Agronomy Research **22**(2), 794–814, 2024
https://doi.org/10.15159/AR.24.058

Innovative approach to real-time diagnostic of bolted joints and elastic couplings to prevent their fractures

D. Gorbacovs*, P. Gavrilovs, J. Eiduks and M. Gailis

Riga Technical University, Faculty of Mechanical Engineering, Department of Railway Engineering, Transport and Aeronautics, LV-1048 Riga, Latvia
*Correspondence: dmitrijs.gorbacovs@edu.rtu.lv

Received: October 10th, 2023; Accepted: April 3rd, 2024; Published: June 27th, 2024

Abstract. Failure of fasteners can lead to undesirable consequences. Fatigue failure of machine parts is difficult to predict and prevent. Vehicles and agricultural machinery include various systems such as engine, transmission, and many other systems that are fixed and connected using fasteners. Without a doubt, the performance of an individual system depends on the design of its kernel. But for the system to work, it must be properly fixed. Premature failure of bolts is subject of interest of engineers.
The purpose of this study is to identify the causes of the failure of the fixing bolts and develop device and algorithm for early detection of conditions that might lead to bolt failure. The experimental data is collected analysing bolts and elastic couplings of electric passenger trains.
Laboratory studies included the measurement of tensile strength, hardness, microanalysis of the metal structure and chemical analysis of failed old and new bolts. The authors present various visual and numerical results from this study. It also provides detailed conclusions about the causes of failure and recommendations for the selection of bolts for critical mechanical connections under dynamic loads and variable temperatures.
The authors have developed a device that can be used in mechanical engineering, shipbuilding and other industries to control the deformation, vibration and shocks acting on a bolted joint. This device for monitoring the load and vibrations of bolted connections allows to constantly collect and analyse data during the operation of the vehicle in order to reduce the number of unscheduled repairs of vehicles due to its damage, as well as to reduce the number of accidents or other incidents. The authors also have developed a method and algorithm for calculating and evaluating the influence of external factors on the shell of a rubber-cord coupling. The study is based on statistical, material, and mathematical analysis of unexpected failures of rubber couplings. A numerical analysis of the operating conditions of the couplings before failure was performed.
The results obtained are encouraging and prove that the use of an impact force measuring device and real-time data analysis can be cost-effective and can eliminate the problem of bolt and elastic coupling failure in one go, as well as reduce the cost of operating and repairing vehicles.

Key words: rubber cord coupling, fastening bolt, metal structure, chemical composition, hardness, static stress.

INTRODUCTION

In assembly structures, bolts are used as fastening elements to connect various parts and elements, which, in turn, can be part of any mechanisms and devices. Bolts are widely used in almost any production and the construction of almost all engineering structures. Fastening bolt connections allow easily and quickly connect the parts of assembly structures, in the construction of buildings, for connecting parts in cars, airplanes, railway rolling stock, pipelines, for fastening various structures, in the assembly of complex machines and equipment used in industry, as well as in everyday life.

On the other hand, the bolts that are used to fasten various structures and aggregates of the railway rolling stock work in quite severe conditions. So, when working on railway rolling stock, the fastening bolts are subjected to static, dynamic, as well as impact loads, and as a result of the action of impact loads, the strength capacity of the bolt material is exhausted over time. During the further actions of shock loads, microcracks gradually occur and develop in the bolts, and finally grow into cracks. They become stress concentrators and, due to the increasing weakening of the cross-section of the bolts, microcracks and cracks increase, and the bolts become the site of final fracture of the rubber cord coupling attachment. Rubber cord couplings operate under dynamic load conditions with high force and vibration loads, which can cause system resonance.

In order to reduce the failure rate of the rubber cord coupling mounting bolts, a solution to the failure problem of the M24 bolts must be found. For these purposes, it is proposed to create a device that allows you to monitor the impact force received by the rubber cord coupling bolts, and with the introduction of this device into operation, to achieve a reduction in the number of failures during the inter-repair period.

Many international scientific researchers dealt with the problems of researching the destruction of bolts.

In the scientific work (Grigorenko et al., 2014), the reasons for the destruction of M14 bolts made of steel 30ХГСА with a protective cadmium coating were investigated. The chemical and phase compositions, microstructure and fractures were studied to establish the causes of the destruction of bolts made of 30ХГСА steel. As a result of the analysis, the reasons for the destruction of the bolts were determined and recommendations were given for their elimination.

The paper also considers medium-carbon structural steels showing propensity to the delayed destruction at static loadings below yield point in conditions of cyclic (daily and seasonal) temperature changes.

In the scientific work (Grigorenko et al., 2018) various types of fractures of 30ХГСА steel samples with zinc-based coatings are considered, and also operational fractures of 30ХГСА steel fasteners are analyzed, the reasons of workability loss of destroyed parts are established, the mechanisms of fatigue and grain boundary brittle fracture of 30ХГСА steel samples are studied by raster electronic microscopy methods. The carried out researches of parts made of 30ХГСА steel allowed to allocate the basic reasons of the destruction of fasteners during operation. The majority of cases of details destruction is connected with the development of fatigue cracks formed due to the presence of scratches on the surface from machining, dents or embedded particles from sandblasting, as well as friction during operation. On the basis of the conducted researches recommendations on elimination of factors contributing to fracture of 30ХГСА steel samples are given.

The paper (Sapalov & Panfjerova, 2016) analyzes the measurement results of high-strength bolts strength properties with a portable hardness tester used during inspection of structures with the results obtained using a stationary hardness tester.

The researches of properties of high-strength bolts by means of various testing methods confirmed the admissibility and correctness of their strength properties determination in the process of structures examination by portable hardness tester provided that the device is preliminary corrected on comparative results of direct and indirect values.

The scientific paper (Sirokih, 2005) describes the experiment and its subsequent repetition in numerical simulation. The experiment consisted in stretching the friction connection of plates with different arrangement of bolts in the cross-section. Based on the results of the experiments stress distribution plots were obtained in the plate, near the holes and directly in the places of the weakened section, were obtained. a numerical model was created, boundary conditions are assigned, and a load was applied. Experiment and numerical simulation showed good convergence of experimental and calculated results. In conclusion, the author gives recommendations on the design of friction joints in the calculation systems.

In the paper (Zhang et al., 2021) is made an attempt to describe the decline in fatigue life of an aluminum alloy structure containing bolted joints under the conjoint influence of an aggressive aqueous environment and loading that is essentially cyclic in nature. The method proposed in this study provides a convincing approach for reliable estimation of life, or endurance, of an aluminum alloy structure containing joints.

The paper (Yingnan et al., 2020) proposes a cogging high-strength bolt composite joint (C-HSB joint), and introduces its main components and assembly methods.

In the paper (Desai et al., 2021) authors have developed methodology to predict the bolts loosening in dynamic condition using vibration data.

A lot of works are devoted to the rubber-cord couplings.

In the paper (Korneeva et al., 2016) the finite-element research of the intense deformed condition of the highly elastic flat coupling at the shaft axial offset and small twisting angles is presented.

In the paper (Evdokimov & Shikhnabieva, 2017) the results of experimental studies of stress–strain behavior during hardening stages, as well as the stabilization and strength degradation of the rubber-cord shells during the static loading mode have been given.

The paper (Vinogradov, 2016) gave the dynamic and static elastic characteristics of couplings and drive containing the coupling with rubber-cord shells.

In the paper (Klimentyev et al., 2015) advantages of rubber as a construction material are considered. Method of calculation such basic characteristics as the geometric dimensions, static deflection, natural frequencies, stiffness, vibration isolation and damping properties of rubber-cord cushions working under pressure is described. Rubber-cord cushions most typical use as shock absorbers, antivibration mounts, flexible couplings, flexible hoses and pipe work are presented.

The paper (Tribel'skii & Zubarev, 2008) a solution of the steady thermoelastic problem is proposed, taking account of the dependence of the elastic and thermophysical constants of the material on the temperature and strain.

However, analyzing the research and methods of the authors listed above, no answers were found to the following questions, how to predict the cause of failure of a bolted connection and a rubber-cord coupling. An algorithm for early detection of conditions that can lead to failure of these nodes is not explored. The articles did not present detailed studies on bolted connections; issues such as the effect of hardness on a bolted connection were not considered. Issues such as determining the chemical composition of new and old bolts, the influence of loads, and temperature were not considered. In the works discussed above, the factors that affect the operation of the rubber-cord coupling were not considered; there was no numerical analysis. However, premature failure of both the bolts and the rubber-cord coupling is an important factor in any installation and is the subject of research. Analyzing the above articles, it can be seen that the problems of failure, both of bolted connections, and the failure of the cord coupling, took place separately.

The authors propose to consider a common assembly, a rubber-cord coupling and its fastening bolts, and offer a technical solution that will allow to monitor the common node during operation. This idea was not chosen by chance. This will be discussed further.

Answer (1). In addition to standardised, generally accepted research methods, the article proposes innovative approaches that will reduce the number of rubber-cord couplings and its fastening bolts failures. This problem is solved by two new innovative research methods using an impact vibration device:

1. Determination of the shock and vibration load to which the rubber-cord coupling mounting bolts are exposed.
2. The influence of resonant frequencies on a rubber-cord coupling.

For example, on the Latvian Railway, a similar rubber-cord coupling is used on rolling stock, in particular on electric trains. The collection of statistical data was carried out. According to the data obtained, it was found that, the problem of wrinkling of the rubber cord bolts in the period from 2015 to 2021 has become predominant for all EMU trains. In the analysis of unscheduled repairs, the information of the Technical Department of the railway company JSC 'Pasažieru vilciens' was used on the basis of data on unscheduled repairs of EMU trains from which traction drive damage was identified for the period from 2015 to 2021 (Summary of non-scheduled repairs of electric trains…, 2021). Of the total number of unscheduled repairs, which amounted to 385 cases, the largest number of 180 cases was damage to the rubber-cord coupling bolts. The destruction of the rubber-cord fastening bolts is on average more than 49% of the total number of malfunctions in the traction gear. Failure of the rubber-cord coupling bolts occurred in the range of mileage of motor cars from 1628 to 256,646 km. Failure rate depends on a number of random factors and is actually a random variable.

Rubber cord couplings operate under dynamic load conditions with high force and vibration loads. Bolts, which are used to fasten various structures and aggregates of railway rolling stock, work in quite severe conditions. So, when working on the railway rolling stock, static, dynamic, as well as shock loads are applied to the fastening bolts, and as a result of the impact loads, the strength capacity of the bolt material is exhausted over time (Evdokimov & Shikhnabieva, 2017).

The breaking of four bolts out of eight may cause the rupture of the rubber-cord coupling and the ejection of the inner flange, which may cause damage to the track, the part of the rolling stock of EMU trains (rolling gear), the mechanical equipment of the electric train or the car body. The disc of the inner flange can also get into the cabin of the car through the viewing hatch, causing damage to the cabin and even injury to the passengers, (Fig. 1).

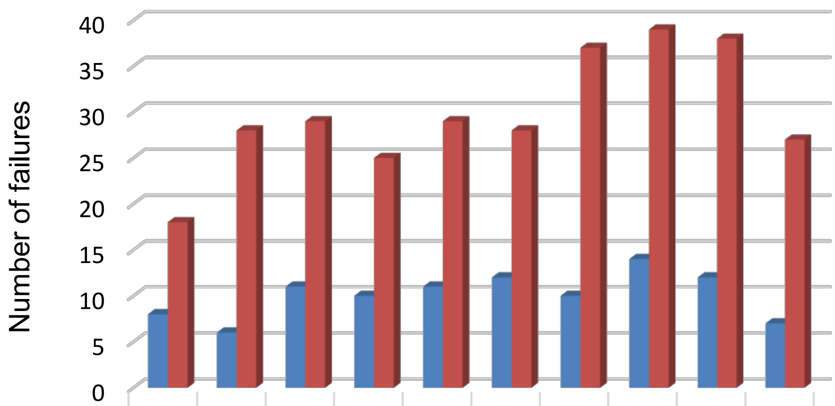
This case took place on the Latvian Railway, when during the movement of an electric train, 5 bolts securing a rubber-cord coupling broke. As a result, the half-disk fastening the rubber-cord coupling flew into the car interior, breaking the protective grille and piercing the inspection hatch of the motor car (Fig. 1).

Figure 1. Ejection of the flange of the rubber-cord coupling in the passenger compartment.

Operating experience in electric train traction drives shows that using a rubber cord coupling due to its durability and reliability ascpect, these elements (coupling and its fastening bolts) are one of the weakest elements in the electric train traction equipment.

In connection with this, the problem of failures of rubber-cord couplings and their fastening bolts requires investigation of the causes of failures.

The failure data of the rubber cord coupling and its fastening bolts for the period from 2012 to 2021 are shown in (Fig. 2).



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
rubber cord coupling failure	8	6	11	10	11	12	10	14	12	7
the rubber cord bolts failure	18	28	29	25	29	28	37	39	38	27

Figure 2. ER2 and ER2T Rubber cord coupling and rubber cord coupling bolt failures.

MATERIALS AND METHODS

To determine the causes of bolt disintegration, check the compliance of the samples with the requirements of ISO 898-1:2013 and EN 10083-3:2007-01 standards for 4Cr41 grade steel was done. Bolt samples, which were dismantled from ER2 and ER2T series motorcars, with numbers No. 1, No. 2, No. 3, No. 4 were chosen for research objects, as well as one sample of a new bolt with No. 5. The operating time of the car (number of days) and its mileage were taken into account.

The research was carried out in the laboratory of the Riga Technical University in the following directions:

1. determination of hardness;
2. chemical composition analysis.

Table 1. Data on the performance of bolts

Sample No.	Operating time days	Mileage, km
No. 1	201	59,348
No. 2	160	64,078
No. 3	43	17,124
No. 4	408	114,400
No. 5	new bolt -	-

The data on the mileage and the service life of the bolts in the railcars are shown in (Table 1).

Determination of hardness

In the laboratory of the Riga Technical University, steel hardness was tested according to the Brinell scale (HB) (Taylor et al., 2021) using the device 'MIC 10' (Kuzu et al., 2021). In order to obtain greater accuracy of the experiment, measurements were made at 5 points along the entire cross-section of the samples. The dependence of the hardness HB on the mileage of the bolts is shown on the graph of (Fig. 3).

According to the results of the graph, we can see that the hardness of the coupling bolts increases with increasing mileage, i.e. the material of the bolts became stronger. The term hardness of a metal is a characteristic that describes its resistance to destruction upon contact with a harder element. An increase in metal hardness is usually associated with an increase in brittleness and a decrease in the ductility of the metal (Boguslavskij, 2016). This is explained by the fact that the atoms introduced into it form a chemical bond with the metal atoms and this significantly complicates the sliding of some planes of the densely packed structure of the metal along other planes, which determines the malleability of pure metals. At the same time, the presence of embedded atoms does not have a significant effect on the electrical conductivity of metals. This means that the intervening atoms little change the nature of the chemical bond between metal atoms (Slejbo, 2005). It can be assumed that over time there is an increase in fragility and a decrease in ductility, resulting in its fracture.

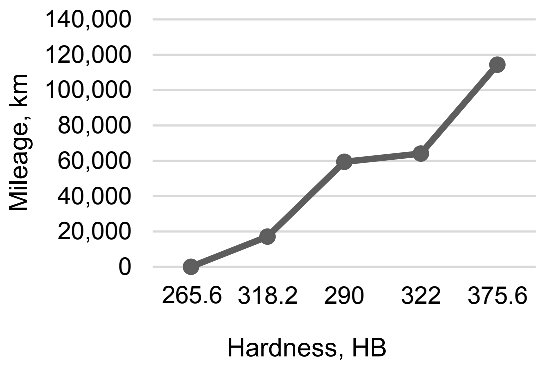


Figure 3. The hardness of the coupling bolts dependence on the mileage.

Chemical composition analysis

According to the results of determining the chemical composition of steel, it was found that:

steel grade of sample No. 1 – not determined;

steel grade of sample No. 2 – 34Cr4;

steel grade of sample No. 3 – not determined;

steel grade of sample No. 4 – not determined;

steel grade of sample No. 5 – 34Cr4.

During the investigation of the chemical composition of the steel, the following inconsistencies with the requirements of the standard EN 10083-3:2007-01 were discovered.

The carbon (C) content in four samples is less than the norm and amounts to:

for sample No. 2 – 0.366%;

for sample No. 3 – 0.261%;

for sample No. 4 – 0.316%;

for sample No. 5 – 0.322%;

however, in sample No. 1, the carbon content exceeds the norm and is 0.505%.

According to the requirements of the EN 10083-3:2007-01 standard, the carbon content in steel for the manufacture of bolts for fastening rubber-cord couplings must be in the range of 0.38–0.45%, which corresponds to steel grade 4Cr41. However, studies show that the material of the steel grade differed from the standard. As the amount of carbon in the steel decreases, its plasticity improves and rigidity (impact resistance) increases. As the carbon content in the steel increases, the hardness, strength and rigidity of the steel increases, the yield strength σ_t and tensile strength σ_s also increase, but at the same time plasticity and impact resistance decrease, and machinability and weldability also deteriorate (Zadel et al., 1985; Birjukov et al., 1986).

Harmful impurities of phosphorus and sulphur were found in the material of the bolts during the research process. The percentage of phosphorus (P) in sample No. 1 is – 0.125%; in sample No. 2 – 0.0050%, in sample No. 3 – 0.0813%, in sample No. 4 – 0.0898%, in sample No. 5 – 0.0671%. In four samples, the phosphorus content significantly exceeds the norms set by the EN 10083-3:2007-01 standard, which should be less than 0.025%.

As you know, phosphorus is one of the harmful impurities of steel, the source of which is charge materials, mainly cast iron. It is capable of dissolving in significant quantities in ferrite, which leads to distortion of the crystal lattice. At the same time, there is an increase in tensile strength and yield strength, a decrease in ductility and viscosity. An increase in phosphorus content causes an increase in the cold brittleness threshold and a decrease in the work of crack development.

Phosphorus is highly susceptible to segregation, which leads to a sharp decrease in viscosity in the central part of the ingot. Currently, there is no technology for deep purification of steel from phosphorus (Bhadeshia & Honeycombe, 2017).

Accordingly, the question arises of how increased hardness and an increase in harmful impurities in the metal affect the performance of the bolt and what measures can be proposed to identify them at an early stage, before it breaks.

The investigation of the causes of disintegration of the bolts of the rubber cord coupling fastening M24 bolts was carried out in the RTU laboratory in the following directions:

1. determination of the type and nature of disintegration in three specimens under static loading;

2. determination of the type and nature of disintegration for three specimens under cyclic loading.

Determining the type and nature of decomposition under static loading

In order to determine the type and nature of the disintegration stress, three samples of M24 bolts were tested in the RTU laboratory: No. 6; No. 7; No. 8 static tests for breakage. Bolt samples were taken from rail cars with the following mileage data:

Sample No. 6 mileage – 214,596 km;

Sample No. 7 mileage – 105,764 km;

Sample No. 8 without mileage (zero mileage).

The tests were performed in the RTU laboratory using a Zwick/Roell Z600 electromechanical testing machine with a load increase rate of 1 mm per minute. 1 mm was not chosen by chance – the minimum tensile load of the installation.

Determining the type and nature of decomposition under cyclic loading

In order to determine the type and nature of the bolt M24 decomposition, cyclic tests were carried out on three samples of the bolt numbered No. 9; No. 10; No. 11 (stretching and unloading – 10 tests and 11 tests for stretching the sample until decomposition) considering three different mileage ranges:

Sample No. 9 with mileage 22,543 km;

Sample No. 10 with mileage 155,365 km;

Sample No. 11 with mileage 210,298 km.

A stress cycle is understood as a set of varying stress values in one period of change. Cyclic tests were performed in the RTU laboratory using a Zwick/Roell Z60010 electromechanical testing machine with progressive loading and unloading. Load levels respectively: 25 kN; 50 kN; 75 kN 100 kN; 125 kN; 150 kN; 175 kN; 200 kN; 225 kN; 250 kN; decomposition. The speed of increasing the load is 7 mm per minute (Fig. 4). The rate of increase in load of 7 mm is the maximum tensile load.

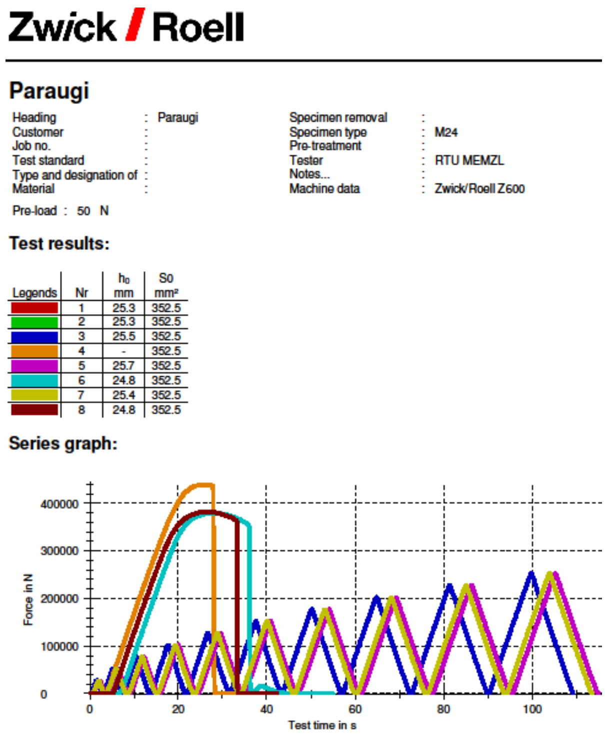


Figure 4. Bolts decomposition diagrams.

According to the test results it was found that the fractures of all the samples occurred at the connection point of the bolts with the insert, without cupped fracture. According to the test results, the fatigue decomposition of the samples was found as a result of the accumulation of defects from the action of shock vibration load. Müller & Choteborský (2016) have shown that the temperature of the specimens influenced the impact strength, the toughness and the maximum deformation of the adhesives. To carry out diagnostics of bolted connections in real time, a shock vibration device was designed and developed.

The purpose of the invention is to create a device for monitoring the impact and vibration force of bolt fastenings, which would make it possible to constantly accumulate and analyze data on the impact force perceived by the bolts during the operation of the vehicle in order to reduce the number of unplanned repairs of rolling stock of railway transport or vehicles of other industries due to its damage, as well as to reduce the number of accidents or other accidents (Stauffer, 2004). As a result, the costs of operating and repairing vehicles will be reduced. The block diagram of the invented device is shown in (Fig. 5).

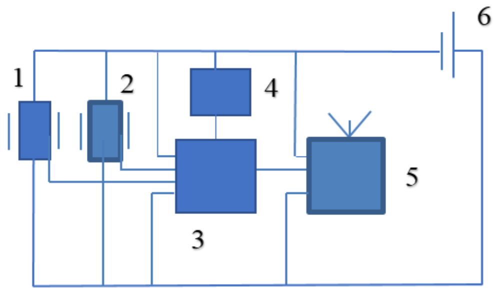


Figure 5. Block diagram of the invented device: 1 – vibration sensor; 2 – shock sensor; 3 – microcontroller; 4 – memory module; 5 – data transmission unit; 6 – power supply unit.

The purpose of the invention is achieved as follows: the device for monitoring the impact and vibration force of bolt fasteners consists of a housing, inside which the following elements are installed: a vibration sensor (4) and an impact sensor (5), a microcontroller (6), a data transmission unit (7) and a power supply unit (8). A piezo-accelerometer can be used as a vibration sensor (4) and shock sensor (5) – sensors that convert the value of vibration or shock force into an electric signal (Leonardson & MacGugan, 1994; Komorska, 2011).

When processing the information and finding that the allowable load on the rubber-cord coupling fastening bolts has been exceeded several times, the decision to replace the bolts was made in more than 10 cases during week. Thus, unplanned repairs due to damage to bolts and other components of the vehicle have been prevented. Putting the invented device into operation will allow obtaining objective data on the impact force and vibration loads on the bolts. Accumulating information and processing it regularly can prevent damage to rubber-cord coupling bolts and, accordingly, reduce the number of unplanned repairs of electric trains. The invention can be used in any type of railway rolling stock, as well as metro cars. The invented device can be used in mechanical engineering, shipbuilding and other industries to control the defect of bearings, deviations of shafts, the condition of transmission gears and other structures on which the fixing bolts are subjected to deformation forces. If, when processing the information received from the invented device during technical maintenance (or restoration repair), it is found that the allowable loads have been exceeded many times, then the bolts must be replaced with new ones. Thus, the need to perform unplanned repairs due to bolt damage, which are associated with large financial costs for the company, is avoided.

Shock vibration device testing

After a test using an impact stand, the impact load was determined in the railway undertaking AS 'Pasažieru vilciens'. In order to do this, it was necessary to determine the impact force F, which is received by the bolts when the motor car passes the rail joints. The impact force F, which is absorbed by the bolts of the rubber cord coupling, is determined according to the formula (1), in order to determine it, it is necessary to determine the acceleration with which the motor car passes the rail joint. For this purpose, we use the empirical formula (2).

$$F = \omega_r \cdot q \quad (1)$$

where q – half the mass of the wheelset, t; ω_r – the acceleration with which a car passes a rail joint, m s^{-2}.

$$\omega_r = \left[2 + 0.13 \frac{V}{\sqrt[3]{(2q)^2}}\right] \cdot g \quad (2)$$

where V – car speed, km h^{-1}; q – half the mass of the wheelset, kg; g – gravitational acceleration, 9.81 m s^{-2}.

The data of acceleration and impact force calculations are presented in (Table 2).

Further, in order to determine the impact load, tests of the disintegration load of the rubber cord coupling fixing bolts were carried out in the JSC 'Pasažieru vilciens' company, in which the developed impact vibration device was used, with different, but close to the calculated data of the impact force F. The experimental data was shown in (Table 3).

Table 2. Acceleration and impact load calculation data

Car speed V, km h^{-1}	Acceleration of the wheelset ω_r, m s^{-2}	Impact force F, N
20	28.122	42,183
40	36.624	54,936
60	45.126	67,689
80	53.628	80,442
100	62.13	93,195
120	70.632	105,948

Table 3. Testing the impact vibration device on the bench

Trial No.	Quantity of bolts, pcs	The size of the impact force, F, N	Quantity of blows, pcs.	Impact level size, cond. units
1	16	20,000	1,000	305–317
2	16	40,000	730	329–338
3	16	60,000	467	354–362
4	16	80,000	354	383–395
5	16	100,000	136	418–430

Analyzing bolt impact test data, it was found that with an impact force equal to:

- 20,000 N (2 tons) – bolts do not break;
- 40,000 N (4 tons) – after the 730th impact, one bolt broke;
- 60,000 N (6 tons) – after the 467th impact, one bolt disintegrated, but after 500 hits the other bolt was found to have disintegrated during the inspection of the bolts.
- 80,000 N (8 tons) – after the 354th impact, one bolt disintegrated, but after 360 impacts, the disintegration of the second bolt was found during the inspection of the bolts;
- 100,000 N (10 tons) – after the 136th impact, it was found that two bolts were subject to disintegration at once, after testing of 150 impacts, it was found that disintegration took place in two more bolts, which are critical in operation.

Metallographic analysis of bolts subjected to impact force from 20,000 N (sample 12, a, b); 80,000 N (sample 13, a, b) and 100,000 N (sample 14, a, b) is shown in (Figs. 6–8).

Metallographic analysis confirmed the formation of critical defects and cracks is shown in (Figs. 6–8) in the microstructure at different values of the impact force, which caused the bolt to disintegrate. Müller (2017) has shown that adding the filler into the resin changed a fracture surface. An analysis of a scanning electron microscopy (SEM) proved a good wettability of the filler, the resin and the adhesive bonded material (a structural carbon steel S235J0). A crack propagation was concentrated around the filler B112 (151.59 ± 53.04 µm), namely at higher value of the loading speed, i.e. 10 mm min^{-1}. The crack propagation is a consequence of this.

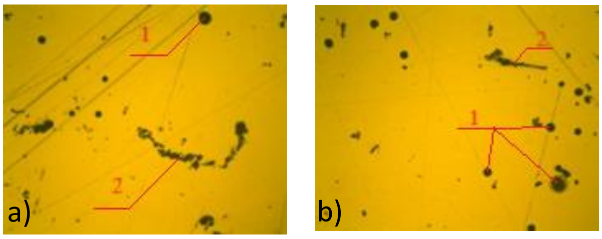


Figure 6. Metallographic analysis after 360 impacts with a force of 20000 N, magnification –x50, sample 12: 1 – inclusion; 2 – craks.

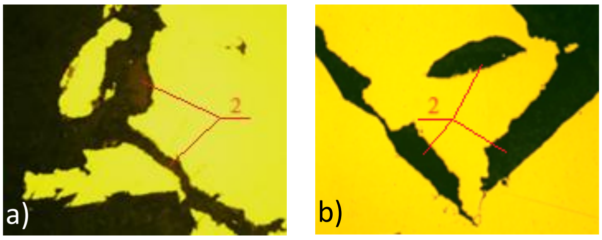


Figure 7. Metallographic analysis after 360 impacts with a force of 80000 N, magnification – x50, sample 13: 2 – craks.

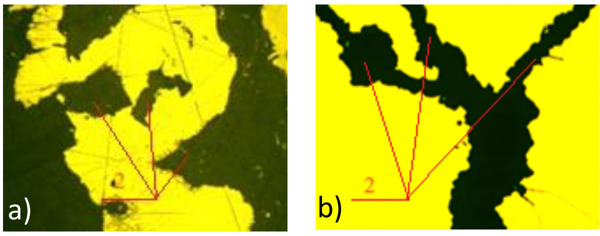


Figure 8. Metallographic analysis after 360 impacts with a force of 100000 N, magnification – x50, sample 14: 2 – craks.

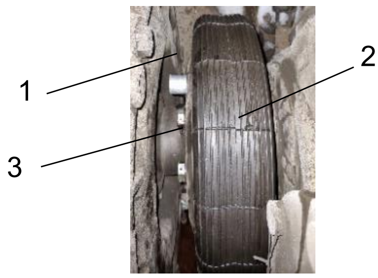


Figure 9. Placement of the impact monitoring device for bolted anchorages and rubber cord coupling: 1 – impact monitoring device; 2 – rubber cord coupling; 3 – fastening bolts.

To check the shock vibration load received by the rubber cord coupling bolts, a shock vibration device was installed on the rubber cord coupling flange. The installation location of the device is shown in (Fig. 9). The operation test of the shock vibration device was performed on electric train motor car No. 7118-10 starting from 15.04.2023.

To check the shock vibration load received by the rubber cord coupling bolts, a shock vibration device was installed on the rubber cord coupling flange. The installation location of the device is shown in (Fig. 9). The operation test of the shock vibration device was performed on electric train motor car No. 7118-10 starting from 15.04.2023. coupling bolts, a shock vibration device was installed on the rubber cord coupling flange. The installation location of the device is shown in (Fig. 9). The operation test of the shock vibration device was performed on electric train motor car No. 7118-10 starting from 15.04.2023.

Answer (3). Since all trains are used on the same identical directions and routes with a daily mileage of an average of 500 km per day, car 7118-10 was randomly selected for research. Based on data on the mileage of cars, where mileage not exceed more than 100 thousand km from repair (the standard mileage to the scheduled repair is 240 thousand km ± 10%), in order to monitor on daily basis the shock and vibration load during 6 months. The mileage of car 7118-10 from the scheduled repair at the time of installation of the shock-vibration device was 55 thousand km.

Answer (2). The device was used to test shock and vibration loads and control resonant frequencies during operation of a motor car in operation (on the line). Over the course of 6 months, the shock and vibration load was monitored under operating conditions of Latvian railway with daily shock load monitoring in order to ensure trouble-free operation of rolling stock and improve the quality of service and transportation of passengers.

The results obtained from the impact monitoring device for bolted anchorages and rubber cord are shown in (Fig. 10).

(Fig. 10) shows the amplitudes of vibrations (in conventional units) taken from the vibration sensor while the motor car is moving. Measurements were carried out throughout the day (24 hours). As can be seen from the graph, the amplitude of the vibration was at around 280 conventional units. However, 3 cases were recorded when the amplitude of oscillations reached up to 300 conventional units. The maximum amplitude of oscillations was 396 conventional units. The mileage of the car is 486 km.

Figure 10. Shock vibration load graph for one working day.

Once a month, when the motor car reaches 10–15 thousand km mileage, one bolt was dismantled for metallographic analysis. The purpose of the metallographic analysis is to detect and confirm the existence of defects and microcracks in the microstructure at certain and determined impact loads and at a known distance of the motorcar bolts. The data of the study of the performance of bolts using an impact monitoring device for bolted anchorages and rubber cord coupling were shown in (Table 4).

Table 4. Impact load determination.

Sample No.	M24 bolt performance indicators				
	Mileage, km	The size of the shock sensor readings, cond. units			
		300–330	331–360	361–390	391–420
15	12,682	52	14	3	0
16	25,632	116	21	1	2
17	38,850	187	33	1	1
18	52,512	236	42	5	0
Critical level	264,000	700	250	150	40

During the monitoring, the maximum impact vibration level of the impact load is 396 conditional units.

Knowing the maximum value of the shock-vibration load to which the fastening bolts of rubber-cord couplings can be subjected, it is proposed to collect data on the shock-vibration loads. When the maximum impact load ascertained during operation of the rubber-cord couplings fastening bolts is reached, it is proposed to carry out measures for their replacement. This significantly reduces the likelihood of bolt failures and the associated need to perform unscheduled repairs of units, which entails a significant reduction in the costs for the company.

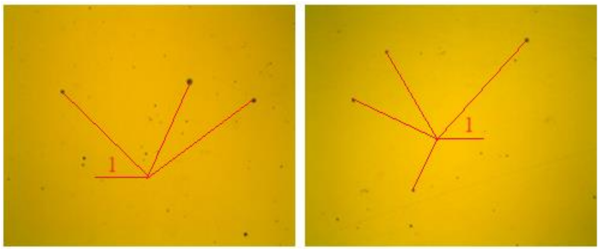


Figure 11. Bolt sample 15 metallographic analysis, mileage 12,882 km.

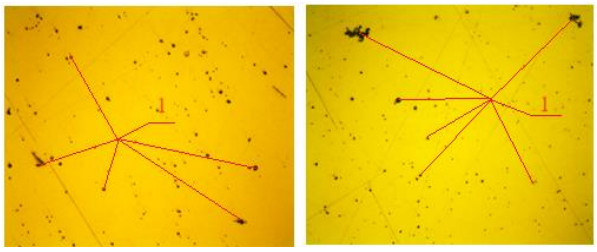


Figure 12. Bolt sample 18 metallographic analysis, mileage 52,512 km.

For metallographic analysis, bolts with mileage of 12,682 km and 52,512 km were taken. The results of metallographic analysis of bolt samples 15 and 18 are shown in (Figs. 11, 12).

The results of the metallographic analysis showed the gradual formation of defects in the microstructure, (Figs. 11, 12, poz. 1).

Frequency analysis of rubber cord coupling

The critical-frequencies of the coupling depend on the rigidity - the fastening method and on the mass of the coupling. For this purpose, we use the empirical formula (3) (Myakishev & Bukhovtsev, 2004).

$$w = (\frac{K}{M})^{0.5} \tag{3}$$

where K – coupling stiffness, N m^{-1}; M – coupling mass = 9.24 kg.

Based on the results of studies of 40 resonant frequencies, it was found that the total contribution of the coupling mass in these vibrations reaches 61.8% in the axial direction of the coupling, 50% in the vertical and horizontal radial directions. Since the total part of the mass of the coupling involved in the oscillations is greater than 60%, the further participation of the mass is not significant and therefore we stop at

Table 5. Summarized critical-frequency results

Number of test	Critical-oscillation frequency, Hz	Coupling mass participation coefficients by axles		
		X	Y	Z
1	54.87	**0.5719**	$1.28 \cdot 10^{-6}$	$8.34 \cdot 10^{-9}$
2	56.27	**0.0194**	$2.66 \cdot 10^{-6}$	$3.23 \cdot 10^{-6}$
3	56.37	**0.0260**	$1.97 \cdot 10^{-8}$	$5.89 \cdot 10^{-7}$
11	88.25	$1.82 \cdot 10^{-8}$	**0.0533**	**0.3882**
12	88.36	$2.14 \cdot 10^{-9}$	**0.3881**	**0.0532**
22	126.05	$4.85 \cdot 10^{-7}$	**0.0511**	**0.0028**
23	126.22	$1.89 \cdot 10^{-7}$	**0.0048**	**0.0484**

the first 40 frequencies. We distinguish the main masses involved in the formation of oscillation modes. A summary table of resonance frequencies with the largest coupling mass contribution is shown in the (Table 5).

These fluctuating masses represent a portion of the energy that acts on the coupling shell and can cause its damage (Medvecka-Benova et al., 2015). For the largest masses specified in in the (Table 5), histogram was created a histogram of mass participation in fluctuations in each direction, shown on (Fig. 13).

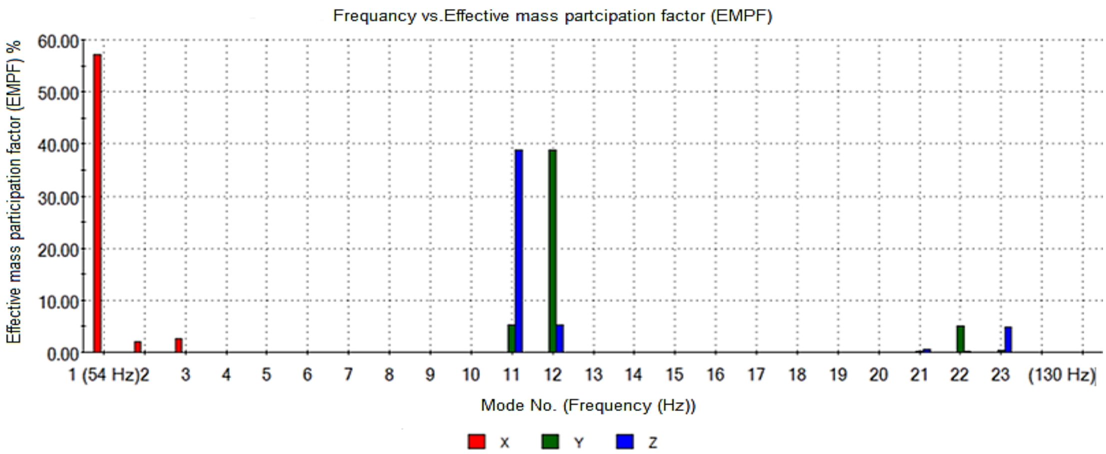


Figure 13. Histogram representing the mass participation in the oscillations.

To estimate the total mass participation coefficient from the oscillation frequencies, created a graph of the total mass participation (Fig. 14).

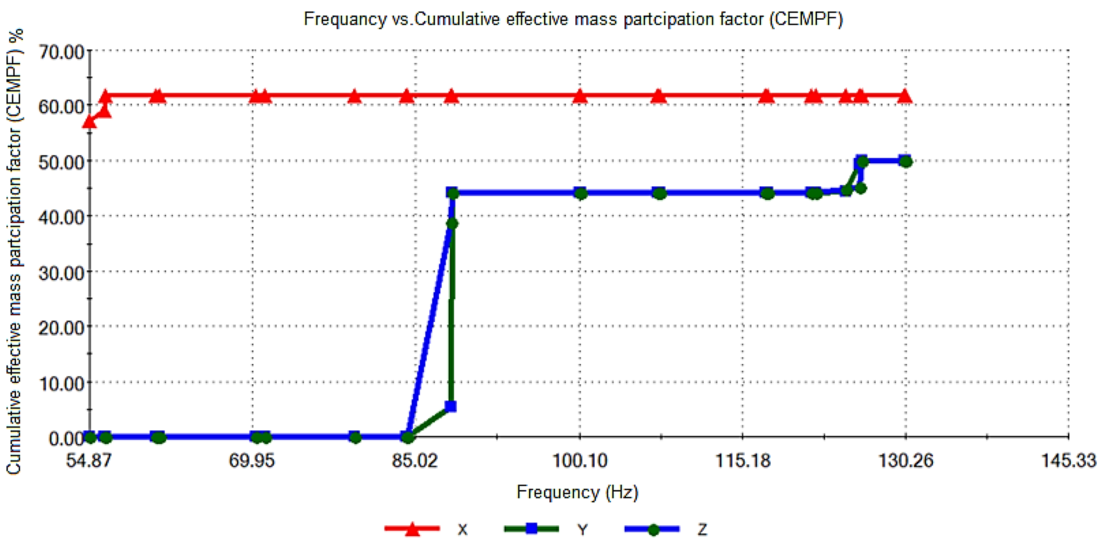


Figure 14. A graph showing the overall coefficient of mass participation as a function of the oscillation frequencies.

As a result of the analysis of the histograms (Figs. 13, 14), we determine the main vibration modes corresponding to the frequencies with the largest coupling mass, and the mass participation indicates which frequency modes are the most dangerous (Sheshenin et al., 2021).

As can be seen on the (Fig. 15), the first and main form of oscillation at 54.87 Hz with the largest part of the mass of the coupling 57.19% loads the side wall of the coupling shell in the axial direction. The loaded zone coincides with the coupling failure zone during operation.

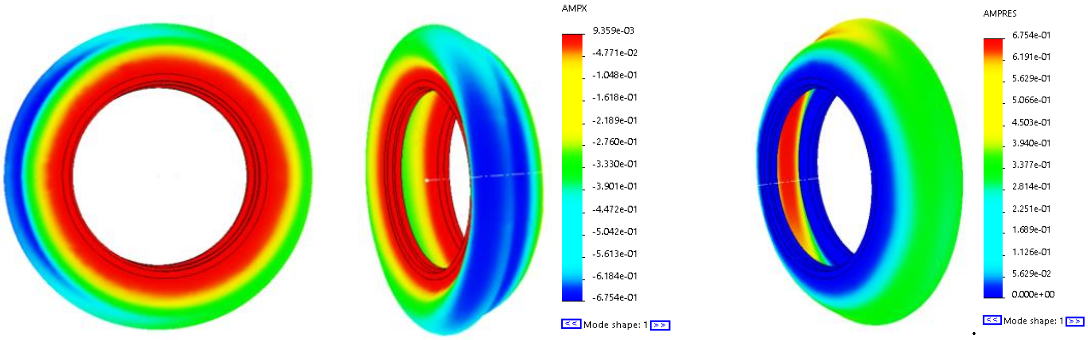


Figure 15. Coupling vibration along the X axis at frequency of 54.87 Hz.

As can be seen on (Figs. 16, 17), the shape of the oscillation at the frequencies of 88.25 Hz and 88.36 Hz with the largest part of the mass of the coupling, 38.82% and 38.81%, respectively, directed in the radial, horizontal and vertical directions, stretches the upper surface and the side of the coupling shell in the radial direction. During operation, the stressed areas partially coincide with the area of coupling damage.

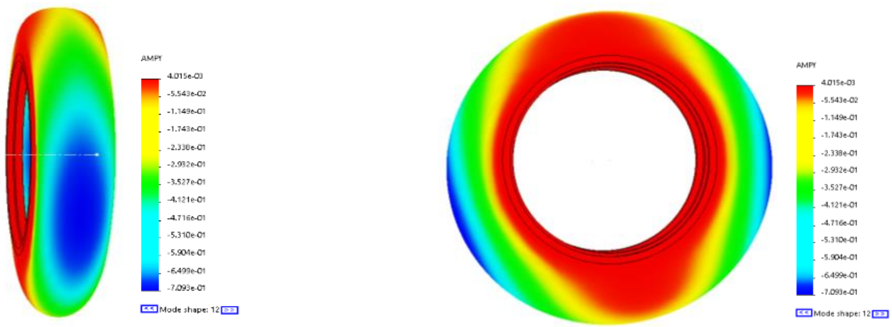


Figure 16. Coupling vibrations along the Y axis at frequency of 88.25 Hz.

At frequencies 56.37 Hz, 56.27 Hz, 126.05 Hz and 126.22 Hz, the coupling loses its stability, however the mass contribution at these frequencies is not significant and the place where the coupling is attached to the flanges is not under stress. At resonance frequencies of 56.37 Hz, 56.27 Hz, 126.05 Hz and 126.22 Hz, no more than 5% of the mass of the rubber cord coupling participates and its contribution does not affect the oscillations.

Using Solid Works software critical (dangerous) frequencies to which rubber-cord couplings may be exposed during operation were identified. In turn, use a shock-vibration device is proposed to collect data on the real frequencies to which the coupling (or other unit) is exposed during operation. Shock and vibration load data is monitored in real time and stored on a server that can be accessed via the Internet.

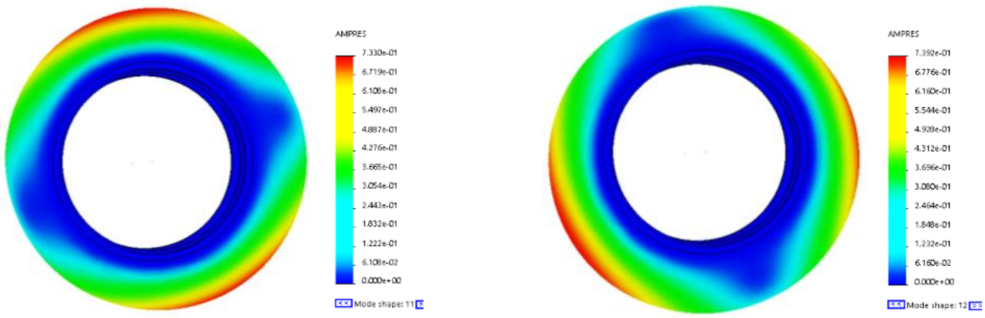


Figure 17. Coupling vibrations along the Z axis at frequency of 88.36 Hz.

The initial moment of resonance of the rubber cord coupling was determined using a impact monitoring device for bolted anchorages and rubber-cord coupling. The value of the oscillation frequency can be determined for individual stages of movement at a known speed. The results for different speed ranges for the 1 s period are shown in (Figs. 18–21).

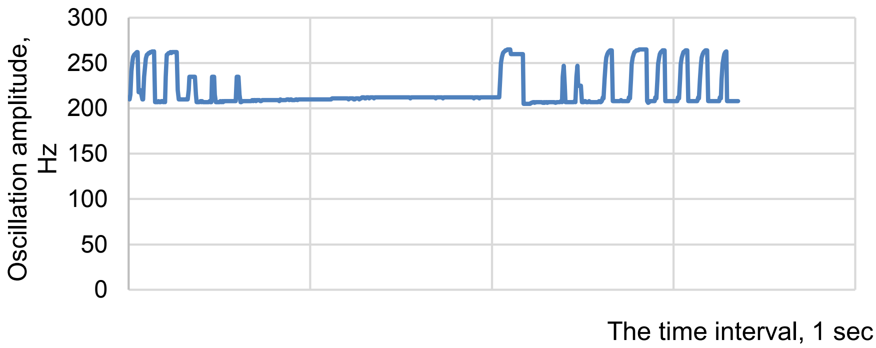


Figure 18. Study of resonance frequencies at speed of 10–20 km h^{-1}.

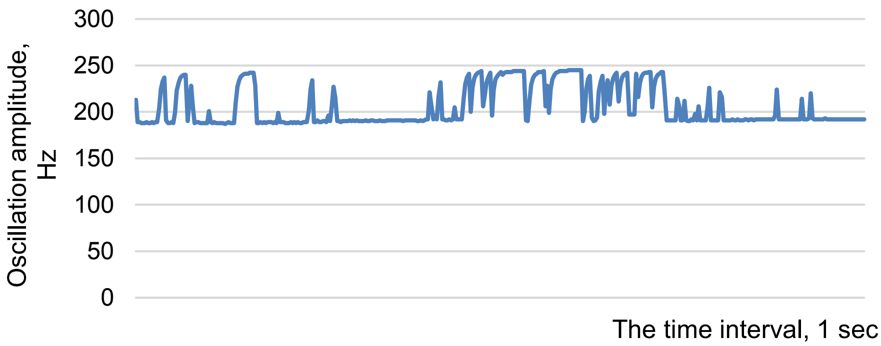


Figure 19. Study of resonance frequencies at speed of 40–60 km h^{-1}.

According to the results of the analysis of (Figs. 16–21), the oscillation frequencies to which the rubber cord coupling is exposed at different speeds from 20 to 120 km h^{-1} were determined and found:

- at a speed of 20–100 km h^{-1} resonance does not occur in the system;
- at speeds in the range of 110–120 km h^{-1} resonances occur periodically in the system and the frequency range in which the couplings operates is 53–57 Hz.

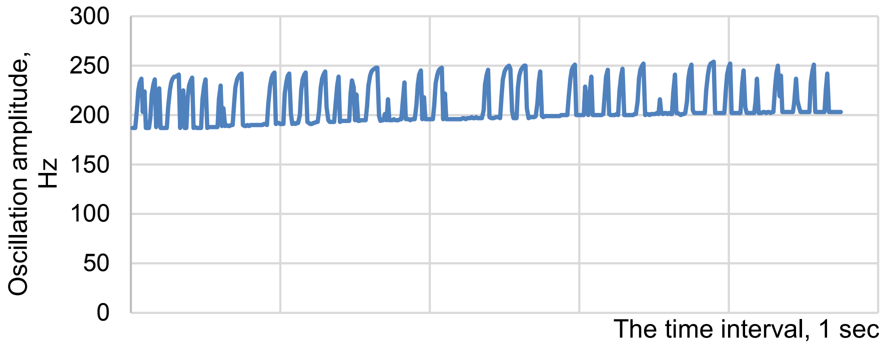


Figure 20. Study of resonance frequencies at speed of 80–100 km h^{-1}.

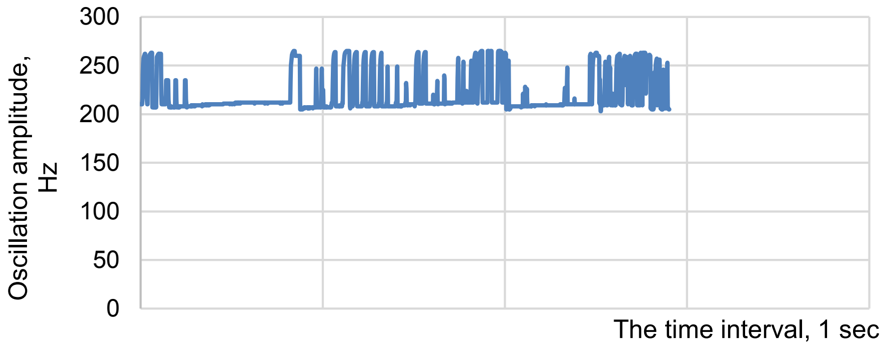


Figure 21. Study of resonance frequencies at speed of 110–120 km h^{-1}.

The critical resonance frequency of the oscillation determined by SolidWorks is 54.85 Hz along the X-axis. This means that the rubber cord coupling resonance may happenat the most dangerous resonant frequency.

RESULTS AND DISCUSSION

Metallographic analysis revealed a large number of non-metallic impurities in all samples. Decomposition of M24 bolts during service can often start from initial defects of metallurgical origin caused by non-metallic impurities. Which, with the increase in the life of the bolt (mileage), increase in number and size, which later cause fractures.

The implementation of the impact-vibration force monitoring device in service provided objective information on the impact loads perceived by the bolts for fastening the rubber cord coupling.

If, during technical maintenance, based on the data collected from the device, it is found that the level of permissible loads exceeds the critical level, then the M24 bolts of the rubber cord coupling must be replaced with new ones. Thus, it eliminates the need to perform unplanned repairs of the M24 bolts of the rubber cord coupling due to disintegration, which calls for large financial investments. In the future, the finished product can be offered to European and other countries by installing the impact vibration device on railway rolling stock and metro cars or using it in other industries. In addition, this invention can be applied in mechanical engineering, aircraft construction, shipbuilding and other fields to control the technical condition of bolts and flexible coupling. Answer (4) having a certain set of shock-vibration load data in real time, it is possible to make adjustments to the repair system for servicing the rubber-cord coupling and its fastening bolts or other technical equipment, which is subject to shock-vibration loads. This means a change from a system of planned preventative repairs to repairs based on actual conditions.

According to the analysis of the stresses acting on the rubber cord coupling in different operating modes, calculated in the Solid Works program, it was found that at a speed above 110 km h^{-1} (1,673 rpm), the stress spreads throughout the cross section of the coupling.

As a result of the analysis of the first 40 frequencies, the critical frequencies and oscillation modes of the coupling shell were found. The calculated load of the coupling cover zones coincides with the damage zones of the coupling in service. Answer (4) knowing the most dangerous frequencies to which rubber-cord couplings can be exposed, it is proposed to use a shock-vibration device to collect data on the real frequencies to which the coupling (or other unit) is exposed under operating conditions. Answer (4) Knowing the most dangerous frequencies to which rubber-cord couplings can be exposed, it is proposed to use a shock-vibration device to collect data on the actual frequencies to which the coupling (or other unit) is exposed in operation.

To reduce the risk of damage to the coupling housing, it is necessary to prevent long-term operation of the coupling at the calculated critical frequencies – 54.87 Hz; 88.2 Hz; 88.36 Hz.

Answer (4). If values of resonant frequencies are coinciding with identified critical values, it is necessary to take measures to prevent the rubber-cord coupling from operating at dangerous frequencies or to accelerate their passage. This way it is possible significantly reduce the likelihood of rubber-cord couplings failure and the need for unscheduled repairs associated with replacing the coupling. All of the above measures lead to a cost reduction for the company.

Answer (4). Using the impact vibration device, it is possible constantly accumulate and analyse data on the impact force in order to reduce the number of unplanned repairs of railway rolling stock or other industries vehicles due to their damage, as well as to reduce the number of accidents or other incidents.

The results of the calculations in the SolidWorks program package confirmed that the most stressed area of the coupling is its wall 10–20 mm distance from the outer diameter of the mounting disc. This area is mainly loaded with loads from the shaft deviation and from the maximum moment at the beginning of the movement.

Usage of the impact monitoring device for bolted anchorages and rubber cord coupling and the methodology will give the following results. The costs for unplanned repairs will be eliminated, however the human factor still must be taken into account. The costs will be related only to the implementation of the impact vibration device. Data on unplanned repair costs and the impact monitoring device for bolted anchorages and rubber cord coupling implementation and operation are presented in (Table 6).

Answer (5) According to (Table 6) result data in the example of JSC 'Pasažieru vilciens', a company that operates electric trains, implementation of the device would be done for all EMU trains, and the implementation costs would not exceed 15 thousand Euros, then the costs would be repaid within 2 years (the use of the device becomes profitable) due to the reduction in the number of unplanned repairs, and in the 3rd year, the company will have a profit of no less than 15 thousand. Euro (article Mihailovs et al., 2021).

Table 6. Comparison of costs for unplanned repairs and implementation of impact monitoring device

The name of the unplanned repair	One unplanned repair, EUR	Unplanned repairs during 10 years, EUR	Implementation of impact monitoring devices, EUR
Replacement of rubber-cord coupling bolts	429	103,895	15,000
Replacement of rubber cord coupling	575	58,842.28	

Answer (5) The impact vibration force monitoring device provided objective information on the impact loads perceived by the rubber cord coupling fastening bolts, and its serial introduction into operation makes possible monitoring of the rubber cord coupling and their fastening bolts technical condition and prevent unplanned repairs due to bolt damage.

CONCLUSIONS

Based on the experiments conducted, it was proved that the failures of the rubber cord coupling fastening bolts are related to the disintegration processes due to fatigue from the accumulation of defects in the microstructure as a result of exposure to impact loads, which is confirmed by metallographic analysis.

According to the results of the experiments, the critical value of the impact load was determined, and the load on the rubber-cord coupling fastening bolts exceeding several times the allowable values were found.

The implementation of the impact-vibration force monitoring device provided objective information on the impact loads perceived by the M24 bolts used for the rubber cord coupling fastening. Its serial introduction into operation makes possible to monitor the technical condition of rubber cord couplings fastening bolts.

If, during maintenance, the data collected from the device shows that the level of permissible loads exceeded the critical level, then the M24 bolts of the rubber cord coupling must be replaced by new ones. Thus, it eliminates the need to perform unplanned repairs of the rubber cord coupling due to M24 bolts disintegration, which requires large financial inputs.

When studying the influence of resonance frequencies, the stress zones of the rubber cord coupling were determined in the SolidWorks finite element modeling software, and it was found that the critical frequencies of resonance are influencing coupling oscillations in X; Y; and Z-axes directions, involving a certain amount of coupling mass. The most dangerous resonance frequency is along the X axis, when more than 57% of the coupling's own mass participates in the oscillations. At this frequency, the coupling areas are subject to deformation and coincide with damage areas found in operation.

As a result of the vibration level monitoring, using the impact vibration device, the oscillation frequencies to which the rubber cord coupling is exposed at different speeds from 10 to 120 km h^{-1} are determined. It was established that resonances in the system periodically occur at speeds in the range of 110–120 km h^{-1} and the frequency range in which the coupling operates is 53–57 Hz. The critical resonance frequency of the oscillation determined by SolidWorks is 54.85 Hz along the X-axis.

Appearance of critical resonant frequencies 88.25 Hz; 88.36Hz along the Y and Z axes by a shock vibration device not ascertained. In order to reduce the risk of coupling breakdown, it is necessary to limit the long-term operation of the coupling at a speed of more than 110 km h^{-1} (1,700 rpm) due to the effects of the action of the resonant frequency.

The developed and tested shock vibration device was tested on the rolling stock. Using this device, the data of shock vibration load levels in real operating conditions were obtained. The shock-vibration control device provided objective information about vibration and shock loads. By introducing the shock-vibration monitoring device into serial operation, it is possible to predict a significant reduction in the number of unplanned repairs of motor cars, as well as to reduce the costs of motor car downtime. In addition, this invention can be applied in mechanical engineering, aircraft construction, shipbuilding and other fields to monitor the technical condition of bolts.

ACKNOWLEDGEMENTS. This work has been supported by the European Social Fund within the Project No 8.2.2.0/20/I/008 'Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization' of the Specific Objective 8.2.2 'To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas' of the Operational Programme 'Growth and Employment'.

REFERENCES

Bhadeshia, H. & Honeycombe, R. 2017. *Steels Microstructure and Properties*, Fourth edition, 2017, Elsevier Science, 488 pp.

Birjukov, I., Beljajev, A. & Ribnikov, E. 1986. *Traction transmissions of electric rolling stock of railways.* M.: Transport, 256 pp. (in Russian).

Boguslavskij, B.L. 2016. *Metalhead's Handbook*. Volume 2. Edition 3, 2016.

Desai, A., Telukala, H., Jadhav, S. & Kurna, S. 2021. Strength Evaluation and Validation of Structural Joints. *SAE Technical Paper* 2021-26-0315. https://doi.org/10.4271/2021-26-0315

EN 10083-3:2007-01 Technical delivery conditions for alloy steels English version of p. 54.

Evdokimov, A.P. & Shikhnabieva, T.S. 2017. Stress–strain behavior and specific friction of toric rubber-cord casings of flexible couplings. *Journal of Machinery Manufacture and Reliability* **46**(2), 1 March 2017, 199–203.

Grigorenko, V., Orlov, M., Morozova, L. & Zuravljeva, P. 2014. Investigation of static destruction of bolts made of 30khgsa steel under operating conditions. *Aviation materials and technologies* **S4**, 125–135 doi: 10.18577/2071-9140-2014-0-s4-125-135 (in Russian).

Grigorenko, V., Morozova, L. & Vinogradov, S. 2018. Features of the destruction of fasteners made of structural steel. *Scientific and Technical Journal "Proceedings of VIAM"*, 66–74. doi: 10.18577/2307-6046-0-4-66-74 (in Russian).

ISO 898-1:2013 *Mechanical properties of fasteners made of carbon steel and alloy steel*. Part 1: Bolts, screws and studs with specified property classes, 27 pp.

Klimentyev, E.V., Zvonov A.O. & Glazkova E.U. 2015. Rubber-cord cushions application in modern engeineeging. *FSUE "RPE "Progress"* Omsk, 55–68. doi:10.1109/Dynamics.2014.7005706

Komorska, I. 2011. *Vibroacoustic Diagnostic Model of the Vehicle Drive System*. Institute for Sustainable Technologies & National Research Institute, 130 pp. ISBN-10: 837789016X, ISBN-13: 978-8377890165.

Korneeva, V.S., Romanyukb, D.A., Korneeva, S.A., Russkiha, G.S. & Vaskovaa, M.V. 2016. Finite element research of rubber-cord flat coupling. *Procedia Engineering* 1**52**, 321–326. doi: 10.1016/j.proeng.2016.07.710

Kuzu, C., Pelit, E. & Meral, İ. 2021. A new design of Rockwell-Brinell-Vickers hardness standard machine at UME. *Acta IMEKO* **9**(5), 230–234.

Leonardson, R. & MacGugan, D. 1994. Design and fabrication of a commercial triaxial accelerometer. *Sensors* (Peterborough, NH), **11**(8), 22–23.

Medvecka-Benova, S., Mikova, L. & Kassay, P. 2015. Material prope rties of rubber-cord flexible element of pneumatic flexible coupling metallurgical. *Metabk* **54**(1), 194–196.

Mihailovs, F., Eiduks, J. & Gorbačovs, D. 2021. Reducing the Number of Unscheduled Repairs of Traction Gear of EMU Trains by Introducing Modern Technical Solutions. No: *10th International Scientific Conference "Rural Development. Challenges for Sustainable Bioeconomy and Climate Change"*, Lietuva, Vytautas Magnus University Academy of Agriculture, pp. 1–6.

Müller, M. & Choteborský, R. 2016. Impact strength behaviour of structural adhesives, *Agronomy Research* **14**(S1), 1078–1087.

Müller, M. 2017. Mechanical properties of resin reinforced with glass beads. *Agronomy Research* **15**(S1), 1107–1118.

Myakishev, V., Bukhovtsev, I. & Sotsky, B. 2014. *Physics.* 10th grade, textbook. Moscow, Enlightenment, 417 pp. (in Russian).

Sapalov, E. & Panfjerova, O. 2016. Study of strength characteristics of high strength bolts of destructive and non-destructive methods, 6. https://3minut.ru/images/PDF/2016/25/issledovanie-prochnostnykh-kharakteristik.pdf.

Sheshenin, S.V., Gritchenko, M.E. & Chistyakov, P.V. 2021. Averging the viscoelastic properties of a rubber-cord ply in a plane stress state. *Mechanics of composite materials*. **57**(4), 673 – 688. https://doi.org/10.22364/mkm.57.4.05.

Sirokih, A., Simulation of friction joints on high-strength bolts by the finite element method. Ufa State Petroleum Technological University, Ufa (Oil and Gas Business, 2005).

Slejbo, Y.N. 2005. *General chemistry*, 2005. Moscow, Academia, 447 pp.

Stauffer, J.-M.2004. Market opportunities for advanced MEMS accelerometers and overview of actual capabilities vs. required specifications. In *Proceedings of the IEE Xplore: Position Location and Navigation Symposium*, Monterey, CA, USA, 26–29 April 2004, pp. 78–82.

Summary of non-scheduled repairs of electric trains JSC 'Pasažieru vilciens' (2015–2021) (template FT-20) (in Latvian).

Taylor, J., Mehmanparast, A., Kulka, R., Moore, P., Farrahi, G.H. & Xu, L. 2021. Compact crack arrest testing and analysis of EH47 shipbuilding steel. *Theoretical and Applied Fracture Mechanics* **114**, art. no. 103004. www.elsevier.com/locate/tafmec

Tribel'skii, I.A. & Zubarev, A.V. 2008. Stress-strain state and thermal state of rubber-cord casings of highly elastic couplings. *Russian Engineering Research* **28**, 1159–1164.

Vinogradov, B.V. 2016. Flexible couplings with rubber-cord shells in dual pinion mill drives.

Yingnan, D., Weibing, X., Yanjiang, C., Jin, W. & Weiming, Y. 2020. Experimental research on seismic performance of precast cogging high-strength bolt composite joint and influence of its arrangement location. *Engineering Structures* **225**, 111294. https://doi.org/10.1016/j.engstruct.2020.111294

Zadel, H., Kogen-Dalin, V., Krimov, V. 1985. *Electrical Engineering*. Moscow: Higher School, 480 pp.

Zhang, W., Sheng-Li, Lv, Wang, Ji-Pu, Gao, X. & Srivatsan, T.S. 2021. Conjoint influence of environment and load on fatigue life of a bolted aluminum alloy structure. *AIP Advances* **11**, 075210. https://doi.org/10.1063/5.0058946