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THE FATIGUE OF MATERIAL AS A RISK ITEM IN THE PROCESS OF THE RELIABILITY AND SAFETY PREDICTION OF VARIOUS TECHNICAL SYSTEMS

Abstract

Material fatigue of parts of different technical systems belongs to the most frequent causes of boundary states rise and relating operation breakdowns. Paper contains general formulation of reliability of technical systems judging, brief characteristic of basic areas to be taken in account as input into calculated prediction of technical systems fatigue life and analysis of risk items by its practical application.

Abstrakt

Únava materiálu častí rozličných technických systémov patrí k najčastejším príčinám vzniku medzných stavov a z nich vyplývajúcich prevádzkových havárií. Článok obsahuje všeobecnú formuláciu problému posudzovania spoľahlivosti technických systémov, stručnú charakteristiku základných oblastí vstupujúcich do výpočtového odhadu únavovej životnosti technických systémov a rozbor rizikových položiek pri jeho praktickej aplikácii.

Keywords: working conditions, fatigue of material, life-time, reliability, safety of technical system, operation breakdowns.

Introduction

An extraordinary attention is dedicated to the evaluation of fatigue life of construction parts of different technical systems all over the world because breakdowns caused by a fatigue failure have often a nature of catastrophe. There should be a dominant effort to bring conditions of calculation or experiment near to the working conditions in which the investigated system is exploited. The aim is to reduce unfamiliarity of acting factors of the surroundings and their interactions with processes in the system itself. A modern way of calculation of any technical systems (e.g. large mechanical or civil structures) therefore demands to respect dynamic and stochastic nature of all influencing working factors and related working loads. The main reason for it is the prevention of their working breakdowns.

The General Procedure of Technical Systems Safety and Reliability Judging

Now presented theory and methods of reliability evaluation and its partial characteristics result in principle from two main approaches from which follow further theoretical starting points and practical methodise focuses on certain group of systems. The first approach is based on the idealization, strict modelling conditions and use of traditional calculation of reliability characteristics. We can talk about so called ***a priory (inserted) reliability***, determined already during research, development and partly a phase of production, which is limited with level of the used calculation, design and technological procedures. The second approach rests on real information of stochastic nature directly connected with concrete working conditions of the examined system. There is a so-called ***a posteriory***

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(working) reliability, which characterizes measure of structure reliability in certain working conditions.

Working reliability depends directly not only on a measure of the inserted reliability but also on real exploitation conditions, discipline of production, level of care, quality of operation etc. The formulation mathematical-symbolic, which gives some ideas about selected element reliability estimation, is the mostly used formulation of technical systems (TS) reliability judgement [1]. It expresses reliability in the form of a series synthesis in the form of

$$\mathbf{F_{(t)} \Rightarrow [TS] \Rightarrow \sigma_{x(t)} \Rightarrow Z_{(t)} \Rightarrow T_{(Zc)} \Rightarrow R_{(t)}},$$

where $F(t)$, $\sigma_x(t)$, $Z(t)$, $T_{(Z\,c)}$ are general random functions of time with the following meaning:

- ***F(t)*** - stochastic working load of technical system [TS] as a time function,
- $\boldsymbol{\sigma_x(t)}$ - stress in x-location, which is a reaction on the input process $F_{(t)}$ and characterises implicitly quality of the tested TS too,
- ***Z(t)*** - process of fatigue failure which is a reaction on the process $\sigma_{x(t)}$ and which takes in account a character of the system [TS] and fatigue characteristics of used material,
- $\boldsymbol{T_{(Z\,c)}}$ - process of life connected with the process $Z_{(t)}$, which follows from the course of fatigue process and when Z_c is order value of failure causing breakdown of the system,
- $\boldsymbol{R_{(t)}}$ - function describing probability of non-failure of the system [TS] during defined working conditions $F_{(t)}$ and inserted qualities which generally characterises reliability as probability of working without failure.

It is obvious that from point of view of complex structure safety judgement the fatigue life of their principal parts is the most decisive criterion. It can be estimated after different theories of fatigue failure. The main reason for difference of predicted life value from the real one reached under real working conditions are namely difficulties which we are meeting during exact determination of acting working load parameters. These are caused by some of the most significant factors of working conditions and their intensities.

The Areas Entering the Algorithm of Fatigue Life Prediction

If we limit our meditation about fatigue life estimation just on strength problems and do not take in an account related theories such as the theory of mechanics dynamics of machine units and further scientific disciplines then generally we can deal with four principle areas of interest related with [1]:

- ***choice of structure critical points, which is analysed further,***
- ***determination of stresses in selected critical points and following elaboration with methods suitable for fatigue life estimation,***
- ***proposal or judgement of strength and fatigue properties of investigate parts material based on chosen material characteristics and***
- ***choice of method of calculation – hypothesis of fatigue failure cumulating, which can correlate the information about loads and material properties of the system parts.*** The output is a qualified estimation of an analysed part fatigue life.

After determination and evaluating of above mentioned groups of information and after their suitable application we can get concrete values of fatigue life estimation of tested parts of the system which significantly determine reliability of the structure on the whole and which are the important information in judgement of risks connected with its safe working.

Working Conditions – A Source of Working Loads

It follows from Fig.1, that working conditions are the main source of working load (excitation), which causes stresses of the examined technical system. Despite of that they are principal input information for quantified estimation of reliability of each technical system.

It was not possible to find any universal way of their complex description until now which could be used in a practical way at any circumstances. Experience from realised analyses of life show that problem of working conditions influence on the level of fatigue failure cumulation is still underestimated. Individual factors of working conditions can have different physical meaning although nearly without any exception they are of stochastic nature. Exploring their influence on system parts stresses we can go out from analysis of real working modes. It should be a model of typical working conditions built on that base so called load collective representing a collection of the most important working conditions factors and frequency of their occurrence [2,3].

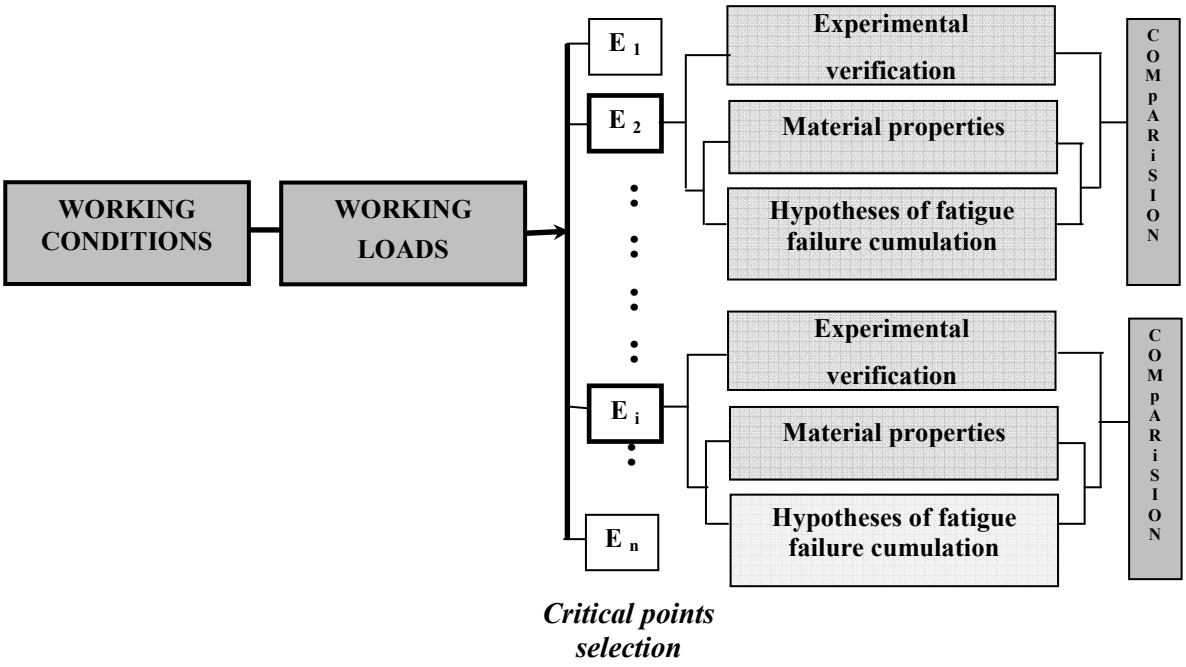

Fig.1.: *General procedure of fatigue life problems solutions*

The review of fatigue life is built on a basic presumption that fatigue failure in always conditioned by cyclic deformation of material of which a measurable cause is in any case force pressure, velocity, acceleration etc. From the point of view of life analysis purpose there are not important working load characteristics and their interactions but just result of their co-operation in the form of stress or deformation of structure parts. In real practice there are most often used two elementary ways in which relevant information is obtaining.

The first one is based on the fact that in most cases it is possible to measure stresses of the structure critical points directly on the structure during its working in real working conditions. If the measurement is realised in order to get input values for fatigue life estimation then the structure cannot be measured at any working condition (although the most aggressive ones) but in conditions which are for the structure typical or relevant. The second way is based on obtaining the most relevant working factors and on computer simulation of their influence on mathematical model of the system (most often FEM) which has as a result calculation of critical parts stresses [3].

Strength and Fatigue Properties of Using Materials

The second relevant area for fatigue life prediction is determination of necessary (namely mechanical) properties of used constructional materials in analysed points of system. Some characteristics (curves) of used construct materials are utilized during a practical realisation of estimation of working fatigue which can characterise fatigue properties of used material. The oldest but until now utilized characteristics of material is the Wöhler curve (Fig.2 a) showing dependence of the harmonic cycle amplitude of force F or stress σ_a on a number of cycles until failure N_f. Sometimes it is used just the only value – fatigue limit σ_c [1,4]. It can be expressed in a mathematical way by equation (1) or taking in account fatigue limit σ_c in form (2) or as the case may be taking in account influence of the mean value in form (3), where m, A, σ_f' and b are the material constants (σ_f' - is called fatigue strength coefficient and b is an exponent of fatigue strength)

$$\sigma_a^{\,m} . N_f = A \tag{1}$$

$$(\sigma_a - \sigma_c)^m . N_f = A \quad \text{respectively} \quad \sigma_a = \sigma_f' . (2.N_f)^b \tag{2}$$

$$\sigma_a = (\sigma_f' - \sigma_m) . (2.N_f)^b \tag{3}$$

More modern material characteristics is the Manson-Coffin curve (Fig.2 b) defining dependability of the amplitude of a deformation harmonic cycle ε_a on a number of cycles until failure $2.N_f$. It is described by equation (4), where ε_f' is coefficient of fatigue ductility (elongation), c is an exponent of fatigue ductility and E is the Young module [2].

$$\varepsilon_a = \frac{\sigma_f'}{E} . (2.N_f)^b + \varepsilon_f' . (2.N_f)^c \tag{4}$$

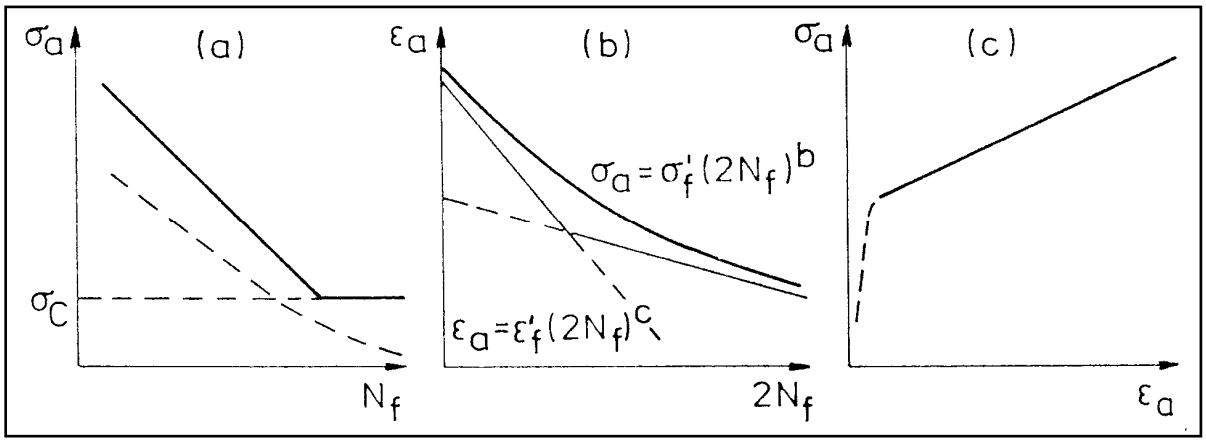

Fig.2.: *The Wöhler curve (a), Manson-Coffin curve (b) and Cyclic deformation curve (c)*

By exploring correlation between Wöhler and Manson-Coffin curves it was found that the dependability exists and holds for the relationship equation which is the so called equation of cyclic deformation curve (Fig.2 c) which is expressed in form [2]

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K} \right)^{\frac{1}{n}}, \tag{5}$$

where K is a coefficient of cyclic strength and n is a coefficient of cyclic strain-hardness. It is important that by repeated loads doesn't hold the classic Hook's law in form $\varepsilon = \sigma / E$ but the decisive role plays just the second part of equation (5) [2,6,7].

Hypothesis of Fatigue Damage Cumulation

It is natural that different ways of treatment and description of stochastic working loads have as a result different methods of fatigue damage estimation. In the area of fatigue these methods are called hypothesis' of fatigue damage cumulation (HFDC) and their purpose is a quantified estimation of fatigue damage level estimation caused by a process of certain length or number of cycles.

Depending on character of evaluated parameters (the block of harmonic cycles) [1,2,3] or statistic characteristics of the process obtained in the frame of correlation theory [1,3,4] or values of autocorrelation function (ACF) or power spectral density (PSD) from an autoregressive model of process [4] it is possible to apply a suitable HFDC based on using some of the mentioned parameters.

A lot of hypotheses based on utilising of the obtained block or macro-block of harmonic cycles were proposed and verified. By their application one goes out mainly from information about the used construction material and about principal characteristics of macro-block of harmonic cycles (e.g. number of block levels, number of cycles, number of cycles until failure on the same level etc.).

Hypotheses based on the correlation theory characteristics are less frequent than the former ones and most of them are too theoretic a computation demanding for concrete practical utilisation. Moreover their accuracy has not been sufficiently proved until now.

Risk Items by Estimate of Fatigue Strength and Life of Technical Systems Elements

A complicated technical system contains lot of different functional units their sub-groups and single elements which one can divide from point of view their function on primary and secondary parts. It can be supposed that an eventual failure of secondary parts does not threat the safety or the function of the whole device and therefore they are not usually object of design calculations and tests. A failure of a primary part of a technical system means however or significant limitation or total failure of system or device functions. Elements from point of view of their failures can be divided in 2 groups:

1. ***Elements which failure does not threat working safety or lives of people*** (when this failure occurs in a mass production it is solved usually ex-post and all of measures accepted are focused on searching and removing of failure causes).
2. ***Elements which failure significantly threaten the safety and usually can cause even a catastrophic consequence.*** Therefore it is necessary to unfold considerable effort to exclude such of failures during expected or projected life (the term "excluding" we can understand as possibility of such failures with extremely low probability).

Number of elements in single groups, production magnitude of single structures types and their technical parameters determine then the philosophy of project of its single elements. The terms as ***safe-life, fail-safe, damage tolerance*** [ ] are used not only in the aircraft industry where such kinds of dimensioning were developed.

- So called ***Safe-life*** way of technical systems dimensioning results from the demand that during projected life can not rise fatigue failure of not any part of the system (eventually probability of its rise during given time interval of technical life is extremely low). This procedure is used namely by parts which cannot be regularly checked during working and by parts which ere not advanced in any way so that their eventual failure would threaten working safety.
- The ***fail-safe*** dimensioning of structure raised from the demand of utilization of system which accepts rise of failures however excludes sudden collapse of the whole system. So understood idea of projecting is based on condition that in the case of primary part failure should be secured during limited amount of time (for example till failure removing) that remaining parts of structure should be able to carry actual working loads (for example a bar structure when during failure of one of bars is the strength flow carried by other bars not to lode a loading capacity of the whole structure).
- Presented approach was gradually generalized into philosophy so called ***damage tolerance***. Failures of fatigue macro-cracks fractures of connecting elements (for example screws threads welds etc.) are not excluded but there are accepted measures which must secure their timely identification and prevent their widening into such measure which could cause a serious or catastrophic failure. It deals namely with the realization of periodic checks system with application of indication methods for failures disclosure. This extremely low probability P can be understood in machine building industry probability less then 10^{-3} to 10^{-5} (in mass production for example car building industry) or in aircraft building industry which accepts probability of catastrophic failure $P=10^{-6}$ in the end of aircraft working life.

The four principal factors which influence the structure design procedure significantly rise in all presented cases are: ***working load*** – usually defined by loading spectrum, ***material*** – especially its strength, cyclic and fracture properties, ***form of the component*** (detail) – over all different stress concentrators, ***production technology*** and acting of the most significant

system ***working factors*** in the certain conditions of utilization and their intensity acting mainly on surface of tested parts.

Working Loads

Life of the structure depends in the large scale on stresses of its single elements and parts are determined by loads during its working. Therefore it is necessary to get as representative record of working loads and their working spectra to be able to create a calculation model of a structure or to make a relevant laboratory tests using structure models or even the structure.

They are built usually by working records of different working conditions which should create the set with the typical composition of working of examined TS. There are worked out one dimensional spectra of loads amplitude frequency or so called rainflow matrixes (two parametrical matrixes of frequencies of upper and lower extremes (or means and amplitudes) usable in procedures of calculations. Load spectra are usually determined using examination of system prototypes or their former generations eventually they can be developed from similar structure spectra. Some design load spectra can be standardized [4].

Properties of Structure Materials

It is important besides of principal material values obtained from pulling rest to determine material properties during cyclic load and fracture characteristics too. It is however necessary to understand the obtaining determination of such material constants is always connected with the certain object examined (especially its form, surface quality, heat treatment and especially its absolute magnitude). It is important to take into account in the case of results extrapolation onto different conditions. The fact is the change in time of the most of material parameters during working of a structure (for example a cyclic softening or hardening etc.) eventually their change due to acting of higher or lower temperatures comparing to the ones detected during tests.

Form of the Detail

The allocation of stresses inside the examined element in the elastic state is determined by the form of the detail, its border conditions (seating), kind of the load and elastic parameters of material. It is necessary to realize a detailed state of stress analysis to be able to perform strength and fatigue calculations. Not only classic methods of elasticity and strength are used but numeric procedures too as Finite Element Method (FEM), Border Element Method (BEM) or some others. When is necessary to perform an analysis of the real local stresses and deformations it is usually necessary to apply calculations behind the limit of proportionality in the elastic-plastic area of material behaviour of to “adapt” into the notch.

Technology and Working

Exactly the surface layer is the determining location for the initiation of different defects by the most of metal building and machine structures where the surface layer structure does not much differentiate from the core of detail. Therefore this initiation depends significantly on the surface quality and on the stresses in the surface layer including the residual stresses (coming from the realisation of former technological operations or loading histories) [2]. The working conditions and outside surroundings factors aggressiveness are

also tightly connected to the changes of surface layer properties during technical life of a part or detail [3]. It is possible to talk about the so called degradation of material during working of a structure connected with the influence of surrounding and the change of material characteristics in time. Its influence is in practice taken in the account by means of choice (increasing) of safety coefficients values.

Fatigue Failures and Safety of Technical Systems

One of areas for application of risk control methods in design and exploitation of technical systems is working strength estimation of their single parts and with it connected fatigue life estimation. The realised analysis of working failure causes and breakdowns of different technical systems shows clearly that nearly in all cases a fatigue process was presented as a result of a repeated dynamic load, mostly in synergy with another damaging process such as corrosion, dry friction, material defects, temperature changes etc.

We must know which risk items influence probability of failure of the system parts and propose to the user some measures for their control it means their minimisation or total elimination. For an illustration is on Fig.3 analysed a causal dependence of a steel structure of a lifting machine failure its related a risk factors depending on its safety level after [5].

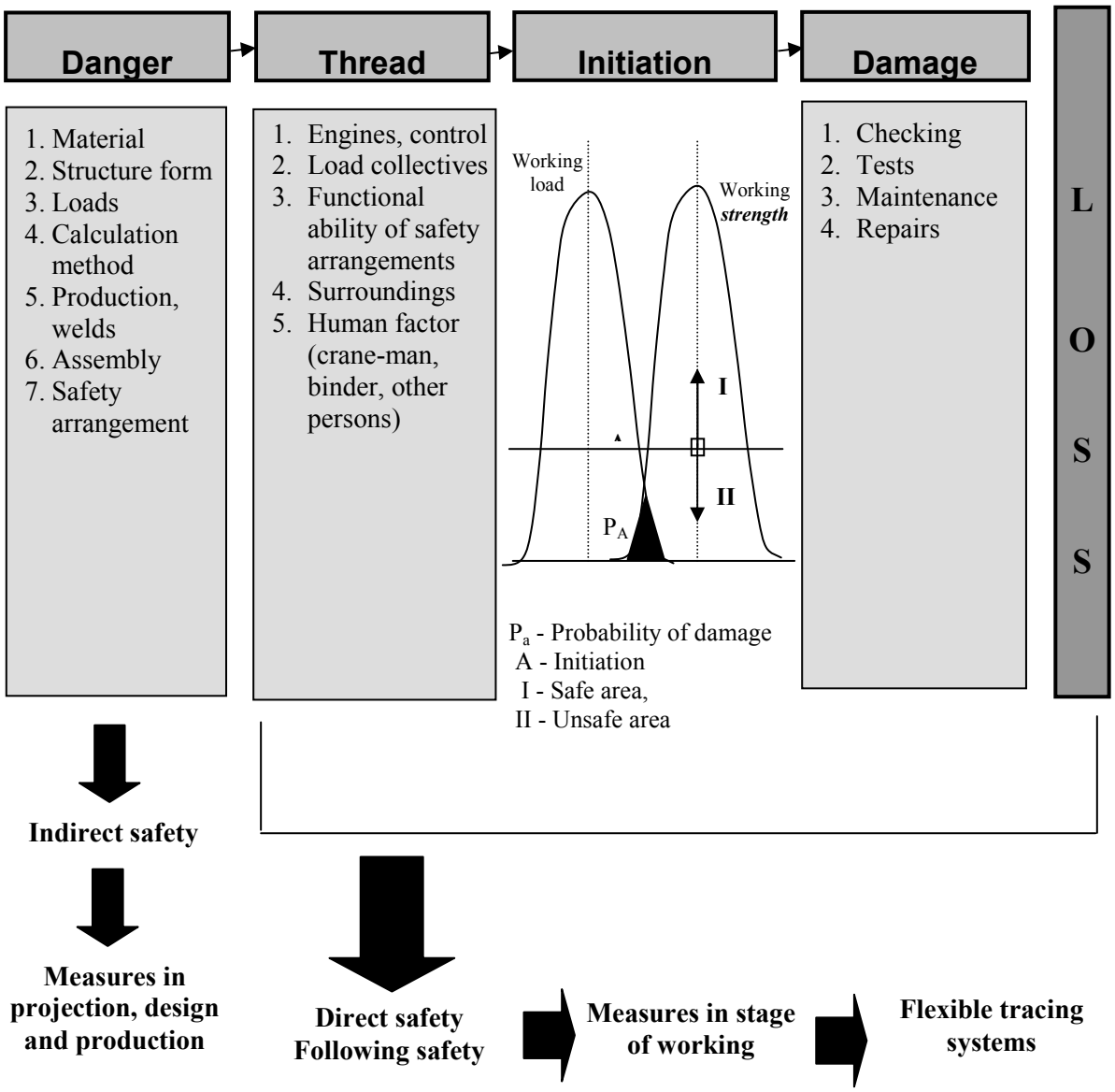

Fig.3.: *Causal dependence of a steel structure of a lifting machine failure [6]*

Procedure of fatigue life estimation of single elements and with it connected risks by prediction of working strength are based on defining of two principle variables – ***load (stress, strength)*** and ***loading capacity***.

1. Real stress of structure part can be recorded just on the base of experimental methods application during technical life of system which is in practice namely for usual types of machine structures just difficult solvable mainly there where the load are of stochastic nature. One of available procedures with high grade of reliability approximation is use of simulation methods based on mathematical model of explored system or its part. This procedure is naturally marked with error which is directly connected with defined risk item – load!

2. Loading capacity is expressed in form of material characteristics which are usually available just for some material samples. Taking in account of working parameters means change of curve form which is called in literature as working life curve.

Fig.4.: *Fracture surface of the axle of the railway bogie [7]*

Further important risk items by fatigue life parameters prediction are also the parameters connected with the detail size, type of notch, loading frequency (Fig.4), state and quality of surface, working temperature etc. which influence material properties and by them form of life curve too. It was proved [6] that especially insufficient knowledge of derivation value of fatigue life curve and not taking in the account the profiles form nonlinearities could lead to the marked divergence in the obtained values of examined parameters.

Conclusions

The estimate of structure part life with respect to its fatigue often distinguishes in fact from the value obtained in the real working. The main reasons are mainly problems with exact determination of outside loads parameters which have an effect on the structure during its working. The values of fatigue strength for examined part of structure are mostly not available. They are usually available just for the specimen of structure materials used. They represent just the ideal state which occurs in the real conditions of applying very rarely. It is obvious that if the information's about acting working conditions factors would not be sufficient they can rise serious inaccuracy in the algorithm of fatigue life estimate and the predicted value would be markedly different from the real one obtained in the real working.

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Resumé

Jednou z oblastí pre aplikáciu metód riadenia rizika pri návrhu a exploatácii technických systémov je problém odhadu prevádzkovej pevnosti jednotlivých častí a s ním súvisiaca predikcia únavovej životnosti (ÚŽ) ich vybraných konštrukčných častí. Analýzy príčin prevádzkových porúch a havárií rozličných TS jednoznačne dokazujú, že takmer vo všetkých prípadoch bol prítomný únavový degradačný proces ako dôsledok opakovaného dynamického namáhania, väčšinou v synergii s ďalším poškodzujúcim procesom, ako korózia, suché trenie, chyby konštrukčných materiálov, výkyvy teploty apod.

Moderný výpočet rozličných technických systémov (najmä veľkorozmerných strojných a stavebných konštrukcií) preto z hľadiska možností vzniku rôznych prevádzkových zlyhaní a havárií vyžaduje, aby v čo najväčšej miere rešpektoval dynamickú, ale najmä stochastickú povahu všetkých pôsobiacich faktorov prevádzkových podmienok a z nich vyplývajúcich prevádzkových zaťažení. Dominantnou snahou je najmä priblíženie priebehu výpočtového odhadu resp. realizovaného experimentu reálnym podmienkam prevádzky, v ktorých je skúmaný systém exploatovaný. Cieľom je najmä redukcia neznalosti pôsobiacich faktorov okolia a ich interakcií s procesmi prebiehajúcimi v samotnom systéme.

Ak úvahy o riešení problematiky odhadu únavovej životnosti obmedzíme výhradne na pevnostnú problematiku a neuvažujeme súvisiace metódy teórie mechanizmov, dynamiky strojných agregátov a ďalších vedných disciplín, potom sa vo všeobecnosti jedná o štyri základné oblasti záujmu :

- *výber kritických miest konštrukcie, ktoré sa stanú predmetom ďalšej analýzy,*
- *určenie namáhania skúmaných kritických miest a jeho následné spracovanie metódami vhodnými pre odhad životnosti,*
- *návrh nových alebo posúdenie aktuálnych pevnostných a únavových vlastností materiálu skúmaných častí na základe zvolených materiálových charakteristík a*
- *výber vhodného výpočtového postupu, tzv. hypotézy kumulácie únavového poškodenia (HKÚP), ktorý uvedie do súvislosti informácie o zaťaženiach a materiálových vlastnostiach. Výstupom je kvantifikovaný odhad ÚŽ analyzovanej časti.*

Po získaní a spracovaní uvedených skupín informácií možno získať konkrétne hodnoty odhadu únavovej životnosti skúmaných častí systému, ktoré sú dôležitou informáciou pri posudzovaní aspektov bezpečnosti ich prevádzkovania. Z pohľadu posúdenia bezpečnosti technických systémov ako celku je rozhodujúcim kritériom najmä predikcia životnosti do porušenia ich hlavných častí, realizovanú s ohľadom na rôzne teórie kumulácie únavového poškodenia. Hlavným dôvodom odlišnosti predikovanej hodnoty únavovej životnosti a hodnoty dosiahnutej v reálnej prevádzke je najmä problém dostatočne presného určenia parametrov pôsobiaceho prevádzkového zaťaženia, vyvolaného synergiou pôsobenia jednotlivých faktorov reálnych prevádzkových podmienok a ich intenzít. Jedná sa predovšetkým o problémy súvisiace s presným určením parametrov vonkajšieho zaťaženia, ktoré počas prevádzky na konštrukciu pôsobí. Vo väčšine prípadov taktiež nie sú k dispozícii hodnoty únavovej pevnosti pre skúmaný uzol konštrukcie, ale obvykle iba pre vzorky použitých konštrukčných materiálov, ktoré však predstavujú ideálny stav, ktorý sa v reálnych podmienkach nasadenia vyskytuje iba zriedka. Z uvedeného je zrejmé, že ak informácie

o pôsobiacich faktoroch prevádzkových podmienok nebudú dostatočné, v algoritme predikcie spoľahlivosti sa objavia vážne nepresnosti a predikovaná hodnota bude výrazne odlišná od skutočnej hodnoty dosiahnutej v reálnej prevádzke.