FATIGUE OF MATERIAL - A RISK FACTOR OF DESIGN AND EXPLOITATION OF TRANSPORT MACHINES

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Anotácia: *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.*

Kľúčové slová: dopravný stroj, spoľahlivosť, únava materiálu, kumulácia únavového poškodenia, odhad únavovej životnosti, zaťaženie, únosnosť.

Summary: Material fatigue of different technical systems' parts belongs to the most frequent causes of boundary states' occurrence and relating operation breakdowns. Paper contains general formulation of reliability of technical systems' judging, brief characteristic of basic areas to be taken into account as an input into calculated estimation of technical systems' fatigue life and analysis of risk factors during practical application of fatigue damage estimation.

Key words: transport machine, reliability, fatigue of material, cumulating of fatigue damage, fatigue life prediction, load, loading capacity.

1. INTRODUCTION

Material fatigue of different technical systems' parts belongs to the most frequent causes of boundary states' occurrence and relating operation breakdowns 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.

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2. JUDGING OF A TECHNICAL SYSTEM RELIABILITY

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 **apriory (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 **aposteriory (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 [3].

It expresses reliability in the form of a series synthesis in the form of

$$\mathbf{F(t) \Rightarrow [TS] \Rightarrow \sigma_x(t) \Rightarrow Z(t) \Rightarrow T(Z_c) \Rightarrow R(t).}$$

$F(t)$, $\sigma_x(t)$, $Z(t)$, $T(Z_c)$ are general random functions of time with the meaning:

$F(t)$ - stochastic working load of technical system [TS] as a time function,

$\sigma x(t)$ - 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 [TS] and fatigue characteristics of used material,

$T(Z_C)$ - 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,

$R(t)$ - 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.

3. BASIC AREAS IN 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 [1,2]:

- *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 judgment 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.

3.1. 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.

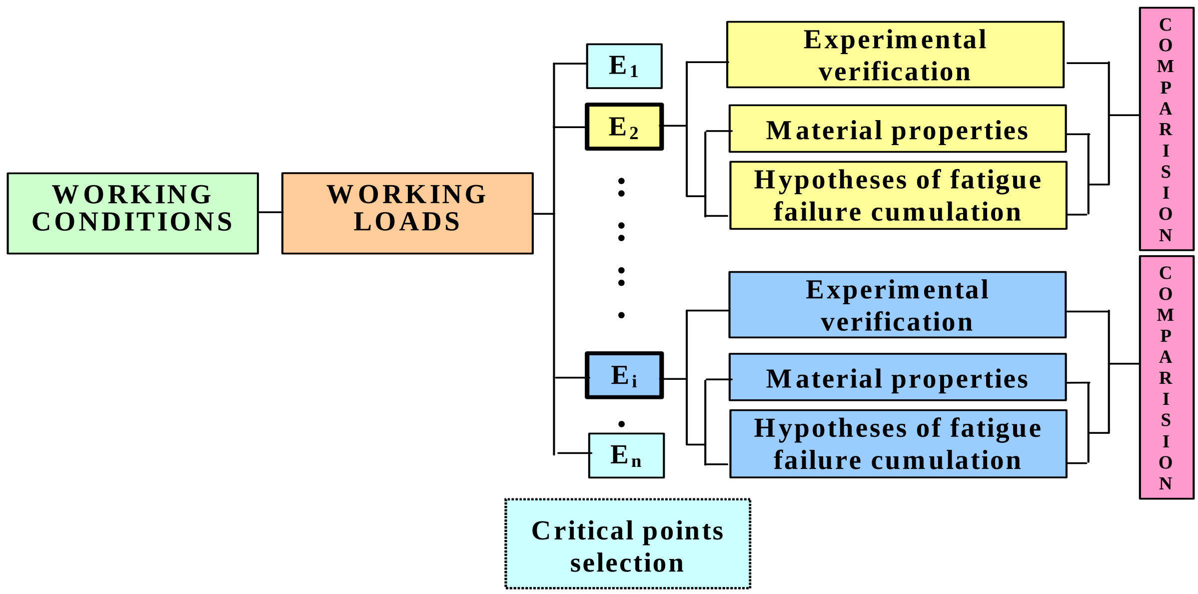

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Fig.1 - General procedure of fatigue life problems solutions

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 realized 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].

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 [3,4].

3.2. Strength and fatigue properties of 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 [3].

The oldest but until now utilized characteristics of material is the ***Wöhler curve*** (Fig.2a) 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 σc [4]. It can be expressed in a mathematical way by equation (1) or taking in account fatigue limit σc 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 - fatigue strength coefficient and b - 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.2b) 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.

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

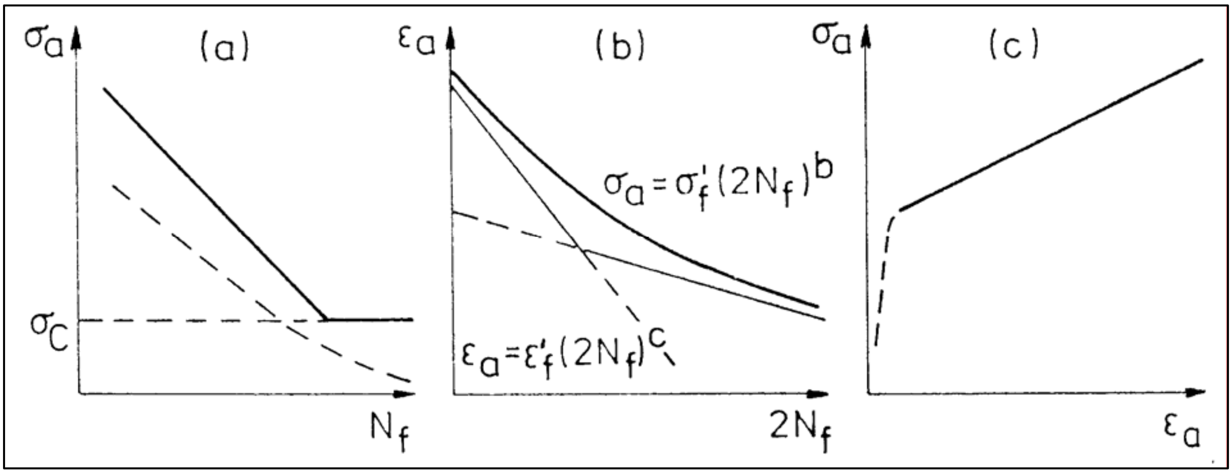

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Fig.2 - Wöhler curve (a), Manson-Coffin curve (b), cyclic deformation curve (c)

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.2c) which is expressed in form [4]

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

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 (4).

3.3. 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) [2,4] 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 [3] 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 [3,4].

4. RISK FACTORS IN FATIGUE LIFE AND SAFETY PREDICTION

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.

In accordance with the guideline Nr. 89/392/EC of European Council each designer should know the risk connected with accompanying effects of the proposed solution it means also the risks which are components of strength check. He must know which risk factors 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 fatigue life estimation after [5].

Calculation or rather estimation of structure parts life often in reality differs from the value reached in real working. Main reasons are namely problems connected with an exact determination of a characteristic parameter of outer loads acting on the structure during its working. Nearly in all cases there are not available values of fatigue strength for tested part of a structure but only the values for material samples. It is an ideal state, which is in real working conditions very rare.

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

The load rises as a result of working conditions. For the purpose of simulation procedures it is often expressed in the form of loading spectrum (collective) which can be constructed on the base of the known procedures. Real working loads of system result in dependence on its structure in different loads in single functional systems. To be able to define load collective in complex of the explored system it is necessary to identify a kind of external load, point of its acting and to know its time dependence. Each kind of working and different production technologies are characterised with different forms of collectives. Relating to the safe dimensioning of the single system parts on fatigue it is suitable for a designer to know the real structure load already in the stage of calculation, for example, in a form of database. Real load collectives are not mostly known in the stage of design and if they are known so just for strictly specified group sort of systems. Therefore, we can define the load collective as a relevant risk factor.

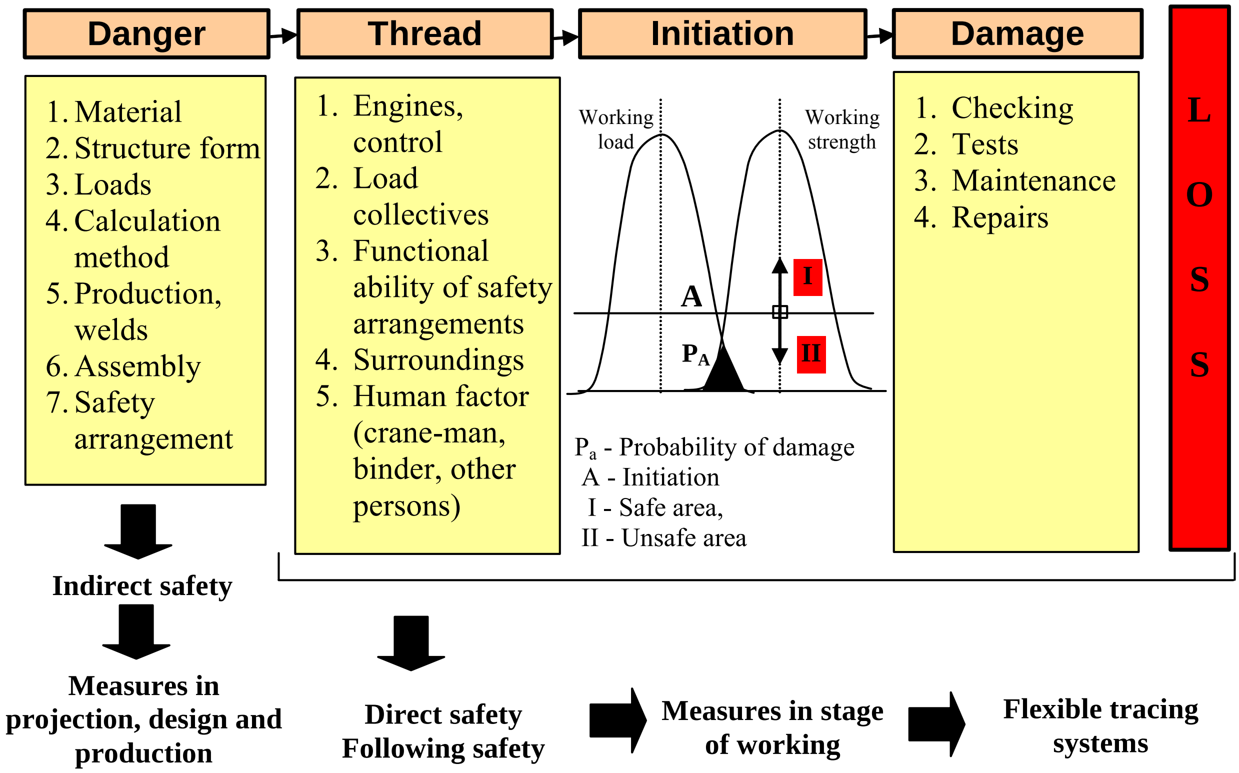

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Fig.3 - Risk factors in estimation of carrying parts of lifting machine life

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 factor – ***load***.

Loading capacity is expressed in form of material characteristics (most often Wöhler curve) 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. Further important risk factors in life estimation are the *parameters related with dimensions of a part, its form, type of notch, state and quality of surface, loading frequency, working temperature etc. which have influence on material properties and connected form of life curve*. It was proved that namely insufficient knowledge of fatigue curve derivation value and insufficient taking in account of form non-linearity of profiles of analysed parts of structures lead to relevant differences calculated values of life from the real ones.

5. CONCLUSION

Relevant occurrence of working failures and breakdowns caused by fatigue process show us all the time that our level of knowledge in this field and namely its application are still not on the wanted level. Therefore, the aim of this paper was to characterise the most relevant factors going into the calculated estimation of fatigue life and to show some of risks connected with defining of factors acting in the procedure of fatigue life estimation and with correlated risks of instability rise of technical systems. It is evident that in case of insufficient information about acting factors of working conditions rise in the algorithm of life estimation relevant errors and estimated value will be significantly different from the real one.

REFERENCE

[1] KLIMAN, V. - JELEMENSKÁ, J.: Fatigue reliability evaluation of structure under random loading using safety criterion - Part I. Methodology. Metallic Materials - Nr.39, SAV Bratislava 2001, p.199-217.
[2] SCHNEIDER, J.: Introduction to Safety and Reliability of Structures. IABSE. Structural Engineering Documents, 1997.
[3] MELCHER, R.: Structural Reliability Analysis and Prediction. Second edition. John Wiley & Sons, 1999.
[4] RŮŽIČKA, M.: Kritéria a postupy při posuzování únavové pevnosti a životnosti konstrukcí (http://mechanika.fs.cvut.cz/sources_old/pzk/obsah.html), ČVUT – FS, Fakulta strojní, Praha 1999.
[5] SINAY, J.: Riziká technických zariadení – manažérstvo rizika. OTA, Košice 1997.

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