fatigue life; experimental tests; calculations

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SELECTED ISSUES CONCERNING CALCULATIONS AND EXPERIMENTAL TESTS OF TRANSPORT MEANS CONSTRUCTION ELEMENTS FATIGUE LIFE

Summary. Development of an algorithm of fatigue life of structural components of road and rail vehicles as well as sea vessels and aircrafts involves three groups of activities connected with: development of fatigue load spectra on the basis measurement of service loads, determination of the construction material fatigue properties and a selection of the best hypothesis for estimating the fatigue damage to be used for a phenomenological description of the fatigue process.

The above listed groups of problems include the main causes of differences that occur between the calculation results and the results of fatigue life experimental tests. Evaluation of these differences is the main goal of this article.

WYBRANE ZAGADNIENIA OBLICZEŃ I BADAŃ DOŚWIADCZALNYCH TRWAŁOŚCI ZMĘCZENIOWEJ ELEMENTÓW KONSTRUKCYJNYCH ŚRODKÓW TRANSPORTU

Streszczenie. Algorytm obliczeń trwałości zmęczeniowej elementów konstrukcyjnych pojazdów drogowych i szynowych oraz statków morskich i powietrznych obejmuje trzy grupy czynności związanych z: opracowaniem widm obciążeń na podstawie pomiarów obciążeń eksploatacyjnych, wyznaczeniem własności zmęczeniowych materiałów konstrukcyjnych oraz doborem odpowiedniej hipotezy sumowania uszkodzeń zmęczeniowych stanowiącej fenomenologiczny opis procesu zmęczenia.

W wymienionych grupach zagadnień kryją się podstawowe źródła różnic pomiędzy wynikami obliczeń a wynikami badań doświadczalnych trwałości zmęczeniowej. Ocena tych różnic jest podstawowym celem artykułu.

1. INTRODUCTION

Fatigue life of structural components is affected by complexity of the object construction properties and its service loads, most often of random character. Although a lot of research has been done on this subject, due to complexity of the processes of material fatigue and fatigue cracking of structural components, the most commonly used methods are still those involving the hypotheses based on fatigue failures summing [1]. These calculations require possession of knowledge of service loads that affect a given element and cyclic properties of the material the element is made of, and the right choice of a hypothesis for summing fatigue failures.

The first group of factors which significantly affect the consistence of calculation results with fatigue life tests is connected with variable loads (fatigue) of a structural component.

Service loads of random character require application of suitable methods for determination of the so called load spectra [2]. These spectra are sets of sinusoidal cycles with variable parameters and of different forms. The material fatigue life and a fatigue crack of structural component are affected by the course of variable stresses or strains in the zones of their concentration [3].

The second group of factors affecting the consistence of calculations with tests results are those which are connected with determination and description of cyclic properties of the materials the analyzed structural components are made of. Many publications deal with the methods of determination of materials cyclic properties e.g. [7], as well as relevant norms. These properties are usually described by fatigue charts in the approach of: stress (Wöhler charts), strain (Manson-Coffin and Ramberg-Osgood charts) or energy.

Acceptance of a suitable calculation method for estimating fatigue failures is of key importance for consistence of fatigue life calculation and tests results [2]. Phenomenological hypotheses have practical application in construction calculations. Literature provides more than 30 different hypotheses, verified experimentally in different ways. Linear hypotheses belong to the group of the best verified ones. The impact of the above listed groups of factors will be discussed in the next section of the paper.

2. COMMENTS ON SERVICE LOADS

According to point 1, the material fatigue life and fatigue cracking is largely affected by the course of variable stresses or strains in their concentration zones referred to as weak links. In complex objects the zones of stress and strain concentration are connected with geometric discontinuities (groove effect) or structural discontinuities (welded joints). Determination of weak links in a complex object requires its division into assemblies, subassemblies of different kinds until elementary nodes are reached (e.g. specimens with notches). The authors of this paper have accepted that an elementary node is a part of a complex object which does not undergo further division due to the analyzed fatigue life. Usually the specimen containing a single notch or a zone of structural discontinuity (e.g. welded joint) is considered to be a component of this kind.

According to Tucker's model [4] fatigue life of an elementary node subjected to variable loads, such that occur in a notch, is equal to the complex object fatigue life. Thus, it is necessary to determine the courses of stress and strain in the place of their concentration (Fig. 1).

Since the cyclic properties of construction materials are determined in the conditions of sinusoidal loads there is a necessity to replace random loads, at the bottom of the notch, by a set of sinusoidal cycles – load spectrum, by using a suitable method of cycles counting.

There are several methods of counting cycles and some more methods for their modification. Methods that find a wider application include [5, 6]: peak counting method – PCM, simple-range counting method – RCM, full cycles counting method – FCM, range pair counting method – RPM, and rain flow counting method – REM.

According to work [5, 6] the spectra developed according to the above listed methods vary considerably, which has a large influence on the results of fatigue life calculations. This influence also depends on the character of service loading – random, described by the function of power density (characteristics of the spectrum width), the level of loading and the kind of material. Briefly speaking, the spectrum width is described by indicator $I = N_o/N_1$ (where: N_o – the number of crossing the chart medium level loads, N_1 – number of local extremes). Experimental tests show that the differences in fatigue life calculated in dependence on the applied cycle counting method and experimental method were as follows:

- for steel elements and $I = 0.56$ – more than 30 times,
- for aluminium alloy 2024 and $I = 0.75$ – more than 7 times,
- for steel and $I = 0.88$ – more than 5 times.

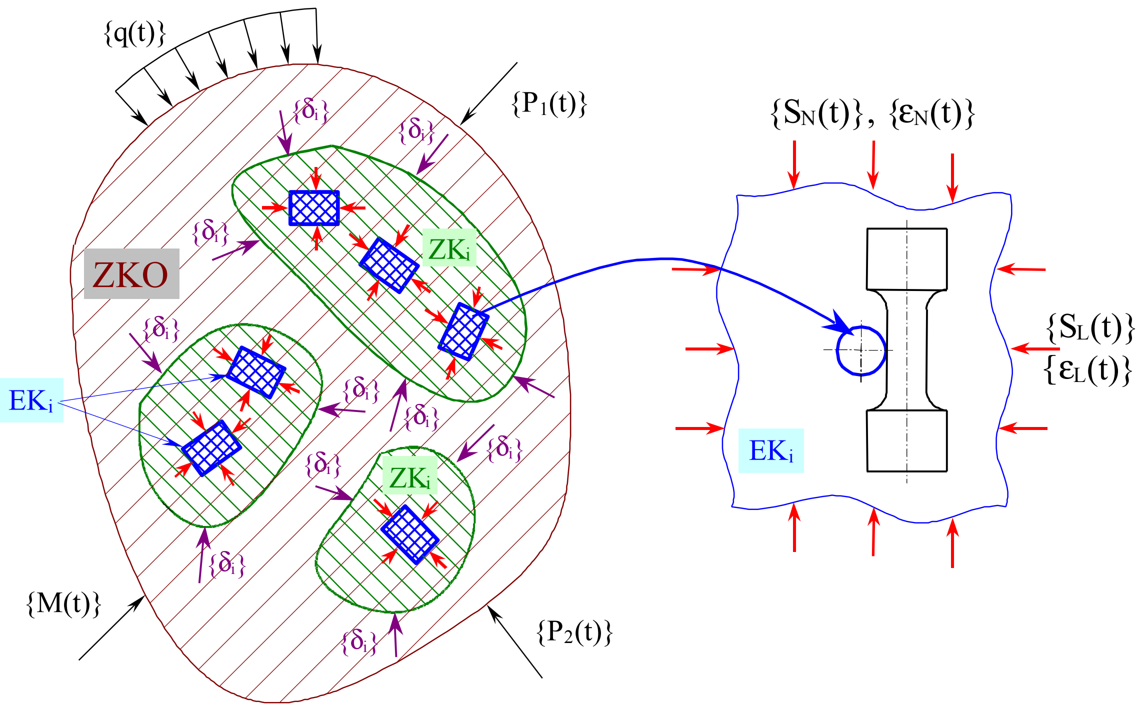

Fig. 1. Segment of decomposition of a complex structure ZKO into construction sets ZK_i until structural component EK_i is reached, where: ZKO – design assumptions of the object, ZK_i – the i-th set ZKO, EK_i – the i-th structural component

Rys. 1. Segment dekompozycji złożonej struktury ZKO na zespoły konstrukcyjne ZK_i do elementu konstrukcyjnego EK_i, gdzie: ZKO – założenia konstrukcyjne obiektu, ZK_i – i-ty zespół ZKO, EK_i – i-ty element konstrukcyjny

The examples of a detailed analysis presented in work [5, 6] prove that the differences between the calculation results performed with the use of particular methods depend on the value of coefficient I. Verification tests and calculation simulations were performed for a switch of a passenger car in variable service conditions. A comparison of calculation results performed according to particular cycle counting methods is presented in table 1, and selected exemplary fragments of service load charts with respective charts of spectrum power density, are shown in figure 2, where there are also values of coefficient I.

Table 1

Relative fatigue life calculated with the use of different cycle counting methods depending on the value of coefficient I

Cycle counting method	Coefficient of spectrum width I					
	0.8411	0.7588	0.7003	0.4455	0.3828	0.2570
PCM	1.0	1.0	1.0	1.0	1.0	1.0
RCM	11.3	9.5	7.0	3.5	20.6	129.4
FCM	2.9	2.4	3.0	3.5	3.3	19.0
RPM	2.7	2.2	3.1	1.6	2.8	13.2
RFM	6.4	5.6	7.0	5.2	5.6	62.7

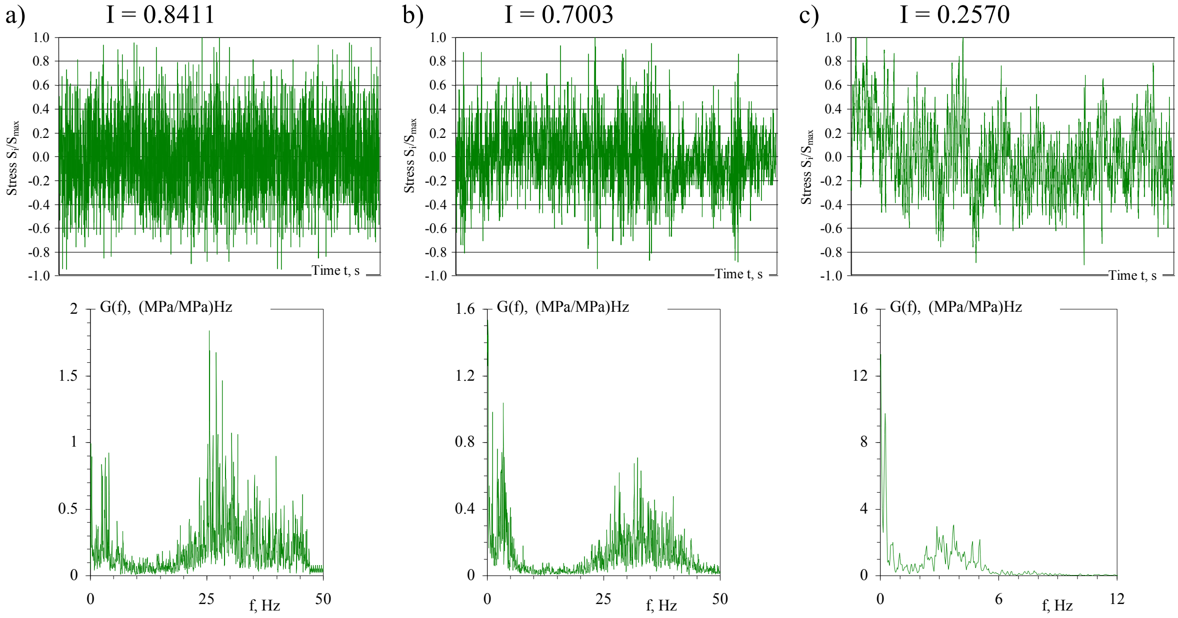

Fig. 2. Exemplary courses of loads applied to a passenger car switch: a) on cobblestones, b) on tarmac, c) field road

Rys. 2. Przykładowe przebiegi obciążeń zwrotnicy samochodu osobowego: a) na bruku, b) na asfalcie, c) na drodze polnej

The data presented in table 1 shows that the service spectrum width has a strong influence on the calculation results. In boundary cases, for I = 0.2570 these differences reach values nearly 130 times higher for RCM method than values for PCM method. Experimental verification of the considered cycle counting methods has proved that the methods which provide the most consistent results with experimental tests are: RPM, FCM and RFM.

3. INFLUENCE OF FACTORS CONNECTED WITH THE DESCRIPTION OF THE MATERIAL CYCLIC PROPERTIES ON THE RESULTS OF FATIGUE CALCULATIONS

Materials cyclic properties are described by means of fatigue life charts: in the stress approach – Wöhler charts, in the strain approach – Manson-Coffin and Ramberg-Osgood charts, and in the energy approach.

These charts are determined during fatigue tests in the conditions of sinusoidal loads and at different load levels. As we know, the results of fatigue tests, due to the process high complexity, are characterized by considerable differences in values and they require appropriate statistical approach as the number of carried out tests has a big influence of the description accuracy of the material cyclic properties.

Fig. 3 shows a fatigue chart determined on the basis of tests results performed on 321 steel specimens [8]. The chart line running through mean values of N is of complex shape, revealing distinct transition zones from the range of high cycle fatigue (HCF) into the range of low cycle fatigue (LCF), and in the transition zone from (HCF) to the range of fatigue limit (FL).

Charts of this type are approximated by means of straight lines in semi-logarithmic (S_a, logN) or bi-logarythmic (logS_a, logN) coordinate systems. Figure 3, where the basic chart has been replaced by a broken line, illustrates such an approximation.

The comparison of the basic chart with the approximation shows that there are significant differences between them especially in range I for transition from (HCF) into (LF) and in range III for transition from (HCF) into (LCF).

Moreover, the chart contains a schematic representation of the problem connected with the impact of lower stresses on fatigue life accounted for by modification of fatigue life charts 1 and 2 in the range below fatigue limit (FL).
The currently existing calculation methods for range III – LCF, offer a description of a fatigue chart in the approach of strain and energy. However, the calculation problem is connected with the fact that the load spectra mentioned in point 2 of this study, contain load cycles belonging both to range II – HCF and range III – LCF. For this specific case a hybrid method of fatigue life calculation has been proposed in work [8], which combines the stress approach within HCF with the strain approach of LCF.

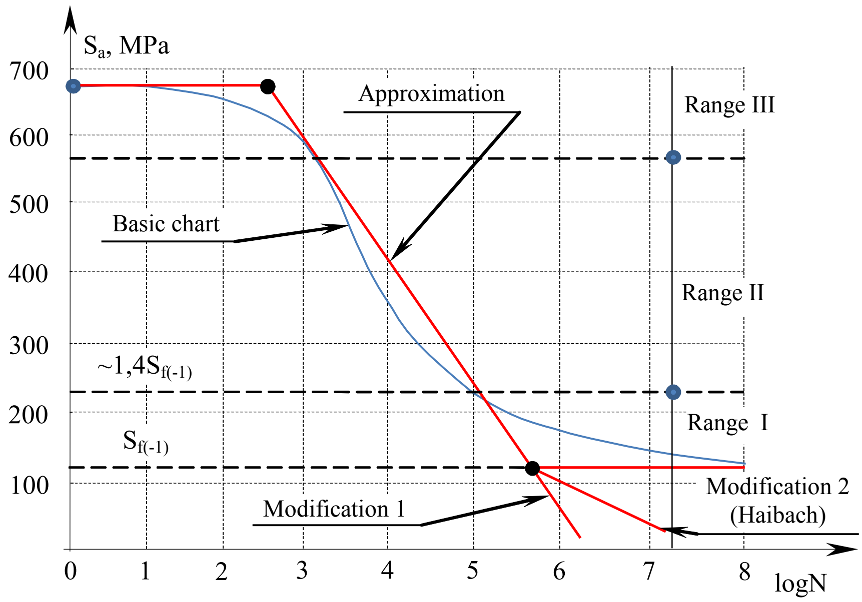

Fig. 3. Scheme of fatigue life chart approximation
Rys. 3. Schemat aproksymacji wykresu zmęczeniowego

A detailed analysis of factors connected with models of fatigue charts in the approach of strain which have an influence on the calculated fatigue life and consistence of these calculation results with the results of fatigue tests has been presented in work [8].

4. THE INFLUENCE OF FATIGUE FAILURES SUMMING HYPOTHESIS ON FATIGUE LIFE CALCULATION

Among numerous hypotheses used for summing fatigue failures it is the linear one of Palmgren-Miner (PM) that has found wide application. The basic form of this hypothesis is as follows: $\sum n_i/N_i = 1$, where: n_i – is the number of cycles with amplitude S_{ai}, N_i – the number denotes the amount of cycles until occurrence of fatigue crack under stress S_{ai}. Numerous verification tests, discussed also in work [8] reveal poor efficiency of the linear hypothesis in its basic form. Therefore, there has been a proposal for its modification to $\sum n_i/N_i = a$ form, where the coefficient depends on many factors which makes it more difficult to carry out the right choice of its values. The coefficient value is also the measurement of consistence of tests results with fatigue life calculation results $a = N_{ex}/N_{cal}$. This data has been confirmed, among others, in work where also the influence of load conditions, type of material and the form of specimens on coefficient a has been analyzed.

This analysis proves that the value of maximum and minimum stresses of the load spectrum is of large significance for the coefficient value, whereas high values a >> 1,0 can be reached in the conditions where S_{max} lies in the range FL of the fatigue life chart. Approximate variability ranges for ranges I, II, III from figure 3 are presented in table 2.

Table 2

Values of coefficient a for LCF, HCF and LF

Range	Value of coefficient a
I – FL	1.5 < a < 30
II – HCF	0.4 < a < 1.5
III – LCF	0.75 < a < 1.3

On the basis of 468 tests performed by the authors of this paper there have been elaborated charts of values of coefficient a for steel C45, steel X5CrNi18-10 and aluminum alloy AW-2017A shown in figure 4.

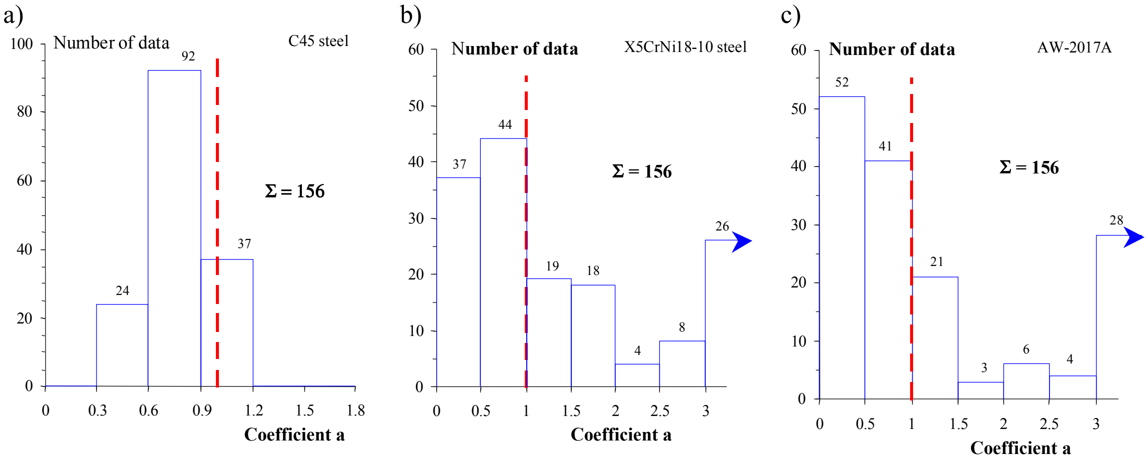

Fig. 4. Histograms of coefficient a for steel C45 (a), steel X5CrNi18-10 (b) and aluminum alloy AW-2017A (c)
Rys. 4. Histogramy wartości współczynnika a dla stali C45 (a), stali X5CrNi18-10 (b) i stopu aluminium AW-2017A (c)

The data presented in the charts reveal a significant spread of values of coefficient a, especially for steel X5CrNi18-10 and aluminum alloy AW-2017A significantly different from value a = 1.0.

The above presented data proves that for fatigue life calculations it would be advisable to recommend the following values of coefficient a: for steel C45 – a = 0.5, for steel X5CrNi18-10 and aluminium alloy AW-2017A – a = 0.3. Acceptance of these values provides high probability that the result will be on the safe side, that is the calculated fatigue life value will be lower than experimental fatigue life.

5. CONCLUSION

The analysis presented in this paper proves that there are many factors that affects consistence of calculation results with the results of tests on fatigue life of structural components exposed to loads of random character in service conditions. This is of key importance for designers who need to make a detailed analysis of loading conditions and materials cyclic properties in order to match them so that an appropriate assessment of fatigue life can be possible.

For development of load spectra according to measurements of service loads the following methods are recommended:

a) rain flow method for cycles counting, regardless of the service load spectrum width. For the analysis of internal loads distribution of complex structures (the system decomposition) and the course of variable stresses and strains, it is recommended to use the hybrid method: numerical-experimental in which measurements provide the basis for boundary conditions to perform numerical analyses by e.g. the finite elements method.

b) determination of materials cyclic properties should be consistent with adequate norms, whereas in case of welded joints – with appropriate procedures of e.g. classification institutions or the international institute of welding.
c) selection of a proper correction coefficient plays a significant role in the linear hypothesis of fatigue failures summing. A wide range of variability of the above mentioned coefficient involves the necessity to analyze its value on the basis of literature data on tests results performed on similar objects. Although the calculation methods are far from being perfect they are still a good tool for initial computing within a wide range of conditions variability. They are characterized by relatively low costs which limit the possibilities of experimental tests.

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