UDC 539.43:620.178.3(045)

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CALCULATION METHOD OF AEROTECHNICS PRODUCTS FATIQUE STRENGTH SUBJECT TO CYCLIC LOADING

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Abstract. *This article considers calculation method of structural strength coefficient, that ensures the required serviceability. The special emphasis is placed on limiting stress evaluation when structures are subject to multi-cycle asymmetric loading. The suggested approach enables to evaluate proof strength more correctly within the design process.*

Keywords: aerotechnics products fatigue strength; asymmetric cyclic loading; constructional proof strength; constructional materials; limiting state model.

1. Introduction

Lifetime enhancement and reliability improvement of designed engineering structures are inextricably associated with the need to perform a great complex of experimental and analytical studies and to improve strength calculations taking into account specific service conditions. First of all, it relates to the component parts subject to cyclic loads.

This is because the resistance to this type of loading greatly depends on effect of various factors, i.e. design, technology, service ones.

2. Analysis of researches and publications

There is a large number of monographs of domestic and foreign scientists [1, 3, 8, 11, 12] dedicated to the study of materials and products resistance against cyclic loads, including aerotechnics.

Many of them contain recommendations (methods) on the strength calculation at alternate loads [3, 7, 10]. However, these issues are still relevant and need further research.

3. Problem status

The calculated proof strength (n) is the principal characteristic that specifies reliable serviceability of construction subject to cyclic loads. Its calculation is based on comparison of limiting strength characteristic (fatigue limit) and service stress values in a component part

$$n = \frac{\sigma_r}{\sigma_{\text{oper.}}}, \quad (1)$$

where σ_r are limiting characteristic of material fatigue resistance;

σ_{oper} is a component part's stress level under operational conditions.

In the majority of cases structural elements being under operational conditions are subject to asymmetric loading, i.e., when the static load is overlapped with cyclic loads. Aircraft wings, subject to their own weight and added weight effect (e.g., fuel) effect and air flow gusts may be an example of these elements.

Smith diagram, showing static component dependence of maximum $\sigma_{\max}$ (minimum $\sigma_{\min}$) stresses is a basis for determination of fatigue resistance limiting characteristics at asymmetric loading (fatigue limits, restricting fatigue limits) [3, 7, 10]. The construction of this diagram is based on linear or parabolic dependence between stresses $\sigma_{\max}$, $\sigma_{\min} - \sigma_m$ using experimentally determined fatigue limit σ_{-1} and strength limit σ_B or yield limit σ_Y. The author [10] offers schematized Smith diagram. To construct this diagram it is necessary to determinate additionally in an experimental way the restricting fatigue limit σ_0 at zero-to-compression loading cycle, when the static component σ_m is equal to cyclic component σ_a. By adjusting limiting stresses, that represent strength characteristics of smooth cylindrical samples, and by introducing coefficients, that take into account design and technology factor effects, one can determine σ_r limiting stress values using Smith diagram.

Regarding the asymmetric cyclic loading, limiting characteristics for the used material may be also determined using the stress cycle limiting amplitude diagrams. These diagrams are constructed in "$\sigma_r - \sigma_m$" coordinates taken into account the results of σ_{-1} fatigue limit values and σ_B strength limit experimental determination.

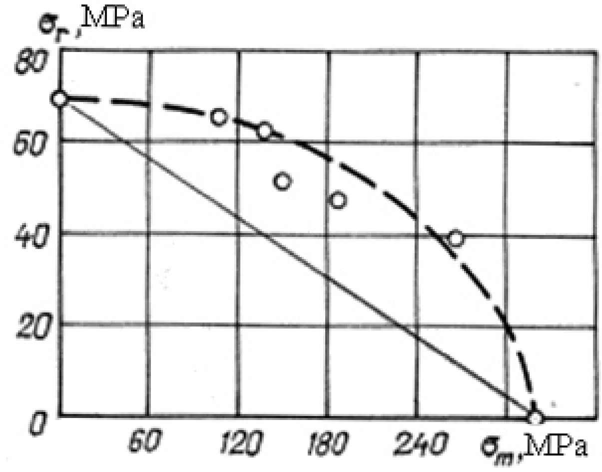


Fig. 1. Stress cycle limiting amplitude diagrams

Figure 1 shows limiting amplitude diagrams: linear (solid line) and parabolic (dotted line). Points show the results of structural material samples experimental studies.

4. Problem setting

Mostly, linear or parabolic dependence between $\sigma_{\max}(\sigma_r)$ and σ_m lie in the basis of above listed diagrams construction. However, analysis of numerous test data on fatigue resistance for the wide range of structural materials clearly indicates that neither first, nor second dependence is not universal and it adequately represents real material response on asymmetric cyclic loading only in particular cases [3, 10, 11]. It does not ensure reliable determination of limiting characteristics at asymmetric loading and introduces noticeable inaccuracies in the proof strength calculation while structural elements design. The same result is achieved when other known dependences (quadratic, elliptical, etc.) are used. Thereby, it is necessary to find additional model expressions, that give the adequate response of tested materials to asymmetric cyclic loading.

In some studies [4, 5, 6] generalized models were offered, describing structural material resistance to asymmetric cyclic load effect, based on the use of exponential transcendental functions that show the dependence between σ_a and σ_m values. Offered models were carefully and comprehensively verified regarding calculation and construction of diagrams showing structural material limiting stress. They have demonstrated high correlation of calculations with experimental data.

5. Calculation of limit state and proof strength

Using generalized models [4, 5], it is possible to write limiting amplitude diagram expressions σ_a for the asymmetric stress-strain in the form of

$$\sigma_a = \sigma_n \left[\cos\left(\frac{\pi}{2} \frac{\sigma_m}{\sigma_B} \right) \right]^{\eta} \tag{2}$$

and

$$\sigma_a = \frac{2}{\pi} \cdot \sigma_n \left[\arccos\left(\frac{\sigma_m}{\sigma_B} \right)^{\frac{1}{\eta}} \right]. \tag{3}$$

Here, σ_n is smooth cylindrical samples restricting fatigue limit at symmetrical cycle, determined from fatigue curve equation, experimentally obtained on the results of standard sample series test;

σ_B is a strength limit of the tested material sample;

η is a material sensibility factor to the load asymmetry, which determination procedure is described in the studies [6]. Experience has shown that the expression (2) better describes behaviour of plastic materials, whereas the expression (3) is better for fragile materials.

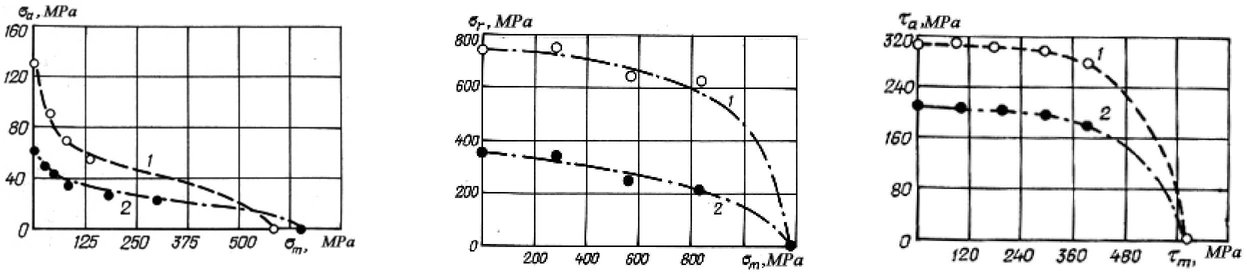
Expressions (2) and (3) may be used for calculation of limiting state diagrams for structural materials subject to asymmetric bending and asymmetric torsion, taking into consideration the required initial characteristics, received at respective load types.

Lets consider limiting diagrams, calculated using expressions (2) and (3) for cases of asymmetric stress-strain load, asymmetric bending and asymmetric torsion.

Figure 2 shows limiting diagrams at asymmetric cyclic loading of some structural materials, stress-strain (*a*) [9]; bending (*b*) [2]; torsion (*c*) [10].

Chart lines represent calculation results, whereas points represent experimental test results. Comparison of chart data shows high precision of performed calculations using generalized fatigue strength generalized models.

Lines 1 characterize limiting resistance of smooth cylindrical samples to asymmetric load effect. The charts simultaneously shows lines 2, representing stress concentration effect on the test materials fatigue resistance taking into consideration concentrator shape in the sample working zone. In the same manner, effect of other factors may be considered allowing more precious limiting stresses determination when calculating proof strength for designed component part, which is associated with rather labor-consuming and complex experimental tests.



a *b* *c*

Fig. 2. Diagrams of stress cycle limiting amplitude for smooth (1) and notched (2) 75S-T6 aluminium alloy samples, subject to asymmetric load, $n = 10^7$ cycle (*a*); SAE 4340 steel, bending, $n = 10^5$ cycle (*b*); chromium-nickel steel, torsion, $n = 10^5$ cycle (*c*)

Thereby, proof strength may be reliably determined based on calculated values of cyclic stress amplitude σ_a according to equations (2) or (3) at one or another static component σ_m using adjusting factors. In this case expression for n may be written in the following form

$$n = \frac{\sigma_a \cdot K_{\sigma D}}{\sigma_{\text{oper.}}}, \tag{4}$$

where σ_a is limiting stress amplitude, characterizing standard cylindrical samples resistance to asymmetric loading according to the diagram;

$K_{\sigma D} = \frac{\varepsilon_\sigma \cdot \delta}{k_\sigma}$; ε_σ is a ratio, representing scaling factor effect;

δ is a ratio, characterizing surface quality and other technology factors effect;

k_σ is a stress concentration effective ratio.

It's harder to determine service stresses $\sigma_{\text{экс.}}$ in designed structural elements. Usually the choice of the value $\sigma_{\text{экс.}}$ is determined by means of calculations or based on service experience of such structures.

Projected component part is considered serviceable, if the proof strength value exceeds normative values, i.e. $n > [n]$ for this component part grade. Generally, in machine building $[n]$ =1,5–2,5.

For example, normative proof strength value $[n]$ for crankshafts, con-rods and some other component parts of reciprocating aviation engine is 1.3÷1.5; for rolling-stock locomotive bogies – $[n]$ = 2 [7]. $[n]$ values are usually established based on experience received in the process of calculation and design of component parts of specific machine building products.

5. Conclusions

The suggested approach to proof strength calculation of designed components is based on asymmetric cycle stress limiting amplitude evaluation, by means of structural material limiting state models which are based on exponential transcendental functions. The models rather correctly describe experimental data with minimum scope of preliminary studies. In its turn, it enables to enhance the precision of proof strength calculation when designing structural elements.

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Received 10 June 2014.

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В роботі розглядається метод розрахунку запасу міцності елементів конструкцій, які забезпечують їх необхідну працездатність. Основну увагу приділено оцінці граничних напружень за асиметричного багатоциклового навантаження. Запропонований підхід сприяє більш коректній оцінці запасу міцності під час виконання проектних робіт.

Ключові слова: асиметричне циклічне навантаження; запас міцності конструкції; конструкційні матеріали; модель граничного стану; утомлісна міцність виробів авіаційної техніки.

А.Д. Погребняк[1], М.Н. Регульский[2], Е.И. Юрченко[3], А.С. Тугаринов[4]. Метод расчета запаса прочности изделий авиационной техники при циклическом нагружении

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В работе рассматривается метод расчета запаса прочности элементов конструкций, обеспечивающий их необходимую работоспособность. Основное внимание уделяется оценке предельных напряжений при асимметричном многоцикловом нагружении. Предложенный подход способствует более корректной оценке запаса прочности при выполнении проектных работ.

Ключевые слова: асимметричное циклическое нагружение; запас прочности конструкции; конструкционные материалы; модель предельного состояния; усталостная прочность изделий авиационной техники.

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