JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
52, 2, pp. 443-458, Warsaw 2014

ASSESSMENT OF THE FATIGUE LIFE OF MACHINE COMPONENTS UNDER SERVICE LOADING – A REVIEW OF SELECTED PROBLEMS

Włodzimierz Będkowski
Opole University of Technology, Opole, Poland; e-mail: w.bedkowski@po.opole.pl

Based on a literature review, the author provides a historical outline of the fatigue analysis and describes the current trends aiming at comprehension of the fatigue life of engineering structures under service loading. Next, an algorithm for multiaxial fatigue life prediction is identified, describing steps of calculation. Classification criteria of fatigue failure and components of the stress state in multiaxial loading conditions are also presented, recognising the importance of the so-called Standarised Load Histories (SLH) used in the comparative analysis of fatigue life of finished products.

Keywords: fatigue life prediction, multiaxial fatigue, service loading

1. Introduction

The phenomenon of mechanical damage of structural materials of machine components, technical appliances, constructions and other systems, causes, in the course of their normal operation, local decohesion of a material. It is the reason for many failures and even accidents. The term structural material is used deliberately because, as Kocańda (1985) presents in the preface to his book, it is not the material that is damaged but an element made from it. Both, the effects and costs of this phenomenon can be unpredictable. They range from a temporary exclusion of a machine until it is mended, through serious and costly repairs of complex machines or processing lines, and finally, to the loss of health or even the loss of life of the users. As described by Stephens *et al.*. (2000), the estimated costs of mechanical damage in the United States in 1978 amounted to $119 billions, i.e. 4% of the country's Gross Domestic Producs.

Mechanical decohesion of materials (cracking) is a very complex issue, and it occurs as a result of interaction of many different factors, such as:

- loads: external (forces and moments affecting the element under loading) and internal (residual, assembly and technological stresses), which may be static, monotonic, percussive or changing in time fixed with a constant or variable amplitudes, mean value and frequency. The loads may be simple, i.e. uniaxial (e.g. axis under rotary bending) or multiaxial (e.g. transmission shafts under bending and torsion),
- time of loads duration: may vary from a fraction of a second – percussive (e.g. fire from a gunshot) to centuries (e.g. bridges),
- temperature: from cryogenic (rocket liquid fuel tanks) to hundreds of degrees (rocket engine turbines). Temperature can be constant or variable in an element,
- corrosion: it occurrs due to the direct influence of aggressive environments on the material, such as fumes from a vehicle engine or salt water.

These factors may interact with each other, which often intensifies their destructive effects, and in connection with the element structure, (e.g. notches, joints,), manufacturing technology (e.g. quality of a surface, heterogeneity of the metallographic structure, grain structure, grain size, defects of materials), mechanical properties of materials (e.g. anisotropy), etc., give an evidence on the complexity of this phenomenon and the diversity of mechanical damage. However, 70-90% of all mechanical damages of structural elements occur due to material fatigue during its normal operation (Billy, 1988; Stephens *et al.*, 2000). At the same time, this type of damage is considered to be the most dangerous one – the crack initiation in structural elements is difficult to predict, and it leads to damage of the elements. Cracks commonly occur in simple, every-day use devices. Far more problematic is the occurence of fatigue cracks in more complex structural objects that must be reliable. Examples are huge constructions subjected to variable winds, tectonic movements, sea waves (e.g. bridges, chimneys, sea oil rigs), vehicles, where the load comes from vibrating masses moving on uneven roads or ground, or variable driving speed (e.g. vehicle suspension components, steering systems, wheel hub drives, bolt joints, connecting rods), vessels affected by sea waves (e.g. roofing, ship propeller shafts) or air fleet subjected to changeable air movements, turbulences during take-off and landing (e.g. chassis, suspension, aircraft wings, engine casings, electronic and hydraulic components).

Since the 80s of the last century, computer-aided engineering methods (CAD, CAM, CAE) have been intensively developed. Their integration with modern materials science made constructions relatively safe and optimally designed in terms of their lifetime characteristics as well as production and maintenace costs reduction.

At present, therefore, a significant issue in terms of technological and mainenance safety and cost reduction (Jakubczak and Sobczykiewicz, 1999; Kuropatnicki and Jakubczak, 2004) is to recognize a phenomenon of damage of structural materials under loading changing in time with a complex character corresponding to service loading conditions, i.e. problems of multiaxial fatigue of materials in the most general aspect, namely – macroscopic approach. Such an approach might offer a possibility of practical fatigue life prediction of designed elements already at the early stage of the design process.

2. A brief historical review on the research fatigue phenomenon

Time histories of service loadings usually have variable amplitudes with different frequencies and with a complex generating system giving multiaxial, non-synchronic loadings. They are difficult to determine in terms of types and time histories. It is recognized that the nature of these charges is stochastic, i.e. random in the time domain (Bagci, 1980; Będkowski, 2005a,b; Billy, 1988; Kocańda and Szala, 1985) with defined mean values and with different cross-correlations of loads and their probability distributions. With a simplified approach, it is assumed that these sequences are stationary, i.e. their statistic parameters can be determined on the basis of a registered for a sufficiently long time observation.

Globalization and global market competitiveness, adaptability of products to fit user needs and high requirements imposed by global standards force designers to quickly develop new equipment solutions for the enhanced durability, reliability and safety and being capable of operating under random multiaxial load, while reducing their technology and operating costs. This requires developing of effective methods for fatigue life prediction of structure elements for given operational conditions.

Fundamental researches on fatigue life estimation have been carried out for over 170 years. Historically, it dates back to the 40s of the 19th century, when repetitive damage of rails was observed in the rail industry. At that time, in order to reduce the occurrence of this unwanted phenomenon, the elimination of the existing sharp edges in rails was proposed.

The precursor of systematic fatigue studies and research was, in the 50s and 60s of the 19th century, Wöhler who performed many laboratory tests under uniaxial variable sinusoidal loading. He elaborated solid foundations for further analysis (Wöhler curve, $\sigma_a - N_f$, or S-N) and gave possibility to compare fatigue properties of different materials. Until present, Wöhler's curve, is regarded as a standard characteristic of materials for a given type of loading. It is used for fatigue lifetime assessment as a number of cycles to failure versus the stress amplitude for a high cycle fatigue (HCF) range, i.e. under disregarded nominal plastic strains. He also observed that for the tested materials there is a certain stress amplitude value below which the fatigue failure of the material does not occur; the value of the amplitude is currently called the fatigue limit.

In 1910, Busquin demonstrated that the dependency of the stress amplitude vs. the number of cycles to failure in the range of HCF $(\sigma_a - N_f)$ is linear in the log-log scale, Fig. 1. Therefore, the fatigue characteristics of the material can be described using Eq. $(2.1)_1$ or $(2.1)_2$

$$\log N_f = -m \log \sigma_a + A \qquad\qquad \sigma_a = \sigma'_f (2N_f)^{-\frac{1}{m}} \tag{2.1}$$

where

$$A = m \log \sigma_{af} + \log N_0 = \text{ const} \qquad\qquad \sigma'_f = 10^{\frac{A+\log 2}{m}}$$

and m, σ_{af}, N_0 and σ'_f denote material constants for a given type of loading determined on the basis of standard fatigue test specimens.

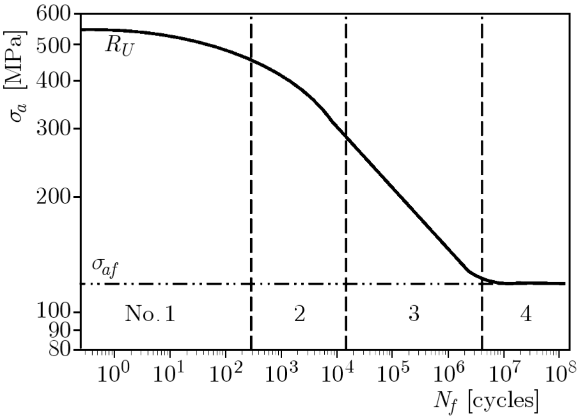

Fig. 1. Ranges of fatigue lifetime of structural steel in an exemplary diagram

To describe the fatigue limit of materials in the LCF range, the Manson-Coffin (Manson, 1960) characteristics are used. Equation (2.2) describes the fatigue test results in form of the amplitude of plastic strain ε_{ap} against the number of reversals of the load to failure $2N_f$

$$\varepsilon_{ap} = \varepsilon'_f (2N_f)^c \tag{2.2}$$

or dependencies of the total strain ε_{ac} of $2N_f$ given by Morrow (1965) and described as

$$\varepsilon_{ac} = \varepsilon_{ae} + \varepsilon_{ap} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f (2N_f)^c \tag{2.3}$$

These are experimentally generated dependencies, where the material constants σ'_f and b are determined on the basis of standard high-cycle fatigue tests under the controlled stress amplitude, while ε'_f and c are determined under the controlled strain in the low-cycle fatigue (LCF).

A full fatigue characteristic of material is presented schematically in Fig. 1, depending on the kind of the material and the type of loading, and comprises 4 areas of lifetime:

1) quasi-static, from 0.25 to 100-500 cycles,
2) Low Cycle Fatigue (LCF), from 100-500 to 10000-50000 cycles, strain field is used, Eqs. (2.2) and (2.3),

3) High Cycle Fatigue (HCF) from 10^4-$5 \cdot 10^4$ to 10^6-10^8 cycles, stress field is used, Eqs. (2.1),
4) infinite (below fatigue limit), more than 10^6-10^8 cycles, in which it is assumed that the material does not undergo fatigue damage. In this area, the methods of fatigue endurance estimation are formulated.

Nowadays, the research is carried out to formulate the mathematical description of processes leading to initiation and development of fatigue cracks in structural materials. There are many scientific papers concerning sinusoidal loading in phase (Achtelik *et al.*, 1983; Dietman *et al.*, 1989; Nishihara and Kawamoto, 1945; Troschenko and Sestopal, 1975) or with a phase shift between the components of the stress state (Dietman *et al.*, 1989; Kanazawa *et al.*, 1977; McDiarmid, 1985; Nishihara and Kawamoto, 1945; Rotvel, 1970; Simburger, 1975; Susmel *et al.*, 2003; Zamrik and Frishmuth, 1973) or taking into account the impact of load mean values (Bardenheier and Rogers, 2004; McDiarmid, 1985; Pawliczek, 2004; Susmel *et al.*, 2003). These models for fatigue life assessment have a limited range of applicability and cannot be used under random or service loading conditions.

From the beginning of the 1980s, owing to the widespread computer access, software development and implementation of digital microprocessor technology in the control systems of fatigue test machines, scientific analyses have been intensely developed in the subject of multiaxial fatigue under random loading.

In general, as was found by Leese and Mullin (1991), at present, the multiaxial fatigue research is being realized in the following three ways:

1) computer modelling with the use of numerical methods in mechanical engineering and CAD, CAM, CAE, or a specialised commercial software in connection with the state-of-the-art and commonly accepted standards (Chen *et al.*, 2001; Dannbauer *et al.*, 2004),
2) tests of finished components and equipment in laboratory or polygon conditions, or in the simulated load supplies, or monitoring facilities during their normal use by users (Bächström *et al.*, 2004; Kocańda *et al.*, 2004; Sonsino, 2003),
3) fundamental fatigue research under multiaxial loading conditions, verification of the proposed mathematical models based on fatigue tests of specimens under complex, variable amplitude loading conditions (Bardenheier and Rogers, 2004; Będkowski, 2005; Saathoff *et al.*, 2004).

The first group of activities concerns design and technological offices with engineers working on development of new structures with the use of commercial programmes offered by well known engineering software producers.

The second group – the tests are conducted primarily in large laboratories, mainly for the automotive, aviation and space industries with cooperation with scientific centres. Due to their commercial nature, the obtained results are not disseminated. An example of such type of research is testing of the horizontal flight stabilizer of Airbus A320 using 17 hydropulses at the Spanish CASA company in the aerospace laboratory presented by Cabralles and Diez (1990).

The third group of the research aims to recognize and to describe fatigue cracks in materials. The goal is to formulate general calculating methods which allow one to effectively evaluate lifetime of a given type of structural material under any selected loading conditions. In this group, two main approaches can be distinguished:

- Analytical methods, which rely on the assumption that the fatigue life is a function of the spectral characteristic of load histories (Będkowski *et al.*, 2004; Grinienko and Szefer, 1976; Lachowicz *et al.*, 1996; Moril *et al.*, 1998; Wirshing and Haugen, 1974). The basis for assessing the lifetime is the comparison of the spectral characteristics of random loading in structural elements under service conditions with some characteristics obtained in experimental tests carried out under similar loading conditions for the specimens. Methods that belong to this group are most commonly used at the designing stage, assuming a priori the expected lifetime of a device based on the known spectrum of loading.

- Algorithmic methods are based on realisation of instantaneous values of stress or strain state components (Będkowski and Macha, 1987; Szala, 1979; Wirshing and Shekata, 1977). An important issue in these models is the transformation of a random course of stress or strain on the equivalent factor in terms of fatigue life, i.e. a number of cycles with given amplitudes. For this purpose, methods for schematisation of random histories called the cycle counting methods are used.

Loading histories, stress or strain components are obtained by measurements on real objects or calculations with the use of numerical methods. Thus, the calculated results are used in the algorithms which take into account the proposed mathematical models of the fatigue life assessment and for accurate reconstruction or generation of loadings for given statistical parameters on test stands – in order to obtain fatigue test results which can be used for verification of the proposed theoretical models (Heuler and Klätschke, 2003; Xie and Hobbs, 1999).

Another comprehensive approach to the problem of fatigue design of structural elements subjected to fatigue loading is the concept of Sobczykiewicz (1974), which relies on "dimensioning fatigue" of bearing structures for objects produced at least in small series. This method is implemented within the process as research, development, implementation (RDI) of a new product. It is based on a sequential lifetime assessment, in which as further information in the range of lifetime and loading is obtained, as the results realising the RDI process. Then, decisions are made about the general size of the overall and local structural nodes, connections, also in intensity, types, location and size of allowable defects (for example in weld joints) provide the required information about fatigue properties of the materials and production technologies. The results of it should lead to the fulfillment of the required fatigue life conditions determined at the initial stage of the RDI process with the total manufacturing and exploitation costs established as the lowest. Such a determined dimensioning concept is introduced into the algorithms which include sets of carefully selected, interrelated, fatigue life estimation methods.

3. General algorithm for fatigue life evaluation under multiaxial service loadings

The general algorithm of the fatigue life assessment in the third group of investigations has already been presented by Będkowski and Macha (1987). For multiaxial random loading conditions, the procedure does not differ from the one used in the complex cyclic loading conditions, and it is composed of several calculation blocks as shown in Fig. 2. Each block of this algorithm requires selection of a suitable mathematic model for the existing loading conditions, material used, geometry of the element, computational capabilities, technical experience, etc.

Block 1 is based on the information about damage and failures that occured during machine operation or as a result of a real object testing in field. An analysis of the critical spots in the structure is performed, where the cracks appeared, which determines the endurance of the component. This process of obtaining a sufficiently large database is time-consuming and costly. Another method is to use numerical methods in mechanical engineering. They enable one to determine stress or strain distribution on a virtual object for given conditions, and then to identify the most strained spots in the structure. However, there is a need for proper identification of the component external loads and a thorough knowledge of structural properties of the tested material. This method is much faster and cheaper, especially at the stage of designing new constructions. It requires a high level of engineering experience, though.

Block 2 is realised through measurements of the dynamic strain state or digital simulation by generating time courses with given parameters, representative measurement lengths in time of strain state components. Also, by using an appropriate mathematical model, distribution

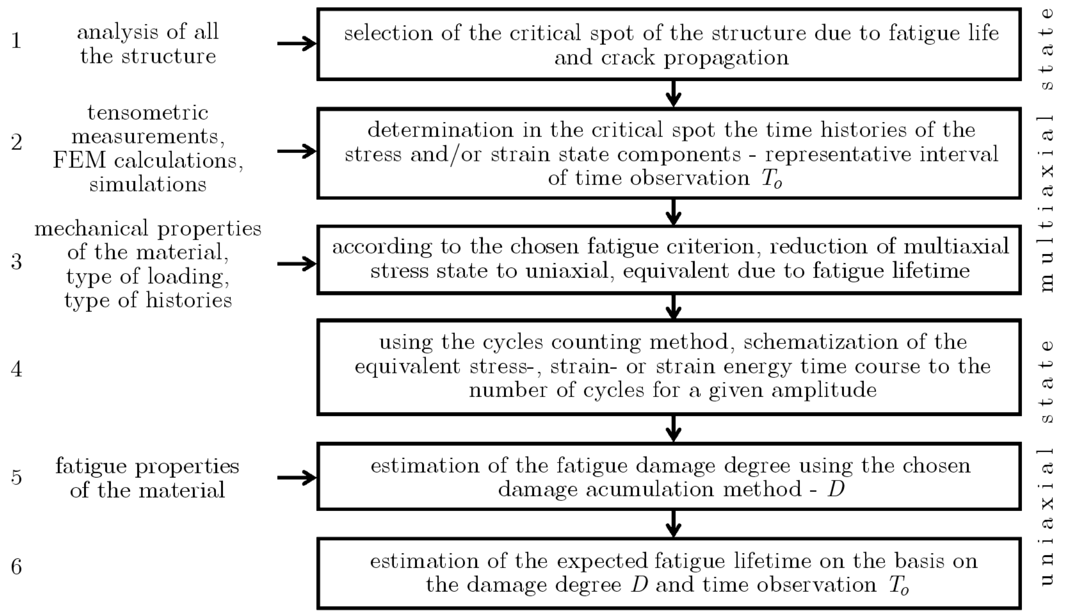

Fig. 2. Algorithm for fatigue life assessment of machine components under multiaxial service loading

components of the stress state in critical spots of the structure are indirectly received. It should be noted that the length of the observation T_o cannot affect the calculated fatigue life, so this algorithm can only refer to stationary time courses. In addition, it has to be assured that the selection of the optimal length of measurement should be chosen together with a proper frequency sampling. This will allow for correct assessment of the damage degree D, and at the same time, minimization of its calculation time (Macha and Stężała, 1985).

In Block 3 there is a reduction of the multiaxial stress or strain state to the equivalent one in terms of fatigue life in the uniaxial state. Selection of the appropriate for the used material and loading conditions strength criterion, is the most important and difficult element in the presented algorithm. For over 100 years, a number of fatigue failure criteria with various scopes of application, which often gave results different from the actual ones, have been formulated. Classification of the fatigue failure criteria, sometimes referred to as strength hypotheses, is very complex and depends on the nature of loading, the fatigue strength range, the period of the fatigue process (initiation or crack propagation) and the state of the material.

The most general division of these criteria is the following:

- In the stress field, mostly used in the range of long-term (HCF) and unlimited fatigue strength, based on components of the stress state.
- In the strain field, used for the short-term (LCF) fatigue strength formulated by components of deformation.
- In the energy field, based on the strain density or stress-strain, where components of stress and strain states occur as dimensions deciding about lifetime. They are used in a wide range of the fatigue strength.

Several of these criteria, most widely used nowadays, rely on the assumption that what decides about the fatigue life is the parameter specified in the criterion. It acts on a certain critical plane which is related to the analysed point in the structure. The orientation of this critical plane depends on material properties, the load history and nature of the stress- or strain-state that acts in it. An overview of the most commonly applied theories on the background of factors affecting the orientation of the critical plane was presented by Będkowski and Macha (1987), Brown and Miller (1992), Garud (1981), Sines and Ohgi (1981), You and Lee (1989), Zenner (2004), among others. An exhaustive analysis of the fatigue critical planes was described by Będkowski *et al.* (1989, 1995), where the following methods of prediction of the critical plane direction were presented: the method of *weight function*, method of *damage accumulation* and method of *variance of the equivalent stress*. The last one, based on fatigue tests carried out under multiaxial random loading for different kinds of materials, gives the best accuracy in the fatigue life prediction (Będkowski *et al.*, 1986, 1988, 1989, 1995, 1999).

Block 4 – here the time course of the equivalent stress or strain formulated according to the previously adopted criterion is replaced by the distribution of amplitudes and frequency in the measured observation time. Many methods of cycle counting have been developed (Wirshing and Haugen, 1974), among which the most common are: full cycles, range pairs, hysteresis loop and rain flow. These well known methods have been widely described, among others, by Dmitricenko (1967), Dowling *et al.* (1972, 1982), Kocańda and Szala (1985), Okamura *et al.*, (1079), Szala (1979). The rain-flow method is characterised by clarity, easiness of programming and by giving the best results. It is the most widely used and refered to the world standards (AFNOR A03-406, 1993, BS 5400, 1980, E 1049-85, ASTM, 1991).

Block 5 – here the linear or non-linear hypothesis of damage accumulation is used. It is assumed in them that each fatigue cycle (whose amplitude is above a certain level, determined in the hypothesis) causes a certain degree of damage. It depends on the strength of the material for a given value of the amplitude of the cycle. Once all degrees of damage for all amplitudes included in the observation time are added according to the method specified in the hypothesis, the cumulative damage is obtained. The most widely applied fatigue damage accumulation hypotheses are: linear hypothesis of Palmgren-Miner (Palmgren, 1924; Miner, 1945) by Haibach (1970), Serensen *et al.* (1975) and non-linear hypotesis of Corten-Dolan (1956). These hypotheses were presented also by Fatemi and Yang (1988), Yono (2003), Szala (1979).

Block 6 is used to estimate the predicted fatigue life based on the degree of damage calculated in block 5 for given measurements and observation time.

An interesting, comparative analysis of seven different commercial computer codes for prediction of fatigue life was made by Sonsino *et al.* (2004). By comparing the results of calculations and fatigue tests, it was shown that there is a very large scatter and uncertainty of the calculated fatigue lives. It was also indicated that these calculating codes require a lot of experience of the user and, in order to achieve a better compliance of the calculated results with the real ones, they need continuous upgrading with new mathematical models.

A valuable synthesis concerning the foundations of multiaxial fatigue, both theoretically and practically was made by Zenner (2004). He pointed out the direction and scope of the future work on the multiaxial fatigue: "...collection and evaluation of experimental data on the fatigue strength of samples and components..., analysis of methods for calculation in simple and complex load cases..., comparision between calculation and experiment on a broad basis, and thus validation and elimination of the field of application, ...development and improvement of methods for calculation; designing of software for general access...". On the basis of analysis of wear and damage of motor vehicle elements, he concluded how significant for a correct life prediction a proper classification of the observed loads is. Moreover, he also proved that even uniaxial loading can cause the multiaxial stress state in a structural material.

4. Classification of stress state histories under multiaxial loadings

The classification of time loading histories of stress at the critical spot is very important owing to range of use of the proposed stress/strain criteria and fatigue damage accumulation hypothesis.

This classification distinguishes:

1) the shape of wave form of loading: sinusoidal (harmonic), triangular, rectangular, trapezoid;

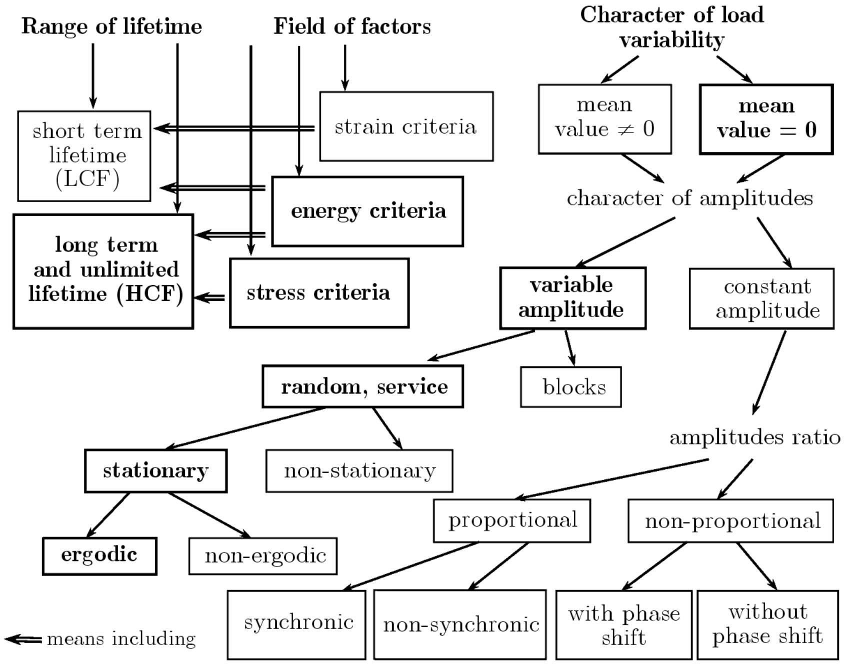

Fig. 3. Classification of load histories and fatigue failure criteria

2) the nature of amplitude:
   a) constant-amplitude (cyclic) or
   b) variable-amplitude:

   block (programmed), which are blocks of stress or strain courses with a specific number of cycles at a given amplitude level, mean value and frequency, (Kocańda and Szala, 1985; Szala 1979),

   random (stochastic – variables indexed in time):
   - stationary, i.e. their probabilistic relationships do not change with a shift in time,
   - ergodic, there are stationary, in which all realisations are "typical", i.e. the knowledge of a single implementation for a sufficiently long time observation allows one to determine the probability distribution and other parameters, while in other, hypotetically identical (governed by the same probabilistic relationships), or for a different time segment of the same process. This means that by determining the effect of action of the course within an infinite time interval, one can estimate the effect of action of the entire course,
   - service time course of the components of the stress state occurring in real structural elements during their normal operation. It is generally assumed that they are variable-amplitude, random, with different character and type of correlation relationships, however in the case of long-term fatigue or unlimited strength they can be assumed stationary and ergodic;

3) the relationships between histories of the stress state:
   a) proportional, with a constant ratio of instantaneous values of components for random loading, called correlated, or with a reciprocal correlation coefficient $r_{Xi,j}$ close to 1 or -1, where Xi,j are the components of stress or strain state,
   b) non-proportional or non-correlated,
   c) synchronous, compatible according to the shape, direction of change and frequency, where proportional waveforms are always synchronous, but not all of those synchronized are proportional,

   d) non-synchronic,
   e) with a phase shift between components of the stress/strain state for sinusoidal runs – with a non-zero angle of phase shift φ_f, for variable amplitude courses, time interval τ_f specifying the time offset of the courses;

4) the mean value:
   a) with the zero mean value $\sigma_m = 0$ for cyclic loads, called the symmetrical load,
   b) with a non-zero mean value $\sigma_m \neq 0$, for sinusoidal histories with the characteristic parameters used: the stress ratio $R = \sigma_{min}/\sigma_{max}$ or stability of load $\kappa = \sigma_m/\sigma_a$.

The above described classification of loading histories, together with the classification of fatigue failure criteria according to the range of liftime is shown in Fig. 3. It is seen quite complex as its particular types often occur at the same time, for example, the histories may be sinusoidal with a constant amplitude, non-zero mean value, and synchronic. In this digram, the paths, which are the author's research field concerning the fatigue life assessment of machine components are marked in bold.

5. Standarized load histories

As previously highlighted, the fatigue life of a stuctural component significantly depends on the loading. Standard fatigue tests under constant-amplitude loadings are valuable for determination of fatigue characteristics of materials. They also allow to initial selection of appropriate materials for a structure and are used in the algorithms to evaluate fatigue lifetime or endurance as material constants. It is also known that the obtained test results and proposed models under a constant-amplitude loading may be inadequate or unsatisfactory for accurate prediction of the fatigue life under the real operation with multiaxial loading of changeable amplitudes. Therefore, tests of components or whole constructions under loading in the conditions approximate close to the real ones are performed in industrial laboratories. The tests aim at developing the optimal design or at obtaining fatigue endurance certificates for the already existing solutions of constructions. In order to obtain comparable tests results of different structural elements or subsequent versions of engineering solutions or machines of similar types, but produced by different manufacturers, standard time variable-amplitude histories have been developed and applied giving benefits both in terms of general knowledge of the phenomenon as well as the practical application. These load histories are obtained through their recording on respective groups of devices in real service conditions, which are then processed in order to obtain the maximum reduction of the test time while maintaining relevant in terms of fatigue strenght conditions. An example of such a method of transforming a waveform load was proposed by Palin-Luc *et al.* (2004). It consists in the fact that the extremes of waveforms are filtered below a certain limit for loads that do not result in the initiation of micro-cracks and their development, thus they do not affect fatigue durability. As shown by the authors, the use of such a compressed time course gives 6-10 times shorter time of testing.

Standarised Load Histories (called SLH) are now available, which offer a choice of possible types of loads appropriate for given constructions, components or elements as well as loading conditions. An extensive list of such waveforms, currently used in industrial laboratories and research centers together with their characteristics and the range of application were presented by Heuler and Klätschke (2003). Table 1 presents a list of the currently used SLH in Europe, and Table 2 presents a list of the currently used SLH in USA. According to Heuler and Klätschke, the use of standard loading histories is recommended because of the following reasons:

- determination of fatigue lifetime of specimens or elements made of different materials, or based on different technologies,

- optimisation of machine components or structures,
- determination of acceptable stress limits in the preliminary stage of fatigue design of machine parts,
- analysis of methods increasing the fatigue life,
- verification of models for fatigue life prediction and crack propagation,
- investigation of the scatter band in fatigue test results,
- development of joined research programs in cooperation with a number of laboratories on the general problem of fatigue and crack propagation,
- generation of the database for comparison of measurements with the actual results,
- fatigue tests of prototypes until detailed loading conditions are made available.

Table 1. Standarised load histories used in Europe, according to Heuler and Klätschke (2003)

No.	Name	Range of application	Components or machines	Description of load history	Block velocity [cycles]	Relevant service lifetime	Year of issue
1	WASH 1	sea offshore platform	components of platforms	narrow-band loadings with 6 sates of sea intensity	$5 \cdot 10^5$	1 year	1989
2	WAWESTA	drive rolls	set of drive components	sequences of 10000 rolls	28200	1 month	1990
3	CARLOS	standard loads of car (3-axis sequences)	forces acting on suspension parts: a) vertical b) transverse c) longitudinal	random with fragments of deviation of the mean value, combination of 5 types of road	a) 136000 b) 95200 c) 84000	40000 km	1990
4	CARLOS multi	standard loads of car (multiaxial)	4 channels loads of the front suspensions components	time courses, sampling period 0.005 s, correlation functions of loaded items based on directing functions	such as CARLOS uniaxial	40000 km	1994
5	CARLOS PTM	vehicle drive system (manual gearbox)	parts of gearbox, i.e. clutches, gears, shafts, bearings, universal connections	loading histories and torque moment sequences and speed, separately for 5 gears, variants of test optimized for different groups	depends on transmission gear	6000 km	1997
6	CARLOS PTA	vehicle drive system (automatic gearbox)	similar to CARLOS PTM	similar to CARLOS PTM	depends on transmission gear	6000 km	2002
7	CARLOS TC	connection of the trailer with car	connection components	load courses (longitudinal, transverse, vertical), optimized in terms of time and test comfort	3 short blocks	verification of total endurance	2003

8	TWIST	transport airplanes	bending moment of wing root	constant, positive mean value for loading from blow winds, cycles of overload at takeoff and landing (GAG – ground-air-ground)	402000	4000 flights	1973
9	Mini TWIST	short version of TWIST	bending moment of wing root	skipping small cycles of blast of wind	62000	4000 flights	1979
10	GAUSSIAN	general used, random sequences	random, narrow to wide band, (3 levels of irregularity)	$I = 0.99$ –constant σ_m $I = 0.70$ – small changes of σ_m $I = 0.33$ – significant change of σ_m	$10 \cdot 10^6$ $1.4 \cdot 10^6$ $3.3 \cdot 10^6$	—	1974
11	FALSTAFF	fighter aircraft	wing root	spectrum of the maneuvers, moderate changeability of mean value, GAG	18000	200 flights	1975
12	HELIX, FELIX	helicopter joints and fixings of rotors	bending of rotor blade	blocks of cycles with different amplitudes and mean values	$2.3 \cdot 10^6$ $2.1 \cdot 10^6$	140 flights	1984
13	HELIX/32, FELIX/28	shortened versions HELIX, FELIX	bending of rotor blade	blocks of cycles with different amplitudes and mean values	$2.9 \cdot 10^5$ $3.2 \cdot 10^5$	140 flights	1984
14	Cold TURBISTAN	tactical aviation	components with holes	extremes of cycles with a high mean value and without compression of loading	7700 3200 1000	100 flights	1985
15	Hot TURBISTAN	tactical aviation	rims	like Cold TURBISTAN, with controlled periods (in total 8 hours/100 flights) with different mean values of stress	8200	100 flights	1989
16	ENSTAFF	FALSTAFF + temperature	wing root	like FALSTAFF with additional 6 levels of temperature	18000	200 flights	1987
17	WISPER/ WISPERX	wind turbines (X-short version)	anti-plane bending of blade	blocks of loading histories from blast of winds with constant mean value	132700/ 12800	2 months	1988

The benefits of using loadings similar to service loadings are as follows:

- availability at each stage of development,
- reduction in the number of test parameters,
- comparability of test results,
- relative reliability of lifetime estimation for currently ongoing projects and selected loads based on fatigue properties determined under comparable conditions,
- possibility of using as a certificate of fatigue reliability under service loading.

More examples regarding practical application of standard loadings in fatigue analysis and design of machine elements such as parts of vehicles, railways, pipelines and their welded or

Table 2. Standarised load histories used in USA, according to Heuler and Klätschke (2003)

No.	Name	Range of application	Type of load	Block size No. of cycles)	Year of issue
1	TRANSMISSION	gear boxes of tractors	torque moment	854	1977
2	SUSPENSION	suspension of vehicle	bending moment	1253	1977
3	BRACKET	bearing brackets of vehicle, frames (rough road)	bending moment torque moment	2968	1977
4	AGRICULTURE TRACTOR	agricultural tractors, drive half-axle, several typical operations	bending moment torque moment	31800	1989
5	LOG SKIDDER	drive half-axle, operations in forests	bending moment torque moment	$3.1 \cdot 10^5$ $3.1 \cdot 10^5$	1989

threaded joints, as well as the methodology and theoretical basis of the fatigue life analysis is given by various authors in the book *Fatigue Design of Components*, 1997.

The range of usage of most of these histories is clearly defined since 1984 when the multiaxial loads have been introduced and corresponded more closely to real loading conditions of tested objects. Merely, the GAUSSIAN history, Table 1 item No. 10, has a general scope of application and seems to be the most appropriate for verification of experimental models for the assessment of fatigue life under multiaxial loading. Such a type of time courses is used by the author in his multiaxial fatigue test carried out on cruciform and tubular specimens made of different kinds of structural materials (Będkowski *et al.*, 1999, 2004, 2007). Implementation of standard loading histories which must be specifically reproduced on a test stand the process of fatigue testing, was possible only after using servo-hydraulic fatigue machines equipped with control systems working in a closed-loop. Examples of suitable stands for random biaxial tension-compression of cruciform specimens and for axial with torsion of tubular specimens, was described by Będkowski *et al.* (2005, 2007).

6. Summary

The paper presents an overview of the assessment of fatigue life of machine parts and structures under service loads. At the same time, the complexity of the problem and its multithreading is shown. In the author's opinion, the main problem is to formulate an appropriate fatigue criterion based on a load parameter (stress, strain, energy or other) which should allow including as many factors determining fatigue life of machine components and structures under operating conditions as it is necessary to determine the extent of applicability to a wide range of different structure materials. Such an accepted hypothesis, as a part of the overall assessment of the fatigue life algorithm, must be verified on the basis of results of fatigue tests carried out, in the first place, on samples subject to random multiaxial loadings and then on the real construction components.

References

1. Achtelik H., Macha E., Jakubowska I., 1983, Actual and estimated directions of fatigue fracture plane in zl250 cast iron under combined alternating bending and torsion, *Studia Geotechnica et Mechanica*, **N**, 2, 9-30
2. AFNOR A03-406, 1993, Fatigue of metals under variable amplitude loads – rainflow cycle counting method (in French), *AFNOR*
3. Bächström M., Koski K., Siljander A., Liukkonen S., Tikka J., Marquis G., 2004, Fatigue assessment of an aging aircraft's wing under complex multiaxial spectrum loading, *Pro-*

ceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF, Berlin, 595-600

4. Bagci C., 1980, Fatigue design of machine elements using the "Bagci line" defining the fatigue failure surface line (mean stress diagram), *Mechanical Engineering*, **17**, 2, 22-34
5. Bardenheier R., Rogers G., 2004, Experimental simulation of multiaxial stress states in material testing, *Proceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Berlin, 527-534
6. Będkowski W. Macha E., Ohnami M., Sakane M., 1995, Fracture plane of cruciform specimen in biaxial low cycle fatigue – estimate by varinace metod and experimental verification, *Journal of Engineering Materials and Technology, Transaction ASME*, **117**, 2, 183-190
7. Będkowski W., 2005a, Fatigue tests of materials under biaxial loading, test stands and methodology, [In:] New Results in Fatigue and Fracture, Vol. 2, *Zeszyty Naukowe Politechniki Opolskiej*, **306**, *Mechanika*, **84**, 9-30
8. Będkowski W., 2005b, Model for fatigue life estimation under multiaxial random loading and its verification based on fatigue tests results, *Zeszyty Naukowe Politechniki Opolskiej*, **304**, *Mechanika*, **82**, 1, 21-28
9. Będkowski W., Lachowicz C., Macha E., 1988, Predicted fatigue fracture planes according to variance of shear stress under random triaxial stress state, *Proceedings of the 9th Biennial European Conference on Fracture*, E. Czoboly (Edit), **I**, 281-283
10. Będkowski W., Lachowicz C., Macha E., 1989, The variance method of predicting the fatigue fracture plane under multiaxial random loadings, *Proceedings of 3rd International Conference on Biaxial/Multiaxial Fatigue*, Stuttgart, **1**, 7.1-7.18
11. Będkowski W., Łagoda T., Słowik J., 2007, Strain controlled tests for determining the change of the material fatigue parameters, *Materials Science*, **43**, 4, 492-498
12. Będkowski W., Macha E., 1986, The expected position of fatigue fracture plane according to variance of the reduced stress, *Proceedings of the 6th Biennial European Conference on Fracture*, Amsterdam, **2**, 1345-1352
13. Będkowski W., Macha E., 1987a, Computational – experimental methods to assess the fatigue life of machine components under multiaxial random loads (in Polish), *Prace Naukowe Instytutu Konstrukcji i Eksploatacji Maszyn Politechniki Wrocławskiej*, **50**, *Konferencje*, **13**, 163-170
14. Będkowski W., Macha E., 1987b, Methods for assessing the fatigue life of machine components under service loads (in Polish), *Przegląd Mechaniczny*, **21**, 87, 5-7
15. Będkowski W., Macha.E., 1989, Methods for estimating the position of the expected fatigue fracture plane under complex random stress state, *Prace Naukowe, Politechnika Warszawska, Mechanika*, **121**, 27-35
16. Będkowski W., Macha E., 1992, Fatigue tests of cruciform specimens under random loadings, construction of the stand and preliminary results, Reliability and Structural Integrity of Advanced Materials, *Proceedings of the 9th Biennial European Conference on Fracture*, Varna, **I**, 371-376
17. Będkowski W., Macha E., Niesłony A., 2004, Verification of the spectral method determining the fatigue life on the basis of steel 10HNAP (in Polish), *Przegląd Mechaniczny*, **12**, 13-1618.
18. Będkowski W., Weber B., Macha E., Robert J.-L., 1999, Comparison of variance method and damage indicator methods for prediction of the fracture plane orientation in multiaxial fatigue, [In:] *Multiaxial Fatigue and Fracture*, E. Macha, W. Będkowski, T. Łagoda (Edit,), ESIS Publication 25, ELSEVIER, 147-165
19. Billy M., 1988, *Fatigue Life under Stochastic Loads* (in Czech), Slovenska Akademia Ved, Ustav Materialov a Mechaniky Strojov, Bratislava
20. British Standard BS 5400: 1980, Part10: Appendix B, 29

21. Brown M.W., Miller K.J., 1992, Two decades of progress in the assesment of multiaxial low-cycle fatigue, [In:] *Low Cycle Fatigue and Life Prediction*, ASTM STP 770, C. Amzallag, B.N. Leis and P. Rabbe (Edit,), 482-499

22. Cabralles J.S., Diez P.C.G., 1990, A new facility for aircraft structural testing, *Closed Loop MTS*, **17**, 3, 2-10

23. Chen C.-S., Krause R., Petit R.G., Banks-Sills L., Ingraffea A.R., 2001, Numerical assessment of t-stress computation using a p-version finite element method, *International Journal of Fracture*, **107**, 177-199

24. Cheng X., Ohkawa I., Misumi M., 2004, Mean stress efect on cyclic deformation and short crack growth behaviour in torsional fatigue of steels, *Proceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Berlin, 259-264

25. Corten H.T., Dolan T.I., 1956, Cumulative fatigue damage, *International Conference on Fatigue of Metals*, London

26. Dannbauer H., Gaier C., Steinbatz M., 2004, A statistical measure of non-proportionality of stresses investigations and applications, *Proceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Berlin, 623-628

27. Dietman H., Bhonghibhat T., Schmid A., 1989, Multiaxial fatigue behavior of steels under in-phase and out-of-phase loading including different wave form and frequencies, *Proceedings of 3rd International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Stuttgart, 61.1-61.17

28. Dmitricenko S.S., 1967, Modern methods of accelerated tests of machines for fatigue strength (in Russian), *Vestnik Masinostrojenija*, **2**

29. Dowling N.E., 1972, Fatigue failure prediction for complicated stress-strain histories, *Journal of Materials, ASTM*, **7**, 71-87

30. Downing S.D., Socie D.F., 1982, Simple rain flow counting algorithms, *International Journal of Fatigue*, **5**, 31-44

31. E 1049-85, in: Annular Book of ASTM Standards, 1991, Section 3, Vol.03.01

32. Fatemi A., Yang L., 1998, Cumulative fatigue damage and life prediction theories: a survey of the state-of-the-art for homogeneous materials, *International Journal of Fatigue*, **20**, 1, 9-34

33. Marquis G., Solin J., edit., 1997, *Fatigue Design of Components*, ESIS Publication 22, Elsevier

34. Garud Y.S., 1981, Multiaxial fatigue: a survey of the state-of-the-art, *Journal of Testing and Evaluation*, **9**, 3, 165-178

35. Grinienko N.I., Szefer L.A., 1976, Spectral method for evaluating the fatigue life under random loadings (in Russian), *Problemy Prochnosti*, **1**, 9-22

36. Haibach E., 1970, Modified linear damage accumulation hypothesis to account the progress of damage for fatigue strength (in German), *Laboratorium fur Betriebsfestigkait, Darmstadt, Technische Mitteilungen TM*, **50/70**

37. Heuler P., Klätschke H., 2003, Generation and use of standardised load spectra and load-time histories, *Proceedigs of Conference on Fatigue Damage*, Seville, 175-185

38. Jakubczak H., Sobczykiewicz W., 1999, Valuing hydraulic excavator attachments, the concept of quality (in Polish), *Materiały XII Konferencji Naukowej Problemy Rozwoju Maszyn Roboczych*, Zakopane, **1**, 111-118

39. Jono M., 2003, fatigue damage and crack growth under variable amplitude loading and counting method of stress strain ranges, *Proceedigs of Conference on Fatigue Damage*, Seville, 54-62

40. Kanazawa K., Miller K.J., Brown M.W., 1977, Low cycle fatigue under out-of-phase loading condition, *Journal of Engineering Materials and Technology*, **9**, 222-228

41. Kocańda D., Kocańda S., Torzewski J., 2004, The speed of fatigue cracks in aerospace aluminum alloy with a programmable load spectrum, *Materiały XX Sympozjum Zmęczenie i Mechanika Pękania*, Bydgoszcz, 179-186

42. Kocańda S., 1985, *Fatigue Failure of Metals* (in Polish), WNT, Warszawa

43. Kocańda S., Szala J., 1985, *Fundamentals of Calculations of Fatigue* (in Polish), PWN, Warszawa

44. Kuropatnicki A., Jakubczak H., 2004, Evaluating in designing the supporting structures of machines - nominal stress concept (in Polish), *Materiały XX Sympozjum Zmęczenie i Mechanika Pękania*, Bydgoszcz, 209-216

45. Lachowicz C., Łagoda T., Macha E., 1996, Comparison of analitical and algorithmical methods for life time estimation of 10hnap steel under random loadings, *Fatigue'96*, G. Lutjering and H. Nowack (Edit.), vol. I, Berlin, 595-600

46. Leese G.E., Mullin R.L., 1991, The role of fatigue analysis in the vehicle test simulation laboratory, *SAE Technical Papers 910166*, Detroit, 12

47. Macha E., Stężała H., 1985, Modelling of stress random histories by sinusoidal histories of real time when fatigue life of machine or constructure elements is determined, [In:] *System Analyssis and Simulation*, 2nd ed., A. Sydow *et al.*, Akad-Verlag Berlin, 385-388

48. Manson S.S., 1960, Thermal stress in design. Part 19, Cyclic life of ductile materials, *Machine Design*, 139-144

49. Marin J., 1956, Interpretation of fatigue Strengths for Combined Stresses, *Proceedigs of International Conference on Fatigue of Metals*, London, 184-194

50. McDiarmid D.L., 1985, Fatigue under out-of phase biaxial stresses of different frequencies, multiaxial fatigue, *ASTM STP 853*, K.M. Miller and W.M. Brown (Edit.), Philadelphia, 606-621

51. Miner M.A., 1945, Cumulative damage in fatigue, *Journal of Applied Mechanics*, **12**, 159-164

52. Morill J.H., Achatz T., Khosrovaneh A., 1998, An application for fatigue damage analysis using power spectral density from road durability events, *SEA Technical Papers 980689*, Warrendale, 55-62

53. Morrow J., 1965, Cyclic plastic strain energy and fatigue of metals, [In:] Internal Friction, Damping and Cyclic Plasticity, *ASTM STP 378*, 45-87

54. Nishihara T., Kawamoto M., 1945, The strength of metals under combined alternating bending and torsion with phase difference, *Memoirs of the College on Engineering, Kyoto Imperial University*, **11**, 5, 85-112

55. Okamura H., Sakai S., Sususki I., 1979, Cumulative fatigue damage under random loadings, *Fatigue of Engineering of Material and Structure*, **I**, 409-419

56. Palin-Luc T., Banvillet A., Lasserre S., Vittori J.-F., 2004, A technique to reduce the duration of multiaxial fatigue tests under service loadings, *Proceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Berlin, 421-426

57. Palmgren A., 1924, Die Lebensdauer von Kugellagen, *VDI-Z*, **68**, 41, 339-341

58. Pawliczek R., 2004, The sensitivity of the material on load average in the fatigue (in Polish), *Materiały XX Sympozjum Zmęczenie i Mechanika Pękania*, Bydgoszcz, 311-318

59. Rotvel F., 1970, Biaxial fatigue tests with zero mean stresses using tubular specimens, *International Journal of Mechanical Sciences*, **12**, 597-613

60. Saathoff A., Stolze F.-J., Zenner H., 2004, Creation of a synthetic road for multiaxial fatigue limit simulation on automobiles, *Proceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Berlin, 541-546

61. Serensen S.V., Kogaev V.P., Snajdorovic R.M., 1975, The bearing capacity and strength calculations of machine parts (in Russian), *Mashinostroenie*, **3** 62.

62. Simburger A., 1975, Strength behavior of tough materials with a phase-shifted multi-axis vibration stress with body-fixed and variable principal stress directions, LBF Bericht, Nr FB-121, Darmstadt
63. Sines G., Ohgi G., 1981, Fatigue criteria under combined stresses or strains, *Journal of Engineering Materials and Technology*, **103**, 82-92
64. Sobczykiewicz W., 1994, Dimensioning of welded construction machine bearing in fatigue life (in Polish), *Prace Naukowe Politechniki Warszawskiej, Mechanika*, **157**, Warszawa
65. Sonsino C.M., 2003, Structural durability of cast aluminium gearbox housing of underground vehicles under variable amplitude loading, *Proceedigs of Conference on Fatigue Damage*, Seville, 134-142
66. Sonsino C.M., Zenner H., Yousefi-Hashtyani F., Küppers M., 2004, Present limitation in the assesment of components under multiaxial service loading, *Proceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Berlin, 17-25
67. Stephens R.L., Fatemi A., Stephens R.R., Fuchs H.O., 2000, *Metal Fatigue in Engineering*, John Wiley & Sons Inc., 2nd ed.
68. Susmel L., Tovo R., Lazzarin P., 2003, The mean stress influence on fatigue under multiaxial out-of-phase loading, *Proceedigs of Conference on Fatigue Damage*, Seville, 103
69. Szala J., 1975, The problem of approximation of load random variations on programmable fatigue life tests (in Polish), *Akademia Techniczno-Rolnicza w Bydgoszczy, Zeszyty Naukowe*, **26**, *Mechanika*, **11**, Bydgoszcz
70. Szala J., 1979, *Research and Fatigue Calculations of Machine Components under Random and Programmed Loads* (in Polish), IPPT PAN, Warszawa
71. Troschenko V.T., Sestopal L.F., 1975, Criteria of fatigue strength of metals in torsion (in Russian), *Problemy Prochnosti*, **2**, 3-7
72. Wirshing P.H., Haugen E.B., 1974, A general statistical model for random fatigue, *Transactions ASME, Series H*, **96**, 1, 34-40
73. Wirshing P.H., Light M.C., 1980, Fatigue under wide band random stresses, *Journal of the Structural Division*, July, 1593-1607
74. Wirshing P.H., Shekata A.M., 1977, Fatigue under wide band random stresses using the rainflow method, *Transactions ASME, Series H, Journal of Engineering Materials and Technology*, 205-211
75. Xie M., Hobbs R.E., 1999, A computer simulation approach for fatigue life prediction of engineering structure under random loading, [In:] *Engineering Against Fatigue*, J.H. Beynon, M.W. Brown *et al.* (Edit.), A. Balkema, 447-452
76. You B.R., Lee S.B., 1989, A critical review on multiaxial fatigue assesment of metals, *International Journal of Fatigue*, **11**, 353-359
77. Zamrik S.Y., Frishmuth R.E., 1973, The effects of out-of-phase biaxial strain cycling on low-cycle fatigue, *Experimental Mechanics*, 204-208
78. Zenner H., 2004, Multiaxial fatigue – methods, hypotheses and applications an overview, *Proceedings of 7th International Conference on Biaxial/Multiaxial Fatigue and Fracture, ICBMFF*, Berlin, 3-16

Manuscript received May 13, 2013; accepted for print September 6, 2013