FAILURE ANALYSIS OF RUBBER-CORD COUPLINGS OF ER2 SERIES ELECTRIC TRAINS

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Abstract. The article analyzes the statistics of rubber-cord coupling failures during 2015 till 2022. The analysis of failures shows that prevailing cases are rupture of the rubber-cord coupling side surface. It should be noted that the cost of eliminating the consequences of a rubber-cord coupling rupture is on average 575.21 EUR for one unscheduled repair. To study the possible reasons of the rubber-cord coupling rupture, the couplings removed from the motor cars after unscheduled repairs were taken. In the process of research, the warming temperature of the rubber-cord coupling, hardness at various temperatures and forces acting on the rubber-cord coupling during operation, i.e. the operational conditions of the rubber-cord coupling were determined. The purpose of these studies is to determine the possible causes of the rubber-cord coupling side surface. The research process of rubber-cord couplings consisted of four stages. 1. Determination of the geometric dimensions of the coupling and comparison of the obtained data with the data of ISO 14691:2008. 2. Theoretical determination (calculations) of: torque, centrifugal force, shear stress and radial load acting on the coupling. 3. Determination of hardness on the Shore A scale depending on the temperature of the rubber-cord coupling in three temperature ranges t = -20 ºC; 0 ºC; + 22 ºC; + 60 ºC in the RTU laboratory. Comparison of the obtained data with the data of ISO 14691:2008. 4. Drawing the main conclusions about the possible causes of rupture of the rubber-cord coupling. The purpose of these studies is to determine the possible causes of the rubber-cord coupling side surface. The forces and stresses acting in the zones of damage to rubber-cord couplings are determined. According to the results of calculations, the values of the forces P_c; P_{c1} and stresses τ_k caused by the torque M_a acting on the rubber-cord coupling in the destruction zones and the values of forces and stresses capable of causing the destruction of rubber-cord couplings are determined. In the article hardness of the rubber-cord coupling was also studied at various temperature conditions.

Keywords: traction gear, rubber, force, stresses, Shore A, temperature, hardness.

Introduction

On the EMU trains rubber-cord couplings are used to transfer torque from the traction motor shaft to the wheelset gearbox [1] and attached on one side – to the traction motor shaft flanges, and on the other side – by bolts – to the traction gearbox small gear shaft flange. The use of rubber-cord couplings on the rolling stock allows soften dynamic loads and makes the rolling stock run smoothly [2]. In publications on the EMU trains design, the authors describe the purpose, design and operation of rubber-cord couplings [3]. The design of the coupling is shown in Figure 1.

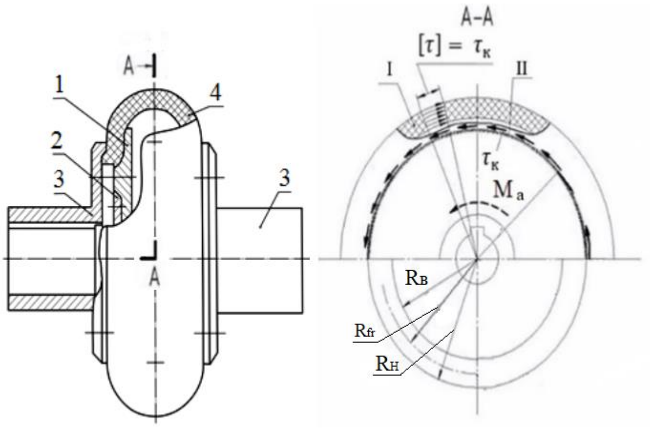

Fig. 1. **Fastening scheme and forces acting on the rubber-cord coupling:** 1 – inner flange for fastening the rubber-cord coupling; 2 – connecting ring; 3 – flange on the side of the traction motor and traction gearbox; 4 rubber-cord coupling; τ_k – torsional shear stress; $R_в$ – inner radius of the ring; R_{fr} – friction radius; $R_н$ – ring outer radius

When transmitting torque from the traction motor, the coupling, together with the coupling fastening to the flange, is subjected to a tangential torsional shear stress τ_k. The highest value of the shear stress τ_k is achieved in the circular section at the flange clamp with a diameter D_1, during the acceleration of the EMU train, when the greatest (maximum) torque M_a is realized by the traction motor Figure 1.

Every year, JSC "Pasažieru vilciens" records a significant number of unplanned repairs related to the failure of the elastic coupling. Failure of the elastic rubber cord coupling leads to suspension of the traction rolling stock unit for unscheduled repairs. Consequently, unplanned repairs require funding to restore the equipment's operability.

Many companies, institutes, laboratories and researchers are involved in the design, calculation, modelling and testing of elastic couplings. Research is carried out in the direction of improving material properties, looking for new highly flexible element shapes according to the technological requirements or damping efficiency requirements.

Rubber-cord couplings are used in power and auxiliary drives in various power and auxiliary equipment of different railway rolling stock. On the EMU trains rubber-cord couplings are used to transmit torque from the electric motor shaft to the wheelset gearbox. The use of rubber-cord couplings on the rolling stock allows soften dynamic loads and makes the rolling stock run smoothly. In publications on the EMU trains design, the authors describe the purpose, design and operation of rubber-cord couplings [3].

The study of the action of forces on the rubber-cord coupling was carried out by S. Medvecka - Benova, Ľ. Mikova, P. Kassay [4]. This paper describes the material properties of the rubber-cord elastic element necessary for assessment of the pneumatic resilient element by means of FEM.

In their study V Krmelová and O Pozovnyi deal with determination of material parameters of elastomer (rubber) for computational modeling based on experiment data – hardness and also determination of material parameters of specific composite materials for next-generation tyres. To describe the elastomeric parts of tyre carcasses, several material models of the viscoelastic behavior of the material are used – constitutive models, the most commonly used is the Mooney-Rivlin (MR) model. To determine the MR parameters, tensile tests of elastomers according to ISO 37:2017 [Rubber, vulcanized or thermoplastic] were carried out in the work and the hardness was determined according to the Shore A method [5].

In the scientific article [11], the results of the experimental studies on the state of stress-strain in strengthening, stabilization and reduction of strength of the rubber cord coupling casings were proposed in the static load mode. The reduction of the effect of these characteristics on the dynamic load of the actuator was shown. The physical processes of the specific friction in the elastic element of the coupling are considered. The graphs of the dependence of the specific friction on the dynamic moment, vibration frequency, torsion angles and coupling body temperature were proposed in the scientific article.

In the scientific work [12], the calculated and experimental results of torsion studies in the couplings of electric train drives, rubber cord shells are offered. In this work, the type of cord and reinforcement parameters were proposed, where the shell provides the required torque depending on the twist angle. The research carried out in the scientific work demonstrated an effective and sufficiently adequate torsion reflection for the constructions of rubber cord coupling shells, based on the theory of the application of fibber-reinforced materials at small and large deformations.

Work [13] is devoted to the study and determination of viscoelastic properties of a layer of rubber cord under plane stress. This work is devoted to the determination of relaxation functions of rubber and rubber cord and includes the following aspects: experimental determination of viscoelastic properties of rubber and rubber cord and calculations of viscoelastic properties with viscoelasticity with the help of linear theory, using the approximation method and alignment. In operation, the parameters of the relaxation function were experimentally determined for samples of two-layer rubber cord using the Proni method, periodically changing the stress-strain state.

Analyzing the above mentioned studies of international authors, it can be concluded that in these articles the authors did not consider such issues as measuring the hardness of the coupling material at various temperatures, the measurement of the geometrical parameters of the rubber-cord coupling was not taken into account. The stresses acting on the coupling were not studied, studies on the coupling side surface rupture were not carried out, the same is valid also for determination of tangential torsional shear stresses, as well as the rubber-cord coupling failure statistics. Accordingly, the question arises how all these parameters affect the reliability of the rubber-cord coupling, and what the possible causes of the rupture of its side surface are. In this article the authors decided to investigate this problem.

Materials and methods

The problem of rubber-cord coupling failures is one of the main problems associated with traction gear failures. According to the data presented in the reports on unscheduled repairs by the railway JSC "Pasažieru vilciens" for the period from 2015 to 2022, 239 cases of unscheduled repairs of the ER2 series train motor cars were identified due to traction gear failures, of which 58 cases were rupture of the rubber-cord coupling shell [6]. That is 20% of the total number of traction gear failures [10]. Analysis of statistical data is shown in Figure 2.

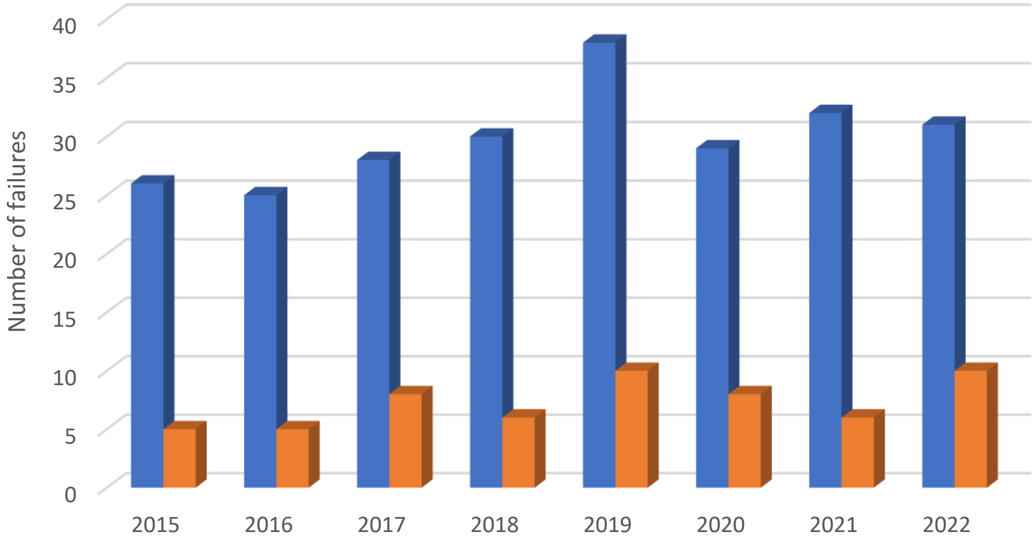

Fig. 2. **Number of unplanned repairs and rubber-cord damage in ER2 traction gear (2015-2022)**

When ascertaining a rupture of the coupling shell, the motor car of the ER2 series EMU train needs to undergo unscheduled repair related to the replacement of the rubber-cord couplings. The data on financial costs caused for such unscheduled repairs are presented in Table 1.

Table 1

Expenses for unscheduled repairs to replace the rubber-cord coupling

Rubber cord cupling replacement	One unplanned repair for coupling replacement	During 2022	During 8 years
sum	575.21 EUR*	5752.10 EUR	33362.18 EUR

* Average replacement price for a rubber cord coupling – 575.21 EUR; Price of a rubber cord coupling – 147.23 EUR per peace; Associated shunting operations – 427.15 EUR; Employee allowances for unscheduled repairs – 10.32 EUR; Electricty cost for lifting – 4.51 EUR.

According to the results of the visual examination of 10 failed rubber cord couplings in the period from 12.2021 till 12.2022 it was found that for all 10 couplings the cause of failure was a partial circular rupture of the coupling side surface in the place of coupling attachment to the flange on the traction motor side [9]. Examples of coupling damages are shown in Figure 3. a; b.

In this regard, the question arose, for what reason does the shell of the rubber-cord coupling break?

To find the causes of the damage, 2 rubber-cord couplings were taken for the research:

1. removed from the motor car ER2 2021-02 (Figure 3. a);
2. removed from the motor car ER2 989-04 (Figure 3. b).

As the rubber cord couplings have been produced in Russia, their parameters are taken in accordance with GOST 33118-2014 standard, with further validation of the results according to ISO 14691:2008 standard.

a) b)

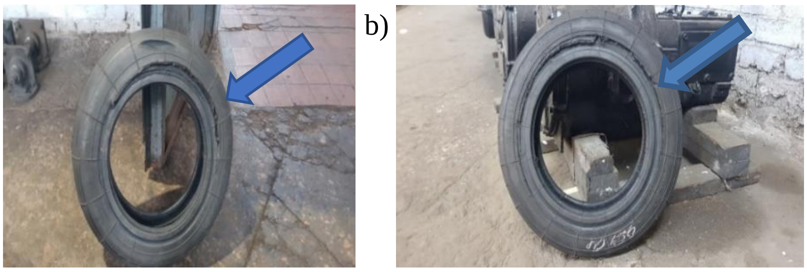

Fig. 3. **Rubber cord coupling damage:** a – car ER2 2021-02; b – car ER2 989-04

1st stage – determination of the geometric dimensions of the coupling

For these purposes, fragments were cut out from the rubber-cord coupling taken for the research from the motor car ER2 2021-02 (Figure 3. a) and car ER2 989-04 (Figure 3. b).

Measurements of the diameter of the outer surface of the coupling, the inner mounting surface diameter and the bead thickness were carried out using a caliper 0-550 mm with an accuracy class of 0.1 mm. The obtained measurement results were compared with the data of ISO 14691:2008 and are given in Table 2.

Table 2

Determination of the geometric dimensions of the coupling

Measurement	Results of specimen measurements, mm		Parameters stated by ISO 14691:2008, mm
	ER2 2021-02	ER2 989-04	
Diameter of the outer surface of the coupling *D*	$586.5_{-0.1}^{+0.1}$	$580.5_{-0.1}^{+0.1}$	580^{+2}
Inner diameter of the coupling *d*	$354.5_{-0.1}^{+0.1}$	$354.8_{-0.1}^{+0.1}$	354_{-2}^{+2}

To determine the value of the shear stress τ_k, measurements of the side surface of the coupling were carried out using a 0-150 mm caliper with an accuracy class of 0.1 mm.

2nd stage – determination of the forces acting on the cord coupling

When calculating rubber-cord couplings, the initial data is the maximum torque. The buckling of a rubber-cord coupling is the inability of the coupling to maintain its original position or shape. According to “Traction gears of electric rolling stock” Biryukov I.V., loss of stability of the rubber-cord shells of couplings occurs at: $1.2 \cdot 10^4$ N·m [7].

Expression (1) defines the maximum torque M_a:

$$M_a = \frac{30 \cdot P}{\pi \cdot n} \cdot \eta , \tag{1}$$

where P – traction motor power – 130 kW;
π – mathematical constant that is the ratio of a circle’s circumference to its diameter, approximately equal to 3.14159.
n – traction motor speed, rpm;
η – traction motor efficiency 86-92%.

Table 3 gives the results of the maximum torque M_a at speeds of 5, 10 and 20 km·h^{-1}.

At suburban traffic conditions with short sections and frequent stops, the maximum torque M_a is achieved at low speeds of the traction motor during the acceleration of the EMU train. Loss of coupling stability occurs regularly every time the train starts movemement.

Table 3

Determination of the torque

Speed, km·h^{-1}	Torque value, N·m	Value of stability loss, N·m	Difference, N·m
5	$1.74 \cdot 10^4$	$1.2 \cdot 10^4$	$0.54 \cdot 10^4$
10	$8.65 \cdot 10^3$	$1.2 \cdot 10^4$	-
20	$4.32 \cdot 10^3$	$1.2 \cdot 10^4$	-

During operation, the following forces act on the rubber-cord coupling: centrifugal forces P_c; P_{c1}.

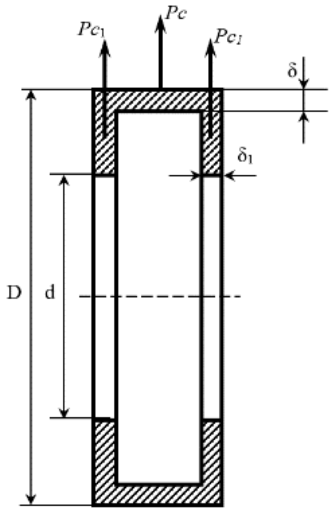

Fig. 4. **Centrifugal force acting on the coupling and its intensity**

1. Determination of the centrifugal force P_c; P_{c1} (Figure 4). The data of the coupling parameters for performing the calculations were obtained as a result of measurements and have the following values and it was determined for hourly operation mode speed of 60 km·h^{-1} and a maximum speed of 120 km·h^{-1}.

Expression (2) defines the force acting in the centre of the coupling:

$$P_c = \int_0^{b-2\delta} q dz = \int_0^{b-2\delta} \rho\delta \frac{D-\delta}{2} \omega^2 dz = \rho\delta \frac{D-\delta}{2} \omega^2 (b-2\delta), \quad (2)$$

where b – coupling width, mm.

Expression (3) defines the force acting in the lateral surface:

$$P_{c1} = \int_0^{\delta_1} q_1 dz = \int_0^{\delta_1} \rho \frac{D^2-d^2}{4} \omega^2 d \cdot dz = \rho \frac{D^2-d^2}{4} \omega^2 d\delta. \quad (3)$$

Determination of torsional shear stress

With this type of deformation, the torque acts in the cross sections of the coupling, as well as friction forces in the coupling Figure 5.

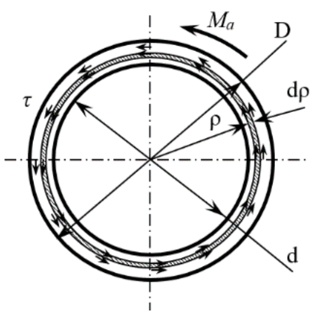

Fig. 5. **Calculation model for determining shear stress**

Expression (4) defines tangential torsional shear stress relative to friction point:

$$\tau = \frac{M_a}{\frac{\pi D^4}{32}\left(1-\frac{d^4}{D^4}\right)} \cdot \rho \cdot \tag{4}$$

Expression (5) defines shear stress of the coupling relative to the coupling mounting flange:

$$\tau_k = \frac{M_a}{\frac{\pi D^4}{32}\left(1-\frac{d^4}{D^4}\right)} \cdot \frac{D}{2} = \frac{16M_a}{\pi D^3\left(1-\frac{d^4}{D^4}\right)} \le [\tau], \tag{5}$$

where $[\tau]$ – allowable shear stress 0.70-0.75 MPa [8].

The results of coupling shear stress calculations are given in Table 4.

Table 4

Results of the coupling shear stress

Car No	EMU train speed, $km \cdot h^{-1}$	τ, MPa	τ_k, MPa
ER2 2021-02	5	1.713	2.057
	10	0.855	1.028
	20	0.427	0.513
ER2 989-04	5	1.725	2.071
	10	0.862	1.035
	20	0.430	0.517

3rd stage –determination of hardness according to the “Shore A” ISO 14691:2008 scale depending on the temperature. In the RTU laboratory, using an Elcometer 3120 Shore Dustomer A hardness tester according to standard ISO 7619-1:2010, the hardness of 2 rubber-cord couplings according to ISO 14691:2008 specimen was tested at three different temperature conditions: t = + 60 ºC; t = + 22 ºC; t = 0 ºC; t = -20 ºC.

The obtained hardness measurement data were compared with the data of ISO 14691:2008 The measurement results are shown in Table 5.

Table 5

Determination of the hardness of the rubber-cord coupling specimen

Shore A hardness for rubber, units	Car ER2 2021-02				Car ER2 989-04				ISO 14691:2008
	Average				Average				
	t + 60, ºC	t + 22, ºC	t 0, ºC	t -20, ºC	t + 60, ºC	t + 22, ºC	t 0, ºC	t -20, ºC	
Side A* top	60.7	67.3	68.5	75.9	60.0	69.4	72.6	76.9	from 50.0 to 65.0
Side A middle	56.6	62.9	66.9	73.7	61.3	68.3	71	73.7	from 50.0 to 65.0
Side A bottom	57.3	63.1	70.6	74.0	61.6	69.9	73.8	76.4	from 50.0 to 65.0
Side B* top	59.9	66.0	71.4	75.3	59.9	68.6	72.3	74.4	from 50.0 to 65.0
Side B middle	56.6	61.7	68	73.4	60.1	67.0	71.1	75.7	from 50.0 to 65.0
Side B bottom	56.9	64.3	68.5	71.4	63.1	67.4	71.8	73.1	from 50.0 to 65.0

Notes: *Side A (on the side of the gearbox); side B (traction motor side)

Results and discussion

According to the results, it was found:

1. At a speed of 5 km·h^{-1}, the torque on the shaft of the traction motor, according to calculations, is $1.74 \cdot 10^4$ N·m. At this torque value, the coupling experiences a loss of stability that exceeds the specified parameter by $0.54 \cdot 10^4$ N·m;

2. There is no loss of stability of the coupling shell at 10 km·h^{-1}. The condition for the loss of stability of the rubber cord coupling shell is met.

3. According to the results of calculations, it was found that the maximum tangential stress in relation to the coupling mounting flange τ_k is reached at the moment when the electric train starts movement at a speed of 5 km·h^{-1} and the permissible tangential stress is exceeded:

- for sample No 1 by 1.30 MPa;
- for sample No 2 by 1.32 MPa.

At a speed of 10 km·h^{-1}. ($M_a = 8.65 \cdot 10^3$ N·m) for coupling sample No 1 it is 1.028 MPa. In this case, the permissible tangential stress is exceeded by 0.278 MPa. For coupling sample No 2, it is 1.035 MPa and exceeds the permissible tangential stress by 0.285 MPa.

4. Based on the obtained measurement results, it was found:

4.1. At a temperature of -20 ºC, both couplings for all average measurement values exceed the hardness parameters by 6.4-11.9 units, according to ISO 14691:2008.

4.2. At a temperature of 0 ºC, both couplings for all average measurement values exceed the hardness parameters by 1.9-8.8 units, according to ISO 14691:2008.

4.3. At a temperature +22 ºC:

- for the coupling from the car ER2 989-04 at all average measurement values exceed the hardness parameters by 2.0-4.9 units according to ISO 14691:2008.
- for the coupling from the car ER2 2021-02 two average measurement values exceed the hardness parameters by 1.0-2.3 units according to ISO 14691:2008.

At a temperature of + 60 ºC, both couplings do not exceed the hardness values.

Conclusions

1. The first reason for failures of rubber-cord couplings is the loss of stability by the coupling at a speed of 0-5 km·h^{-1}, the parameter of stability loss exceeds the permissible limit by more than $0.5 \cdot 10^4$ N·m, while the coupling temporarily loses its operability. At a speed of 5 km·h^{-1}, the torque on the armature shaft, according to the calculations, is $1.74 \cdot 10^4$ N·m. At this torque value, the coupling becomes unstable, the coupling deforms with changes in geometric dimensions, which does not comply with the requirements DIN EN 13913:2003-08 and exceeds the parameter by $9.5 \cdot 10^3$ N·m. Acceleration to a speed of 5 km·h^{-1} according to the results of the test trial is an average of 2.5 seconds.
2. The second reason is that the torsional shear stress τ_k exceeds the maximum allowable torsional shear stress [τ]. According to the results of calculations at a speed of 5 km·h^{-1}, it exceeds the allowable torsional shear stress [τ] for the car ER2 2021-02 by 1.30 MPa, and for the car ER2 989-04 by 1.32 MPa.
3. As a result of the study, it was found that the hardness of the couplings did not meet the requirements of the ISO 14691:2008 standard. As a result of increased hardness, the coupling loses its elastic properties, which can lead to braking the coupling.

Acknowledgements

The authors would like to thank the Riga Technical University, employees of the metallographic laboratory and the laboratory of the strength of materials for supporting this research.

Author contributions

D. G. was responsible for manuscript writing and editing, data analysis, content planning. P. G. and G. S. was responsible for literature search, data collection and analysis, content planning. J. E. was responsible for manuscript editing, content planning and research guidance.

All authors have read and agreed to the published version of the manuscript.

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