IDENTIFICATION AND MODELING OF MULTIAXIAL FATIGUE LOADING NON-PROPORTIONALITY

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Summary

The importance of fatigue non-proportional loadings in the estimation of fatigue life has been explained in the paper. The classification of computational methods of description of such load state has been presented. Authors introduced own fatigue criterion too. Also they presented a proposal of an experimental modeling of non-proportionality degree of fatigue loading, based on the methodology of programmed loading.

Keywords: fatigue, multiaxial loading, non-proportional loading, criteria.

IDENTYFIKACJA I MODELOWANIE NIEPROPORCJONALNOŚCI WIELOOSIOWEGO OBCIĄŻENIA ZMĘCZENIOWEGO

Streszczenie

W artykule wyjaśniono znaczenie zmęczeniowego obciążenia nieproporcjonalnego w szacowaniu trwałości zmęczeniowej. Przedstawiono klasyfikację metod obliczeniowych opisu tego stanu obciążenia. Zaprezentowano własne kryterium zmęczeniowe. Przedstawiono także propozycję eksperymentalnego modelowania stopnia nieproporcjonalności obciążenia zmęczeniowego, opartą na metodologii obciążeń programowanych.

Słowa kluczowe: zmęczenie, obciążenie wieloosiowe, obciążenie nieproporcjonalne, kryteria.

1. INTRODUCTION

Components of machines, vehicles and structures are frequently subjected to repeated loading which may lead to their failure due to fatigue. The majority of fatigue failure for the components in service is the multiaxial fatigue failure. The accuracy of prediction of fatigue properties on the basis of computational models depends, inter alia, whether rightly determined load quantities (such as: components of the stress/strain tensor, energy, stress intensity factor) and load parameters of these quantities (like amplitudes, the ranges of variability, the maximum values, average values or gradients) which affect the fatigue process. One of the load quantities, which may have a significant impact on the process of fatigue, is the loading non-proportionality. It exists always when there is non-proportionality between the stress and strain tensor components. Then we have to deal with the principle axis rotation.

The loading non-proportionality may cause different consequences. Depending on the non-proportionality degree and type of material, the effect of the non-proportionality may even lead to a 10-times decrease in fatigue life in relation to the proportionate loading of the same values of equivalent amplitudes [1]. The destructive influence of non-proportionality decreases with the decreasing of load level [2], but in the range of fatigue limit is also visible. In the least favorable conditions, a decrease of fatigue limit may be reduced to 25% [3]. Changes in life and fatigue strength under non-proportional loading are accompanied by characteristic formations of dislocation structures, additional material hardening and the characteristic development of fatigue cracks.

There are very many, very different ways of assessing the non-proportionality degree, while very few methods of modeling. The paper contains a summary of methods for assessing the degree of loading non-proportionality and presentation of the author's method of non-proportionality modeling.

2. METHODS OF DETERMINING THE DEGREE OF LOADING NON-PROPORTIONALITY

2.1. Non-proportionality measures determined on the basis of the nominal stress or strain

The angle of the phase shift between the sinusoidal components of the load variables is a simple example of the quantity describing the course of the nominal size of the load, which affects the degree of non-proportionality. The idea was used in case of S. B. Lee's criterion [4], where non-proportionality parts being functions of phase shift φ angle were proposed. However, this solution is always restricted to a particular loading case.

In the case of a random state of stress or strain to describe the degree of loading non-proportionality the correlation relations between the components of the state are used [5].

2.2. Non-proportionality measures formulated on the basis of the loading path geometry in one selected plane

The first sub-solutions are those for the load paths in the physical plane. Simple function of the non-proportionality for sinusoidal waveforms was proposed by Kanazawa [6]. To describe the non-proportional loading path of the coefficient called rotation factor was defined. This is a ratio of shear stress range at an angle of 45 degrees to the plane of maximum deformation range to the range of shear strain. For the phase shift angle $\varphi=0°$ this quantity assumes a value equal zero.

In author’s proposition the non-proportionality degree was described with a filling coefficient, defined as a quotient of the area within the loading path and the area of the circle described on the hodograph [7].Using weight function would mean acceptance of the assumption that loading non-proportionality is connected not only with the value of rotating vectors but also with their positions.

Loading paths may be considered not only in the physical plane but also on the octahedral plane. This way you'll be able to modify the criteria formulated on the basis of the stress tensor invariants. Methods of formulating non-proportionality measures of this group consist in replacing the shear octahedral stress amplitude by quantity formulated on the basis of the lading path lying on the octahedral plane. For example Duprat [8] considers load trajectory curve (ellipse) in the hyperplane of the deviatoric tensor.

2.3. Non-proportionality measures formulated on the basis the loading path geometry in two planes

The idea of formulating of the non-proportionality measures by examining the stress/strain components in the two planes was used in the energy parameter criteria and the fatigue damage accumulation models. Solutions of this type are based on ideas proposed by Kanazawa [6].

An example can be a method based on a virtual strain-energy concept proposed by Liu [9]. Method introduces two parameters as a measure of fatigue damage on critical planes of crack nucleation, which precedes actual cracking. Mode-I fracture occurring on a critical plane is driven by the maximum principal stress and strain, and Mode-II fracture occurring on a different critical plane is driven by the maximum shear stress and strain.

2.4. Non-proportionality measures formulated on the basis the loading path geometry in many planes

The idea of using multiple planes to describe the non-proportional load underlies the integral approach. This idea is based on the assumption that for a proper assessment of the fatigue behavior one must sum a cumulative damage parameter at all planes passing through the considered material point. For each of the planes the fatigue damage parameter is defined. Integral approach requires the calculation of the average square of the parameter.

As an example of this approach can be used Shear Stress Intensity Hypothesis developed by Zenner [10].

2.5. Non-proportional measures in cyclic plasticity models

In many fatigue models, such as energy models knowledge of the relationship between stress and strains in terms of plastic strain is required. These relationships are described by models of plasticity. In a complex multiaxial load models must recognize the impact of non-proportionality such as material hardening and changes of the average plastic strain during force controlled by the stress of the average (ratcheting). Describing the impact these models are describing the degree of loading non-proportionality simultaneously. Some models can be found in [11].

3. MODELING METHOD OF LOADING NON-PROPORTIONALITY

3.1. Description of the approach

In comparison with the number of numerical models, the number of experimental methods of modeling is small. In the section the method of non-proportional fatigue load modeling proposed by authors has been described [12]. The tests involved modeling non-proportional loading by two blocks loading program, whose blocks differed with the positions of principal axes. Control over the principal positions was gained using different types of loading for each block. Block I consisted of fully reversed torsion cycles whereas block II consisted of biaxial reversed cycles, that is, fully reversed torsion with biaxial torsion and compression. Change of the principal axes position range was controlled by principal axes position change in block II with invariable position of axes in block I. Position of axes in the block of torsion was the basic one from which positions of principal axes were calculated for other loading cases. Certain values of the principal axes position in block II was reached by establishing adequate values of the shear to normal stress ratio. Equivalent stress values were identical for both blocks. Lengths of blocks were also identical consisting of 5 000 cycles. Details of the research program were presented in Table 1 and Figure 1.

Table 1. Description of fatigue tests making up the research program

Denotation of the test kind	Description of the test		Position of the maximal shear stress vector β [º]	Ratio of nominal stresses $\sigma_{x(a)}/\tau_{xy(a)}$
‘1’	uniaxial loading, reversed torsion		0.0	0.0
‘2’	biaxial loading, torsion with tension/compression		7.5	0.5
‘3’	biaxial loading, torsion with tension/compression		15.0	1.2
‘4’	biaxial loading, torsion with tension/compression		22.5	2.0
‘5’	programmable loading	block 1 – uniaxial '1'	0.0	0.0
		block 2 – biaxial '2'	7.5	0.5
‘6’	programmable loading	block 1 – uniaxial '1'	0.0	0.0
		block 2 – biaxial '3'	15.0	1.2
‘7’	programmable loading	block 1 – uniaxial '1'	0.0	0.0
		block 2 – biaxial '4'	22.5	2.0

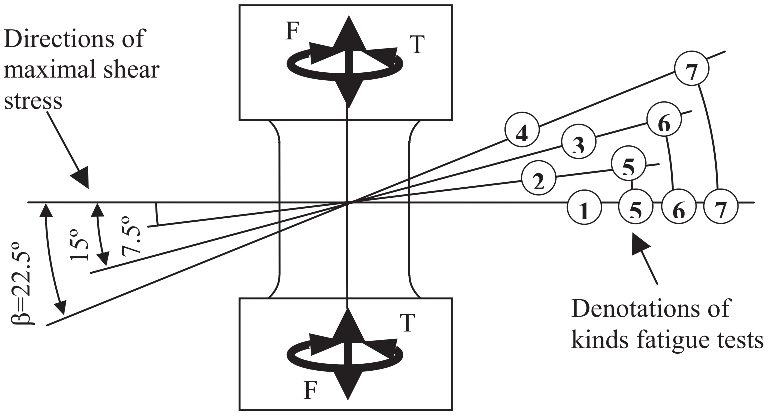

Fig. 1. Positions of maximal shear stress vectors for 7 kinds of fatigue tests.
F – tension/compression, T – torsion.

Tests were carried out for two materials: austenic steel X5CrNi 18-10 and aluminum alloy AW 6063. Austenic steel is characterized by very high sensitivity to loading non-proportionality whereas aluminum alloy shows no sensitivity to such loading. At the microlevel, the material sensitivity is related to the material stacking fault energy. The materials with a high level of the stacking fault energy do not exhibit sensitivity to non-proportional loading, while those with a low energy are sensitive to a loading non-proportionality.

It was recognized that the examined effect of the modeled loading non-proportionality influence should be fairly visible with the use of austenic steel. If the results obtained for a sensitive material are only the effect of modeled loading non proportionality then in the case of aluminum alloy such effects should not be noticeable.

3.2. Results

Fatigue life mean values were calculated for each kind of the test and they were presented in Fig. 2 and 3. Fatigue life for reversed torsion (test ‘1’) corresponding to the level of principal tests stresses is marked in black color. Mean fatigue lives corresponding to the proportional loading, obtained in tests ‘2’, ‘3’ and ‘4’ are marked in grey color. Mean lives obtained in non-proportional tests ‘5’, ‘6’ and ‘7’ are marked in white color.

For X5CrNi18-10 steel fatigue life obtained in test ‘5’ i.e. for small changes of the principal axes angle between loading blocks is statistically consistent with the base fatigue life (Fig. 2). In this case changes of the principal axes position angle do not affect the obtained fatigue life. For wider ranges of angle changes, i.e. for tests ‘6’ and ‘7’ the obtained lives are smaller in relation to the basic one and decreases along with the increase of β angle.

‘5’, ‘6’ and ‘7’ fatigue lives do not vary from the lives obtained in uniaxial test ‘1’ and biaxial proportional tests ‘2’, ‘3’ and ‘4’.

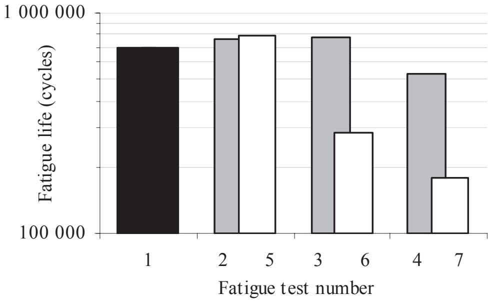

Fig. 2. Setting up of tests results for X5CrNi18-10

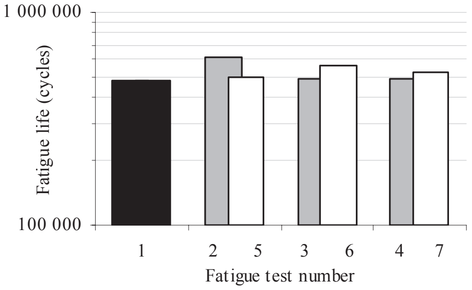

Fig. 3. Presentation of tests results in the form of mean fatigue lives for AW6063

On the basis of carried out tests it can be established that in case of material sensitive to loading non-proportionality there is an influence of the principal axes rotation range on fatigue life during programmable fatigue tests. In the case of material insensitive to load non-proportionality such a relationship is not found. The method can therefore be used to model the non-proportionality of fatigue load.

4. CONCLUSIONS

1) Development of fatigue damage parameters are in a state of rapid change. It can be said that researchers today are focusing most attention on critical plane damage parameters and some works continues to progress in the development of integral approaches for non-proportional loading cases.
2) In comparison with the large number of fatigue criterion the number of experimental methods of non-proportionality modeling is very small. Due to the large scatter of the calculated lives, the experimental structural durability tests under non-proportional loading must be carried out.

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