Analysis of reliability of a prefabricated conductive rail joint in context of heavy traffic

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Abstract. In this paper, the calculation of reliability indicators has been carried out in the article for two configurations of a prefabricated conductive rail joint: with fish plates, a welded and bypass connector, and a spring rail bond. The sections of the track where the probability of failure of the prefabricated conductive rail joint is increasing are identified. The destabilizing factors influencing the onset of failure of a prefabricated conductive rail joint earlier than the calculated values of the durability indicators are considered. A model for evaluating the reliability of the second configuration of a prefabricated conductive rail joint based on the Markov analytical model has been developed, and such reliability indicators have been calculated as the probability of its being in working condition, as well as the probability of failure of the prefabricated conductive rail joint due to the inoperability of the fish plates and the spring rail bond. The features of the configuration of a prefabricated conductive rail joint with a spring rail bond are taken into account, which consist in the fact that in order to eliminate the failure due to the inoperability of the spring rail bond, it is necessary to remove the fish plates.

1 Introduction

The prefabricated conductive rail joint is an integral part of the traction rail network [1]. The reliability of its operation determines the reliability of the traction rail network as a whole. The failure of such joint elements as a welded, duplicating or spring rail bond leads to a decrease in conductivity, as well as an increase in the likelihood of excessive asymmetry of the traction current and drain of the traction current into the ground. The failure of fish plates and butt bolts with nuts affects not only the electrical parameters that determine the quality of the passage of traction current from the electric rolling stock to the traction substation, but

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also the safety of train traffic. Replacing a link track with a jointless one makes it possible to simplify the process of monitoring of the technical condition of a prefabricated conductive rail joint and reduce the maintenance time along the length of the track section [2]. At the same time, a prefabricated conductive rail joint is used on the development of railway tracks gridiron and in curved sections of the track. As a rule the curved sections of the track are located on long descents and ascents, where the current consumed by the electric rolling stock reaches its maximum values. A similar situation occurs at the moment of train departure from the station.

2 Problem statement

The destabilizing factors affecting the durability of the prefabricated conductive rail joint also include the axial load from the wheelsets passing through it in combination with their number [3]. The assessment of the reliability of the prefabricated conductive rail joint is carried out based, as a rule, on the failure rate of the butt connector. The paper [4] proposes a method according to which the analysis of the reliability of a prefabricated conductive rail is carried out by decomposing it into a system of elements that have their own reliability indicators, and also taking into account the influence of heavy traffic. In this article, it is necessary to determine the reliability of various configurations of a prefabricated conductive rail joint.

3 Research questions

To analyze the reliability of a prefabricated conductive rail joint as an object consisting of n elements with their own reliability indicators, we apply the Markov analytical model [5,9].

First, consider the configuration of the joint, which consists of $n = 3$ elements - fish plates, welded and duplicating rail bonds. In this case, the prefabricated conductive rail joint is a recoverable system with double loaded redundancy, each element of which has different reliability indicators.

4 Materials and methods

There are some assumptions in the analysis. The fish plates and the bolted connections used to fasten them are considered as one element, since the failure of at least one of the fish plates, as well as the bolted connection, leads to the inoperability of the prefabricated conductive rail joint due to the failure of the fish plates. Breakage of the collar or breakage of more than 30% of the strands of the stranded connector leads to failure of the welded connector. Failure of the attachment point or excessive breakage of the wires leads to the failure of the duplicating bond. The technical state in which the elements of the prefabricated conductive rail joint can be located is set to m=2 - operable and inoperable, excluding intermediate ones. The proposed approach makes it possible to effectively apply the analytical Markov model. For the considered configuration, the graph consists of $N=n^m=2^3=8$ vertices (Figure 1):

1. prefabricated conductive rail joint is in operational condition;
2. down state of fish plates;
3. down state of welded connector;
4. down state of duplicating bond;
5. down state of fish plates and welded connector;
6. down state of fish plates and duplicating bond;
7. down state of welded and duplicating bonds;

8. failure of the prefabricated conductive rail joint due to the down state of all elements.

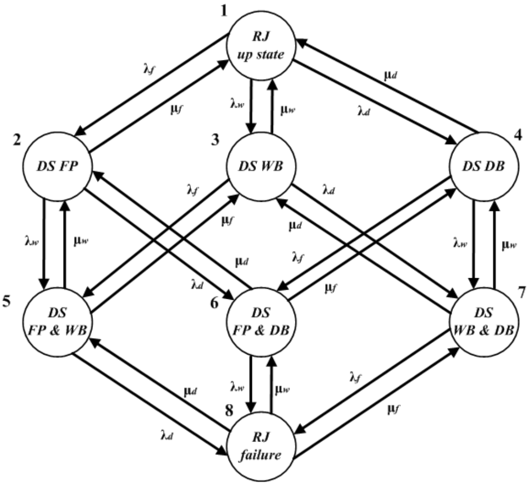

Fig. 1. Markov State Graph the first configuration of the prefabricated conductive rail joint.

5 Results

The second joint configuration is a set of n=2 elements - fish plates and a spring rail bond. Despite the fact that the spring rail bond duplicates the fish plates, in fact, reliable electrical contact of the bond is provided only with reliable contact of the fish plates at the junction with the rail. Due to this fact the failure of the fish plates leads to the failure of the spring rail bond. In case of failure of the spring rail bond, the operable state of the fish plates is preserved, however, to restore it, it is necessary to disconnect the fish plates. It means that the prefabricated conductive rail joint is inoperable while it is being restored by the repair team. Assuming that the restoration of an inoperable element begins immediately after its transition to this state, the configuration can be considered as a successive restorable system with dependent functioning of the elements. The number of vertices of the graph of such a system *is* $N = n + 1 = 3$ vertices (Figure 2):

1. prefabricated conductive rail joint is operational;
2. failure of the prefabricated conductive rail joint due to the down state of the fish plates;
3. failure of the prefabricated conductive rail joint due to the down state of the spring rail bond.

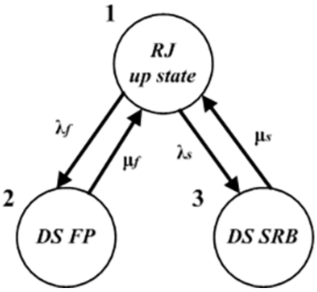

Fig. 2. Markov State Graph of the second configuration of prefabricated conductive rail joint.

The probability of occurrence of each of the states of a prefabricated conductive rail joint is determined by compiling matrices based on the considered graphs and then solving the Kolmogorov system of differential equations [6,7].

6 Findings

Based on the state graph of the first configuration of the prefabricated conductive rail joint, a matrix of transition intensities between them is composed.

$$\lambda_{RJ1} = \begin{vmatrix} 0 & \lambda_f & \lambda_w & \lambda_d & 0 & 0 & 0 & 0 \\ \mu_f & 0 & 0 & 0 & \lambda_w & \lambda_d & 0 & 0 \\ \mu_w & 0 & 0 & 0 & \lambda_f & 0 & \lambda_d & 0 \\ \mu_d & 0 & 0 & 0 & 0 & \lambda_f & \lambda_w & 0 \\ 0 & \mu_w & \mu_f & 0 & 0 & 0 & 0 & \lambda_d \\ 0 & \mu_d & 0 & \mu_f & 0 & 0 & 0 & \lambda_w \\ 0 & 0 & \mu_d & \mu_w & 0 & 0 & 0 & \lambda_f \\ 0 & 0 & 0 & 0 & \mu_d & \mu_w & \mu_f & 0 \end{vmatrix} \tag{1}$$

The probability of occurrence of each of the states of the prefabricated conductive rail joint is determined by applying the system of Kolmogorov differential equations (2):

$$\begin{cases} P_{RJUS}(t+\Delta t) = P_{RJUS}(t) - (P_{RJUS}(t) \cdot P_{\lambda f}(\Delta t)) - (P_{RJUS}(t) \cdot P_{\lambda w}(\Delta t)) - (P_{RJUS}(t) \cdot P_{\lambda d}(\Delta t)) + \\ +(P_{DSFP}(t) \cdot P_{\mu f}(\Delta t)) + (P_{DSWB}(t) \cdot P_{\mu w}(\Delta t)) + (P_{DSDB}(t) \cdot P_{\mu d}(\Delta t)); \\ P_{DSFP}(t+\Delta t) = P_{DSFP}(t) - (P_{DSFP}(t) \cdot P_{\mu f}(\Delta t)) - (P_{DSFP}(t) \cdot P_{\lambda w}(\Delta t)) - (P_{DSFP}(t) \cdot P_{\lambda d}(\Delta t)) + \\ +(P_{RJUS}(t) \cdot P_{\lambda f}(\Delta t)) + (P_{DSFW}(t) \cdot P_{\mu w}(\Delta t)) + (P_{DSFD}(t) \cdot P_{\mu d}(\Delta t)); \\ P_{DSWB}(t+\Delta t) = P_{DSWB}(t) - (P_{DSWB}(t) \cdot P_{\mu w}(\Delta t)) - (P_{DSWB}(t) \cdot P_{\lambda f}(\Delta t)) - (P_{DSWB}(t) \cdot P_{\lambda d}(\Delta t)) + \\ +(P_{RJUS}(t) \cdot P_{\lambda w}(\Delta t)) + (P_{DSFW}(t) \cdot P_{\mu f}(\Delta t)) + (P_{DSWD} \cdot P_{\mu d}(\Delta t)); \\ P_{DSDB}(t+\Delta t) = P_{DSDB}(t) - (P_{DSDB}(t) \cdot P_{\mu d}(\Delta t)) - (P_{DSDB}(t) \cdot P_{\lambda f}(\Delta t)) - (P_{DSDB}(t) \cdot P_{\lambda w}(\Delta t)) + \\ +(P_{RJUS} \cdot P_{\lambda d}(\Delta t)) + (P_{DSFD}(t) \cdot P_{\mu f}(\Delta t)) + (P_{DSWD}(t) \cdot P_{\mu w}(\Delta t)); \\ P_{DSFW}(t+\Delta t) = P_{DSFW}(t) - (P_{DSFW}(t) \cdot P_{\mu w}(\Delta t)) - (P_{DSFW}(t) \cdot P_{\mu f}(\Delta t)) - (P_{DSFW}(t) \cdot P_{\lambda d}(\Delta t)) + \\ +(P_{DSFP}(t) \cdot P_{\lambda w}(\Delta t)) + (P_{DSWB}(t) \cdot P_{\lambda f}(\Delta t)) + (P_{RJFL}(t) \cdot P_{\mu d}(\Delta t)); \\ P_{DSFD}(t+\Delta t) = P_{DSFD}(t) - (P_{DSFD}(t) \cdot P_{\mu d}(\Delta t)) - (P_{DSFD}(t) \cdot P_{\mu f}(\Delta t)) - (P_{DSFD}(t) \cdot P_{\lambda w}(\Delta t)) + \\ +(P_{DSFP}(t) \cdot P_{\lambda d}(\Delta t)) + (P_{DSDB}(t) \cdot P_{\lambda f}(\Delta t)) + (P_{RJFL}(t) \cdot P_{\mu w}(\Delta t)); \\ P_{DSWD}(t+\Delta t) = P_{DSWD}(t) - (P_{DSWD}(t) \cdot P_{\mu d}(\Delta t)) - (P_{DSWD}(t) \cdot P_{\mu w}(\Delta t)) - (P_{DSWD}(t) \cdot P_{\lambda f}(\Delta t)) + \\ +(P_{DSWB}(t) \cdot P_{\lambda d}(\Delta t)) + (P_{DSDB}(t) \cdot P_{\lambda w}(\Delta t)) + (P_{RJFL}(t) \cdot P_{\mu f}(\Delta t)); \\ P_{RJFL}(t+\Delta t) = P_{RJFL}(t) - (P_{RJFL}(t) \cdot P_{\mu d}(\Delta t)) - (P_{RJFL}(t) \cdot P_{\mu w}(\Delta t)) - (P_{RJFL}(t) \cdot P_{\mu f}(\Delta t)) + \\ +(P_{DSFW}(t) \cdot P_{\lambda d}(\Delta t)) + (P_{DSFD}(t) \cdot P_{\lambda w}(\Delta t)) + (P_{DSWD}(t) \cdot P_{\lambda f}(\Delta t)), \end{cases} \tag{2}$$

where P_{RJUS} is the probability of finding a prefabricated conductive rail joint in an operable state, P_{DSFP} is the probability of finding the fish plates in an inoperable state, P_{DSWB} is the probability of finding a welded connector in an inoperable state, P_{DSDB} is the probability of finding a duplicating bond in an inoperable state, P_{DSFW} is the probability of simultaneous presence of fish plates and welded connector in an inoperable state, P_{DSFD} is the probability of simultaneous presence of fish plates and backup connector in an inoperable state, P_{DSWD} is the probability of simultaneous presence of welded and backup connector in an inoperable state, P_{RJFL} is the probability of failure of a prefabricated conductive rail joint due to the inoperability of all elements.

After several transformations, a system of algebraic equations is finally obtained. This system has a following form:

$$\begin{cases} 0=-P_{RJUS}(\lambda_f+\lambda_w+\lambda_d)+P_{DSFP}\mu_f+P_{DSWB}\mu_w+P_{DSDB}\mu_d; \\ 0=-P_{DSFP}(\mu_f+\lambda_w+\lambda_d)+P_{RJUS}\lambda_f+P_{DSFW}\mu_w+P_{DSFD}\mu_d; \\ 0=-P_{DSWB}(\mu_w+\lambda_f+\lambda_d)+P_{RJUS}\lambda_w+P_{DSFW}\mu_f+P_{DSWD}\mu_d; \\ 0=-P_{DSDB}(\mu_d+\lambda_f+\lambda_w)+P_{RJUS}\lambda_d+P_{DSFD}\mu_f+P_{DSWD}\mu_w; \\ 0=-P_{DSFW}(\mu_w+\mu_f+\lambda_d)+P_{DSFP}\lambda_w+P_{DSWB}\lambda_f+P_{RJFL}\mu_d; \\ 0=-P_{DSFD}(\mu_d+\mu_f+\lambda_w)+P_{DSFP}\lambda_d+P_{DSDB}\lambda_f+P_{RJFL}\mu_w; \\ 0=-P_{DSWD}(\mu_d+\mu_w+\lambda_f)+P_{DSWB}\lambda_d+P_{DSDB}\lambda_w+P_{RJFL}\mu_f; \\ 0=-P_{RJFL}(\mu_d+\mu_w+\mu_f)+P_{DSFW}\lambda_d+P_{DSFD}\lambda_w+P_{DSWD}\lambda_f. \end{cases} \tag{3}$$

The presented system of equations when solving is reduced to seven equations with 8 unknowns, which requires the introduction of the equation:

$$P_{RJUS}+P_{DSFP}+P_{DSWB}+P_{DSDB}+P_{DSFW}+P_{DSFD}+P_{DSWD}+P_{RJFL}=1 \tag{4}$$

Solving the system using the mathematical modeling package Mathcad 15, taking λ_f =1.43 10^{-6} h^{-1}, λ_w=11 10^{-6} h^{-1}, λ_d=0.87 10^{-6} h^{-1}, μ_f=1.45 h^{-1}, μ_w=1.1 h^{-1}, μ_d=1.35 h^{-1} as per [7], the probabilities of finding a prefabricated conductive rail joint in each of the states are obtained: P_{RJUS} = 0.999988, P_{DSFP} = 9.86 10^{-7}, P_{DSWB} = 10^{-5}, P_{DSDB} = 6.44 10^{-7}, P_{DSFW} = 6.44 10^{-12}, P_{DSFD} = 9.86 10^{-12}, P_{DSWD} = 6.35 10^{-13}, P_{RJFL} = 6.35 10^{-18}.

The graph of the second configuration of the prefabricated conductive rail joint is described by the following matrix of intensities of the transition between states (5):

$$\lambda_{RJ2}=\begin{vmatrix} 0 & \lambda_f & \lambda_s \\ \mu_f & 0 & 0 \\ \mu_s & 0 & 0 \end{vmatrix} \tag{5}$$

The probability of occurrence of each of the states of the prefabricated conductive rail joint is determined by applying the system of Kolmogorov differential equations (6):

$$\begin{cases} P_{RJUS}(t+\Delta t)=P_{RJUS}(t)-(P_{RJUS}(t)\cdot P_{\lambda f}(\Delta t))-(P_{RJUS}(t)\cdot P_{\lambda s}(\Delta t))+ \\ +(P_{DSFP}(t)\cdot P_{\mu f}(\Delta t))+(P_{DSSRB}(t)\cdot P_{\mu s}(\Delta t)); \\ P_{DSFP}(t+\Delta t)=P_{DSFP}(t)-(P_{DSFP}(t)\cdot P_{\mu f}(\Delta t))+ \\ +(P_{RJUS}(t)\cdot P_{\lambda f}(\Delta t)); \\ P_{DSSRB}(t+\Delta t)=P_{DSSRB}(t)-(P_{DSSRB}(t)\cdot P_{\mu s}(\Delta t))+ \\ +(P_{RJUS}(t)\cdot P_{\lambda s}(\Delta t)). \end{cases} \tag{6}$$

After several transformations a system of algebraic equations is finally obtained. It has the following form:

$$\begin{cases} 0=-P_{RJUS}(\lambda_f+\lambda_s)+P_{DSFP}\mu_f+P_{DSSRB}\mu_s; \\ 0=-P_{DSFP}\mu_f+P_{RJUS}\lambda_f; \\ 0=-P_{DSSRB}\mu_s+P_{RJUS}\lambda_s. \end{cases} \tag{7}$$

While solving the presented system of equations is reduced to two equations with 3 unknowns, which requires the introduction of the equation:

$$P_{RJUS}+P_{DSFP}+P_{DSSRB}=1 \tag{8}$$

To obtain the probability of finding the second configuration of the prefabricated conductive rail joint in each of the states, it is necessary to determine the failure rate of the spring rail bond (λ_s):

$$\lambda_s = \frac{1}{T_m}, \tag{9}$$

where T_m is the mean time to failure:

$$T_m = \frac{T_\gamma}{\ln \frac{1}{\gamma}}, \tag{10}$$

where T_γ is the gamma-percentage time to failure. Substituting (10) into (9) the following equation is obtained:

$$\lambda_s = \frac{\ln \frac{1}{\gamma}}{T_\gamma}. \tag{11}$$

According to the data of the manufacturer [8], the gamma-percentage resource for assessing the assigned resource is taken as $\gamma=80\%$, and the indicator T_γ is calculated based on the time required to pass a load with a mass of m_{rj} = 500 million gross tons through the prefabricated conductive joint. Based on the average weight of freight trains circulating at the range of the railway network of Russian Railways, which in 2021 amounted to m=4058 tons and traffic intensity n_i = 24 trains per day, T_γ is defined as:

$$T_\gamma = \frac{m_{rj}}{m \cdot n_i} \cdot 24 = \frac{500 \cdot 10^6}{4058} = 123.213 \cdot 10^3 \text{ hours} \tag{12}$$

Then the failure rate of the spring rail bond for the calculation will be taken equal to λ_s = $1.81 \cdot 10^{-6}\,\text{h}^{-1}$. In connection with the design feature of the spring rail bond, the intensity of restoration will be taken equal to the intensity of restoration of the fish plates $\mu_f = \mu_s = 1.45$ h^{-1} .

Solving the system using the Mathcad 15 mathematical modeling package, the probabilities of finding the second configuration of the prefabricated conductive rail joint in each of the states are obtained: $P_{RJUS} = 0.999998$, $P_{DSFP} = 9.86 \cdot 10^{-7}$, $P_{DSSRB} = 1.25 \cdot 10^{-6}$.

7 Discussion

The analysis showed that a prefabricated conductive rail joint containing a spring rail bond in its configuration is less reliable compared to a prefabricated conductive rail joint containing fish plates, welded and duplicating bonds, despite the fact that such a configuration is more modern and aimed at reduction of the number of welded and bolted connections.

A reliability graph has been constructed to assess the probability of stay of a configuration of a prefabricated conductive rail joint with a spring rail bond in each of the technical states.

At the next stage of the study, it is necessary to develop a reliability model for the configuration of a prefabricated conductive rail joint with a spring rail bond, supplemented with elements that allow to reach higher reliability indicators in comparison with the configuration of a prefabricated conductive rail joint containing fish plates, welded and duplicating bonds.

8 Conclusion

In context of the development of heavy traffic, it is necessary to transform the infrastructure complex of the railway, which cannot be done without introduction of innovative solutions aimed at improvement of the design of its individual elements. At the same time, advanced developments require a thorough approach while calculating performance features, including reliability indicators. The performed study allowed to conclude that the most modern configuration of a prefabricated conductive rail joint needs to be improved for heavy traffic polygons and reliability indicators shall be recalculated.

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