assumed, so that all of recorded stress levels are taken into account while performing the assessment.

The lifetime is assessed basing on the previous mean values of the damage accumulation ratio encompassing all periods. Fig. 7 shows how the fatigue damage increases in time for each notch. It presents that most of supervised joints consume their lifetime quite slowly, although the significantly greater ratio of damage accumulation for notches #9 and #10 can be noticed, comparing to the rest of them. For the notch #9, the results of periodical FLC have been made (after a few selected periods), with the use of the trend line extrapolating information about the stress history acquired so far (dashed lines in Fig. 8 – each corresponding to FLC after selected period of time). The trend line is extended to the level of critical damage D_{CRIT} = 0,5

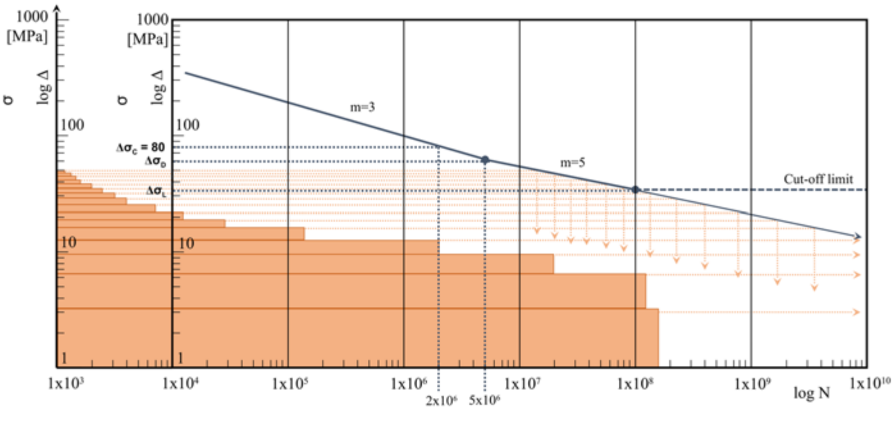


Fig. 6. The principle of damage calculation – example (notch #1, after 3,428 [h])

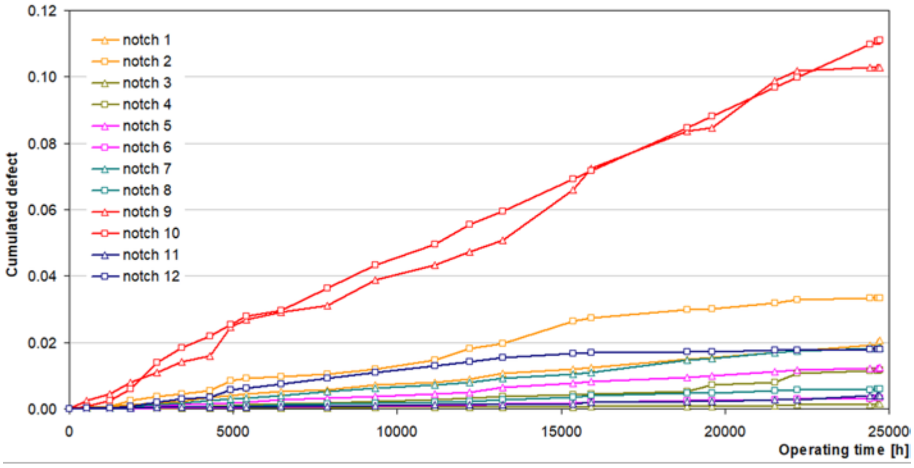


Fig. 7. Damage accumulation ratio in structural joints, containing 24,645 hours of machinery operating

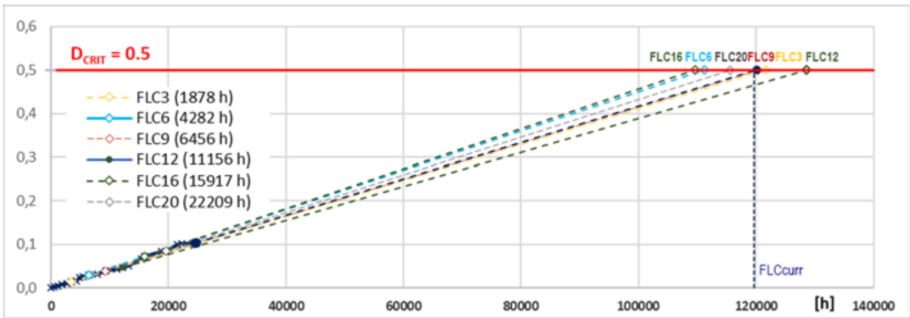
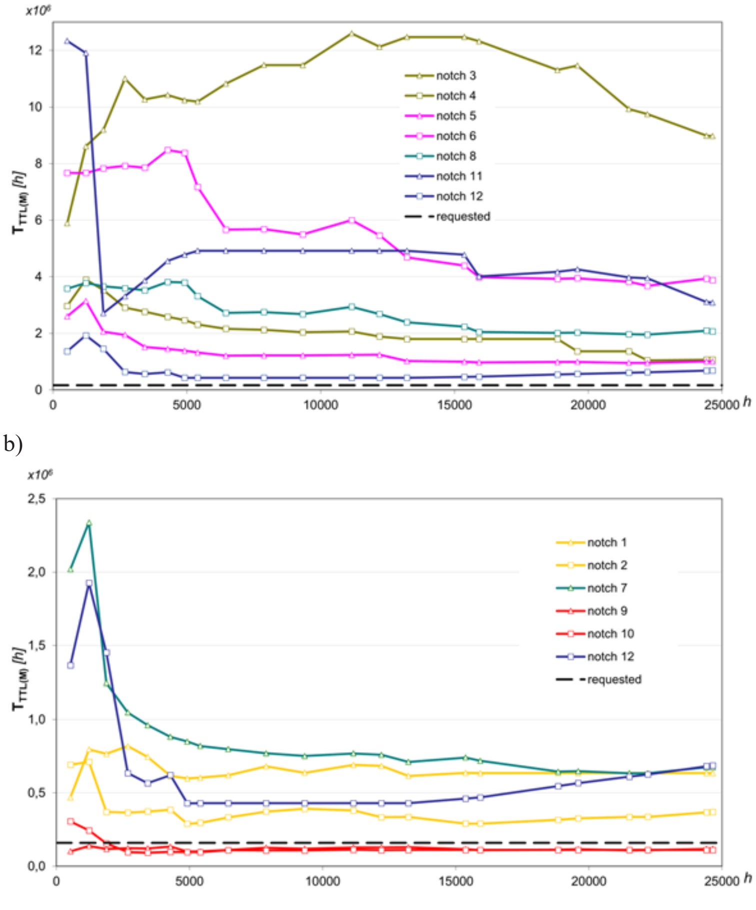


Fig. 8. Fatigue damage ratio trend line extrapolation for notch #9, to critical value of D=0,5

(continuous horizontal line in the diagram) – this value is assumed to be the criterion for exhaustion of FL.

Such assumption of critical damage value results from the necessity to use value consistent with the one used during the pre-design stage in order to prove that the object fulfills fatigue lifetime conditions, according to ISO 20332-1. It is noticeable that the lifetime corrected to the real operating conditions alternates between 110,000 and 130,000 [h], which means that for this notch it is lower than the requested one (160,000 h). Therefore, in this notch the fatigue crack initialization is more probable than in the others before reaching pre-designed service life, if working conditions remain similar to those observed so far. This observation holds true also for the similar notch #10 (notches marked red in the table 1). In contrast to them, the significant prolongation of corrected FL can be observed for the most of notches (the green ones in the table). Table 1 contains the results of the total FL assessments for each notch, corrected with respect to the real service conditions of the excavator. Symbols used in the table mean, respectively: D_{CURR} – calculated current value of fatigue damage (acc. to Palmgren-Miner's rule); D_{CRIT} – critical fatigue damage value (as described in the previous paragraph); $T_{TTL(M)}$ – total fatigue life of the notch, assessed after a specified time period. The results are also shown in Fig. 9, where the corrected fatigue lifetime of each notch is plotted against the time, after which correction has been carried out.

a)



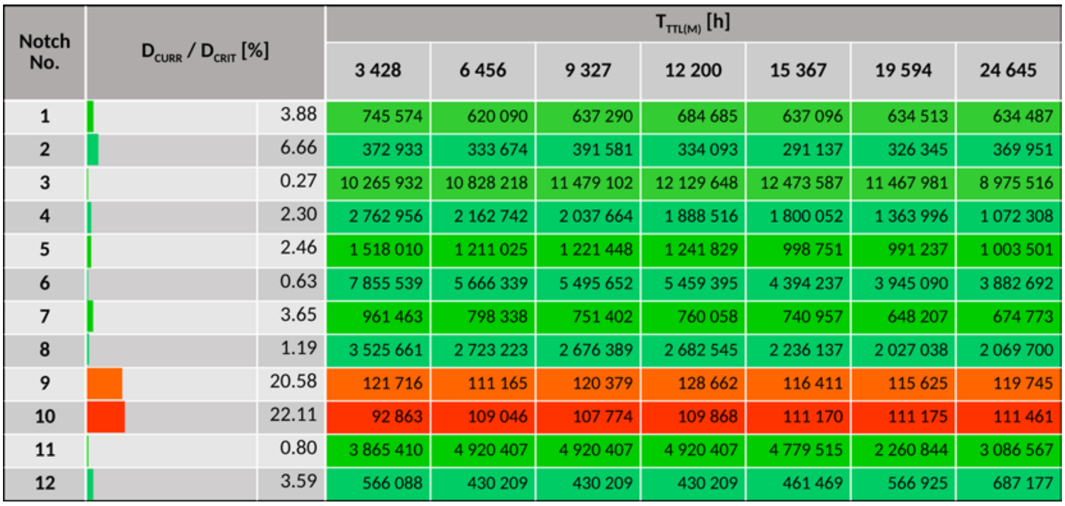
b)

Fig. 9. Corrected total fatigue lifetime of notches, caused by real service conditions

Since the results of those corrections are quite different from each other, it justifies the necessity to repeat analyses periodically. It is noticeable especially for notches #6 and #8, where the difference between FL corrected after 5,000 hours and after the last period is twice as big – it reveals how strongly the stress of structural joints and operating conditions may vary during the object's life.

It is also worth to mention that in some periods the gaps within data records were observed. These have been caused by technical problems with data acquisition hardware (e.g. failures). As a result, in some of the considered periods of time, it was impossible to evaluate damage accumulation ratio directly. This problem, which introduces some difficulties in FL assessment procedure, has been extensively described in paper [22]. In such situation, some equivalent methods can be involved to evaluate the ratio. During research that had been made [23], analyses of substitutive regressive methods were investigated, in order to recognize the estimated function which might give the most satisfactory results (the most accurate FL assessment). Damage accumulation ratio values obtained with substitutive functions were then compared to the ones with known real (actual) values. Analyses also contained evaluation of joints behavior and load character in comparison to other respective joints of the same structure (e.g. symmetrical ones). It revealed that in those periods an unknown actual damage accumulation ratio for the period can be replaced by the estimated value basing on previous mean rate (the mean value calculated basing on earlier stages of operating the machinery) without significant loss of the lifetime assessment credibility. Taking average estimated rate into account is especially visible in Fig. 9 for notches #11 and #12 between ca. 7 and 13 thousand operating hours. It is also important, that such approach is quite easy to apply in engineering practice and does not complicate too much the overall procedure.

Table 1. Fatigue lifetime assessments after every ca. 5000 operating hours.



Notch No.	D_{CURR} / D_{CRIT} [%]	$T_{TTL(M)}$ [h]						
		3 428	6 456	9 327	12 200	15 367	19 594	24 645
1	3.88	745 574	620 090	637 290	684 685	637 096	634 513	634 487
2	6.66	372 933	333 674	391 581	334 093	291 137	326 345	369 951
3	0.27	10 265 932	10 828 218	11 479 102	12 129 648	12 473 587	11 467 981	8 975 516
4	2.30	2 762 956	2 162 742	2 037 664	1 888 516	1 800 052	1 363 996	1 072 308
5	2.46	1 518 010	1 211 025	1 221 448	1 241 829	998 751	991 237	1 003 501
6	0.63	7 855 539	5 666 339	5 495 652	5 459 395	4 394 237	3 945 090	3 882 692
7	3.65	961 463	798 338	751 402	760 058	740 957	648 207	674 773
8	1.19	3 525 661	2 723 223	2 676 389	2 682 545	2 236 137	2 027 038	2 069 700
9	20.58	121 716	111 165	120 379	128 662	116 411	115 625	119 745
10	22.11	92 863	109 046	107 774	109 868	111 170	111 175	111 461
11	0.80	3 865 410	4 920 407	4 920 407	4 920 407	4 779 515	2 260 844	3 086 567
12	3.59	566 088	430 209	430 209	430 209	461 469	566 925	687 177

3. Summary

In opencast mining machinery, as well as other large-scale machines manufactured one-off or semi one-off, with similar life cycles and working conditions, the fatigue degradation of welded structural components is crucial for a machine to reach the designed time of life and to ensure safe and economical operating.

The paper presents the proposition of Fatigue Lifetime Correction method which can be applied in very specific group of machinery and thus helps a designer to provide expected fatigue lifetime, to which he is obliged by legal regulations. In turn, involving a designer into the whole machinery life cycle (“through-life design”) extends his knowledge about service conditions of the considered group of machines, making their design process much easier. The revision and correction of FL on the later stage of operating of technical objects of such kind reduces inconveniences existing during its design, caused by many problems in evaluating the lifetime correctly. Moreover, including FLC into the design process decreases risk during operating the object at the stable fatigue crack growth stage, providing important diagnostic clues about the supporting structure’s technical condition. As a result, the method introduces the rules of machinery operating according to its technical condition into practice – this strategy seems to be the most justified economically for such machinery.

Proposed procedure can be applied to maintain the technical condition not only of an open-pit mining machinery, but for almost every technical object which principles of design, operating and maintenance are similar to those – this usually means unique large-scale long-life cost-absorptive machinery, with a limited design service life, which welded superstructures are subjected to fatigue loading.

As the methodology does not disturb the original design stage of the machine lifecycle, thus it remains in compliance with obligatory design procedures and standards. The design engineer may still use indexes and parameters, which are characteristic to the designed object (such as dynamic effects factor, stress history parameter, division of cranes into classes, etc.). This is also why adaptation of the procedure to various groups of technical objects seems to be quite simple.

The functionality of described method has been developed and successfully verified on the real object being operated in Silesian opencast mine – bucket wheel excavator. The last part of the paper depicts the use of results of measurements collected from the BWE monitoring system during its service life. Obtained results point out the structural joints where FL is consumed much slower than a manufacturer predicted – their FL will probably be significantly prolonged (economical factor of the method). Also the hazard of earlier consumption of FL by some notches is shown – in this case the method proves to be important as far as the risk of operating of machinery is considered, allowing marking these components where more attention should be paid during regular inspections.

Stress monitoring requires an individual approach to every supervised object. However, it shall not significantly prolong the development time or increase costs of machinery, since design of this kind of machinery requires an individual approach in general, in turn of uniqueness of every piece. Therefore, it has to be pointed out that investments during machinery development shall not dominate over significant advantages resulting from application of the method.

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