PROSPECTS FOR DEVELOPMENT OF LOAD-CARRYING ELEMENTS OF FREIGHT CAR BOGIE

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In recent years accidents related to fracture of cast load-carrying elements of three-piece bogies of freight cars have become more frequent in the railways of Ukraine and Russia. The work substantiates the rationality of development and application of all-welded load-carrying elements of freight car bogie (FCB), improving their operational reliability. Welded structures of FCBs are widely applied in West Europe. Attempts to develop structures of all-welded elements of FCBs irreplaceable with cast structures are made in Ukraine and Russia. However, none of the developed welded structures is currently applied at regular cargo transportation, because of non-optimal design of bogie welded elements in terms of ensuring the required fatigue resistance margin. To develop a competitive welded solebar and bogie bolster it is, first of, all necessary to increase the fatigue resistance of bogie elements, improve the accuracy of solebar fabrication to avoid skewing of wheelset axles, leading to fast wear, lower their weight and cost, increase element run between scheduled depot repairs. Strength analysis of bogie welded elements should be performed in keeping with the norms currently in force, as well as current world standards, norms and recommendations, allowing for the most recent achievements in the field of dynamics of railway cars and methods to determine welded joint fatigue resistance. 20 Ref., 8 Figures.

Keywords: *welded structure, three-piece bogie of freight car, solebar, bogie bolster, solebar fracture, fatigue resistance*

In recent years accidents related to freight car bogie (FCB) fracture (Figure 1) have become more frequent in railway transportation. By the data of OJSC «RZhD» in 2011, 25 fractures of FCB solebars occurred, and in 2012, 23 accidents took place [1], by December 1, 2013, 37 cases of solebar fractures were recorded (Figure 2) with human casualties.

Analysis of operating reliability of cast structures of bogie solebar of 18-100 type freight car showed that fatigue crack initiation is the main cause for solebar failure [2], as the solebar of this bogie model does not have a sufficient margin of fatigue resistance and survivability [3]. Therefore, the task of improvement of its fatigue resistance is quite urgent. Large steel castings of FCB elements have several disadvantages of technological and design nature. Steel casting walls have a quite large scatter of thickness [4]. Moreover, casting has inherent defects such as pores, blowholes, etc., repair of which is labour-consuming [5].

Modern economic situation motivates manufacturers to look for an alternative to traditional cast elements of FCBs (solebars and bogie bolsters), the quality and reliability of which is not high enough. One of the optimum variants is

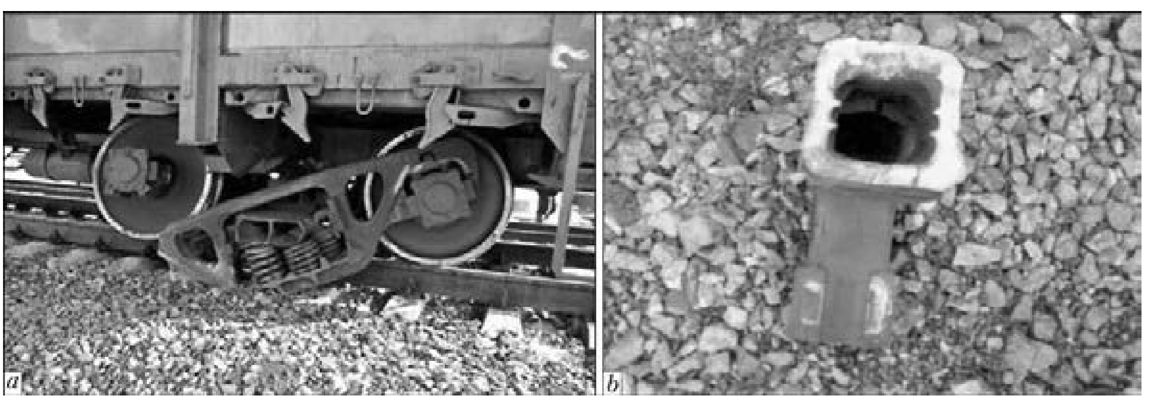

Figure 1. Fatigue fracture of cast structure of freight car solebar along R55 radius (*a*) and its fragment (*b*)

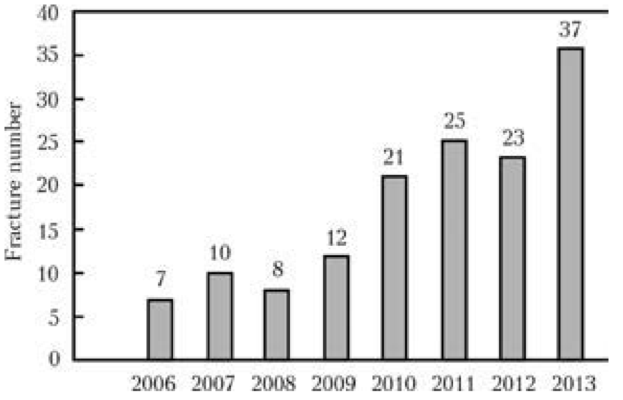

Figure 2. Dynamics of cases of solebar fracture in FCBs along R55 by years [1]

manufacture of the above parts by the technology of welding using rolled sheets.

Transition to all-welded structures of bogie elements can primarily ensure higher reliability of freight car structure, leading to lower number of operational failures and considerable reduction of the cost of unscheduled repair and reconditioning operations, respectively. Moreover, reduction of these elements mass by 5 to 10 % compared to cast variant can be achieved, that is a quite significant value in the overall freight traffic volume. In fabrication of solebar welded structure it is possible to ensure basic size accuracy within ±1 mm, that eliminates the possibility of wheelset axles skewing at bogie formation and will essentially reduce wheel wear for this reason. Putting bogie elements into production with application of welding technology is not so costly, compared to casting technology, and it can be implemented in practically any mechanical engineering plant, that can create the conditions for market saturation with quality elements of the bogie, namely solebar and bolster beam with improved fatigue resistance characteristics.

Known are different variants of welded structures of FCBs. In 2002, V.M. Bubnov Chief Specialized DB of Car Construction (GSKBV Ltd.) (Mariupol, Ukraine) together with SUE «NVTs Vagony» (St.-Petersburg) developed a welded structure of three-piece bogie of 18-1711 model with 25 tf axle load (Figure 3). However, the first test samples of solebars and bolster beams did not pass bench testing. With the assistance of PWI specialists bogie bolster design has been improved: fatigue resistance of its welded joints has been increased [7]. During performance of abbreviated accelerated tests of two test samples of bogie bolster for cyclic load, 30 mm long macrocrack was found in the first bolster at $2.745 \cdot 10^6$ load cycles, in the second bolster no fatigue macrocrack was found after $6 \cdot 10^6$ load cycles and testing was stopped. These tests showed that welded bolsters provide the required fatigue life, are not inferior to cast products in terms of strength and weight characteristics, and can be recommended for performance of the complete test cycle.

In 2004, OJSC «Kryukovsky Railway Car Building Works» (KVZ) (Kremenchug, Ukraine) developed a welded structure of FCB (Figure 4), in which solebars and bogie bolsters were made welded from rolled sheets of low-alloyed 09G2D or 09G2S steel (GOST 19281–89) of not lower than 295 strength class [8].

Development prototype was bogie of 18-100 model. It was anticipated that putting the devel-

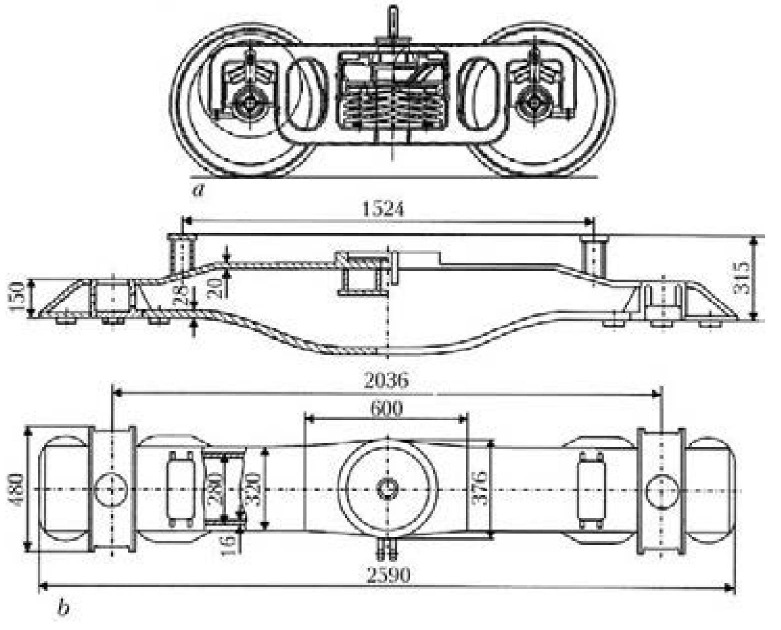

Figure 3. Schematics of welded structure of three-piece bogie of freight car developed by GSKBV together with company «Vagony» [6]: *a* — bogie from solebar side; *b* — bogie bolster developed with participation of PWI specialists

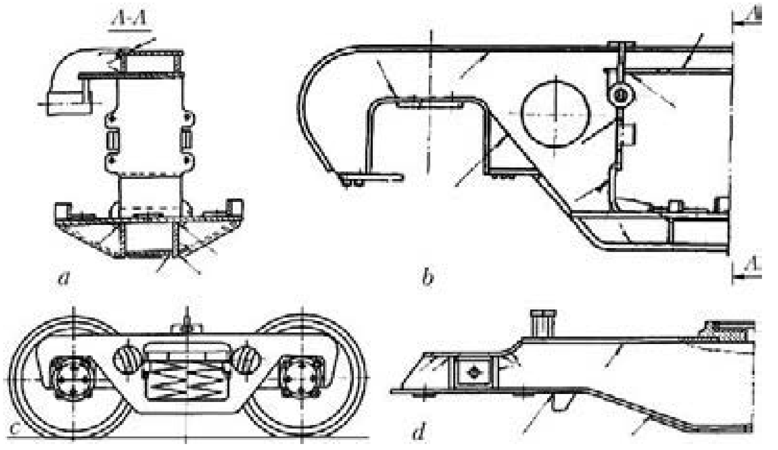

Figure 4. Schematic of welded structure of FCB of KVZ [8]: *a* — sectional view of solebar along the axis of symmetry; *b* — solebar; *c* — bogie; *d* — bogie bolster

oped design into production will improve the quality of large-sized parts of solebars and bogie bolsters and co-axiality of wheelsets in the bogie lower product cost, and reduce the dependence on casting suppliers.

In 2004, company «Vagony» and CJSC «Tver Institute for Car Construction» (TIV) (RF) developed the basic two-axle bogie of 18-9750 model of the typesize range with 25 tf static axle load (with the possibility of application for axle load of 23.5 tf), with welded structure of solebar and bogie bolster [9]. Its solebar (Figure 5) has closed box-like section along its entire length and consists of the upper and lower chords connected by an inclined chord. Note that widened form of spring opening allows a significant increase of rounding-off radii in its corners to lower stress concentration, as well as provides access for brake block examination.

In 2007, FSUE «F.E. Dzerzhinsky Uralvagonzavod» (Nizhny Tagil, RF) developed a stamp-welded variant of FCB [10]. Main load-carrying parts of box-like section (bogie bolster and solebar) are made of two parts, each of which is one stamped blank joined to its counterpart along a vertical longitudinal part plane (Figure 6).

However, despite a whole number of attempts to create in CIS territory welded structures of load-carrying elements of three-piece bogies of freight cars, irreplaceable with cast structures, none of the developed welded structures is currently applied at regular cargo transportation. One of the causes is related to the fact that they do not ensure the required reliability and fatigue life. Welded structures were poorly optimized in terms of fatigue resistance of welded joints.

In the railways of the USA, Canada, China and Japan three-piece two-axle bogies are mainly used, which are similar to bogie of 18-100 model, with cast load-carrying elements. In West Europe a unified bogie of Y25 type and its numerous modifications with axlebox suspension and with rigid H-shaped welded frame is used (Figure 7). Wide application of welded bogies of Y25 type (1435 mm track, 25 t capacity per axle) is due to high reliability of the structure, as well as low cost of their fabrication and maintenance. New designs of welded FCBs with high operating characteristics are developed, for instance RC25NT bogie (1435 mm track, 25 t capacity) manufactured by ELH Company (Halle, Germany) with frame structure and central spring suspension (Figure 8).

In order to develop a competitive welded solebar and bogie bolster irreplaceable with cast variant of solebar of 18-100 type bogie, the following problems should be solved: first, fatigue resistance and reliability of bogie elements should be improved; secondly, accuracy of solebar fabrication should be increased to eliminate skewing of wheelset axles leading to fast wear of wheels, third, solebar weight and cost should be lowered through application of rolled sheets and welding fabrication technology; fourth, bogie element run between scheduled depot repairs should be in-

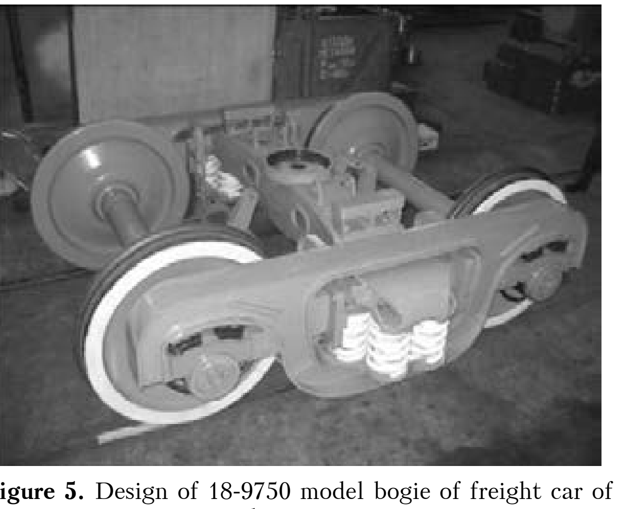

Figure 5. Design of 18-9750 model bogie of freight car of companies «Vagony» and TIV

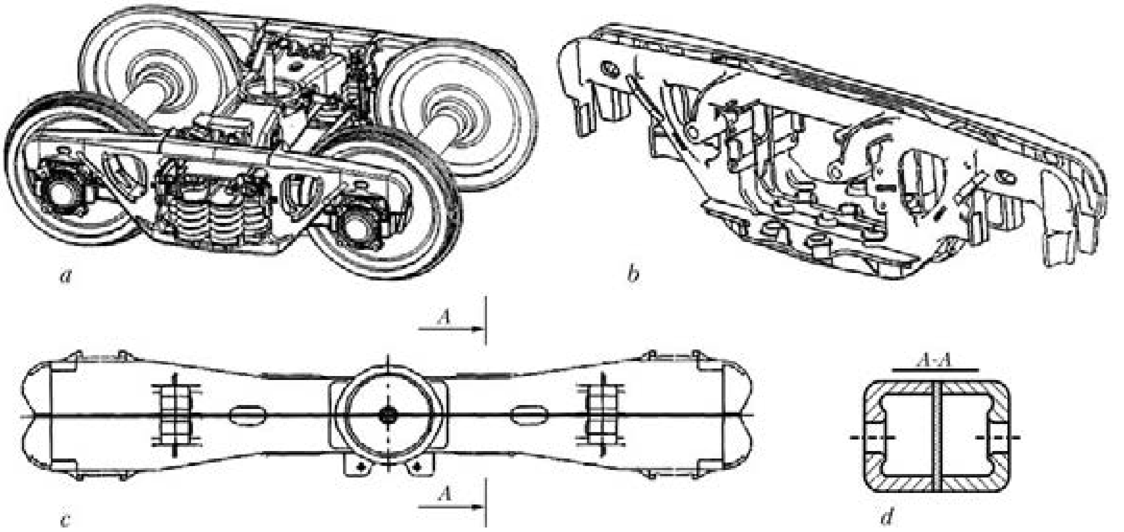

Figure 6. Schematic of bogie of freight car of company «Uralvagonzavod» (*a*), its solebar (*b*), bogie bolster (*c*) and *A–A* section of bogie bolster (*d*)

creased. Additional complexity of solving these problems consists in strict limitations in design of welded structures, associated with a large number of unchanged overall dimensions of seats.

Thus, the main objective is ensuring the reliability of welded variant of load-carrying elements of three-piece two-axle bogie, in particular, due to improvement of fatigue resistance and survivability compared to cast structure. In development of all-welded structures, it should be taken into account that in keeping with the norms [11], strength of FCB elements is assessed by working stresses in the main design conditions (I and III).

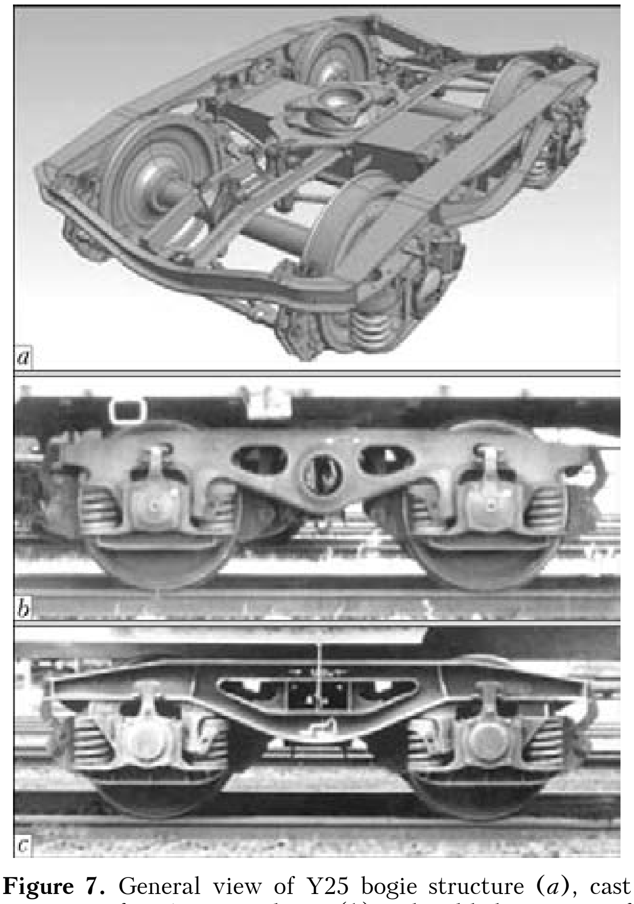

Figure 7. General view of Y25 bogie structure (*a*), cast structure of Y25Cm type bogie (*b*) and welded structure of Y25C bogie (*c*)

In design condition I a relatively rare combination of extreme loads is considered. In this case the main requirement in strength analysis is prevention of residual deformations (damage) in the assembly or part. In operation, condition I corresponds to backup and breakaway of heavy trains at manoeuvring, in particular at automatic shunting from hump yards, and emergency braking in trains at low movement speeds.

In design condition III a relatively frequent combination of medium loads is considered, which is characteristic for normal operation of a car in a moving train. Main requirement in design by this mode is prevention of fatigue fracture of the part assembly. In operation this design condition corresponds to the case of car movement as part of the train along straight and curvilinear track sections and points at allowable speed, at periodical adjusting braking, at periodical medium jerks and jolts, and at normal operation of the car mechanisms and assemblies.

Fatigue resistance of the developed all-welded structures of FCB elements should be calculated

Figure 8. General view of RC25NT bogie welded structure

in keeping with the norms [11] by the coefficient of fatigue resistance for different evaluated zones (base metal and welds) and allowing for the distribution of vertical dynamic factor in the operating speed ranges (load spectrum) [12].

Fatigue resistance coefficient of a structure is evaluated by the formula

$$n = \frac{\sigma_{a,\,N}}{\sigma_{a,\,e}} \geq [n], \tag{1}$$

where $\sigma_{a,\,N}$ is the fatigue limit (by amplitude) at symmetrical loading cycle at test base of N_0 = $= 10^7$ cycles; $\sigma_{a,\,e}$ is the design value of dynamic stress amplitude of a conditional symmetrical cycle, equivalent to real condition of service stresses during part operating life in terms of damaging impact, which is determined based on linear damage accumulation (Palmgren–Miner method); $[n]$ is the allowable minimum value of fatigue resistance coefficient, assumed in keeping with the norms [11], for the newly designed bogie $[n] = 2$.

It is rational to perform strength analysis at loads corresponding to static strength testing and abbreviated accelerated fatigue resistance testing, which are specified by currently valid normative documents [13, 14].

Proceeding from the most recent achievements in the field of determination of welded joint fatigue resistance, it is rational to perform fatigue resistance design of bogie elements also in keeping with IIW recommendations [15] by the condition of fatigue fracture initiation (macrocracks) in different evaluated zones of the structure (welded joint zones), allowing for the specified service load spectrum. This document generalizes a large scope of experimental studies for typical welded joints that allowed determination of the admissible range of nominal stresses at regular loading for each of them:

$$[\Delta\sigma] = \frac{\mathrm{FAT} f_1(R) f_2(N) f_3(\delta) f_4(T)}{\gamma_M}, \tag{2}$$

where FAT is the joint class or admissible range for a given joint based on $2\cdot10^6$ cycles of regular loading (constant parameters of loading cycle) at $f_1 = f_2 = f_3 = f_4 = \gamma_M = 1$; $f_1(R)$ is the coefficient of the impact of loading cycle asymmetry; $f_2(N)$ is the coefficient allowing for limited fatigue; $f_3(\delta)$ is the correction for adjacent element thickness; $f_4(T)$ is the correction for working temperature of joint operation; γ_M is the safety factor.

In the case of allowing for the load spectrum of 10 regular cycles in keeping with the norms [11] structure fatigue life can be determined from the condition of accumulated damageability not exceeding a unity:

$$\sum_{j=1}^{10} \frac{n_j}{N_j} \leq 1, \tag{3}$$

where n_j is the number of j-th cycles with range $\Delta\sigma_j$; N_j is the fatigue life limit at regular loading with range $\Delta\sigma_j$ for j-th element of the spectrum:

$$N_j = C\left(\frac{\mathrm{FAT} f_1(R) f_3(\delta)}{\Delta\sigma_j \gamma_M}\right)^m; \tag{4}$$

$C = 2\cdot10^6$, $m = 3$ at $N < 10^7$ cycles, at $10^7 < N <$ $< 10^9$ cycles $C = 1\cdot10^7$ and $m = 22$, or it can be assumed that the amplitude does not change [15].

If $n_j = Pv_j N_{spec}$, where Pv_j is the fraction of j-th loading in the total loading on the base of N_{spec} cycles, then it follows from (3) that fatigue life limit for the spectrum is

$$[N_{spec}] = \frac{1}{\sum_{j=1}^{10} \frac{Pv_j}{N_j}}. \tag{5}$$

Among the normative documents currently in force in Ukraine the most modern approaches to fatigue analysis of steel structure elements, including welded elements, are given in document [16]. According to these approaches, limit admissible cycle number N_j at calculation of steel structure accumulated damageability and at stresses σ_i is determined as follows:

$$N_i = \frac{A_\rho}{\ln\left[\frac{2\sigma_i}{(1-\rho_i)R_\rho}\right]} - B_\rho, \tag{6}$$

where R_ρ is the design fatigue limit of the calculated cross-section; A_ρ, B_ρ are the parameters determined from the tables [16]. By design-technological features base metal, welded joints, high-strength bolted connections of elements and assemblies of the structure are divided into 7 groups, allowing for the impact of forces relative to design cross-section. Fatigue limit value R_ρ for element groups is given by the following formula:

$$R_\rho = \frac{2\sigma_{-1}}{2 - D_N(1+\rho)}\left(1 - 1.63\,\frac{S_{\sigma-1}}{\sigma_{-1}}\right). \tag{7}$$

Values of parameters σ_{-1}, D_N, $S_{\sigma-1}$ in (7) are taken from the tables [16].

As reported by European developers the following standards are the most often used in design of load-carrying welded structures of railway vehicles [17]: TSI standard [18], British standard prEN 12663-2:2007 [19] and Eurocode 3 standard, Pt 1.9 [20]. TSI specifies standard loads at testing of freight cars, as well as all the types of loads, which are applied to car structures in operation. In keeping with the requirements of prEN 12663, static loads applied to car structure are determined: horizontal and vertical loads, and the most unfavourable combination of horizontal and vertical loads. In calculation of dynamic strength of freight cars, dynamic load is taken in the range of ±30 % of the static one along the vertical, because of vertical loads, in keeping with TSI standard and prEN 12663. In fatigue analysis of car welded joints Eurocode 3 standard, Pt 1.9, is used.

It should be noted that the design and test loads specified by European standards, differ essentially from those accepted in Ukraine, Russia and other CIS countries. This is, primarily, related to railway track condition and operating conditions of railway cars. Therefore, in development of welded structures of load-carrying elements for FCBs it is highly rational to apply, alongside the norms currently in force, also the most recent achievements in the field of dynamics and strength of railway cars, as well as recommendations on welded joint fatigue resistance analysis.

Conclusion

On-going upgrading of freight car fleet determines the high demand for their bogies. As shown by railroad accident statistics, production of cast load-carrying elements of the bogies is characterized by a high degree of probability of internal defect formation and, therefore, by instability of strength values, particularly at cyclic loads. Therefore, development of all-welded load-carrying elements of FCBs, which will be more reliable and irreplaceable with those currently manufactured, is expedient. It should be further noted that fabrication of all-welded variants of bogie load-carrying elements does not require any expensive equipment as in casting production that makes element manufacture more affordable and lowers the dependence of car manufacturers on casting suppliers.

In order to develop a competitive welded solebar and bogie bolster, irreplaceable with the cast variant of the bogie of type 18-100, it is necessary to, first, increase the fatigue resistance of bogie elements; secondly, improve the accuracy of solebar manufacturing to prevent skewing of wheelset axles leading to rapid wearing of wheels; third, lower the weight and cost, and fourth, increase bogie element run between scheduled depot repairs.

Strength analysis of bogie elements should be performed in keeping with the norms currently in force, as well as allowing for the current world concepts, standards, norms and recommendations in the field of railway car dynamics, and methods of welded joint fatigue determination.

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