Computational and experimental assessment of the fatigue strength dissipation characteristics of power lugs

Georgy Kravchenko[1*], *Konstantin* Kravchenko[1], *Alexander* Osipov[2], and *Vladimir* Bazanov[3]

[1] Moscow Aviation Institute (National Research University), Volokolamskoe shosse, 4, 125993, Moscow, Russia
[2] Voronezh State Technical University, 20th Anniversary of October, 84, 394006, Voronezh, Russia
[3] Moscow State University of Civil Engineering, 26, Yaroslavskoe shosse, 129337, Moscow, Russia

Abstract: Methods for experimental and computational assessment of the dissipation indicators of the endurance limit and cyclic durability of power lugs of machines and mechanisms are presented. Based on a generalization of the results of fatigue tests, the dependences of the standard deviation of the logarithm of the number of cycles before failure of lugs made of high-strength steels on the maximum amplitudes of cyclic stresses were constructed. Formulas are obtained for calculating the coefficient of variation of the theoretical stress concentration coefficient of the lugs from production deviations of their dimensions in plan and from the dispersion of the gap between the bolt and the hole. Based on these formulas, the values of the coefficient of variation of the theoretical stress concentration coefficient for typical lugs are obtained and given.

1 Introduction

To predict the service life and reliability of power elements of machines and structures based on strength conditions under variable loading, it is necessary to have indicators of the dispersion of fatigue resistance characteristics. The main factors causing their dispersion are: 1 – structural heterogeneity of the metal (the presence of various phases, inclusions, distortions of the crystal lattice, different sizes, shape and orientation of grains, random changes in the microgeometry and structure of the surface layer, etc.); the influence of this group of factors determines the statistical nature of the processes of fatigue destruction and leads to dispersion of the fatigue characteristics of samples made from metal of the same heat and not having significant differences in the main dimensions from the nominal ones; 2 – variation in the mechanical properties of a material of the same brand, but different melts or types of procurement operations (forging, stamping, pressing, etc.), deviations in heat treatment modes within one process (hardening, tempering, etc.); 3 – deviations of the actual dimensions of parts from the nominal ones (errors in the radii of curvature in zones of stress concentration, where the geometry is often not controlled, have an especially

* Corresponding author: gnkrav@mail.ru

significant impact); 4 – deviations of technological parameters during manufacturing, finishing and hardening of the surface of the part; 5 – differences in operating conditions (temperature, corrosion, surface damage, etc.); 6 – deviations of technological parameters during repair and restoration. To calculate parts for fatigue resistance and durability in a probabilistic aspect, distribution functions of their endurance limit or cyclic durability distribution functions are required. These functions make it possible to determine the endurance limit and durability of a part corresponding to a certain, predetermined probability of destruction P. The endurance limit of a part corresponding to the probability of destruction P, under the normal distribution law, is determined by the formula

$$\left(s_{R_D}\right)=\bar{s}_{R_D}\left(1+Z_P V_{s_{R_D}}\right) \tag{1}$$

$\bar{s}_{RD}$ - where is the median value of the endurance limit (corresponding to 50% probability of failure); Z_p – quantile of the normal distribution corresponding to the probability of destruction P;

$V_{s_{R_D}}=\dfrac{S_{s_{R_D}}}{\bar{s}_{R_D}}, S_{s_{R_D}}$ - coefficient of variation and mean square endurance limit deviation, respectively/

The durability of a part, corresponding to the probability of destruction P, under the normal law of distribution of its logarithm at one stress level is determined from the formula

$$\left(\lg N\right)_P=\overline{\lg N}\left(1+Z_P v_{\lg N}\right) \tag{2}$$

where $\overline{LgN}$ - median value of logarithm of durability;

$n_{LgN}=\dfrac{S_{LgN}}{LgN}$ - the coefficient of variation; S_{LgN} - standard deviation LgN at a constant voltage amplitude σ_a.

Dispersion indicators of the main characteristics of fatigue resistance ($S_{s_{RD}}$, S_{LgN} and etc.) can be determined either on the basis of mass testing of parts, or by calculation, using test results of samples, models and reference information on the patterns of dispersion of the physical and mechanical properties of the material of the part, its geometric dimensions and the stability of technological processes, especially finishing treatments. Due to the fact that carrying out mass testing of full-scale parts in the statistical aspect is very difficult, labor-intensive and, therefore, expensive, it is advisable to pay increased attention to the development and implementation of computational and experimental methods for assessing dispersion indicators of fatigue resistance characteristics. For statistical assessment of the fatigue resistance characteristics of the main elements of hinge-bolt joints, in particular lugs, it is possible to construct complete probabilistic fatigue diagrams that establish the relationship between three quantities: σ_a - the amplitude of cyclic stresses, N - the number of cycles before failure and P - the probability of failure.

2 Materials and Methods

To construct these diagrams, fatigue tests are carried out on samples, models or parts, preferably made from metal of the same heat, at several levels of stress amplitudes (usually 4 to 6 levels are selected). Moreover, at each level at least 10 samples are tested. Arranging the logarithms of the numbers of cycles before destruction in a variation series and determining estimates of the probability of destruction $P = \frac{i - 0,5}{n}$ (i – serial number of the sample in the variation series; n – number of samples tested at one stress level), construct empirical durability distribution functions. This construction is usually carried out on lognormal probability paper. In graphical form, the durability distribution functions represent a family of curves in P–N coordinates, each of which corresponds to a certain stress level σa. Similar curves for eyes made of steel 30XGCH2A are shown in Fig.1.

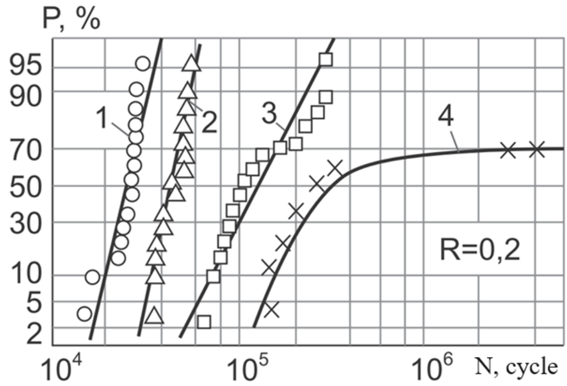

Fig. 1. Durability distribution functions of lugs made of steel 30KhGSN2A (d = 20 mm, D = 38 mm, t = 11 mm) at different stress levels σ_{max} (in MPa): 1 – o – 520; 2 – Δ – 420; 3 – □ – 320; 4 – × – 260

The full probabilistic fatigue diagram can also be represented in coordinates σ_{max} – N with parameter P, i.e. in the form of a family of fatigue curves corresponding to different probability of failure P. Such a diagram in the form of fatigue curves for lugs made of steel 30XGCH2A, corresponding to different probability P, is shown in Fig. 2.

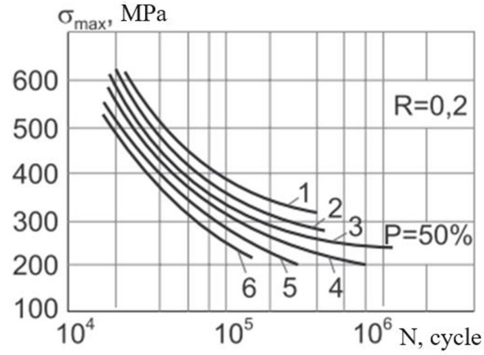

Fig. 2 Fatigue curves for lugs made of steel 30XGCH2A, corresponding to the probability of destruction: 1 – 90 % ; 2 – 70 %; 3 – 50 %; 4 – 30 %; 5 – 10 %; 6 – 2 %

It should be noted that the extrapolation of fatigue curves that have a horizontal portion should not exceed the durability corresponding to the breaking point of these curves.

In some cases, it is convenient to represent the full probabilistic fatigue diagram in coordinates P – σ_{max} with parameter N, i.e. in the form of distribution functions of endurance limits corresponding to different values of the base number of cycles N_b.

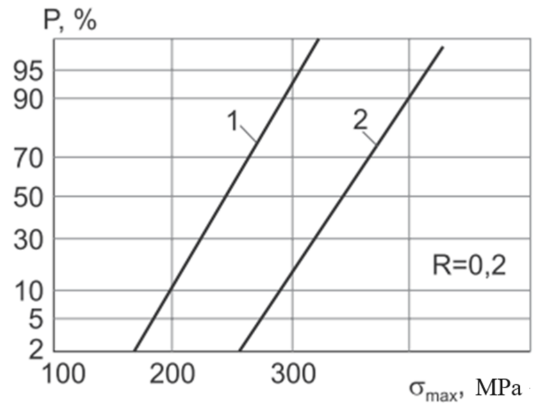

Fig. 3. Distribution functions of the endurance limit of lugs made of steel 30KhGSN2A at different values of the base number of cycles N_b: 1 – 10^6; 2 – 10^5

All three families of curves presented in Fig. 1–3 are variations of the full probabilistic fatigue diagram. By statistically processing the data used as the basis for constructing this diagram, it is possible to obtain estimates of the mathematical expectation and standard deviation of the values σ_{Rd} и lgN at given values N_b and $\sigma_{max,}$ respectively.

In table Figure 1 shows the dispersion indicators of the cyclic durability of lugs made of high-strength steels, obtained by statistical processing of experimental data from [1]. Durability dissipation increases with decreasing cyclic stress level. Moreover, the relationship S_{lgN} with σ_{max} for lugs made of steels 30KhGSN2A and 40KhGSNZVA, qualitatively and quantitatively approximately the same. Correlation analysis of the results of many fatigue tests suggests that there is a power-law relationship between the standard deviation of the logarithm of the number of cycles before failure and the stress level in the form:

$$S_{\lg N} = K_1 s_{\max}^{K_2} \tag{3}$$

where K_1 and K_2 – empirical coefficients. Based on the data in Table 1, the following values of the coefficients of equation (3) were obtained: for lugs made of 30KhGSN2A $K_1 = 7{,}3 \cdot 10^5$, $K_2 = –2{,}20$; for lugs made of 30XGCH2A $K_1 = 8{,}9 \cdot 10^4$, $K_2 = –1{,}82$. Graphic dependencies for eye data are shown in Fig. 4.

Table 1. Durability dissipation indicators for steel lugs (d = 20 mm; D = 38 mm)

Steel grade	**Stress level σ_{max}, MPa**	**Number of tested samples n**	$\overline{\lg N}$	$S_{\lg N}$	$V_{\lg N}$
30KhGSN2A	260	8	5,47	0,415	0,076
	320	15	5,11	0,210	0,041
	420	15	4,67	0,086	0,018
	520	15	4,39	0,101	0,023
30XGCH2A BAA (EI643)	260	8	5,53	0,421	0,076
	460	11	4,44	0,092	0,021
	570	15	4,14	0,071	0,017
	690	16	3,91	0,084	0,021

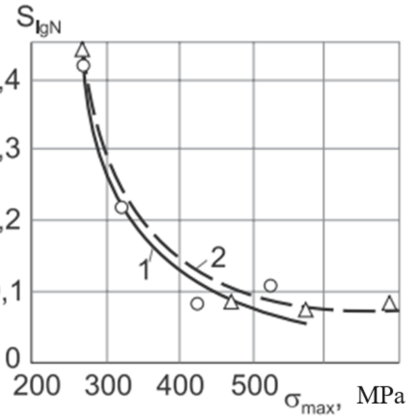

Fig.4. Dependence of SlgN on the level of maximum cycle stresses σmax for lugs made of steel: 1 – · – 30XGCH2A (d = 20 mm, D = 38 mm, t = 11 mm); 2 – – Δ – – 30XGCH2A (d = 20 mm, D = 38 mm, t = 9 mm)

Experimental data [2] show that the dissipation of the cyclic durability of steel lugs depends little on the technology of processing contact surfaces and applying various coatings and lubricants to them. The distribution functions of the durability before the destruction of these lugs are shown in Fig. 5.

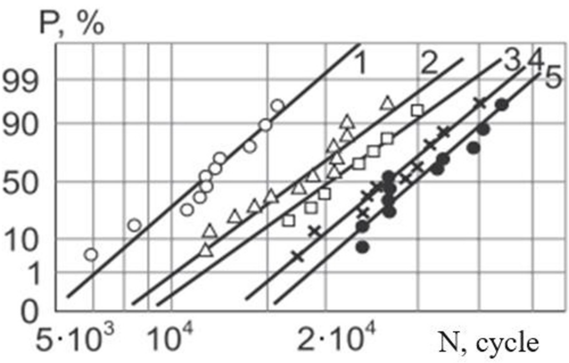

Fig. 5. Distribution of cyclic durability of lugs made of steel 30XGCH2A with different technologies for processing contact surfaces [2]: 1 – O – without lubrication; 2 – Δ – lubricant CIATIM-201; 3 – the bolt is coated with silver; 4 – × – the bolt is coated with VAP-2; 5 – the surfaces of the hole and chamfers are hardened by work hardening.

Coefficient of variation of lug endurance limit $V_{s_{Rd}}$ can be calculated using the formula

$$V_{s_{Rd}} = \frac{S_{s_{Rd}}}{s_{Rd}} \tag{4}$$

where $S_{s_{Rd}}$, s_{Rd} – respectively, the standard deviation and the average value (on the totality of all metal melts) of the endurance limit of the lugs.

The value of the coefficient of variation $V_{s_{Rd}}$ in the absence of surface hardening and without taking into account deviations in manufacturing technology, we determine it using the formula [3]

$$V_{(s_{Rd})} = \sqrt{V^2_{(s_{\max})} + V^2_{(\bar{s}_R)} + V^2_{(a_s)}} \tag{5}$$

where $V^2_{(s_{\max})}$ – coefficient of variation of maximum destructive stresses in the concentration zone, corresponding to the endurance limits of the lugs (when testing identical lug samples made from metal of the same heat);

$V^2_{\bar{s}_R}$ – coefficient of variation of average (on different heats) values of endurance limits of smooth laboratory samples with a diameter of 7.5 mm;

$V^2_{a_s}$ – coefficient of variation of the theoretical stress concentration coefficient near the eye hole.

Coefficient of variation of maximum breaking stresses $V^2_{(s_{\max})}$ takes into account the structural heterogeneity of the metal (the presence of various phases, inclusions, distortions of the crystal lattice, etc.). With a fairly stable technology, uniform properties of the metal in the volume of the part or eye, and the absence of residual stresses, the coefficient $V^2_{(s_{\max})}$ calculated by the formula.

$$V_{s_{\max}} = \frac{0,1}{1 + q^{V_s}} \tag{6}$$

Coefficient of variation of average values of endurance limits of smooth samples $V^2_{\bar{s}_R}$ takes into account inter-melt dispersion of the mechanical properties of the metal. Size $V^2_{\bar{s}_R}$ determined by statistical data of inter-fuse dispersion of endurance limits or, in the absence of such data, one can use inter-fuse dispersion of strength limit.

The coefficient of variation of the theoretical stress concentration coefficient V_{a_s} takes into account the influence of deviations of the actual dimensions of parts or lugs in the area of the holes from their nominal values on the dissipation of the endurance limit. Deviations in actual dimensions are generated by the instability of the technological parameters of the production process, as well as differences in operating conditions and load of parts (for example, differences in the intensity of wear and loosening of holes in the eyes). The coefficient of variation of the theoretical stress concentration coefficient is determined by the formula

$$V_{a_s} = \frac{S_{a_s}}{\bar{a}_s} \tag{7}$$

where S_{a_s} and $\bar{a}_s$ – respectively, the standard deviation and the average value α_σ.

The importance of taking into account the coefficient of variation V_{a_s} in calculations for the fatigue life of parts is illustrated in Fig. 6 [4]. As can be seen, at low probabilities of destruction (P < 1%) only due to a change in the value V_{a_s} with one nominal value of the radius of the fillet transition, the fatigue life of the part can change by 10 times. S_o, with increasing coefficient V_{a_s} durability is doubled, durability drops eightfold.

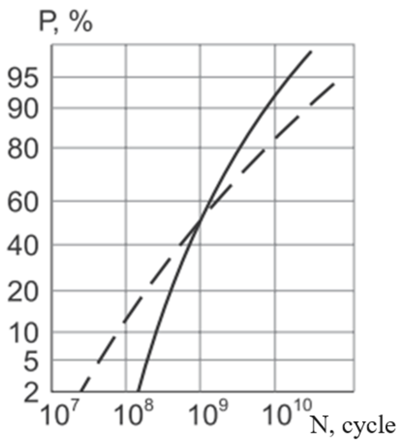

Fig. 6. Distribution functions of the cyclic durability of a part upon destruction in the fillet transition for different values of the coefficient of variation $V_{\alpha\sigma}$: 1– 0,08; 2 – 0,15

3 Research and results

Coefficient value α_σ lugs is a function of several parameters characterizing their shape in plan, type of loading, bolt fit in the hole, etc.

$$\alpha_\sigma = \varphi(d, D, \varepsilon, H, B \ldots), \tag{8}$$

where *d, D, H, B* – geometric parameters of the eye in plan; $e = \frac{d_0 - d_b}{d_0} = \frac{\text{V}d}{d_0}$ - clearance and interference value; d_b – bolt diameter; d_0 – hole diameter.

Based on a large number of experimental studies [3, 5, 6], it has been established that such geometric parameters of the eyelet as the width of the base B, the thickness of the upper bridge H and a number of others, as well as the direction of application of the external force, have little effect on the value of the theoretical concentration of the eyelet. The main influence on α_σ is exerted by the geometric parameters d and D (or their ratio) and the amount of clearance or interference between the bolt and the eye hole *ε*.

The influence of the parameter ratio d/D on the value of the theoretical stress concentration coefficient of the lugs is shown in Fig. 7.

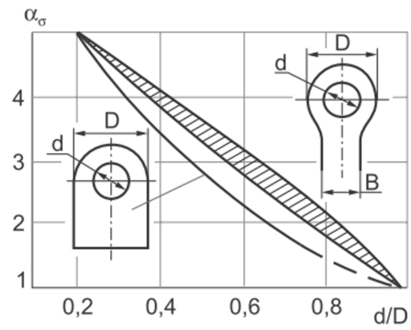

Fig. 7. Dependences of ασ on d/D for different shapes of the lug bases

To describe the dependency α_σ from d/D you can use the following empirical expressions:

1) $\varepsilon = 0{,}2\ldots0{,}3$ % in the range $0{,}2 \le d/D \le 0{,}8$,

$\alpha_\sigma = 0{,}85 + 0{,}95\ D/d$ at $A/D = 0{,}5$,

$$\alpha_\sigma = 0{,}6 + 0{,}95\ D/d \text{ at } A/D = 1; \tag{9}$$

2) For $\varepsilon \approx 0$ in the range $0{,}33 \le d/D \le 0{,}75$,

$\alpha_\sigma = 0{,}45 + 0{,}95\ D/d$ at $A/D = 0{,}5$.

The nature of the dependence of the theoretical stress concentration coefficient of the lugs on the gap size is shown in Fig. 8.

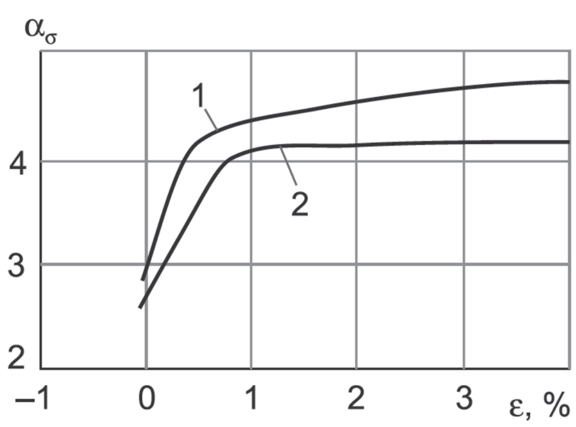

Fig. 8. Dependences of ασ on the gap size ε for lugs with d/D=0.4; d = 20 mm: curve 1 – base width B=0.5D; curve 2 – B=D.

Increasing the gap from 0 (tight fit) to 1% increases the value of α_σ by 30% (Fig. 8), with a further increase in the gap ($\varepsilon > 1\%$) its effect on α_σ is negligible. The dependences shown in Fig. 8 can be approximated by the expression

$$\alpha_\sigma = a_1 - a_2 \exp(-a_3\ \varepsilon), \tag{10}$$

where a_1, a_2 and a_3 – options.

It has been experimentally established that for standard steel lugs with A/D = 0.5 and *d/D* = 0.4...0.7, with $\varepsilon > 0$ $a_1 = 4{,}25$, $a_2 = 1{,}35$ and $a_3 = 310$.

It is known from mathematical statistics [7] that if in the function $y = f(x_1, x_2, \dots, x_n)$ random variables $x_1, x_2, \dots, x_n$ are uncorrelated.

To assess the impact of dimensional deviations d_{ot}, D and d_b from their nominal values for the dispersion of the value α_σ, we use formulas (9) and (10), establishing the dependences of α_σ on d/D and α_σ on ε, respectively

From expressions (7), (9) and (11) we obtain a formula for estimating the value V_{a_s}, taking into account the dispersion of the eye stiffness parameter d_{ot}/D

$$V'_{a_s} = \frac{\sqrt{V^2_{d_{ot}} + V^2_D}}{1 + 0{,}9\bar{d}_{ot} / \bar{D}} \tag{11}$$

where $V^2_{d_{ot}}$, V_D, $\bar{d}_{ot}$, D – respectively, coefficients of variation and average values of d_{ot} and D.

For the most common lugs of aircraft structures (with parameters d_{ot}/D = 0.3...0.8 and ε = 0.002...0.006), formula (12) can be represented in the form

$$V'_{a_s} = (0{,}6...0{,}8)\sqrt{V^2_{d_{ot}} + V^2_D} \tag{12}$$

From expressions (7), (10) and (11) we obtain a formula for estimating the value V''_{a_s}, taking into account the dispersion of the gap between the bolt and the eye hole:

$$V''_{a_s} = \frac{a_1 a_2(\bar{e} + 1)}{a_3 \exp(a_1 \bar{e}) - a_2} V_e \tag{13}$$

where a_1, a_2, a_3 – constant values that depend for one class of materials on the geometric parameters of the eyelet; $\bar{e} = \dfrac{\bar{d}_0 - \bar{d}_b}{\bar{d}_0}$ – average gap size; V_ε – coefficient of variation of the gap size.

Typically, these measurements are made on separate groups (lots) of bolts and lugs without determining specific clearance values ε. Therefore, to determine V''_{a_s} Instead of formula (14), it is more convenient to use the expression

$$V''_{a_s} = \frac{a_1 a_2 \bar{d}_{ot} / \bar{d}_b}{a_3 \exp[a_1(\bar{d}_{ot} / \bar{d}_b - 1)] - a_2} \sqrt{V^2_{d_{ot}} + V^2_{d_b}} \tag{14}$$

From the results of calculations using formulas (13) and (15), some of which for the hinge joint eyes of the aircraft landing gear are given in Table. 2, it was found that the coefficient of variation V'_{a_s}, taking into account the dispersion of the eyelet parameter d/D, an order of magnitude less than the coefficient of variation V''_{a_s}, taking into account the dispersion of the gap ε in the connection. Therefore, in engineering calculations of lugs for fatigue, in the statistical aspect, the dispersion of the d/D parameter can be ignored and only the formula (14) should be used).

For steel lugs with parameters A/D = 0.5; d/D = 0.4...0.7 and a gap ε = 0...0.02, from experimental studies the values of the constants included in equation (14) were established: a_1 = 310; a_2 = 1.35; a_3 = 4.25. Substituting the values of these constants into equation (14), we obtain

$$V''_{a_s} = \frac{310\bar{d}_{ot} / \bar{d}_b}{3,14\exp[310(\bar{d}_{ot} / \bar{d}_b - 1)] - 1}\sqrt{V^2_{d_{ot}} + V^2_{d_b}} \tag{15}$$

To estimate the size V''_{a_s} of the lugs, determined by formulas (13) or (15), a study was carried out on the variation of geometric parameters of a large group of hinged joints of the aircraft landing gear. As an example in table. 2 and 3 show part of the results of statistical processing of measurements of the main dimensions of the lugs, bolts and bronze bushings of the splined joint link of the main landing gear. Analysis of the results showed that the coefficients of variation of the geometric parameters of the lugs are within the following limits: V_A = 0.0010...0.0250 (A is the distance from the center of the hole to the top point of the jumper); $V^2_{d_{ot}}$ = 0.0001...0.0015; $V^2_{d_b}$ = 0.0001...0.0025; V_H = 0.0010...0.0150 (H is the width of the upper jumper); V_t = 0.0050...0.0300 (t – eye thickness). The magnitude of the coefficient of variation V'_{a_s} is an order of magnitude smaller than the coefficient V''_{a_s}. Therefore, in calculating the fatigue resistance and durability characteristics of lugs when determining the coefficient of variation $V_{s_{Rd}}$ only the dispersion of the actual gap sizes can be taken into account, and deviations of other geometric dimensions of the lugs can be neglected, i.e. to calculate V_{a_s} use only formula (14) or (15).

Table 2 Results of statistical processing of measurements of the elements of the hinge joint of the aircraft landing gear

Name	Geometric parameter, mm	Nominal size, mm (quality)	Average parameter value, mm	Standard deviation, mm	Coeff. variations
Spline joint link, large eye	D_{ot}	56H8	56,028	0,0358	0,0006
	D	79	78,870	0,3376	0,0043
	T	37	37,170	0,7710	0,0207
Spline joint link, small eye	D_{ot}	24H8	24,036	0,0109	0,0005
	D	42	42,540	0,3210	0,0075
	T	17	17,060	0,3620	0,0213
Bolt	*D*b	50*f*8	49,924	0,0510	0,0010
Sleeve	*D*b	56*f*8	55,943	0,0130	0,0002

Table 3 Coefficients of variation of the theoretical stress concentration coefficient of the spline joint eyelets

Spline link eye	Swivel Size and Fit	Eyelet parameters			Coefficients of variation	
		A/*D*	*d*/*D*	*t*/*d*	V'_{a_s} f-la (4.48)	V''_{a_s} f-la (4.51)
Big	56 *H*8/*f*8	0,5	0,72	0,66	0,0034	0,037
Small	24 *H*8/*f*8	0,5	0,56	0,71	0,0060	0,042

4 Conclusion

As a result of the analysis, the following conclusions were made:

– Dependencies were obtained to estimate the standard deviation of the logarithm of the number of cycles before failure of lugs made of high-strength steels on the value of the maximum stress amplitudes of cyclic loading.

– Technological processing of the contact surfaces of the bolt and the hole of the lugs has virtually no effect on the dissipation of the durability of the power lugs until resolution.

– Dispersion of the geometric parameters of power lugs in the stress concentration zone does not significantly affect the dispersion of their endurance limit.

– Dispersion of the geometric parameters of power lugs in the stress concentration zone does not significantly affect the dispersion of their endurance limit.

References

1. G. Kravchenko, Yu Popov, A. Kolosov, A. Smolyaninov, I. Pocebneva, Method of Design Calculation for Strength of Structures Made of Metal and Polymer Composite (2022). DOI: 10.1007/978-3-031-14125-6_54
2. L.N. Aleksandrovskaya, O.B. Kerber, P.A. Iosifov, et al. Russ. Aeronaut. **62**, 199–205 (2019). DOI:10.3103/S1068799819020041
3. G.N. Kravchenko, Russ. Engin. Res. **42**, 365–369 (2022). DOI:10.3103/S1068798X22040219
4. G. Kravchenko, K. Kravchenko, A. Smolyaninov, I. Kudryavtseva, E3S Web Conf. **244** 04001 (2021) DOI: 10.1051/e3sconf/202124404001
5. A. Smolyaninov, et.al., BIO Web of Conferences. **84**. (2024). DOI: 10.1051/bioconf/20248401036
6. A. Yerokhin, et.al., E3S Web of Conferences. **460**. (2023). DOI:10.1051/e3sconf/202346007021
7. V. Bekhmetiev, et.al., E3S Web of Conferences. **376**. (2023). DOI:10.1051/e3sconf/202337601092
8. A. Yerokhin, Yu. Deniskin, *Airfoil smoothing using unconditional optimization.* Aerospace Systems. (2023). DOI:10.1007/s42401-023-00232-7
9. D. Golovin, et.al., E3S Web of Conferences. **363**. (2022). DOI:10.1051/e3sconf/202236304002
10. A. Scherbakov, et.al., E3S Web of Conferences. **413**. (2023). DOI:10.1051/e3sconf/202341304002
11. O. Dolgov, D. Prokopenko, A. Kolosov, I. Abrosimova, Transportation Research Procedia. **63**. 1639-1659. (2022). DOI:10.1016/j.trpro.2022.06.178
12. D.S. Durov, B.B. Safoklov, O.S. Dolgov, et al. Russ. Engin. Res. **43**, 150–153 (2023). DOI:10.3103/S1068798X23030073
13. T. Dolgova, et.al., E3S Web of Conferences. **376**. (2023). DOI:10.1051/e3sconf/202337601095.
14. V. Urazov, et.al., Journal of Physics: Conference Series. **2094**. 042023. (2021). DOI:10.1088/1742-6596/2094/4/042023.

15. Kuznetsov, M. & Gusev, Pavel & Bredihin, A. & Chizhov, M.. (2021). Simulation modeling of the automated system tasks of production technical preparation. AIP Conference Proceedings. **2402**. 050029. DOI:10.1063/5.0071461.
16. Zhuravlev, A. A. Approach to the selection of the optimal sized of the ear – fork lug / A. A. Zhuravlev, S. A. Serebryansky // E3S Web of Conferences. – 2023. – Vol. **383**. – P. 05010. – DOI 10.1051/e3sconf/202338305010
17. Abramov, J. S. Iterative design of aircraft airframe components and assemblies / J. S. Abramov, S. A. Serebryansky // E3S Web of Conferences. – 2023. – Vol. **383**. – P. 05001. – DOI 10.1051/e3sconf/202338305001
18. A. A. Zhuravlev, *Research of the coefficient taking into account the angle of application of the load for the calculation of ear-fork type eyes* / Gagarin Readings - 2023: Collection of abstracts of the XLIX International Youth Scientific Conference, Moscow, April 11–14, 2023 . – Moscow: Pero Publishing House, 2023. – P. 35.
19. D. V. Grinevich, I. V. Gulina, N. O. Yakovlev [etc.] // Factory Laboratory. Diagnostics of materials. – 2023. – T. **89**, No. 6. – P. 76-82. – DOI 10.26896/1028-6861-2023-89-6-76-82.
20. Yakovlev, D. V. Assessment of the load of the eyes of complex hinged joints / D. V. Yakovlev, S. G. Gnezdilov // Seventy-fifth All-Russian scientific and technical conference of students, undergraduates and graduate students with international participation: Collection of conference materials. In 3 parts, Yaroslavl, April 20–21, 2022. – Yaroslavl: Yaroslavl State Technical University, 2022. – P. 529-532.