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ASSESSEMENT OF RISKS RELATED TO FRACTURES AND DEFECTS OF SIDE FRAMES OF FREIGHT CAR BOGIES

The paper presents a method for assessing risks associated with fractures and defects of side frames of freight car bogies. The construction of a risk matrix as per manufacturers of side frames, including the assessment of the impact and the frequency of events related to the fractures and detected defects of side frames, is considered. The proposed method is aimed at providing support for making management decisions as to further operation of freight cars on the basis of risk management.

Keywords: *side frame, freight car, fracture, defect, risk, risk assessment, matrix of risks.*

Introduction

In recent years, there have been more cases of fracture of side frames of freight car bogies on the railway network of Russia and other CIS countries. Each of such fractures is associated with derailment of one or more cars, locomotive, and sometimes leads to severe consequences related to fatalities.

A characteristic feature of this situation is that fractures of bogie frames occur at the time of operation from 1 to 4 years with the warranty period of 5 years, which demonstrates their unacceptably low reliability.

It should be noted that in 2001 they introduced OST 32.183-2001 “Two-axle bogies of freight cars for 1520 mm gauge. Molded pieces. Side frame and bolster. Technical specifications.” Manufacturers began to introduce the standard in 2002. Since mid-2005, two-axle bogies of freight cars have been produced according to GOST 9246-2004 “Two-axle bogies of freight cars for mainline railways of 1520 mm gauge. Technical specifications.”

The statistics show that a significant increase in the number of bogie frame fractures falls on the period from 2006 up to the present (Fig. 1).

Under these circumstances, it is vital to use of methods for support of decision-making as to management of reliability and safety of freight cars on the basis of risk assessment tools [1, 2]. Presentation of risks in the form of a risk matrix allows us to assess risks and define appropriate mitigation measures, as well as to assess the dynamics of risks.

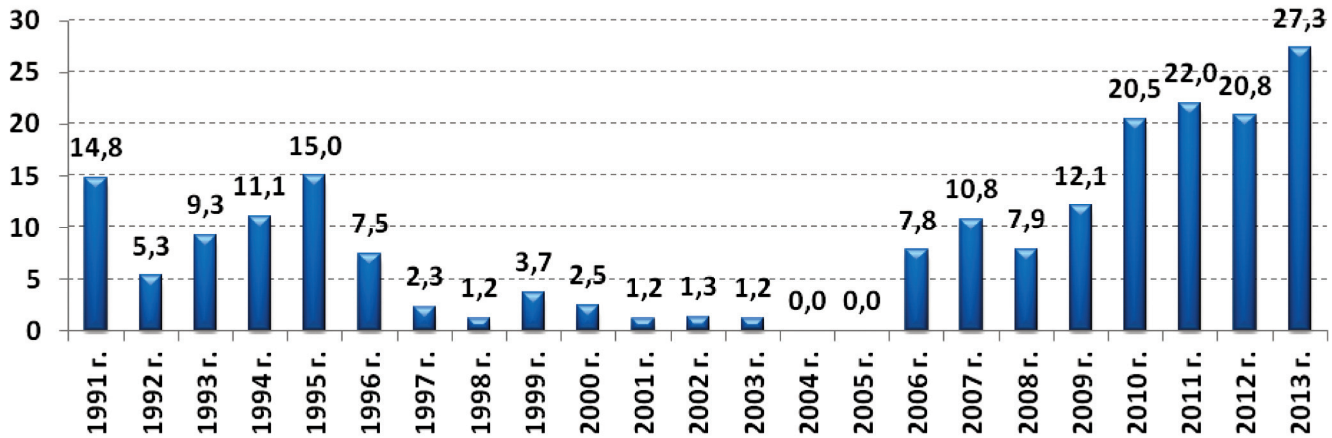

Fig. 1. Number of fractures of bogie frames as per accounted years per 1 mln cars a year

Classification of events as to severity of consequences

According to the classification of levels of consequence severity as to GOST R 54505-2011 "Functional safety. Risk management on railway transport" and in accordance with the Decree of the Ministry of Transport of the Russian Federation of December 25, 2006 #163 "On Approval of the Procedure of official investigation and accounting of transport accidents and other events related to violations of safety rules and operation of railway transport," traffic accidents and events occurring due to fracture of a side frame of freight car bogie it is advisable to assign the following levels of severity:

- Crashes and accidents – "catastrophic",
- Derailment and events without derailment – "critical".

Operation of a freight wagon with bogies having defective side frames is prohibited. In this regard, facts of detecting cracks and other molding defects in side frames during operation or depot repair receive the following levels of consequence severity:

- Defects discovered during operation while maintaining wagons – "insignificant",
- Defects identified during depot repair – "minor".

Estimation of events frequency

Frequency of events is calculated separately for events with different severity of consequences: crashes accidents, derailments and events without derailment, cracks and other defects detected during maintenance, cracks and other defects detected during depot repair.

Event rate is calculated separately for each batch of frames. A batch of frames includes all side frames produced in a particular calendar year specified by the manufacturer.

Event rate is defined as the ratio of the number of events of this type to the volume of the considered batch of side frames divided by the interval of observation, which is taken equal to the operation period of the frames batch, from the year of its release up to the current moment:

$$F = \frac{n}{N \cdot T}, \quad (1)$$

where F is the frequency of crashes and accidents (derailments and events without derailment) caused by fractures of frames, or the frequency of cracks and other nonremovable defect detected during maintenance (depot repair), 1/year,

n is the number of fractures of side frames of the batch caused crashes or accidents (derailments and events without derailment) for the period of observation, or the number of зa of cracks and other nonremovable defect detected during maintenance (depot repair) for the period of observation,
N is the volume of a batch (number of side frames in a batch),
T is the period of observation, years.

Selection of a consequence severity scale

To construct matrices of risks associated with fractures and defects of side frames, a consequence severity scale is adopted in accordance with the standard scale as to GOST R 54505-2011 "Functional safety. Risk management on railway transport." It is a qualitative scale and uses 4 intervals of levels: catastrophic, critical (for events of frame fractures) and insignificant, minor (for events of detecting cracks and other nonremovable defects of frames).

Selection a frequency scale

To construct matrices of risks associated with fractures and defects of side frames, a frequency scale is adopted as similar to the standard scale according to GOST R 54505. Since the values of frequencies for events in these Guidelines are expressed quantitatively, intervals of levels are represented by ranges of quantitative values. A scale step is logarithmic. The number of intervals in these Guidelines is taken equal to 7. If the values of frequencies of events calculated according to (1) are outside the scale, the smaller values are replaced by the minimum value of the scale, and the larger ones by its maximum value.

To assess risks associated with fractures and defects of side frames, it is recommended to take a multiplicity factor of interval limits of the frequency scale as equal to 2 or 2.5.

Assignment of acceptable risk levels

For events that occur as a result of fractures (crashes and accidents, derailments and events without derailment), an acceptable level as to frequency of fractures (dangerous failure) of a side frame $f_{DF} = 1\times10^{-6}$ 1/year per 1 mln of side frames [3] is assigned as an indicator for setting acceptable levels of risks. Such frequency of fractures is accepted to provide the required safety performance of traffic, and in this case there is no need for any corrective activities. Thus, this value corresponds to the boundary between the interval of risk levels "negligible" (green zone), and the interval of risk levels of "acceptable" (yellow area) for events with the worst (catastrophic) consequence severity, i.e. crashes and accidents.

For events of detecting cracks or other defects of side frames during maintenance of a car, a standard share of defective items in the batch $S_S = 2\times10^{-4}$ [3] is assigned as an indicator for setting acceptable levels of risks. The specified value corresponds to the boundary between the interval of risk levels "negligible" (green zone), and the interval of risk levels "acceptable" (yellow area) for events of insignificant consequence severity, i.e. cracks and other nonremovable defects revealed by maintenance.

Smoothing of frequency time series

Before being displayed on matrices, frequency levels of events forming a time series as to years of release of batches are smoothed using a moving average. This is done to mitigate the impact of accidental overshoots on the result of risk assessment (e.g. one occasional fracture within a given year of release may lead to an unacceptable risk).

Smoothing is implemented as follows. Let there be an initial sequence of frequencies of events (time series points) $f(1), f(2), \ldots, f(K)$. For the given time series containing K points, we set the width W of the averaging region, i.e. the number of series points involved in the formation of the smoothed value of the point under consideration. As a rule, the region of averaging is symmetric in relation to the point under consideration and, therefore, W is odd.

For any odd value of $W > 1$, we can set integer symmetrical shifts of the boundaries of an averaging region $i_{\min} = (1 - W)/2$; $i_{\max} = (W - 1)/2$, where a central point will be corresponded to by $i = 0$. For ezch the i-th point ($i = i_{\min}, i_{\min}+1, \ldots -1, 0, 1, \ldots i_{\max}-1, i_{\max}$), in the averaging region we set a corresponding weight coefficient p_i, and $\sum_{i=i_{\min}}^{i_{\max}} p_i = 1$.

The formula for calculation a moving average looks like

$$F(k) = \sum_{i=i_{\min}}^{i_{\max}} p_i \cdot f(k+i). \qquad (2)$$

Therefore, after smoothing each point $f(k)$ of the initial series is replaced by an averaged point $F(k)$, where $k = 1 \ldots K$.

For correct smoothing in the regions of series beginning and end, we assume that:

- if $(k + i) < 1$, then in expression (2) we accept $S(k + i) = S(1)$;
- if $(k + i) > K$, then in expression (2) we accept $S(k + i) = S(K)$.

To smooth single accidental overshoots of a time series without a significant impact on systematic constituents, it is recommended to use the following parameters: $W = 5$; $i_{\min} = -2$; $i_{\max} = 2$, $p_{-2} = 0{,}027$; $p_{-1} = 0{,}135$; $p_0 = 0{,}676$; $p_1 = 0{,}135$; $p_2 = 0{,}027$ (for the time series of 5 and more points) and $W = 3$; $i_{\min} = -1$; $i_{\max} = 1$; $p_{-1} = 0{,}15$; $p_0 = 0{,}7$; $p_1 = 0{,}15$ (for the time series of 3 or 4 points). In case of a smaller number of points in the series, smoothing is not done.

Therefore, the time series of calculated frequencies for each type of events for a given manufacturer is averaged using formula (2) and the selected parameters of averaging. Then smoothed values of frequencies are used in the construction of a risk matrix.

Assignment of a risk category

Risk categories to assess the levels of risks associated with fractures and defects of side frames are accepted in accordance with GOST R 54505. A risk is assessed by 4 interval categories: unacceptable, undesirable, acceptable, negligible. These categories are represented by the following colors of risk matrix cells: red, orange, yellow, green.

Construction of risk matrices

Using the above data on the frequencies and consequences of events for each manufacturer for all batches manufactured during the specified interval of observation, we construct matrices of risks associated with fractures and defects of side frames. The general view of such matrix is shown in Fig.2.

Frequency levels in combination with levels of consequence severity define categories of risks associated with fractures and defects of side frames.

It should be noted that this risk matrix uses two different frequency scales of frequency levels for two types of events under consideration, fracture and defects of side frames.

Level of frequency, 1/year		Fractures and defects detected during depot repair	Fractures and defects detected during maintenance	Derailments/events without derailment	Crashes and accidents
5… 10 fractures per 100 000 frames a year 2...5 defects per 1000 frames a year	$(5...10)\times10^{-5}$ $(2...5)\times10^{-3}$	Unacceptable	Unacceptable	Unacceptable	Unacceptable
2...5 fractures per 100 000 frames a year 1...2 defects per 1000 frames a year	$(2...5)\times10^{-5}$ $(1...2)\times10^{-3}$	Undesirable	Unacceptable	Unacceptable	Unacceptable
1...2 fractures per 100 000 frames a year 5...10 defects per 10 000 frames a year	$(1...2)\times10^{-5}$ $(5...10)\times10^{-4}$	Acceptable	Undesirable	Unacceptable	Unacceptable
5...10 fractures per 1 000 000 frames a year 2...5 defects per 10 000 frames a year	$(5...10)\times10^{-6}$ $(2...5)\times10^{-4}$	Negligible	Acceptable	Undesirable	Unacceptable
2...5 fractures per 1 000 000 frames a year 1...2 defects per 10 000 frames a year	$(2...5)\times10^{-6}$ $(1...2)\times10^{-4}$	Negligible	Negligible	Acceptable	Undesirable
1...2 fractures per 1 000 000 a year 5...10 defects per 100 000 frames a year	$(1...2)\times10^{-6}$ $(5...10)\times10^{-5}$	Negligible	Negligible	Negligible	Acceptable
5...10 fractures per 10 000 000 frames a year 2...5 defects per 100 000 frames a year	$(5...10)\times10^{-7}$ $(2...5)\times10^{-5}$	Negligible	Negligible	Negligible	Negligible
		Insignificant (car damaged insignificantly, requiring current repair)	**Minor** (car damaged, requiring depot repair)	**Critical** (car damaged, requiring overhaul	**Catastrophic** (car damaged severely requiring to be excluded from the inventory

Level of consequence severity

Fig. 2. General view of a matrix of risks related to fractures and defects of side frames for a specified manufacturer for the interval of observation

The cells of the matrix contain points corresponding to a level of consequences and a level of frequencies for a specified risk related to frames of a specified manufacturer for all the batches produced for the given period of observation.

Example of construction of risk matrix

Let us consider the construction of a risk matrix for batches of the manufacturer Bezhitsky steelworks produced during the observation period from 2002 to 2013 as of April 1, 2013.

Initial data for matrices of risks associated with fractures and defects of frames by Bezhitsky steelworks (BSZ) for the observation interval from 2002 to 2013 are presented in columns 1-5 of Table 1 [4,5]. For the number of fractures the observation interval is equal to a frame lifetime, and for that of cracks and other nonremovable defects detected during maintenance of a wagon is equal to 4.3 years, since data on defects is known only since 2009. Data on the number of cracks and defects identified during depot repairs are not presented.

Let us assess frequencies of events using expression (1):

- Calculate frequencies of catastrophic events for the batches produced by BSZ in 2002-2013 using the number of fractures caused crashes and accidents. The results are put into column 6 of Table 1.

Table 1. Data on the number of fractures and defects for batches of Bezhitsky steelworks produced from 2002 to 2013

Year of batch release	Batch volume	Number of fractures (crashes and accidents)	Number of fractures (derailments and events without derailment)	Number of defects	Frequency of fractures (crashes and accidents), 1/year	Frequency of fractures (derailments and events without derailment), 1/year	Frequency of defects, 1/year
2002	23761	0	0	87	0	0	$8,52\times10^{-4}$
2003	34353	0	0	249	0	0	$1,69\times10^{-3}$
2004	47708	0	0	208	0	0	$1,01\times10^{-3}$
2005	36933	0	0	133	0	0	$8,37\times10^{-4}$
2006	46419	0	0	120	0	0	$6,01\times10^{-4}$
2007	41909	0	0	168	0	0	$9,32\times10^{-4}$
2008	38920	0	0	111	0	0	$6,63\times10^{-4}$
2009	21374	0	1	67	0	$1,09\times10^{-5}$	$7,29\times10^{-4}$
2010	40966	0	0	25	0	0	$1,85\times10^{-4}$
2011	44390	0	0	10	0	0	$9,79\times10^{-4}$
2012	48959	0	0	7	0	0	$1,10\times10^{-4}$
2013	13930	0	0	0	0	0	0

Table 2. Basic and averaged data about frequencies of events

Year of batch production	**Frequency of fractures (crashes and accidents), 1/year**		**Frequency of fractures (derailments and events without derailment), 1/year**		**Frequency of defects, 1/year**	
	(basic)	**(averaged)**	**(basic)**	**(averaged)**	**(basic)**	**(averaged)**
2002	0	0	0	0	$8,52\times10^{-4}$	$9,68\times10^{-4}$
2003	0	0	0	0	$1,69\times10^{-3}$	$1,44\times10^{-3}$
2004	0	0	0	0	$1,01\times10^{-3}$	$1,07\times10^{-3}$
2005	0	0	0	0	$8,37\times10^{-4}$	$8,55\times10^{-4}$
2006	0	0	0	0	$6,01\times10^{-4}$	$6,91\times10^{-4}$
2007	0	0	0	$2,94\times10^{-7}$	$9,32\times10^{-4}$	$8,43\times10^{-4}$
2008	0	0	0	$1,47\times10^{-6}$	$6,63\times10^{-4}$	$6,94\times10^{-4}$
2009	0	0	$1,09\times10^{-5}$	$7,36\times10^{-6}$	$7,29\times10^{-4}$	$6,35\times10^{-4}$
2010	0	0	0	$1,47\times10^{-6}$	$1,85\times10^{-4}$	$2,58\times10^{-4}$
2011	0	0	0	$2,94\times10^{-7}$	$9,79\times10^{-4}$	$1,26\times10^{-4}$
2012	0	0	0	0	$1,10\times10^{-4}$	$9,26\times10^{-5}$
2013	0	0	0	0	0	$1,75\times10^{-5}$

- Calculate frequencies of critical events for the batches produced by BSZ in 2002-2013 using the number of fractures caused derailments and events without derailment. The results are put into column 7 of Table 1.
- Calculate frequencies of insignificant events for the batches produced by BSZ in 2002-2013 using the number of fractures identified during maintenance. The results are put into column 7 of Table 1.

Using formula (2), let us smooth time series of frequencies in columns 5, 6 and 7 of Table 1. The result is presented in Table 2.

5) The obtained combinations of consequence severity and corresponding smoothed values of frequencies from Table 2 are put on the pattern of a risk matrix (Fig. 2). As a result, we get a matrix of risks associated with fractures and defects for the batches produced by BSZ in 2002-2013 (Fig. 3).

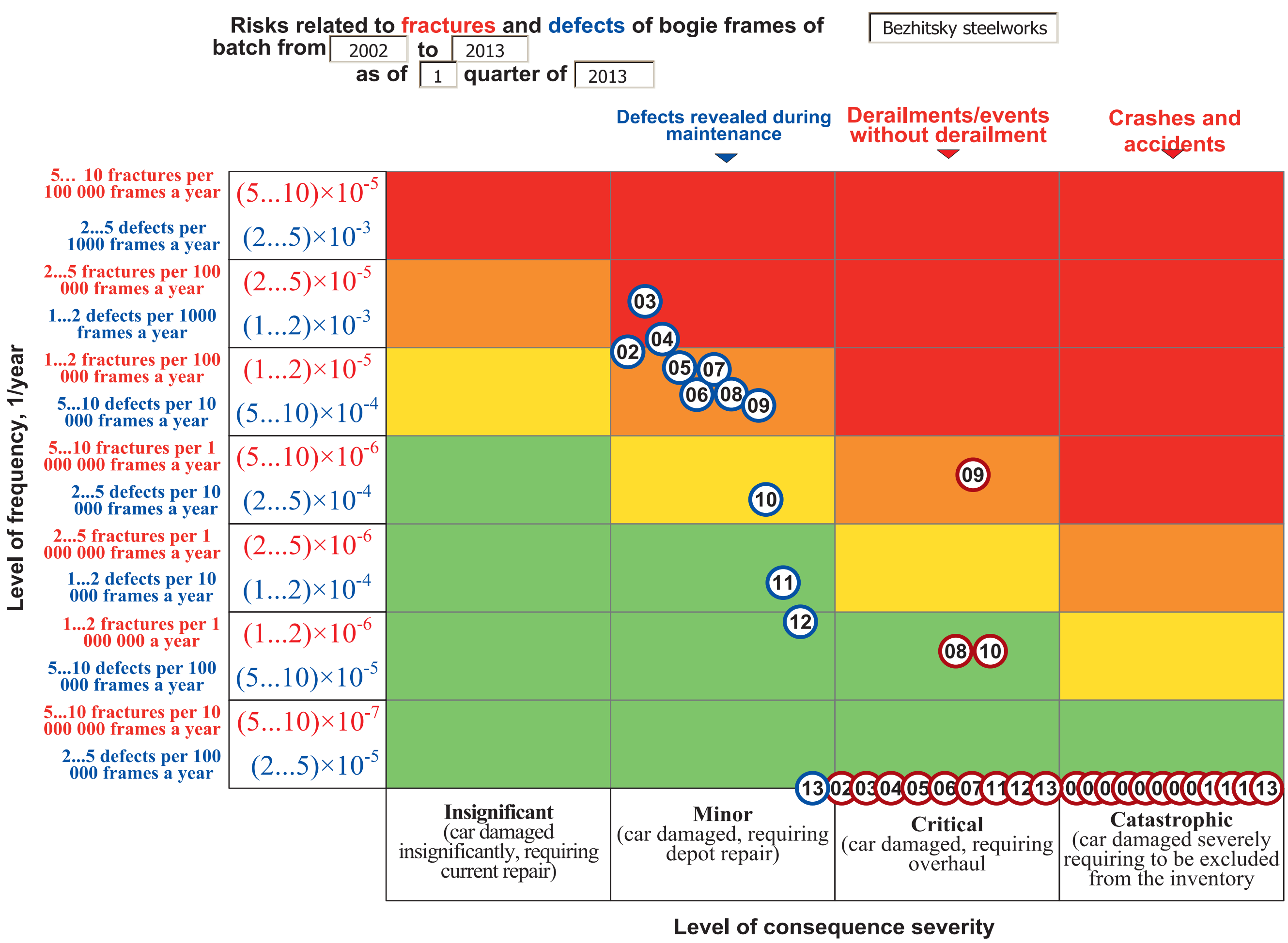

Fig. 3. Matrix of risks related to fractures and defects of frames produced by Bezhitsky steelworks in the period of 2002-2013

Matrices of risks for batches of other manufacturers are constructed in a similar way.

Activities and decision making

Deciding on further use of wagons with the batch of frames produced by a particular manufacturer in a given year is based on the risk category using a risk matrix.

It should be noted that unacceptable risks characterize products of a manufacturer as potentially dangerous, not ensuring the safety and reliability of transportation process. Such risks should be excluded.

When dealing with the risk, we should pay attention to compliance with requirements at the following key stages in the life cycle of a bogie frame:

- Designing,
- Production,
- Repair,
- Operation.

At the designing stage it is necessary to analyze compliance with requirements for:

- A frame design,
- A bogie design,
- Properties of the material.

At the production stage we should analyze compliance with requirements for technology, which comprises:

- Structure of the process of manufacture,
- The equipment used in manufacturing (e.g. the use of ice frameworks),
- Material properties,
- Methods of output nondestructive testing.

During repair, it is necessary to analyze compliance with requirements for technology, which includes:

- Structure of the technological process of repair,
- Methods of input nondestructive testing,
- Methods of output nondestructive testing.

During the operation stage, it is necessary to analyze compliance with requirements for:

- Control for maintenance of bogies,
- Compliance with conditions of rolling stock operation.

The considered method for assessing risks associated with fractures and defects of side frames of freight car bogies allows us to provide support for decision making as to further operation of freight cars that use side frames of a certain batch. On the basis of risk assessment, one can increase the efficiency of reclamation work of an infrastructure operator and car owner with manufacturers of side frames.

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