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ARTICLE

FATIGUE STRENGTH OF ALUMINIUM ALLOY STRUCTURES

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ABSTRACT

This article proposes fatigue strength calculation method for building structures made of aluminium alloys, which has not been included in codes and standards of the Russian Federation until now. For this purpose, conducted complex laboratory tests were made on three aluminium alloys which might be potentially used in building structures production: 1915T, AD35T1, 1565chM. As the result of the tests. stress-strain and fatigue properties of these alloys were obtained. The proposed method is based on home-grown developments for steel building structures fatigue strength calculation and foreign data on aluminium structures fatigue strength calculation. Accuracy of the method has been checked during numerical simulation as well as static and fatigue tests of full-size walking bridge made of 1915T alloy. Deviations from the results of calculation performed using this method were equal to no more than 5-15%.

KEY WORDS
building structure, bridge, test of specimens, calculation method, stress

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INTRODUCTION

Modern trends in industry and building development are based on increasingly wide application of innovative technologies and materials. Aluminium is certainly at the top of the list of such materials due to its wide application in many industries – aviation, electrical engineering, automotive engineering, transport, building structures, etc [1].

Application of aluminium for production of different structures gives some important advantages as compared to conventional materials [2]:

- low specific gravity as compared to other metals;
- high specific strength exceeding specific strength of steel and concrete;
- no tendency to brittle fracture in case of temperature decrease;
- increased seismic stability of structures due to lower weight;
- high corrosion resistance of some alloys;
- manufacturability of structural members having different shapes;
- easy transportation and mounting of large-sized fragments.

At the same time, aluminium alloy structures have some disadvantages:

- increased deformability due to decreased modulus of elasticity;
- relatively low resistance to fatigue fracture;
- risk of galvanic corrosion in the points of contact with other materials.

It should be noted that disadvantages listed above can be minimized or even eliminated in the course of development due to special design solutions and measures.

Until the present time, fatigue strength calculation method for aluminium alloys has not been included in the regulatory documents of the Russian Federation for building structures design [3]. It was mainly due to the lack of scientific research on fatigue behaviour of aluminium alloys in building structures.

The main objectives of this work are experimental studies of the fatigue properties of aluminum alloys and the development of fatigue strength calculation methods for building structures made of these alloys on the basis of the obtained results.

FATIGUE STRENGTH CALCULATION METHOD

As aluminium alloys are widely used in structures being subjected to time-varying cyclical influences such as more and more widespread motor-road and walking bridges, the necessity to provide endurance of such alloys throughout their specified service life becomes more and more important. Service life of such structures may account for several decades and the number of load cycles during their service life may be up to $10^6 \div 10^8$ and more [4].

Basic cyclic load parameters are minimum and maximum cycle stresses σ_{max}, σ_{min}. Cycle amplitude σ_a and mean cycle stress σ_m determined on the base thereof as well as stress ratio r are interrelated by the following equations:

$$\sigma_a = \frac{\sigma_{max}-\sigma_{min}}{2},\ \sigma_m = \frac{\sigma_{max}+\sigma_{min}}{2} \qquad (1)$$

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$$r = \frac{\sigma_{min}}{\sigma_{max}}, \quad (2)$$

Metals (fatigue) strength is characterized by fatigue strength curve obtained as the result of fatigue tests on the series of smooth specimens at different levels of cyclic stresses (σ_a-N curve – [Fig. 1]). This curve presented in coordinates logσ_a – log$N$ (σ_a – cycle amplitude, N – number of load cycles) has a shape of broken curve consisting of straight-line portions.

The main material fatigue characteristic is fatigue strength σ_r, which is determined by fatigue curve and represents the maximum stress, below which there is no fatigue fracture (fatigue crack formation) in material, or material is able to withstand the specified number of load cycles.

Fatigue curve for most steels has two intrinsic portions [Fig. 1a]: slopped portion with slope angle defined by parameter m_1, and plateau conforming to fatigue strength value achieved at approximately10^7 load cycles [5, 6].

In contrast to steels, this curve for aluminium alloys has more complex shape including three portions [Fig. 1b], slopped portions have different slope angles expressed by parameters m_1, $m_2 \cong m_1+2$, and plateau is achieved later than for steels, at approximately 10^8 load cycles [4, 7].

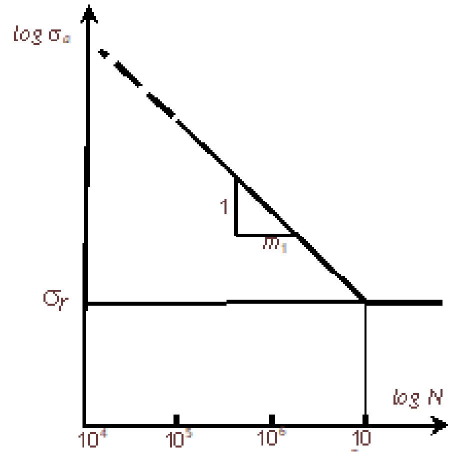

Fig. 1a

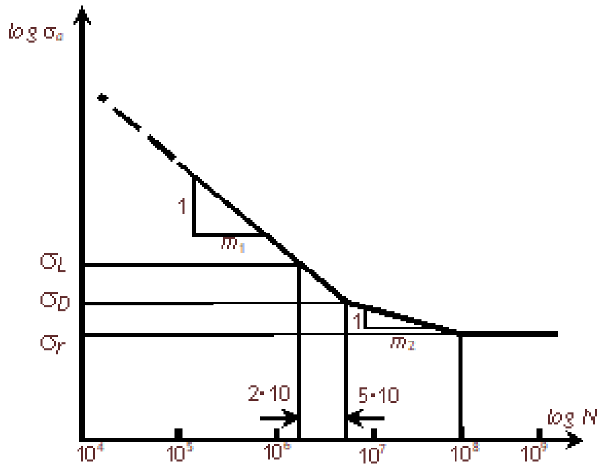

Fig. 1b

σ_r is the fatigue strength at specified load cycle (for symmetric cycle $\sigma_r = \sigma_{-1}$: for steels at 10^7 cycles, for aluminium alloys at $2{\cdot}10^6$ cycles);
σ_D is the fatigue strength for aluminium alloys at $5{\cdot}10^6$ cycles;
σ_L is the damage threshold for aluminium alloys at (10^8 cycles).

Factors influencing fatigue strength value

Stress concentration

Fatigue fracture accompanied by fatigue cracks formation usually occurs in stress concentration areas of the most loaded structural members due to their shape and interconnection methods.

Actual values of cycle amplitude σ'_a and mean cycle stress σ'_m in expected fatigue fracture area are called effective stresses. They are determined by multiplication of nominal values of cycle amplitude σ'_a and mean cycle stress σ'_m by theoretical stress concentration factor K_σ:

$$\sigma'_a = \sigma_a K_\sigma. \quad (3)$$

Nominal stresses σ_a, σ_m in the said zones are determined by static structural calculation without regard to stress concentration effect.

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Structural members manufacturing quality

Structural members manufacturing quality is taken into account in fatigue calculations using manufacturing method dependent safety margin γ_{Mf}, depending on processing method used during fabrication of structural members made of aluminium alloys [Table 1] [8].

Table 1: Method used in fabrication

Manufacturing method	γ_{Mf}
Rolled and molded sections	1,0
Automatic cutting from metal sheet with edges milling and holes broaching	1,1
Automated cutting from metal sheet without edges and holes processing	1,2–1,3
Cold-formed section from metal sheet	1,5

Structural members interconnection method

Structural members interconnection method is taken into account in fatigue calculations using interconnection method dependent safety margin γ_{Sf}, depending on the method used for structural members interconnection in structural units [Table 2] [8].

Table 2: Method used for interconnection of structural units

Interconnection method	γ_{Sf}
Friction stir welding	1,1
Semiautomatic argon arc inert-gas shielded welding	1,3
Manual argon arc welding	1,5
Interconnection using high-strength bolts with tightening force control	1,2

Rolled thickness

Thickness-dependent safety margin γ_{TF}=1.05 is introduced when manufacturing structural members from aluminium alloys with rolled thickness above 50 mm and γ_{TF}=1.0 for lower thickness [8].

Stress ratio r

Stress ratio *r* has great impact on fatigue strength of structural members [6, 7].

Fatigue curves for random aluminium alloy tested with different values of stress ratio *r* are shown in [Fig. 2a].

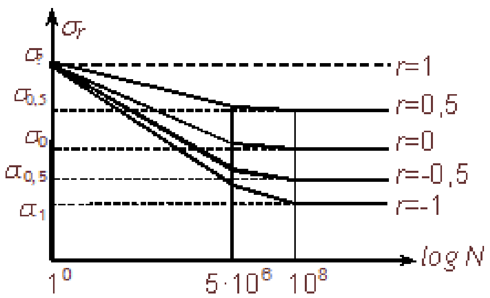

Fig. 2a

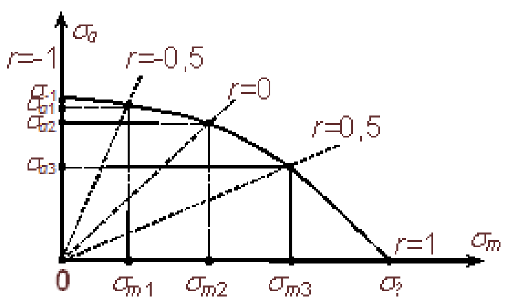

Fig. 2b

Zero point on horizontal axis conforms to static destructive test which gives the value of ultimate strength σ_B on vertical axis (stress ratio *r*=1).

Next curves give fatigue strength σ_r values in the range of $-1< r \leq 1$; the lowest value of fatigue strength σ_{-1} occurs with symmetric cycle (*r*=−1), which is most dangerous in the context of fatigue fracture point.

Fatigue strength values obtained at different values of stress ratio *r* in coordinates σ_a, σ_m (cycle amplitude and mean cycle stress) form so called limiting amplitude diagram [Fig. 2b], conforming to the basic fatigue strength condition, at which maximum cycle stress shall not exceed corresponding fatigue strength σ_r:

$$\sigma_{max} = \sigma_a + \sigma_m \leq \sigma_r \quad (3)$$

Basically, limiting amplitude diagram for specific alloy represents a complex strength characteristic of this alloy providing fatigue strength conditions in the range of stress ratio values $-1 \leq r \leq 1$.

Since it is impossible to perform a large number of fatigue tests, in practice approximated limiting amplitude diagrams [Fig. 3] built based on 2 or 3 standard tests are used [6, 7].

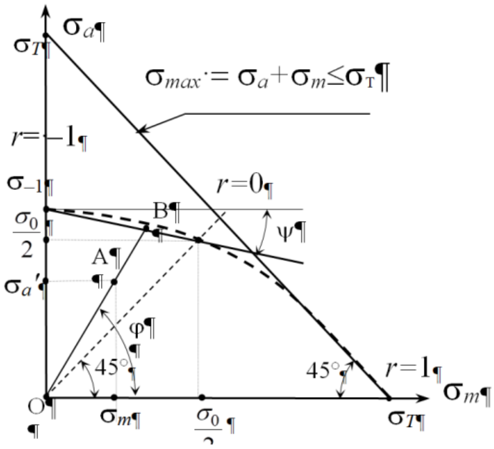

Fig. 3a

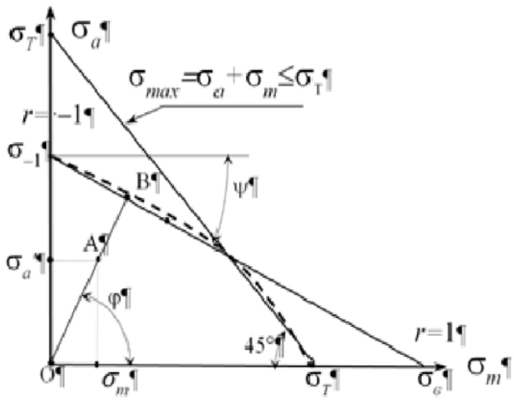

Fig. 3b

Approximated limiting amplitude diagram by Serensen – Kinasoshvili [8] [Fig. 3a] is built based on the results of two fatigue tests with stress ratios r=-1 (symmetric cycle) and r=0 (pulsed cycle) and static test used to determine yield strength σ_T (conventional yield strength $\sigma_{0,2}$ for alloys without yield plateau) which serves, together with fatigue strength condition (3), as static strength condition observance criterion:

$$\sigma_{max} = \sigma_a + \sigma_m \leq \sigma_T \quad (4)$$

Approximated limiting amplitude diagram by Goodman [Fig. 3b] [7, 9] is built based on the results of fatigue test with stress ratio r=-1 (symmetric cycle) and static test used to determine yield strength σ_T and ultimate strength σ_B necessary for diagram construction. When using this diagram, error grows in its right portion together with the growth of stress ratio r positive values.

Effective values of cycle amplitude σ_a' and mean cycle stress σ_m at the given stress ratio r are shown on the diagram as a working point A.

Therefore, the main parameter expressed graphically using approximated limiting amplitude diagram is the actual fatigue fracture dependent safety margin $\boldsymbol{Z_\sigma}$:

$$Z_\sigma = \frac{OB}{OA} \quad (5)$$

Fatigue strength calculation parameters, which are also obtained when building approximated limiting amplitude diagrams, are slope ratio ψ_σ:

for Serensen – Kinasoshvili diagram:

$$\psi_\sigma = \frac{2\,\sigma_{-1} - \sigma_0}{\sigma_0}, \quad (8)$$

for Goodman diagram:

$$\psi_\sigma = \frac{\sigma_{-1}}{\sigma_B}, \quad (9)$$

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and asymmetric cycle slope ratio:

$$\varphi_\sigma = \frac{1-r}{1+r}, \quad (10)$$

where r is the stress ratio (1);
σ_{-1}, σ_0 are the fatigue strength at $2{\cdot}10^6$ load cycles with constant amplitude for symmetric (r=−1) and pulsed (r=0) cycles;
σ_B is the ultimate strength.

In general, the value of actual fatigue strength dependent safety margin Z_σ for specific asymmetric load cycle is defined by geometric similarity analysis of approximated limiting amplitude diagram components [6, 8] and determined using the following equation:

$$Z_\sigma = \frac{\sigma_{-1}}{\sigma'_a + \sigma_m \psi_\sigma} = \frac{\sigma_{-1}}{\sigma_a K_\sigma + \sigma_m \psi_\sigma} = \frac{\sigma_{-1}}{\sigma_a (K_\sigma + \frac{\psi_\sigma}{\varphi_\sigma})}, \quad (11)$$

where σ_a, $\sigma_a{'}$, σ_m are the nominal and effective values of cycle amplitude and mean cycle stress at asymmetric cycle with specified stress ratio r;
K_σ is the theoretical stress concentration factor.

In case of negative values of mean stress $\sigma_m < 0$ in the equation (11), its absolute value $|\sigma_m|$ is used.

In practice, stress concentration is usually taken into account by combination of structural members in groups, for which the nominal value of maximum acceptable cycle amplitude $\sigma_{a0,5}$ is set, that provides structural member fatigue strength at $2{\cdot}10^6$ load cycles depending on connection point types when testing with stress ratio r=0,5 [4, 8, 10].

Maximum acceptable value of nominal amplitude $\sigma_{a\text{-}1}$ (r=-1) of symmetric cycle for specific group of members is defined by the following equation for the purpose of the use of that components group for calculation with asymmetric stress cycle type:

$$\sigma_{a-1} = \sigma_{a0,5}\left(1 + \frac{\psi_\sigma}{\varphi_\sigma}\right) = \sigma_{a0,5}(1 + 3\psi_\sigma). \quad (12)$$

Then the actual fatigue strength dependent safety margin Z_σ for structural member groups at specified stress ratio r value is defined by the equation:

$$Z_\sigma = \frac{\sigma_{a-1}}{\sigma_{ar}\,(1 + \frac{\psi_\sigma}{\varphi_\sigma})}, \quad (13)$$

where σ_{ar} is the nominal cycle amplitude value at specified stress ratio r;
φ_σ is the limiting amplitude diagram slope ratio at specified r value.

FATIGUE STRENGTH CALCULATION FOR STRUCTURES MADE OF ALUMINIUM ALLOYS

Basic conditions of fatigue strength assurance

The final goal of structure fatigue strength calculation is to avoid fatigue cracks formation in load-bearing structural members throughout their specified service life.

The mean standard number of cycles during specified service life, with the exposure of aluminium alloy structures to which shall not lead to fatigue cracks formation, is customary equal to $2{\cdot}10^6$ cycles [8] unless otherwise specified.

Method providing absence of damages throughout specified service life

The principle of method is based on evaluation of damage occurrence during specified service life of the structure using the lower fatigue strength evaluation and the upper fatigue load evaluation which provides service life calculation for safety margin [4, 8] determination.

For this purpose, load history analysis is performed, which consists in generation of stress spectrum in potential cracking areas. This information based on damage rate calculation is used to evaluate design safe service life T_S, which is then compared with specified service life T_L:

$$T_S = \frac{T_L}{D_L}. \qquad (14)$$

Total damage rate D_L for the totality of cycles is calculated based on Miner damage accumulation as a sum of their damage rate shares using the following formula:

$$D_L = \sum \frac{n_i}{N_i} \qquad (15)$$

and shall satisfy the condition:

$$D_L \leq D_{\lim} \leq 1 \qquad (16)$$

where $D_{\lim}$ is the damage rate limit value generally taken to be equal to 1;
N_i is the durability conforming to loading by *i*-type cycles in quantity of n_i.

Fatigue load

Fatigue load is determined by analysis of all variable stress sources in a structure, namely:

- temporary live loads;
- loads caused by wind and seismic impacts;
- dynamic response to resonance effects and movement in constrained conditions;
- temperature variations.

Design values of fatigue load are determined based on analysis of specified load spectrum and cycle count which define certain cyclic load value range and number of repetitions of each range throughout the structure service life.

Variable amplitude fatigue load stress spectrum, for example, is defined by "pool" method [4] consisting in determination of the sequence of cycles with decreasing stress amplitude σ_{ai} [Fig. 4].

If the values of fatigue load F_{Ek} obtained according to the above conditions are not sufficiently reliable, safety margin γ_{Ff} is applied to load F_{Ek} to determine design load F_{Ed}:

$$F_{Ed} = F_{Ek}\,\gamma_{Ff} \qquad (17)$$

where γ_{Ff} is the safety margin for fatigue loads [Table 3].

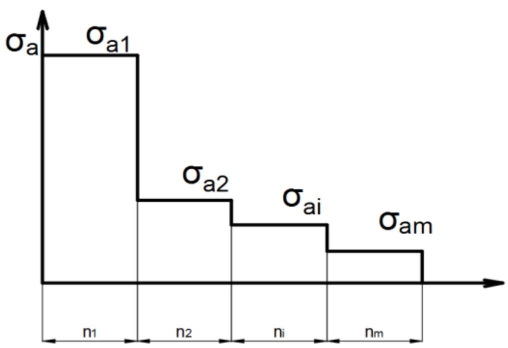

Fig. 4: Design base spectrum of effective load stress amplitudes

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Table 3: The safety margin for fatigue loads

Number of standard deviations from the mean predictive load value K_F	γ_{Ff} at the given number of standard deviations from the mean predictive load cycles number	
	$K_N = 0$	$K_N = 2$
0	1.5	1.4
1	1.3	1.2
2	1.1	1.0

Stress state analysis

Analysis of structures stress state due to fatigue impacts is performed using elastic approach where maximum and minimum values of stresses caused by the given impact are determined taking account of possible dynamic effects.

Design values of effective stresses are obtained by:
– multiplication of nominal stresses by corresponding theoretical elastic stress concentration factors K_σ for linear-elastic material depending on cracking location and stress field type;
– finite element simulation of stress-strain behavior of possible cracking areas using detailed subdivision of these areas by finite elements of corresponding types.

Nominal cycle amplitude and mean cycle stress values according to equations (1-2) are adopted as design values used for fatigue strength evaluation with element clusters.

Fatigue strength calculation

Fatigue strength calculation consists in determination of structure damage rate shares due to the impact of each separate stress range from specified load spectrum [Fig. 4], which collectively provide the basic fatigue strength condition according to the equation (16).

For this purpose, durability values N_i are determined for all stress ranges from specified load spectrum conforming to the limit damage rate D_{lim}=1 due to the impact of each separate range. Total value of damage rate shares from each range is determined based on the equation (15).

Durability (design number of cycles to fracture) N_i for specific stress cycle range is defined using fatigue strength curve [Fig. 1b] [8]. N_i value within $5{\cdot}10^4 \div 5{\cdot}10^6$ cycles is determined using the formula:

$$N_i = N_{C1} \cdot \left(\frac{Z_\sigma}{[Z]}\right)^{m_1}, \tag{18}$$

N_i value within $5{\cdot}10^6 \div 5{\cdot}10^8$ cycles is determined using the formula:

$$N_i = N_{C2} \cdot \left(\frac{Z_\sigma}{[Z]}\right)^{m_2} \cdot C^{\frac{m_2}{m_1}}. \tag{19}$$

where $N_{C1}=2{\cdot}10^6$, $N_{C2}=5{\cdot}10^6$ (cycles);
$C=N_{C1}/N_{C2}=0{,}4$;
Z_σ is the actual fatigue strength dependent safety margin for the given cycle type determined by equations (11, 13);
$[Z]$ is the allowable fatigue strength dependent safety margin (20);
m_1, $m_2 \cong m_1+2$ are the fatigue strength curve portions slope parameters.

Values of allowable fatigue strength-dependent safety margin are determined taking account of structural members manufacturing quality, method of their interconnection in structural units and rolled thickness based on the equation:

$$[Z] = \gamma_{Mf} \cdot \gamma_{Sf} \cdot \gamma_{Tf}, \tag{20}$$

where γ_{Mf} is the structures manufacturing quality-dependent safety margin [Table 1];
γ_{Sf} is the interconnection method-dependent safety margin [Table 2];
γ_{Tf} is the rolled thickness-dependent safety margin (point 4).

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If fatigue strength condition (16) is not met, it is necessary to change structural components cross section dimensions and repeat calculation until this condition is met.

RESULTS

Determination of physicomechanical characteristics of aluminum alloys

In order to validate the possibility of application of the above-mentioned fatigue strength calculation method for aluminium alloy structures, conducted static and fatigue laboratory tests on specimens were made of three aluminium alloys which might be potentially used in building structures production: 1915T, AD35T1, 1565chM [Fig. 5-6] [11].

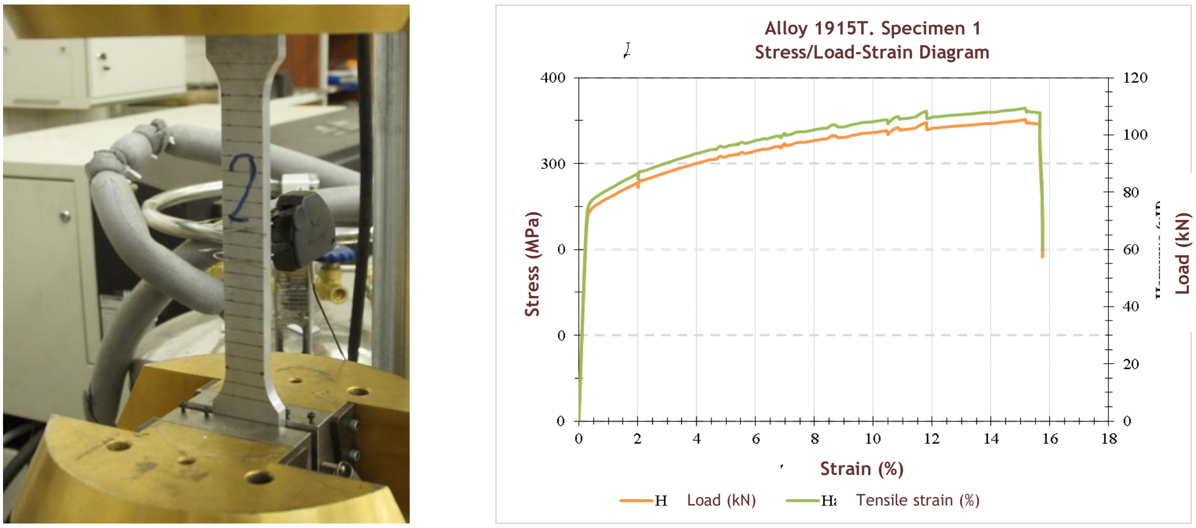

Fig. 5: View and results of static tests on specimens made of 1915T alloy

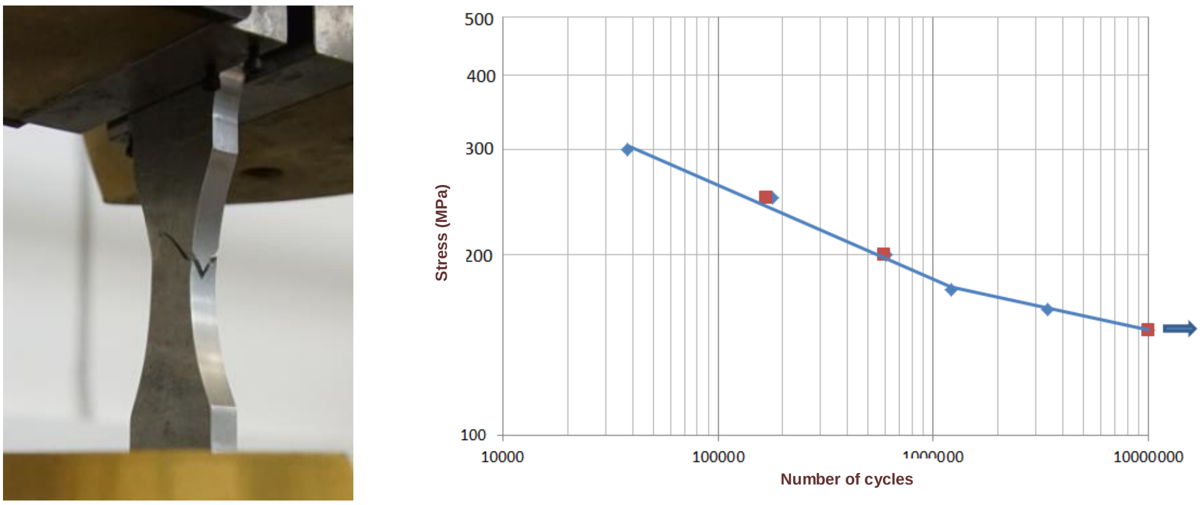

Fig. 6: View and results of fatigue tests on specimens made of 1915T aluminium alloy

During laboratory tests strength and fatigue properties of these alloys were determined. Basic properties are given in [Table 4].

Table 4

Parameter	Fatigue strength σ_{-1}, σ_0, yield strength σ_T, ultimate strength σ_B, MPa for alloys		
	1915T	AD35T1	1565chM
σ_{-1}	100	65	55

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σ_0	150	105	90
σ_T	240	205	180
σ_B	360	320	270

Experimental validation of fatigue strength calculation method

Reliability of presented fatigue strength calculation method for structures made of aluminium alloys has been validated during the tests on structural members and actual walking bridge made of 1915T alloy [Fig. 7] [12].

Identification of the most stressed zones of bridge structures was carried out at the initial stage using finite element modeling, then the bridge was subjected to static loading, the results of which confirmed the conclusions of numerical modeling – the most stressed zones were the areas of the second struts from the edge of the bridge to the lower belts of the bridge load-bearing trusses.

The tests conducted had validated calculation method reliability. Discrepancies between experimental and theoretical data by the number of load cycles to fatigue cracking in the most stressed areas of the bridge were within 5-15%.

Fig. 7: View of the test on walking bridge made of 1915T aluminium alloy

CONCLUSION

The possibility of using the proposed calculation method of the fatigue strength of structures made of other aluminum alloys is determined, first of all, by the presence of their fatigue characteristics (fatigue strength for symmetric and pulsating cycles - σ_{-1}, σ_0). It should be borne in mind that the characteristics of the particular alloy depending on the conditions of its manufacture may differ significantly. For this reason, in the absence of these characteristics, it is necessary to conduct appropriate laboratory tests of samples and by full-scale tests of structures and their fragments made of this alloy. The advantage of the proposed method is in the use of two basic fatigue characteristics: fatigue strength for symmetric and pulsating cycles. This produces more reliable results compared to the main existing method [4] which uses only one value – fatigue strength at a given stress ratio.

CONFLICT OF INTEREST
None

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None

FINANCIAL DISCLOSURE
None

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