Iran University of
Science and Technology

International Journal of

Railway Research

ISSN: 2423-3838

Evaluation of prevailing longitudinal forces in the couplings of electric trains

Vladimir Belyaev
Joint Stock Company “Railway Research Institute” (JSC “VNIIZHT”)

ARTICLE INFO

Article history:
Received: 07.13.2023
Accepted: 10.02.2023
Published: 10.07.2023

Keywords:
Electric train couplers
Normal operation forces
Fatigue resistance requirements
Testing methodology

ABSTRACT

Railway administrations used to have no requirements for the fatigue strength and endurance of electric trains’ couplings. However, mass decommissioning of ICE1 trains in Germany due to cracked couplings and two coupling breakages in an electric train in Russia happened. Forces transferred through couplings are low-levelled which are not compared with couplings’ yield stress. Consequently, the abovementioned problems arise from fatigue damage. The need for detection of forces in electric trains’ couplings, the development of fatigue strength requirements, and test methodologies became obvious.

In 2022, VNIIZHT assessed forces into couplings of different electric trains under low and high temperatures; mileage was 9 600 km. Maximal recorded forces under compression and tension were +117/ 128 kN – far less than the yield stress of electric train couplings (+1500/-1000 kN). It verifies assumed fatigue damage.

After data processing, the statistical distribution of peak-to-peak amplitudes of forces in couplings per run unit and per service life of an electric train (40 years) with the account of their average annual run (130 and 170 thousand km for electric trains with constructional speeds of 120 and 160 km/h, respectively) was derived. The impact of forces of different levels on fatigue strength was calculated with respect to fatigue curves, and the values of peak-to-peak amplitudes were set to 4 (normalized couplings) and 5 (quenched and tempered couplings).

Endurance under cyclic loading depends not only on the quantity of amplitudes of forces at each level but also on the asymmetry coefficient of the load cycle $R = P_{min}/P_{max}$.

The developed methodology contains specific quantities of load cycles depending on the force amplitude and asymmetry coefficient of load cycle R.

1. Introduction

Historically, 1520 mm gauge railways (including Russia) as well as European and American railroads did not have any requirements for the fatigue strength of couplings and automatic couplings. Although coupling breaks have always been a big problem, in 1931 the number of coupling breaks on the USSR railway network peaked at 38 700. At that time, the average train mass was less than 970 t, and the annual cargo turnover was 170 bln t-km. After the SA-3 coupling was introduced, the quantity of coupler breaks significantly dropped, and in 1984 their maximal quantity was 1 540, with a cargo turnover of about 3 600 bln t-km. In the 2020s, the quantity of coupler breaks did not exceed 30 cases per year with a 4050 t average freight train mass and 2 600 bln t-km cargo turnover (only Russian Railways’ net was considered). Consequently, the significance of every coupler break case is higher now.

---

[*] Corresponding author
Email address: belyaev.vladimir@vniizht.ru

Obviously, in past times, breakages usually occurred on freight trains because SA-3 couplings were used on electric and passenger trains as well; thus, they had a huge fatigue reserve factor.

However, since the early 2000s, zero-clearance lightweight couplings have been introduced on electric and passenger rolling stock. These couplings were produced mainly in Russia, and abroad in small amounts (Voith, Dellner, and Faiveley). They have significant functional advantages over CA-3 couplings, specifically considering the option of removing side buffers and the subsequent reduction of car tare weight by 600 kg. However, their fatigue strength was much lower than that of CA-3 couplings, and in 2019 and 2020 two breakages occurred; both on electric trains produced by Siemens (analogue of Siemens Desiro).

In the late 1990s in Germany, 13 of 59 ICE 1 trains with two motorized railcars were decommissioned due to cracks in couplings [1]. By 2019 in Poland, mass decommissioning of whole trainsets of Dart electric trains produced by Pesa had taken place because of cracks in the body liner [2]. Article [3] states vibration as the most likely cause of the cracks; the vibration itself was generated by longitudinal forces that emerge in the electric train during traction and braking processes. These facts do not allow us to consider the forces transmitted through the couplings negligible and do not affect the fatigue strength of the couplings and the vehicle body.

The level of forces in couplings on electric trains with distributed traction does not exceed the tractive efforts of one motorized railcar (which is usually no more than 140 kN as regards the Russian Railways). Every model of electric train coupling undergoes certification tests, where yield absence (yield stress) is checked under +1500/-1000 kN of compression and tension. It is clear that it could be only fatigue that causes the breakages. Today, fatigue tests are compulsory for passenger couplings in Russia and other Customs Union countries. As mentioned above, no railway had reasonable requirements for the fatigue strength of couplings. For this purpose, in 2022, JSC “Railway Research Institute” (JSC “VNIIZHT”), which is the leading railway research entity in Russia, carried out large-scale measurements of longitudinal forces in couplings in two parts of electric trains during routine operation.

2. Determination of loading of electric train coupling

The measurements were made on electric trains of different types and categories under sub-zero and above-zero temperatures. During each of the rides forces with a frequency of 50 Hz were recorded; total mileage amounts to 9 600 km.

Figure 1 demonstrates a sample of force records in the coupling of a suburban electric train with a duration of 5.5 hours. The presented force realization (up to ±80 kN) does not represent noise. Figure 2 shows a fragment of the abovementioned recorded force with a duration

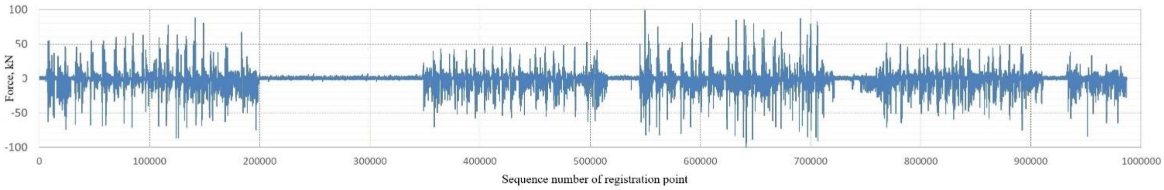

Figure 1. Sample of force realization between cars 7 and 8 from the front during operation and depot switching of suburban electric train.

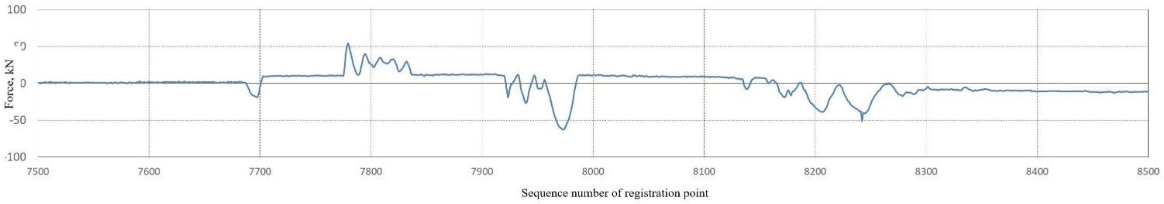

Figure 2. Fragment of the recorded force scaled to 20 seconds.

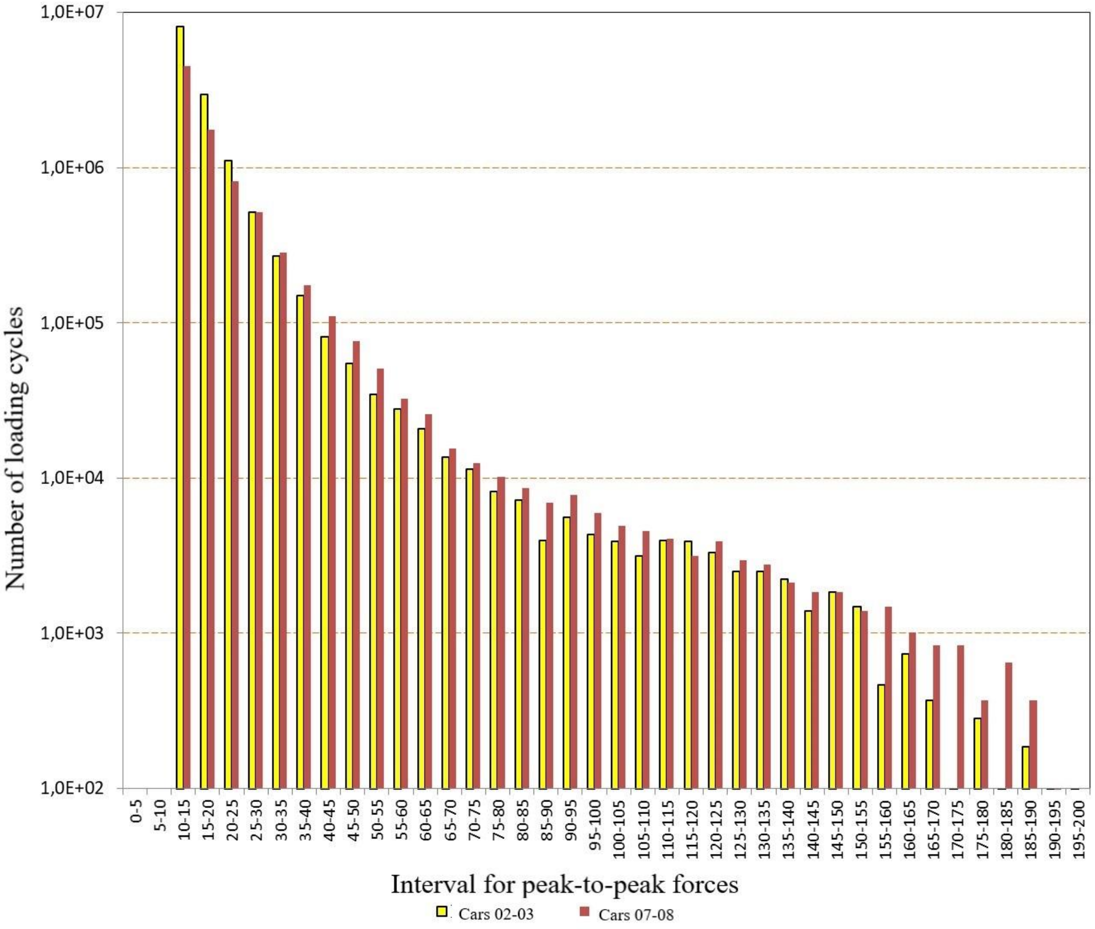

Figure 3. Bar chart for distribution of peak-to-peak longitudinal forces acting on intercar couplings of suburban electric trains for 100 thousand km of mileage.

of 20 seconds and an enlarged scale on the X scale. It can be noticed that the noise level is low.

The findings indicated that the forces shown by a suburban electric train were the strongest among all categories and types of electric trains. The reasons for that will be described below. Singular maximal forces recorded during this research did not exceed +117/-128 kN under compression and tension, which is much less than the standard load for electric train couplings (+1500/ 1000 kN), which proves that coupling damages were caused by fatigue stress.

3. Processing of results

In the course of statistical processing of the results, the recorded forces were schematized by the rain flow method. The name of the method is a common term in the Russian language, and the method itself is specified in the interstate standard GOST 25.101 [4]. It is very useful in terms of comprehension of the below-mentioned bar charts, specifically the reasons for the presentation of peak-to-peak force values, which significantly exceed the levels of the recorded forces.

In the result of statistical processing by the indicated method, the distribution of peak-to-peak longitudinal forces in couplings is plotted, as well as their quantity per ride for 100 thousand km of mileage. Figure 3 presents the bar chart describing the operation of a suburban electric train. The bar chart is plotted with a logarithmic scale for the y-axis.

Amplitudes and their quantity for 100 thousand km of mileage were different for other train types, and they occurred to be much lower. For that reason, these particular results were used for the development of standards, as the coupling may be installed on different types of electric trains, and it should secure performance efficiency and reliability in the electric trains carrying the highest load. Onward, the intermediary and final results only for these train types (suburban electric trains) will be presented.

Coupling fatigue damage accumulation occurs due to the action of fluctuating loads at all levels. The impact degree is described by the fatigue curve, which is written as the following equation (1) for the entire durability range:

$$\overline{A}_i^{\,m} \cdot N_i = const \,, \tag{1}$$

Where $\overline{A}_i$ and N_i are the average peak-to-peak amplitude of the i class and the quantity of loads in that class;

m is a fatigue curve exponent that depends on the coupling's heat treatment type: normalization is $m = 4$, quenching and tempering is $m = 5$ (further in this paper, only the $m = 4$ option will be applied).

With respect to the effect of the loads of different classes raised to the power of $m = 4$, the relevance of the loads of high level becomes very significant (despite their small quantity). The bar chart of parameter distribution for normalized couplings of regional electric trains is presented in Figure 4. The net fatigue effect on the coupling is proportional to the area of this bar chart. It is also obvious from the bar chart that the most significant forces for fatigue damage to couplings are the peak-to-peak forces of 90−170 kN.

Herewith, accumulated fatigue damage is proportional to the area of the presented bar chart. That is why T_r requirements to the coupling's resource for the whole range of loads and service life of a suburban train can be calculated using the following equation:

$$T_r = \sum_{i=1}^{k} (\overline{A}_i^{\,m} \cdot N_i) \cdot T_s \cdot L_r \cdot 10^{-5} \cdot [n]^m \,, \tag{2}$$

where $\overline{A}_i$ and N_i − are the average peak-to-peak value and quantity of loads of the i class for 100 thousand km of mileage;

m is an exponent of the fatigue curve equation;

T_s is an electric train's service life duration (40 years);

L_r is the average annual mileage of an electric train (130 thousand km for electric trains with a constructional speed of 120 km/h; 170 thousand km for electric trains with a constructional speed of 160 km/h);

$[n]$ is an allowable coefficient of fatigue strength safety factor ($[n]=1.7$).

It follows from the foregoing that the values of requirements for the fatigue strength of couplings calculated by equation (2) are $T_p = 7.38 \cdot 10^{15}$ kN^4 for the normalized couplings (for reference, $6.53 \cdot 10^{15}$ and $0.53 \cdot 10^{15}$ kN^4 are corresponding values for urban and long-distance electric trains). The values and dimensions of the parameter do not have a comprehensible physical meaning, but they set certain requirements for the fatigue strength and durability of couplings, which can be proved by tests.

4. Methods of fatigue strength testing

A test method is developed to ensure that the couplings comply with the requirements in terms of fatigue strength. The tests imply cyclic loading in line with one of the variants; cycle ratio $R = P_{min}/P_{max}$, and it equals to -1, 0, 0.1, or 0.2. The peak-to-peak force values A_e and the number of load cycles N_e during tests that correspond to the value of the required loading resource of coupling T_p are calculated by the following equation:

$$A_e^m \cdot N_e = T_r \cdot K_R \,, \tag{3}$$

where A_e is a value of equivalent peak-to-peak force during tests, kN;

N_e is the equivalent quantity of load cycles with force amplitude A_e;

T_r is a value of coupling resource requirements in terms of load, which is calculated by equation (2), $T_r = 7.38 \cdot 10^{15}$ kN^4;

K_R is a correction factor that considers the effect of cycle ratio R.

The purpose of the introduction of correction factor K_R is as follows. Fatigue limit under the cyclic load depends not only on quantity and amplitude of forces, but also on the coefficient of asymmetry P_{min}/P_{max}. The heaviest is the symmetric alternating cycle (R = –1), which predominantly corresponds to the forces transferred through the electric train couplings in operation. Previous coupling fatigue strength testing methods were elaborated by various test

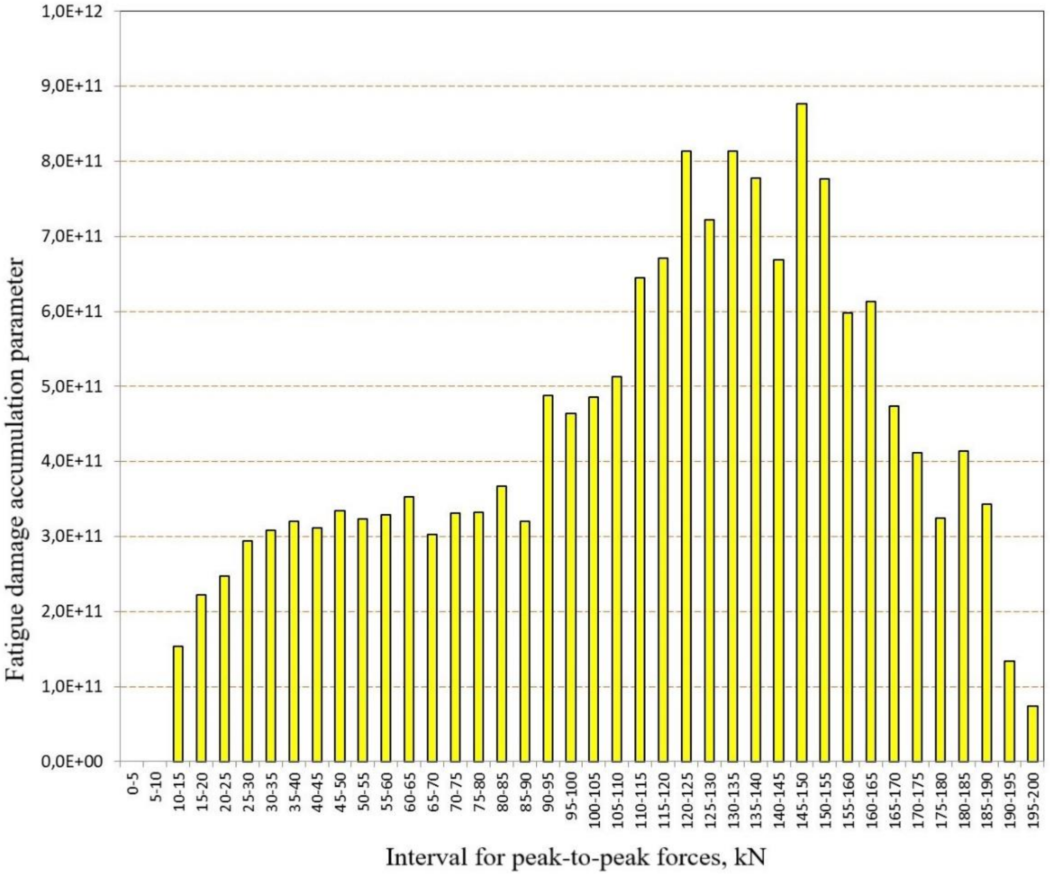

Figure 4. Bar charts of parameter distribution $\overline{A_i}^m \cdot N_i$ (the parameter characterizes fatigue damage accumulation) for every range of longitudinal forces to 100 thousand km of mileage of a suburban train.

centers that did not set requirements for the testing process with the account of certain values of load ratio *R*. This made it possible to use their test benches and set no limitations for carrying out tests in different conditions that significantly affect the results. The results depend upon the test benches used and cannot be considered objective.

The value of K_R indicates the required increase in the quantity of loads on a change in cycle ratio to ensure equal fatigue action. Proceeding from the correlation of fatigue limit values σ_R under various cycle ratio values R presented in source [5], the correction factor may generally be described by the following equation:

$$K_R = \frac{\sigma_R}{\sigma_{-1}} = \frac{2}{(1-R)+\psi\cdot(1+R)} \quad (4)$$

where ψ is a cycle ratio impact coefficient that depends upon the steel strength limit σ_B . The cycle ratio R (within $-1 \leq R \leq 0.5$) can be calculated by the equation, which is set in the GOST 25.504-82 standard [6]:

$$\psi = 0{,}02 + 2\cdot 10^{-4}\cdot\sigma_B \quad (5)$$

Calculations showed that the difference in steel strength limits σ_B that are used for coupling fabrication does not significantly affect the correction factor value (compared to the effect of cycle ratio *R*).

The developed method sets the following correction factor value K_R that considers the effect of cycle ratio R (irrespective of the steel grade):

K_{-1} = 1.00 with R = -1;

K_0 = 1.70 with R = 0;

$K_{0.1}$ = 1.80 with R = 0.1;

$K_{0.2}$ = 1.95 with R = 0.2

During the testing, considering the cycle ratio of 0.2, the quantity of loads should be nearly doubled compared to the symmetric alternating cycle (where R = -1) in order to secure the corresponding fatigue stress. Such tests allow for adequate assessment of compliance with the fatigue stress requirements. It should be noted once more that this all refers to the fatigue strength under multicycle loading conditions when the loads do not exceed the steel yield limit of $\sigma_{0.2}$.

Table 1. Recommended values for the equivalent peak-to-peak forces quantity of loading cycles

Coefficient of asymmetry R	**Max/min force, P_{max}/P_{min}, kN**	**Peak-to-peak forces A_e, kN**	**Quantity peak-to-peak A_e loading cycles N_e**	
			Normalized couplings	**Quenched and tempered couplings**
-1	100/-100	200	$4.61 \cdot 10^6$	$4.47 \cdot 10^6$
	150/-150	300	$9.11 \cdot 10^5$	$5.88 \cdot 10^5$
	200/-200	400	$2.88 \cdot 10^5$	$1.40 \cdot 10^5$
0	200/0	200	$7.84 \cdot 10^6$	$7.60 \cdot 10^6$
	250/0	250	$3.21 \cdot 10^6$	$2.49 \cdot 10^6$
	300/0	300	$1.55 \cdot 10^6$	$1.00 \cdot 10^6$
	350/0	350	$8.36 \cdot 10^5$	$4.63 \cdot 10^5$
	400/0	400	$4.90 \cdot 10^5$	$2.37 \cdot 10^5$
0,1	200/20	180	$1.27 \cdot 10^7$	$1.36 \cdot 10^7$
	250/25	225	$5.18 \cdot 10^6$	$4.46 \cdot 10^6$
	300/30	270	$2.50 \cdot 10^6$	$1.79 \cdot 10^6$
	350/35	315	$1.35 \cdot 10^6$	$8.30 \cdot 10^5$
	400/40	360	$7.91 \cdot 10^5$	$4.26 \cdot 10^5$
	450/45	405	$4.94 \cdot 10^5$	$2.36 \cdot 10^5$
0,2	250/50	200	$8.99 \cdot 10^6$	$8.71 \cdot 10^6$
	300/60	240	$4.34 \cdot 10^6$	$3.50 \cdot 10^6$
	350/70	280	$2.34 \cdot 10^6$	$1.62 \cdot 10^6$
	400/80	320	$1.37 \cdot 10^6$	$8.31 \cdot 10^5$
	450/90	360	$8.57 \cdot 10^5$	$4.61 \cdot 10^5$
	500/100	400	$5.62 \cdot 10^5$	$2.72 \cdot 10^5$

The developed method also proposes values that are recommended for the equivalent peak-to-peak forces A_e and the corresponding quantity of loading cycles N_e for couplings' tests that are calculated with the help of (3). They are presented in Table 1.

For any selected option, the pattern should be the following: half of all the planned loadings should be carried out under the compression forces, and the other half under the tension forces (except for the loadings with the symmetric alternating cycle, where R = -1).

The developed methods also allow testing couplings, including parts with normalization, quenching, and tempering. If couplings have parts manufactured involving different types of heat treatment, then the testing should be carried out in three steps with different peak-to-peak values because when the A_e values are high, the differences in the required quantity of load cycles N_e are very big. But at low peak-to-peak values A_e, the differences are minimal, but the quantity of loadings N_e is great and exceeds 10^6 cycles, and the duration of tests increases substantially.

The abovementioned requirements for the fatigue strength of couplings of electric trains and the fatigue methods of testing couplings on this aspect have been approved as a regulatory document of JSC “Russian Railways.” Almost all interstate standards that are applied on the railway net of 1520 mm gauge and deal with couplings were developed by JSC “VNIIZHT,” and the norms and methods described above will be added in the course of the next planned review of those standards.

5. Effect of preload of draft gears on the fatigue load of a coupling

One more issue is proposed for discussion, namely the reasons why higher loads are applied to suburban trains' couplings than ones of urban electric trains, despite the fact that urban trains have a higher constructional speed and consequently better mileage during 40 years of operation, as well as a greater quantity of braking for stopping and starting, during which the strongest longitudinal forces occur. This issue is quite important.

The research findings showed that it is the preload of draft gear that mainly contributes to the fatigue load of couplings of different types. The matter is that suburban trains in Russia are equipped with SA-3 coupling types installed in line with requirements stated in GOST 3475 [7], and installation principles are the same as for the couplings of AAR standards. In accordance with these standards, draft gear is placed between front stops and back stops, compulsorily preloaded. Moreover, the installation of CA-3 couplings on passenger and electric trains requires side buffers in order to eliminate longitudinal clearance.

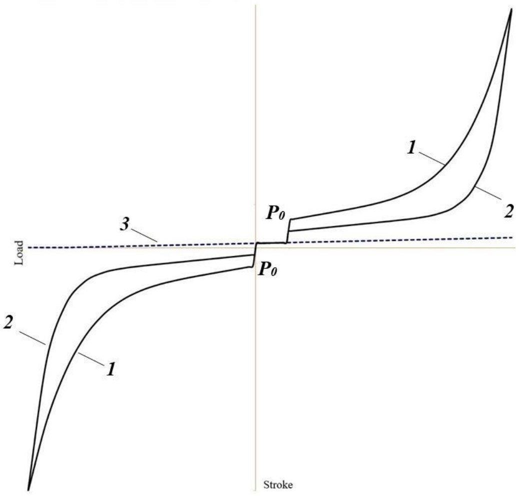

Figure 5. Load characteristics of suburban electric train intercar linkage with SA-3 automatic coupling, side buffers and draft gears installed according to GOST 3475–81. 1 – loading of draft gears; 2 – unloading of draft gears; 3 – loading and unloading of buffers

Load characteristics (dependence of load on the stroke) in this kind of installation are presented in Figure 5.

A 20-second force recording is presented in Figure 6. Buffers eliminate clearances between cars, which provides ride comfort for passengers. However, the point of transfer from compression to tension and vice versa is always associated with one or many load swings that are practically equal to the preload of 25-80 kN without damping. Specifically, the amplitudes of these load swings contribute in large part to the fatigue load of the couplings.

Draft gears installed on urban electric trains are rigidly connected with couplings, and the scenario of their working is different. One group of resilient elements accepts solely compression

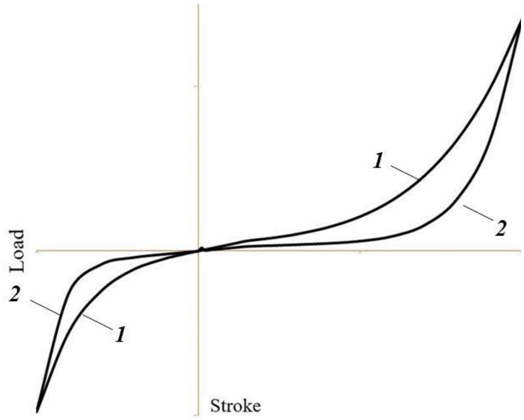

Figure 7. Load characteristics of rolling stock intercar linkage equipped with draft gears integrated with coupling 1 – loading of draft gears; 2 – unloading of draft gears

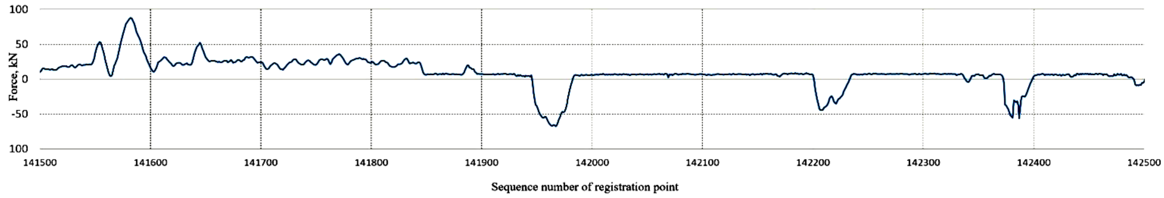

Figure 6. Longitudinal forces in suburban electric train intercar linkage during traction

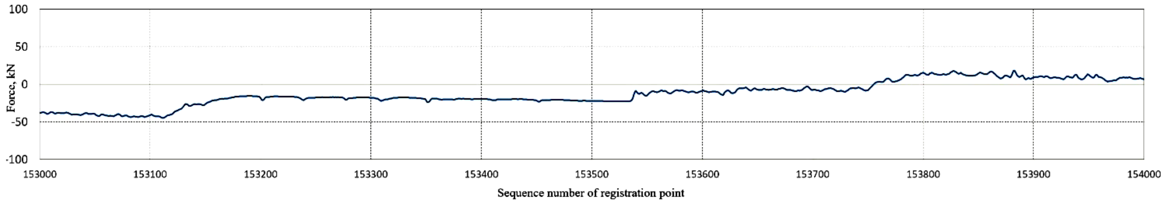

Figure 8. Longitudinal forces in urban electric train intercar linkage during acceleration

load, while the other one accepts only tension load. Both parts are preloaded, and the draft gear load application point is located between these groups, where the preload forces are equal on each side. I.e., any weak force leads to draft gear deformation, regardless of the level of preload of resilient elements. Load characteristics in the case of such an installation are shown in Figure 7, and a 20-second force recording is presented in Figure 8. A comparison of these two ways of realizing longitudinal forces makes it obvious that, in this case, any operational mode has no load swings, as seen in Figure 6.

Such a bad effect of preload force on longitudinal vibrations of passenger cars had been discovered earlier via mathematical simulation of train operation [8].

To a lesser degree, the impact comes from the following factors: location of motorized and non-motorized cars in a train (which is a separate issue having no dependence on draft gear and coupling installation), train construction speed, and average annual mileage. Therefore, the required figures may vary from railway to railway.

Nevertheless, before the acquisition of accurate data on each railway, the abovementioned norms and methods may be applied as references in the course of research and comparison testing.

6. Conclusion

The conducted research has shown the following results:

- The level of forces affecting the couplings of electric trains does not exceed the tractive efforts of one motorized railcar (in any operation mode) and cannot cause coupling damage.
- Cracks and breaks in couplings' components are the result of fatigue damages arising from longitudinal vibrations.
- Parameters of fatigue loads of couplings for the whole period of their operation are calculated based on the results and statistical processing of measurements of forces occurring in couplings during the operation of electric trains of different types.
- A regulatory document for JSC "Russian Railways" has been developed, which sets unified requirements for the fatigue strength of couplings of electric trains as well as the method of fatigue strength testing using equipment with different values of the asymmetry coefficient of the load cycle.
- It has been stated that the reduction of the preload of draft gears in electric trains' couplings leads to lower levels and volumes of longitudinal forces affecting the couplings in operation.

REFERENCES

[1] ICE 1 develops cracks. Modern Railways, Vol. 57, No. 620, (2000).

[2] Krzysztof Śmietana, "A growing problem with cracks on Dart EMUs sheathings. PKP Intercity suspends the sale of tickets". URL: https://forsal.pl/artykuly/1406692,pekniecia-w-pociagach-dart-pkp-intercity-wstrzymuje-sprzedaz-biletow-na-niektore-polaczenia.html (retrieved on 01.03.2023).

[3] Jackiewicz Jacek, "Coupler force reduction method for multiple-unit trains using a new hierarchical control system". Railway Engineering Science, Vol. 29, (2021): 163–182.

[4] GOST 25.101-83. "Strength calculation and testing. Representation of random loading of machine elements and structures and statistical evaluation of results", Moscow: Izdatestvo standartov, (1983).

[5] Zhukov V., Mikhaylov Yu., Mechanics. Basics of calculation and engineering of machine components, Moscow, INFRA-M, (2014).

[6] GOST 25.504-82 Strength calculation and testing. Methods of fatigue strength behaviour calculation. Moscow, Izdatelstvo standartov, (1982).

[7] GOST 3475-81. Automatic coupler equipment of railway rolling stock for railway track gauge 1520 (1524) mm. Assembling dimensions. Moscow, IPK Izdatelstvo standartov, (1998).

[8] Belyaev V., Stupin D., Coupling and automatic coupling devices for railway rolling stock. Moscow, Transinfo, (2012).