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Determination of Fatigue Life of Bicyclic Loaded Metal Structures

Détermination de la durée de vie de structures métalliques soumises à des charges alternées bicycliques

Bestimmung der Lebensdauer von Metallkonstruktionen, die durch Doppelfrequenzbelastung beansprucht werden

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SUMMARY
It was established that at a fixed frequency ratio a linear dependence is observed between the amplitude ratio of two-frequency cycle and the decimal logarithm of fatigue life ratio. It is invariant to the variation of the main factors determining the fatigue strength of materials and joints. The given relationship permits to determine the fatigue life at bicyclic loading from Wöhler curves. Determination procedure is given.

RESUME
Il a été établi que, pour un rapport fixé des fréquences bicycliques, on peut observer une relation linéaire entre le rapport des amplitudes et le logarithme décimal du rapport des durées de vie. Cette relation est indépendante de la variation des principaux paramètres caractérisant la résistance à la fatigue des matériaux et des assemblages. La relation proposée permet de déterminer à partir des courbes de Wöhler la durée de vie sous un chargement bicyclique. On donne le processus de cette détermination.

ZUSAMMENFASSUNG
Es hat sich gezeigt, dass bei konstantem Verhältnis der zwei Frequenzen ein linearer Zusammenhang zwischen dem Spannungsamplitudenverhältnis und dem dekadischen Logarithmus des Lebensdauerverhältnisses besteht. Dieser Zusammenhang ist invariant zu den Grundfaktoren, die die Dauerfestigkeit der Werkstoffe und Verbindungen bestimmen. Diese Gesetzmässigkeit erlaubt es, die Lebensdauer bei der Doppelfrequenzbelastung mit den Wöhlerkurven zu bestimmen. Das Verfahren dazu wird angegeben.

Bicyclic loading (Fig.1), at which smaller value but higher-frequency components generated by all kinds of vibrations are superimposed on the main low-frequency cycles, is characteristic not only of aircraft, ships, reactor bodies, gas-turbine engines, but also of bridges [1], crane girders [2], mast-aerial constructions [3] and other structures (Fig.2). The data in the Table permit to judge frequency-amplitude ratios of loading components typical for the elements of these structures.

The detrimental effect of vibrations is usually not taken into account when calculating the cyclic fatigue life of structures or it is only taken into account by increasing the amplitude of the main alternating loading by a value corresponding to the high-cyclic component. However, as shown by the research, the results of which have been generalized in the previously compiled reviews and separate publications [4,5,6,9, et al.] the fatigue strength under bicyclic loading decreases to a greater extent, than at one-cyclic loading with a maximum amplitude $\sigma_{a.s}$, equal to the total value of the amplitudes of both cyclic components ($\sigma_{a.l}$ and $\sigma_{a.h}$). Here, the fatigue life variation can be affected not only by the amplitude ratio $\sigma_{a.h}/\sigma_{a.l}$ (Fig.3), but also by the frequency ratio f_h/f_l [7,8]. With the increase of f_h/f_l, the fatigue life monotonically decreases. At the same time, in case of small frequency ratios (at bending, axial loading and twist-bending) or when the rotation frequency is higher than that of bending (at testing for rotation bending), not the decrease but the increase of fatigue life was observed in some studies under bicyclic loading (Fig.3).

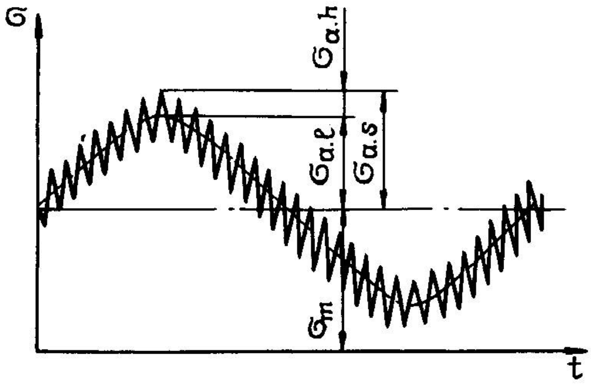

Fig.1.Bicyclic loading (scheme)

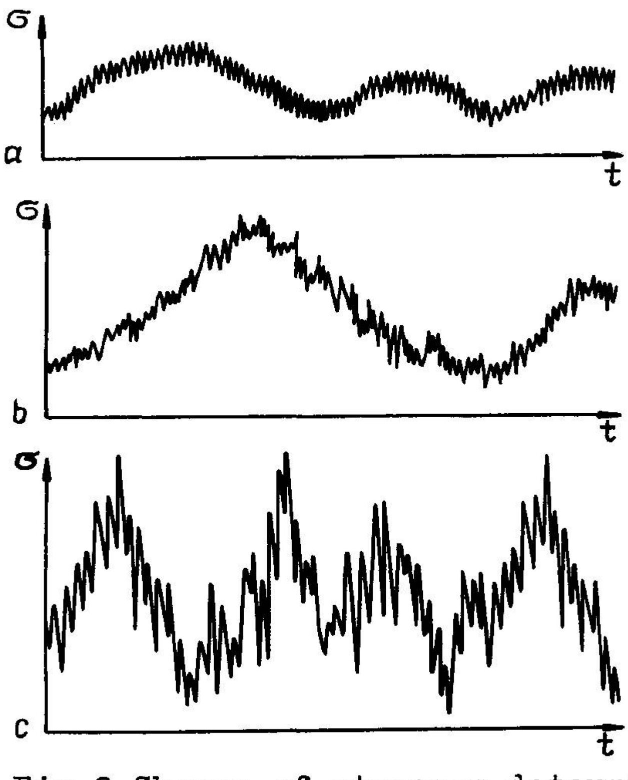

Fig.2.Change of stresses determined by oscillography: a) main beam of a bridge span l =23m; b) in a brace of a bridge lattice girder l =77m; when a train is passing at 83 km/h speed; c) in the mast guy-ropes.

It should be noted that under rotation bending conditions, the bicyclic loading is only ensured when the stress amplitude ratio is not high, and the bending frequency exceeds the rotation frequency. With the amplitude ratio increase and at excess of rotation fre-

Table. Amplitude and frequency ratios of load components

	Elements of structures and workpieces	Possible ratios of	
		amplitudes $\sigma_{a.h}/\sigma_{a.s}$	frequencies f_h/f_l
1.	Main beams and braces of railway bridge girders	0.05...0.25*	30...100*
2.	Metal structures of radio- and telemasts	0.1...0.5*	1.5...150*
3.	Crane girders	0.01...0.25	10...1000
4.	Power plant elements	0.03...0.5	100...1000
5.	Hydraulic turbines	0.1...0.5	2.5...150
6.	Spindles of blooming and rolling mills	0.01...0.5	15...30
7.	Cutting chains of coal cutters	0.1...0.5	15...20
8.	Fuselages, vane suspensions, ailerons and stabilizers of passanger planes	0.03...0.5	1.5...5000

*According to the data of measurements in several installations. It is possible that the amplitude and frequency range can be even greater for bridges and masts.

quency over the bending one, the nature of stress change noticeably differs from the bicyclic case. Here, the fatigue testing results of a different quality are obtained. Investigations of aluminium alloys at similar levels of stresses and frequency ratios showed that in case of rotation bending the superimposition of a high-frequency component increases the fatigue life, and under bending in one plane it considerably decreases. Furtheron, testing results only for axial loading and plane bending are given.

Alongside the experimental evaluation, various authors have made suggestions also for fatigue life calculation under bicyclic loading. They are based on linear cumulative damage hypothesis [3,10, et al.], the hypothesis of spectral summation [11], energy concepts [8], and empirical relationships [6,12,13, et al]. These suggestions mostly referred to specific workpieces, loading conditions and materials. Thus, evidently, their validity, as shown by the comparison of calculated values and experimental data of other authors, is preserved in certain rather narrow ranges of amplitude and frequency ratio variations [14] It is to be noted here that, apparently, Miner's hypothesis

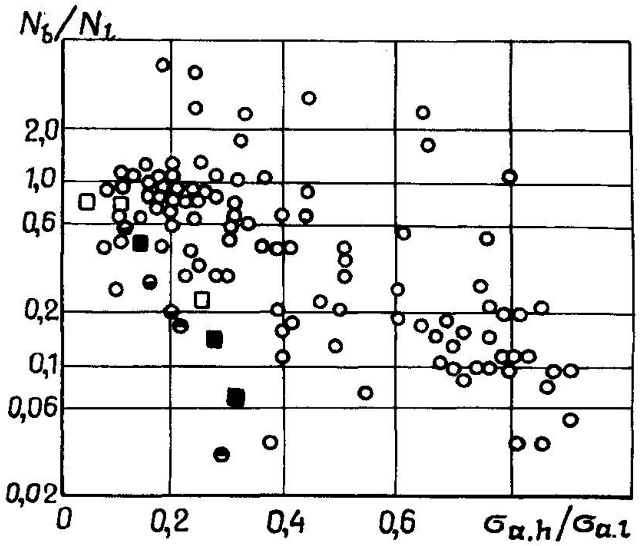

Fig.3. The effect of amplitude ratio on fatigue life change at bicyclic loading. ○ - [5], □ - [9], ■ - [6], ◓ - [4], ◒ - [4].

cannot be used to describe the fatigue damage accumulation. Possibly, it may lead to satisfactory results only in low-cycle region at relatively low f_h/f_l and for conditions not associated with significant temporal processes [15]. The unacceptability of Miner's hypothesis in multicycle area is demonstrated, in particular, by data in the work [16]. Specimen testing at bicyclic loading and at onecyclic loading with an equal value of maximum stresses showed that at bicyclic loading the fatigue life is noticeably decreased even when the average stress value is equal to the maximum average value of low cyclic component (Fig.5).

The suggestions made do not permit to conclude that at present a new quite well-based procedure for bicyclic loading fatigue life evaluation is being established or contemplated. It should be based on the premises or relationships, expressing regular connection between the parameters of bicyclic loading and fatigue strength valid in a wide range of amplitude and frequency ratio variation. The approach to the bicyclic loading parameter selection to obtain the simplest estimation dependences has not yet been sufficiently well grounded, either. In the investigations performed the total stress $\sigma_{a.s} = \sigma_{a.l} + \sigma_{a.h}$ was used to estimate the bicyclic loading fatigue life, and the relationship was established between $\sigma_{a.h}/\sigma_{a.s}$ and $N_b/N_{l.s}$, where N_b - bicyclic loading fatigue life and $N_{l.s}$ - fatigue life corresponding to the summary amplitude $\sigma_{a.s}$. The usage of $\sigma_{a.h}/\sigma_{a.s}$ ratio excludes the possibility of obtaining a linear connection between bicyclic loading parameters and fatigue life N_b since at linear change of $\sigma_{a.l}$ and $\sigma_{a.h}$ amplitudes the ratio $\sigma_{a.h}/\sigma_{a.s}$ varies non-linearly. As will be shown later, it is also expedient to evaluate the relative fatigue life by N_b/N_l ratio, and not $N_b/N_{l.s}$ i.e. to determine the effect of high cyclic component on the decrease of initial fatigue life N_l, corresponding to loading with $\sigma_{a.l}$ amplitude and not to the conditional fatigue life $N_{l.s}$ at hypothetical amplitude $\sigma_{a.s}$.

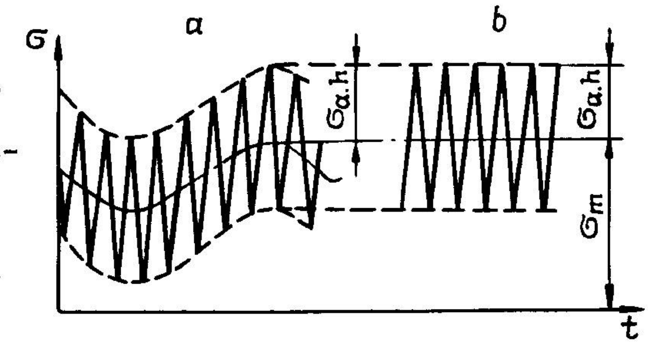

Fig.4.Loadings at pure bending compared in the work [16].

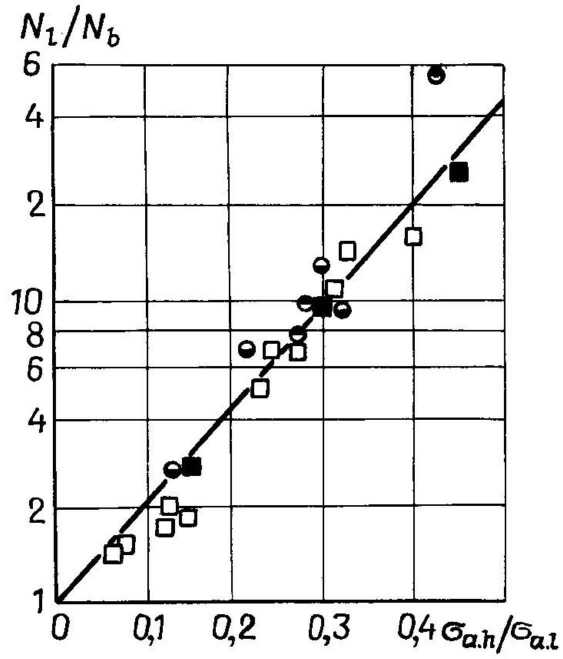

Fig.5.The generalization of testing results at two-frequency loading: □ - D16AT alloy,tension [9] ,■ - D16T alloy,tension [6] , ● -0X12H steel,bending [4] , ◐ - 45 steel,bending [4] .

The advantages of using these ratios are shown in the investigation [14]. Fig.5.in the coordinates $\sigma_{a.h}/\sigma_{a.l}$, $lg(N_l/N_b)$ shows the results of all tests made by different authors with an average range of frequency ratio (mainly f_h/f_l =100...600), which could be converted to the given system. There is an agreement between the test results, despite the fact that the specimens differed in shape and sizes and were fabricated of different materials. In the given coordinate system a linear dependence was observed in a rather wide range between $\sigma_{a.h}/\sigma_{a.l}$ and N_l/N_b .

If we proceed from the existence of such a dependence, then the bicyclic loading frequency can be determined from the fatigue curves of onecyclic loading:

$$N_b = \frac{N_l}{\varkappa} \qquad (1)$$

where $\varkappa$ - factor dependent on $\sigma_{a.h}/\sigma_{a.l}$ amplitude ratio and f_h/f_l frequency ratio.

To confirm the invariance of $\varkappa$ factor at the change of the main factors, affecting the fatigue strength of materials and joints, and also to obtain an appropriate expression for its determination, the large-scale specimens (Fig.6) were tested at one- and bicyclic loading at various stresses - from the level slightly above the endurance limit up to the yield strength. Here, the $\sigma_{a.h}/\sigma_{a.l}$ ratio varies from 0.05 to 0.9.

155x20 mm section flat specimens (Fig.6a) were made of low-carbon steel (σ_T =300 MPa, σ_B =510 MPa) and 12X18H10T chrome-nickel steel (σ_T =350 MPa, σ_B =650 MPa). The concave recesses in the sides created in various samples a stress concentration α_σ , equal to 1.5; 2.5 and 3.5. Specimens of high-strength steel (σ_T =1070 MPa, σ_B = 1120 MPa) had a 80x18 mm section and a stress raiser in the form of a whole in the thinned part of the plate (Fig. 1,c). Taking into account a possible effect of residual stresses [17] on the fatigue strength of welded structures, the role of this factor in $\varkappa$ change was evaluated on specimens with beads (Fig.1,b), and on an actual joint (Fig.1,d). In the stress raiser zone the beads created initial residual stresses close to the base metal yield strength. The tests were performed both at axial loading and at bending. As for the low-cyclic loading, the tests were performed at a symmetrical, zero-to-tension and asymmetrical cycles (r= +0.5). To eliminate the errors associated with a possible effect of frequencies at one- and bicyclic loading, f_l frefuency in a multicycle region did not exceed 20 min^{-1}. f_h frequency was 300 min^{-1} under axial loading and 1800 min^{-1} at bending. The required ratio f_h/f_l with 10^2-5.10^3 range was ensured by varying f_l . An initial stage of crack development was used as a fatigue testing completion criterium. The testing was stopped when crack depth reached 2-3 mm. Part of the specimens were

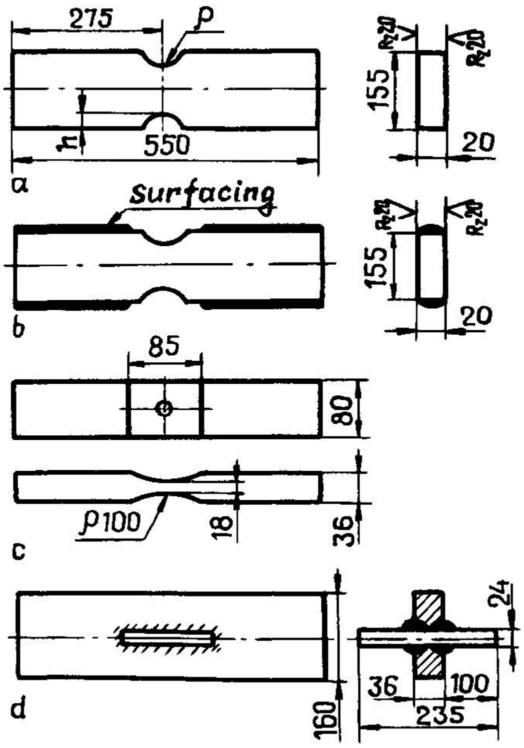

Fig.6.Specimens for testing at one- and bicyclic loading.

tested till they completely broke down.

Each factor studied significantly affected the fatigue strength of samples at one- and bicyclic loading. However, the studies performed have proved that $\varkappa$ coefficient remains invariant to the changes associated with the degree of stress concentration, residual stresses, stress ratio, type and level of loading, temperature and fatigue testing completion criterium. In this case all the relationships between $lg\,\varkappa$ and $\sigma_{a.h}/\sigma_{a.l}$ are of a stable linear type. The main dependences are shown in Fig. 7. At the same time, the change of $\varkappa$ is drastically affected by the amplitude (Fig.7) and frequency (Fig.8) ratios. With the increase of these ratios $\varkappa$ becomes considerably greater. These two factors mostly determine $\varkappa$ factor value. It is to a lesser degree that $\varkappa$ is sensitive to steel properties (Fig.8,b). With the change of frequency ratios and strength properties of material a linear relationship is maintained between $lg\,\varkappa$ and $\sigma_{a.h}/\sigma_{a.l}$

The established dependences give the following expression for determining the factor of bicyclic loading fatigue life decrease.

$$\varkappa = \left(\frac{f_h}{f_l}\right)^{\vartheta \frac{\sigma_{a.h}}{\sigma_{a.l}}} \qquad (2)$$

where ϑ - factor, reflecting the material effect. It may change within 1.3...1.8 for steels. $\varkappa$ value may also be determined according to the nomogram, given in Fig.9.

When $\varkappa$ factor in the initial equation (1) is replaced by its value (2), we obtain a final formula for bicyclic loading fatigue life determination:

$$N_b = \frac{N_l}{\varkappa} = \frac{N_l}{\left(\frac{f_h}{f_l}\right)^{\vartheta \frac{\sigma_{a.h}}{\sigma_{a.l}}}} = N_l\left(\frac{f_l}{f_b}\right)^{\vartheta \frac{\sigma_{a.h}}{\sigma_{a.l}}} \qquad (3)$$

In this formula, N_l - is the fatigue life of material, joint, element, etc., which, in the assigned conditions corresponds to low cyclic loading with $\sigma_{a.l}$ amplitude. According to formula (3) the bicyclic loading fatigue life N_b is always less than N_l . At the same time, as noted above

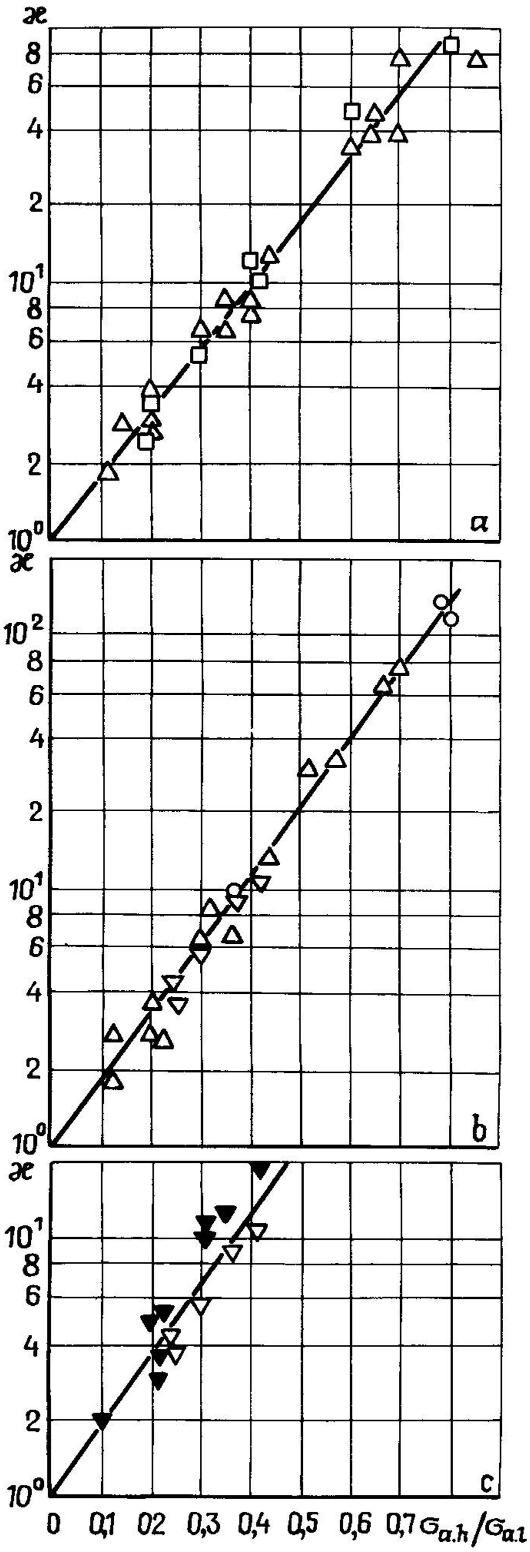

Fig.7.Coefficient $\varkappa$ invariance to the change of: a)stress concentration: □ – α_σ=1.5; △ – α_σ=2.5; △ – α_σ=3.5; b)cycle asymmetry: ○ – r=0.5; ▽ – r =0; ▽ – r =–1; c)residual stressed state: ▽ – Ω =0; ▽ – Ω = σ_T .

at small frequency ratios an increase of bicyclic loading fatigue life was observed in certain investigations. In this connection it becomes necessary to determine the boundaries of formula (3) applicability. In case of small values of f_h/f_l the change of $\sigma_{a.s}$ amplitude depends not only on $\sigma_{a.h}/\sigma_{a.l}$, but also on phase shift between the components. In a certain interval of φ phase shift, the $\sigma_{a.s}$ summary amplitude can decrease to values lower than $\sigma_{a.l}$ [14]. If we take into consideration the fact that $\sigma_{a.h}/\sigma_{a.l} < 0.3$ and the resulting load cycle form $\sigma_{a.s}$ is distorted without the appearance of additional extremums, then the increase of fatigue life in the given conditions under the effect of bicyclic loading is readily explained. When $\sigma_{a.h}/\sigma_{a.l} < 0.5$ the summary amplitude depending upon φ angle, can be both lower and higher than the low-frequency component amplitude. Accordingly, N_b can be increased or decreased compared to N_l. At $\sigma_{a.h}/\sigma_{a.l} > 0.5$ the summary amplitude is higher than the low-cyclic component amplitude. The fatigue life will decrease under the effect of this factor, and, possibly, due to the appearance of additional extremums.

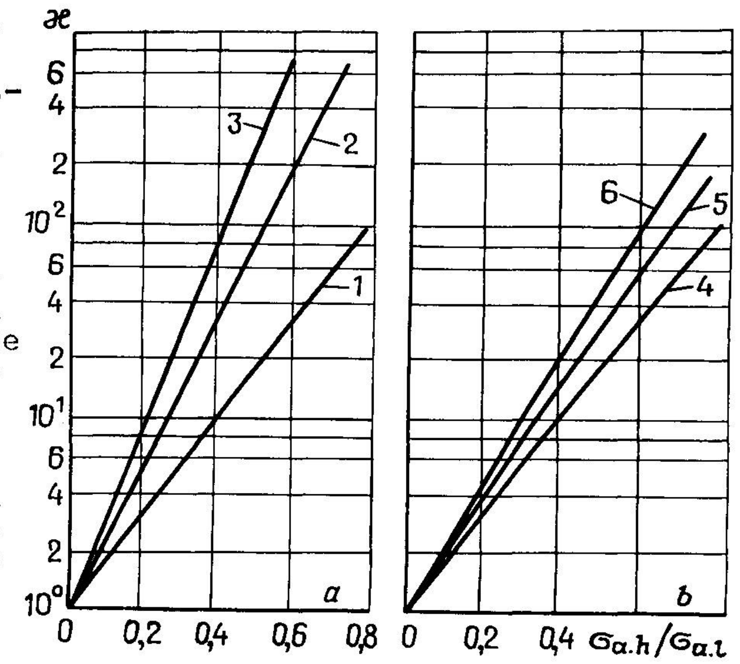

Fig.8.Relationship between æ and frequency ratio(a) and steel type(b): 1- $f_h/f_l = 10^2$; 2- $f_h/f_l = 10^3$; 3- $f_h/f_l = 5.10^3$; 4-low-carbon steel; 5-chrome-nickel steel; 6-high-strength steel.

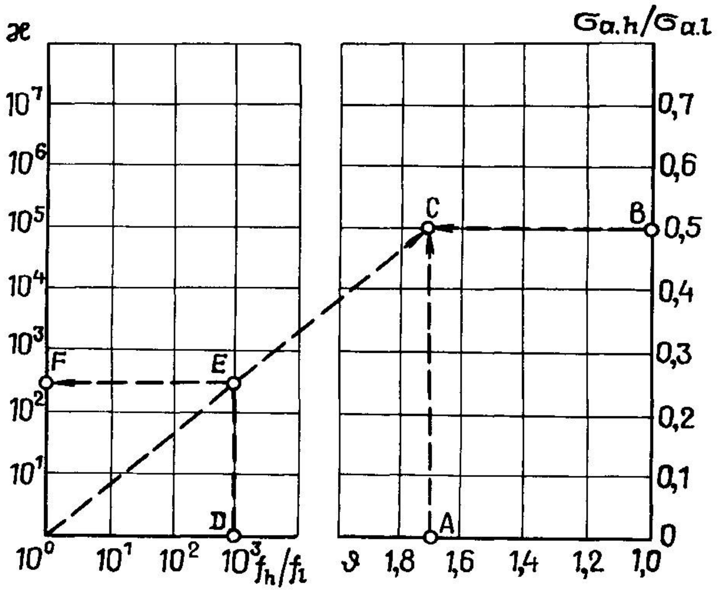

Fig.9.Nomogram for æ determination.

The situation becomes different at $f_h/f_l > 10$. Irrespective of amplitudes and initial phases of loading components $\sigma_{a.s} > \sigma_{a.l}$. The analysis performed showed that $\sigma_{a.s}$ deviation from the maximum possible value at a synphase summation of harmonic loads did not exceed 5% within the whole range of amplitude ratios. The damage accumulation is also favoured by individual stress cycles, changing with f_h frequency. In such conditions, N_b will always be much lower than N_l. Thus, at $f_h/f_l \geq 10$, the formula (3) can be used without restrictions. When $f_h/f_l < 10$, it is valid for a fixed value of phase shift, meeting maximum value of resulting amplitude $\sigma_{a.s}$ .For other values of phase shift the formula (3) can give only under-estimated values of N_b .

The validity of formula (3) was also verified by comparing the experimental data obtained earlier by other authors with the calculated data. In most cases the ratio between calculated data and the experimental ones was close to a unit, while individual deviations lay within the scattering range of 0.75-1.5.

It appears that there is every reason to believe, that the proposed method of bicyclic loading fatigue life estimation is quite suitable for engineering calculations and can be used within a wide range of amplitude and frequency ratio change.

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