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Numerical modeling and experimental estimates of structural member fatigue characteristics

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Introduction. In the algorithm for predicting the resource of machine parts, models of external actions, fracture resistance, and temporal development of a particular type of damage to these units interact. The applied issues of the resistance of machine parts to fatigue failure are considered. The scientific research and regulatory materials are adapted to determine the characteristics of endurance to the specifics of structures and materials of the construction-and-road machinery and agricultural machinery. The work objective is to use the analysis of existing methods to develop recommendations for the calculated determination of the endurance parameters of structural members of the agricultural machines.

Materials and Methods. The initial data were scientific studies on the fracture mechanics of the engineering materials and structures, as well as standards for endurance characterization methods. The need to test methods for determining fatigue characteristics to use them in the road construction machinery and agricultural machinery projects follows from the specifics of their designs, operation conditions and industry-specific range of materials. Based on the analysis of existing methods, it is required to develop recommendations for the calculation of the endurance parameters of structural parts of the agricultural machines. For this, the components of the load-bearing systems of the staged design were presented in the form of a set of plates of the corresponding thickness; and the concept of the critical radius of the stress raiser at the welding sites was also used. Numerical methods using mathematical models were applied. The calculation results were verified through comparing them to experimentally determined fatigue characteristics of the members of a combine harvester on a test bench.

Results. Radius critical values of the stress raisers for various types of welds are obtained. The tables of the calculated and experimental endurance limits of the combine bearing components are well correlated and can be used under designing.

Discussion and Conclusions. The theoretical foundations laid down in the study open up great opportunities for applications to the design of various machines. The considered fragment of adaptation of the theoretical approach to the agricultural engineering objects can be used in the design of load-bearing systems in the related fields of engineering.

Keywords: endurance range, fatigue fracture, fatigue crack, weld joint, computational and experimental methods.

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Introduction. In the computational and computational-experimental methods for predicting the durability of the load-bearing units of ground-based mobile mass-produced vehicles (automobiles, tractors, road construction, irrigation and drainage, agricultural, military equipment, etc.), it is recommended to take the early formation of a fatigue crack of 0.2 – 0.5mm length under conditions of high-cycle fracture as the key reliability criterion[1]. In this case, the initial information on the structural properties is the characteristic of the fatigue curve. Consider the possibility of developing methods for determining the fatigue characteristics of machine parts[2].

[1] Kogaev VP, Makhutov NA, Gusenkov AP. Raschety detalei mashin i konstruktsii na prochnost' i dolgovechnost': Spravochnik [Strength and durability design of machine parts and structures: Reference Guide]. Moscow: Mashinostroenie; 1985. 224 p.

[2] RP 206–86. Raschety i ispytaniya na prochnost'. Metody opredeleniya kharakteristik soprotivleniya ustalosti detalei mashin s uchetom rasseyaniya: Metodicheskie rekomendatsii [Calculations and strength tests. Methods for determining of fatigue resistance characteristics of machine parts considering scattering: Recommended practice] Moscow: VNIINmash; 1986. 50 p..

Structural parts are represented by plates working in push-pull. The stress concentration is caused by a sharp change in the thickness of the plates with a certain radius of curvature ρ at the junctions, up to a sharp cut. The stress concentration associated with the formation of a weld on the plates under study is considered the subject of independent research and is taken into account as a result.

The correct parameter selection to fatigue damage of machine parts and load-bearing systems is the basis for calculating resources and predicting reliability [1]. Consider the methodology and the calculation results of the characteristics of the fatigue resistance of the elements (zones) of the loadbearing structure based on the model shown in Fig. 1.

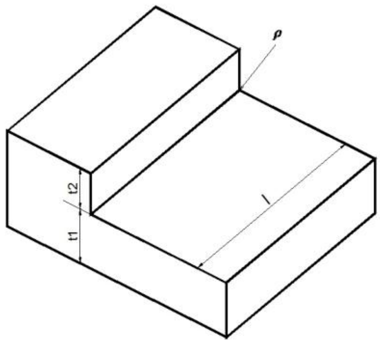

Fig. 1. Scheme for the calculated determination of fatigue characteristics

The model is a fragment of a welded joint of thick-walled units. It is typical of many self-propelled and trailed vehicles of land transport, for example, a frame system of self-propelled combines. The initial data for the calculation are given in Table 1.

Table 1

Initial data for determining fatigue characteristics of joint assemblies shown in Fig. 1

Option	1	2	3	4
Steel grade	09G2	09G2	20	20
Working conditions		corrosion		corrosion
$\bar{\sigma}_b$, MPa	460	460	420	420
$\bar{\sigma}_T$, MPa	300	300	250	250
$\bar{\sigma}_{-1}$, MPa	232	232	213	213
$V_{\sigma-1}$	0.069	0.069	0.062	0.062
$K_{F\sigma}$	0.85	0.55	0.85	0.58
K_V	0.50	0.50	0.50	0.50
K_A	0.95	0.95	0.95	0.95
$t_1 = t_2$, mm	10	10	4	4
ρ, mm	0.1–2	0.1–2	0.1–2	0.1–2
$\bar{\rho}$, mm	0.5	0.5	0.5	0.5
V_ρ	0.36	0.36	0.36	0.36
l, mm	200	200	80	80

The median endurance limit is calculated by the expression[1, 2]:

[1] Kogaev VP, Makhutov NA, Gusenkov AP. Op. cit. P. 112-224.
[2] GOST 25.504–82. Raschety i ispytaniya na prochnost'. Metody rascheta kharakteristik soprotivleniya ustalosti [GOST 25.504–82. Strength calculation and testing. Methods of fatigue strength behaviour calculation]. Available at: http://docs.cntd.ru/document/1200012858 (accessed: 11.12.2019).

$$\bar{\sigma}_{-1g} = \frac{\bar{\sigma}_{-1}}{K},$$

where $\bar{\sigma}_{-1}$ is the median endurance limit determined on smooth laboratory samples of standard diameter $d_0 = 7.5$ mm; K is the endurance limit reduction coefficient:

$$K = \left(\frac{K_\sigma}{K_{d\sigma}} + \frac{1}{K_{F\sigma}} - 1\right)\frac{1}{K_V K_A},$$

where $K_\sigma = \frac{\sigma_{-1d}}{\sigma_{-1g}}$ is the effective stress concentration factor; $K_{d\sigma}$ is the full-size influence coefficient; $K_{F\sigma}$ is the surface condition influence coefficient; K_V is the influence coefficient of surface softening from metallurgical welding processes; K_A is the anisotropy factor of material properties.

For the example considered, we will use the recommendations [2]. We accept $K_V = 0.5$, For normal operating conditions, we accept $K_{F\sigma} = 0.85$. During operation or storage of the machine with the ingress of freshwater, moisture and the formation of corrosion, we accept for steel 09G2 on GOST 5521–93 $K_{F\sigma} = 0.55$, for steel 20 on GOST 2591-2006 $K_{F\sigma} = 0.58$. The initial data for calculating the endurance of the samples and their variation coefficients $V_{\sigma-1}$ are given in Table 1.

To determine the characteristic relations of parameters, the technique[1] recommends the formula:

$$\frac{K_\sigma}{K_{d\sigma}} = \frac{\alpha_\sigma}{0.5\zeta},$$

where α_σ is a theoretical coefficient that determines the degree of increase in stress in the zone of their concentration, it is calculated as per the local stress-strain state using finite element models; ζ is a distribution parameter.

The similarity equation for fatigue failure is close in form to the Weibull distribution. For plate elements, it has the form[2]:

$$J = -2.3\lg(1-p) = \frac{t_1+t_2}{\bar{G}_1}\left(\frac{u}{z}\right)^\beta \frac{1}{(\beta+1)(\beta+2)} \cdot \frac{(\zeta-1)^{\beta+2}}{\zeta^2}, \tag{1}$$

where $\bar{G}_1$ is the gradient of the first principal stress, it is determined by the formula:

$$\bar{G}_1 = 23/\rho; \left(\frac{u}{z}\right)^\beta = 0.0152(\beta+1),$$

here, V_σ is sensitivity of metal to the stress factor:

$$V_\sigma = 0.2 - 0.0001\sigma_b;$$

$$\beta = \frac{1}{V_\sigma} - 0.64.$$

We obtain the median value of the parameter $\bar{\zeta}$ with the probability of destruction $P = 0.5$ from the solution to the similarity equation (1). For the parts in question, the values of $\bar{\zeta}$ are given in Table 2.

[1] RP 206–86. Op. cit. 1986. 50 p.
[2] RP 206–86. Op. cit. 1986. 50 p.

Table 2

Design parameters of the structural fatigue resistance (Fig. 1)

Option	1	2	3	4
$\rho_{кр}$, mm	0.5	0.5	0.5	0.5
$\overline{\alpha}_\sigma$	2.2	2.2	1.7	1.7
$V_{\alpha\sigma}$	0.19	0.19	0.22	0.22
$\overline{\zeta}$	2.12	2.12	2.51	2.51
V_σ	0.154	0.154	0.158	0.158
β	5.85	5.58	5.69	5.69
$\overline{G}_1$, 1/mm	4.6	4.6	4.6	4.6
$K_\sigma / K_{d\sigma}$	2.07	2.07	1.35	1.35
K	4.74	6.09	3.22	4.57
θ	0.49	0.49	0.20	0.20
$V_{\sigma\max}$	0.05	0.05	0.06	0.06
$V_{\sigma-1g}$	0.21	0.21	0.24	0.24
ΔK_{th}, MPa	9.53	9.53	9.53	9.53

The average stress gradient in the zone of radius ρ, which is the place of concentration, is determined for the condition:

$$\rho = \left(\rho_{кр}\right) \approx 0.5 - 0.0004\left(\sigma_b - 500\right).$$

For the steels under consideration, the critical value of the radius of curvature in the connection of parts $\rho_{кр}$ = 0.5 mm was established. It corresponds to the formation of fatigue cracks not running further [1]. By this criterion, the value α_σ was selected. Fig. 2 shows the dependences of the theoretical stress concentration coefficient on the radius of curvature for various geometric design parameters. The calculated median endurance limits for the parts under consideration are presented in Table 3.

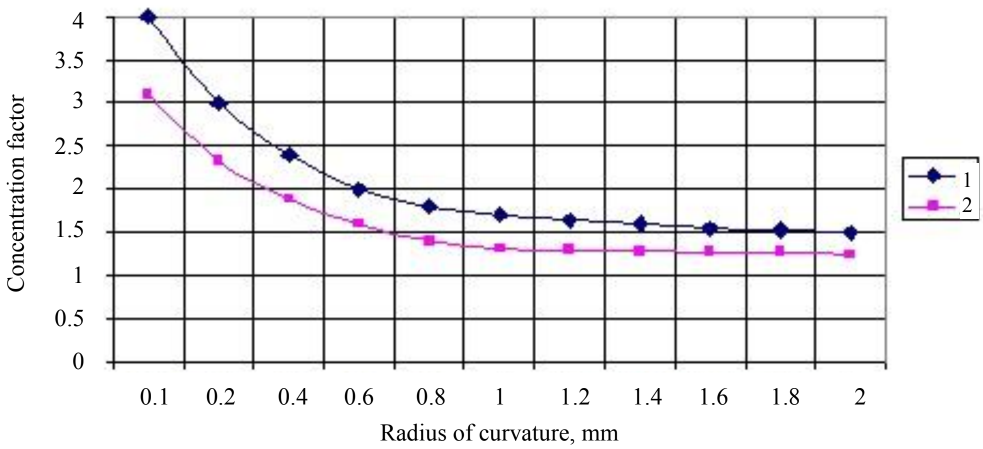

Fig. 2. Dependences of theoretical stress concentration coefficient on radius of curvature: 1 is $t_1 = t_2 = 10$ *mm*; 2 is $t_1 = t_2 = 4$ *mm*

[1] Kogaev VP, Makhutov NA, Gusenkov AP. Op. cit. P. 112-224.

Table 3

Design parameters to define joint assembly characteristics based on the initial data of Table 1 shown in Fig. 1

Option	1	2	3	4
$\tilde{\sigma}-1g$	49	38	66	46
$(\sigma-1g)P=0.05$, MPa	32	25	40	28
$(\sigma-1g)P=0.95$, MPa	66	51	92	64
m	4.54	3.52	6.36	4.48
$N_\sigma, 10^6\,cycles$	2.9	2.6	2.9	2.7
$\psi\sigma$	0.11	0.11	0.10	0.10
$\sigma-1_{gkp}$, MPa	34	-	-	-

The variation coefficient of the fatigue limit is determined from the expression:

$$V_{\sigma-1g}=\sqrt{V_{\sigma\max}^2+V_{\sigma-1}^2+V_{\alpha\sigma}^2}\,, \tag{2}$$

where $V_{\sigma\max}$ is the variation coefficient of maximum stresses in the concentration zone; $V_{\sigma-1}$ is the variation coefficient of the fatigue limit of the sample; $V_{\alpha\sigma}$ is the variation coefficient of the theoretical coefficient in the concentration zone.

The variation coefficient $V_{\sigma-1}$ is set[1] and presented in Table 1 as source data. The variation coefficient $V_{\sigma\max}$ is determined from the expression [2]:

$$V_{\sigma\max}=\frac{0.1}{1+\theta^{\nu\sigma}}\,,$$

where θ is the relative fatigue failure similarity criterion:

$$\theta=\frac{1}{88.3\bar{G}_1}\,.$$

The design values of the parameters are given in Table. 2. The coefficient of variation $V_{\alpha\sigma}$ is determined by the recommendations [3]:

$$V_{\alpha\sigma}=\left|\frac{\partial\alpha_\sigma}{\partial\rho}\right|_{\rho=\bar{\rho}}\cdot\frac{\bar{\rho}}{\alpha_\sigma}V_\rho\,.$$

To find the derivative module, a linear approximation of the function $\alpha_\sigma=\varphi(\rho/t)$, is carried out, which is shown in Fig. 2 in the vicinity of the average value of the parameter $\bar{\rho}$. The calculation results are given in Table. 2. It also contains the results of calculating the variation coefficient of the fatigue limit from the expression (2).

We determine the values of the fatigue limit under the assumption of its normal distribution with a probability of destruction of 5% and 95% from the formula:

$$(\sigma_{-1g})_P=\bar{\sigma}_{-1g}(1+Z_P V_{\sigma-1g})\,,$$

where Z_P is the fractile of the normal distribution. Table 3 shows the fatigue limit values with the indicated fracture probabilities.

Next, we present the dependences for calculating the fatigue curve parameters:

- indicator of the slope of the left branch of the fatigue curve[4]:

$$m=\left(5+\frac{\sigma_b}{80}\right)/K_\sigma\,;$$

- fatigue curve point abscissa:

$$N_\sigma=10^5\bar{\sigma}_{-1g}^{(0.997-0.003m)}\,;$$

- coefficient of sensitivity to cycle asymmetry[5]:

$$\psi_\sigma=0.02+2\cdot10^{-4}\sigma_b\,.$$

[1] Kogaev VP, Makhutov NA, Gusenkov AP. Op. cit. P. 112-224.
[2] RP 206–86. Op. cit. 1986. 50 p.
[3] RP 206–86. Op. cit. 1986. 50 p.
[4] RP 206–86. Op. cit. 1986. 50 p.
[5] Kogaev VP, Makhutov NA, Gusenkov AP. Op. cit. P. 112-224.

The calculation results of these characteristics for the components under consideration are given in Table 3.

The studies have established[1], that in the zones of stress concentration, there are critical radii of curvature in the range of values $\rho_{кр}$ = 0.1–0.6 mm [1]. At $\rho < \rho_{кр}$, there are other patterns of similarity of fatigue failure compared to the area $\rho > \rho_{кр}$. In this case, a crack-like ultimately sharp notch is considered, which is characteristic of the weld zones of the joinable units in various engineering industries [3, 4]. Two fatigue limits are recommended[2] to determine:

1. Fatigue limit σ_{-1g} at $\rho > \rho_{кр}$. It is determined by the criteria for the appearance of the first microscopic fatigue cracks and depends on the radius of curvature.
2. Fatigue limit of final fracture $\sigma_{-1gкр}$ at $\rho < \rho_{кр}$. It does not depend on the radius of notch curvature and is determined from the formula:

$$\sigma_{-1gкр} = \frac{11,5\Delta K_{th}}{\sqrt{t + \rho_{кр}}},$$

where ΔK_{th} is the fatigue crack growth threshold; t is the step depth in the zone of the voltage concentrator.

The threshold for the development of fatigue cracks for mild steels, considering the asymmetry coefficient, can approximately be determined from the formula [3]:

$$\Delta K_{th} \approx 6,74\sqrt{1-R}\,. \tag{3}$$

The parameter ΔK_{th} for the units under consideration is indicated in Table 2 at $R = 1$. The values $\sigma_{-1gкр}$ calculated from the expression (3) are given in Table 3.

To assess the appropriateness of calculating the fatigue of structural elements presented in the form of plates with different transition radii in the connection zones up to an ultimately sharp notch, bench tests of field samples were carried out. The test results are presented in Table 4.

Table 4

Experimental characteristics of fatigue resistance of harvesting machine metal structures

Weld zone	m			(σ_{-1g}), MPa			(σ_{-1g}) P = 0.05 MPa		(σ_{-1g}) P = 0.95 MPa		$V_{\sigma-1g}$	$N_\sigma \cdot 10^6$ cycles
	min	mean	max	min	mean	max	by mean	by min	by mean	by max		
flange and drive axle housing	3.2	3.7	4.3	31	37	43	4	4	70	81	0.54	3.7
gearbox bracket and drive axle housing	3.1	3.9	4.7	31	39	47	24	19	54	65	0.23	3.6
mounting plate and drive axle housing	3.5	4.1	4.8	33	38	43	21	18	55	62	0.27	3.9
frame racks	4.2	4.9	5.6	38	45	52	35	29	55	64	0.14	4.1

For bench testing, the highest accuracy group was selected with a relative error $0.1 \le \varepsilon \le 0.2$, confidence probability $\beta = 0.8$. The number of tested structures was in the range of 11-14 units.

[1] Kogaev VP, Makhutov NA, Gusenkov AP. Op. cit. P. 112-224.
[2] RP 206–86. Op. cit. 1986. 50 p.
[3] RP 206–86. Op. cit. 1986. 50 p.

The data of Table 4 show large scatter of empirical estimates. Even if we exclude the weld zone of the flange and wheel axle beam from consideration, whose spread of values is caused by the instability of the process, in a given confidence interval, the value σ_{-1g} differs by 1.8–2.9 times.

Conclusion. A comparison of the calculated (Table 3) and experimental (Table 4) characteristics of fatigue resistance in the zones of welded joints shows their good compossibility. The confidence intervals of the experimental values overlap similar intervals of the calculated values for the areas of the wheel drive axle. The average values for normal operating conditions differ by 1.3 times, and coincide under corrosion. For frame metal structures, the calculated values under normal conditions differ 1.5 times, and under corrosion conditions, they practically coincide. Good agreement with real values is shown by values $\sigma_{-1gкр}$ calculated by the threshold of development of fatigue cracks.

The materials presented provide for the conclusion that there is sufficient life reliability of the calculated characteristics of fatigue resistance based on the proposed method at the forecasting stage. The correct characteristics of fatigue resistance with a known or obtained from a field experiment distribution can serve as the foundation for calculating the design life with the required probability of failure-free operation resulting from the technical specifications for the corresponding machine [5].

Thus, through analyzing the existing methods, recommendations have been developed on the calculated determination of the endurance parameters of structural elements of agricultural machines. Under the engineering change of a project or a product prototype up to standard durability through structural and technological techniques, the characteristics of fatigue resistance are used in methods of approximate and functional resource estimates [6, 7].

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Claimed contributorship

E.Yu. Man'shina: formulation of the basic concept, objective and task of the study; computational analysis; text preparation; formulation of conclusions. Yu.P. Man'shin: academic advising, analysis of the research results, the text revision, correction of the conclusions.

All authors have read and approved the final manuscript.