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DEVELOPMENT OF WELDED STRUCTURE OF SIDE FRAME OF FREIGHT CAR BOGIE OF INCREASED RELIABILITY

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The accidents occurring on railway track of 1520 mm are often associated with the fracture of cast load-carrying elements of three-element freight car bogies. The level of quality and endurance of such bogie elements as side frame and bogie bolster, which are traditionally manufactured by casting technology, are insufficient, so it is advisable to use welding technology to manufacture the mentioned parts of sheet rolled metal in order to increase the fatigue resistance characteristics. The development of a new all-welded structure of side frame of a three-element freight car bogie with an axial load of 23.5 ts was carried out on the basis of widespread use of mathematical modelling to determine the stress-strain state of welded elements of the bogie under the action of a regulated range of loads and to evaluate the strength according to the valid standards and modem global approaches. The technology of assembly and welding, as well as the appropriate specialized equipment for manufacture of a developed design of welded side frame were created. Two test specimens were manufactured and accelerated fatigue tests were carried out, the results of which showed a significant increase in endurance and vitality under operational cyclic loads as compared to designs of existing cast side frames. Taking into account high values of reliability, availability and manufacturability, ability of a significant reduction in unsprung weight and increase in dimensional accuracy, the welded structure of the side frame of a three-element freight car bogie is very promising for its implementation on railway track of 1520 mm. 9 Ref., 2 Tables, 6 Figures.

Keywords: freight car bogie, side frame, welded structure, technology of production, fatigue resistance, life, vitality, mathematical modelling, calculation, fatigue testing

It is known that on railway track of 1520 mm the accidents occur related to the fracture of cast load-carrying elements of three-element freight car bogies [1–3]. This is caused by the presence of casting defects in the areas with stresses of 0.75–1.0 from permissible stresses, which lead to a significant decrease in the characteristics of fatigue resistance and, according, to premature fracture within 2–23 years of operation [3]. To increase the reliability of side frames and bogie bolsters is possible by improving the casting process and initial nondestructive testing or by manufacturing the mentioned parts by using alternative technologies. For example, the mentioned parts can be manufactured from sheet rolled steel 09G2S by using welding technologies in order to improve the characteristics of fatigue resistance [4]. It should be noted that the use of welding is more technologically attractive, since all the detected defects at the manufacturing stage are easily eliminated, unlike cast parts.

At PWI a considerable amount of works on designing a new all-welded structure of the side frame of three-element freight car bogie with an axial load of 23.5 ts and manufacturing technology were carried out [5]. The development was carried out on the basis of widespread use of mathematical modelling to determine the stress-strain state of welded elements of the bogie under the action of a regulated load spectrum and evaluation of strength in accordance with current standards [6] and modern world approaches [7].

The fatigue resistance of the designed structure of the all-welded side frame of the bogie was calculated in compliance with the Standards [6] according to the coefficients of fatigue resistance for different evaluation zones (base metal and welds) taking into account the distribution of the coefficient of vertical dynamics over the operational speed ranges. Moreover, taking into account the additional spectrum of loading from the longitudinal compressive forces through the autocoupling, it was demonstrated that the designed all-welded structure of the side frame is serviceable under varying loads and satisfies the requirements of the Standards [6] with the coefficient of fatigue resistance $[n] = 2$ both under the condition of nonexceeding the calculated stresses of the values of the allowed stress amplitudes and under the condition of damage accumulation.

The coefficient of fatigue resistance of the structure is evaluated by the formula [6]:

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

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where $\sigma_{a,N}$ is the endurance limit (according to the amplitude) at a symmetric load cycle based on the tests $N_0 = 10^7$ cycles; $\sigma_{a,e}$ is the calculated value of the amplitude of the dynamic stress of the conditional symmetric cycle, equivalent to the damaging action of the real mode of operational stresses over the life of a part; $[n]$ is the permissible minimum value of the fatigue resistance coefficient $[n] = 2$ is selected in accordance with the Standards [6] for a repeatedly designed bogie.

The endurance limit (according to the amplitude) for a symmetric load cycle is determined according to [6]:

$$\sigma_{a,N} = \frac{\overline{\sigma_{-1}}}{\overline{K}_\sigma}(1 - z_d v_\sigma), \quad (2)$$

where $\overline{\sigma_{-1}}$ is the average value of endurance limit of a smooth standard specimen; z_d is the quantile of the distribution of $\sigma_{a,N}$ as a random value; v_σ is the coefficient of variation of the endurance limit; $\overline{K}_\sigma$ is the average value of the coefficient of reduction of the endurance limit of a part relative to the endurance limit of a smooth standard specimen.

The calculated value of the dynamic stress amplitude of the conditional symmetric cycle, equivalent as to the damaging effect of the real mode of operating stresses over the life of the part, is calculated taking into account the distribution of the coefficient of vertical dynamics over ten ranges of operation speeds [6]:

$$\sigma_{a,e} = \max(\sigma_a)\sqrt[m]{\frac{T_p f_e}{N_0}\sum_{i=1}^{10} P(v_i)k_i^m}, \quad (3)$$

where m is the exponent in the equation of the fatigue curve in the amplitudes; T_p is the total time of dynamic loads over the calculated life of the part service; f_e is the effective frequency of the process of changing dynamic loads for spring-suspended parts; $f_e = \sqrt{4c/m_b}$ (c is the vertical rigidity of coil spring group under the gross tonnage of a car; m_b is the weight of the loaded body); N_0 is the base number of cycles of dynamic stresses; i is the number of speed ranges; $P(v_i)$ is the fraction of time that falls into operation in the i-th speed range (v_i is the average value of speed in the i-th range); k_i is the coefficient of vertical dynamics in the i speed range; $\max(\sigma_a)$ is the maximum amplitude of stresses during a symmetric load cycle.

From the formulas given above, the permissible maximum stress amplitudes according to the fatigue resistance criterion are expressed as follows:

$$\left[\max(\sigma_a)\right] = \frac{\sigma_{a,N}}{[n]\sqrt[m]{\frac{T_p f_e}{N_0}\sum_{i=1}^{10} P(v_i)k_i^m}}. \quad (4)$$

In the case of welded structure of the side frame, several values of permissible stress amplitudes are calculated for different evaluation zones of the base material and the welded joint metal according to the fatigue resistance criterion. To evaluate the fatigue resistance of the side frame, the loads were applied corresponding to the normal movement of a car in the train set:

- vertical force reduced by the value of the gross tonnage of the car body;
- transverse component of the longitudinal quasistatic force.

The value (amplitude) of loads is determined by the coefficient of vertical dynamics in the range of speeds of movement to the design one (120 km/h). The coefficient of vertical dynamics is accepted to be the same for the movement on straight and curved regions of the track. The calculated loading spectrum [6, 8] is given in Table 1.

Applying the numerical method based on MCE the maximum stresses at quasistatic loading with a vertical force of 210.6 kN and wedge thrust force of 30.1 kN [8] were determined relative to which the load spectrum was specified (Table 1). The vertical dynamic loading F_{lz} acting on the side frame is applied to the supporting surface of the central spring suspension, the wedge thrust force F_{3x} — to the vertical

Table 1. Normative loads for calculation of fatigue resistance of side frame of the bogie with an axial load of 23.5 ts

Interval of movement speed, m/s	Average speed of interval, m/s	Probability of movement in the speed range $P(v_i)$	Side frame		
			Coefficient of vertical dynamics k_d	Vertical dynamic load amplitude F_{lz}, kN	Amplitude of wedge thrust force F_{3x}, kN
0–12.5	6.25	0.03	0.063	13.27	1.90
12.5–15.0	13.75	0.07	0.138	29.07	4.15
15.0–17.5	16.25	0.09	0.298	62.77	8.97
17.5–20.0	18.75	0.12	0.333	70.14	10.02
20.0–22.5	21.25	0.16	0.368	77.52	11.07
22.5–25.0	23.75	0.19	0.403	84.89	12.13
25.0–27.5	26.25	0.16	0.438	92.26	13.18
27.5–30.0	28.75	0.10	0.473	99.63	14.23
30.0–32.5	31.25	0.06	0.508	107.01	15.29
32.5–35.0	33.75	0.02	0.543	114.38	16.34

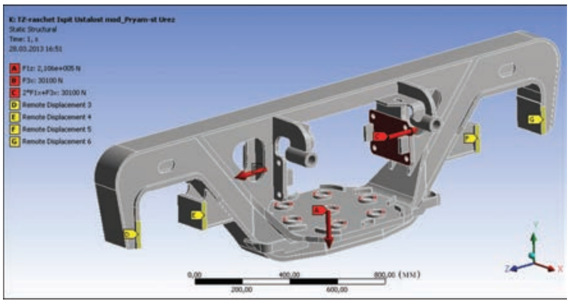

Figure 1. Vertical load F_{1z} = 210.6 kN (A), uniformly distributed over the area of spring suspension on the support surface of the central spring suspension, and the wedge span force F_{3x} = 30.1 kN (B), which are applied to the vertical posts of the central spring hole

posts of the central spring hole (Figure 1). The results of calculations of the distribution of maximum main stresses from the applied quasistatic load are shown in Figure 2 and in Table 2.

The calculation of fatigue resistance of the all-welded structure of the side frame, carried out in accordance with the Recommendations of the International Institute of Welding (IIW) [7] on the condition of a fatigue fracture (macrocrack) initiation in different evaluation zones of the structure (zones of welded joints) taking into account the specified load spectrum during operation [6] showed that the designed variant of the all-welded structure of the side frame has a sufficient level of fatigue resistance of welded joints with a safety factor γ_M = 1.1–1.4.

The Recommendations of IIW summarize a considerable volume of experimental investigations for typical welded joints, which allowed formulating a procedure on determining the range of nominal stresses allowed under a regular load for each joint in the form of:

$$[\Delta\sigma] = \frac{FATf_1(R)\,f_2(N)\,f_3(\partial)\,f_4(T)}{\gamma_M}, \qquad (5)$$

where *FAT* is the class of a joint and its permissible stress range based on $2\cdot10^6$ regular load cycles (constant load cycle parameters) at $f_1 = f_2 = f_3 = f_4 = \gamma_M = 1$; γ_M is the safety factor. In [7] there is a table of *FAT* values for different typical welded joints. The factor $f_1(R)$ takes into account the influence of the asymmetry of the load cycle $R = 1 - \frac{\Delta\sigma}{\sigma_{\max}}$ and also the level of residual stresses in the joining zone. In case if the residual stresses do not exceed $0.2\sigma_y$, where σ_y is the yield point of the material (for steel 09G2S $\sigma_y \approx$ ≈ 390 MPa), then according to [7]:

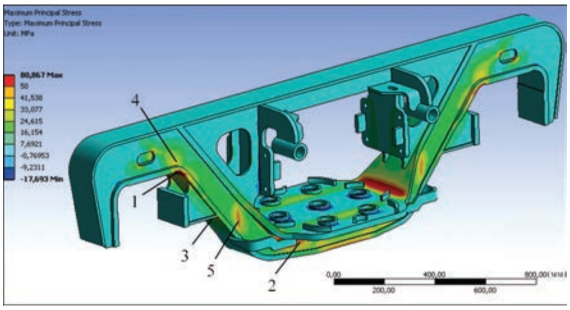

Figure 2. Distribution of main stresses in the structure of welded side frame under the action of loads regulated by the Standards [6] (description 1–5 see in Table 2)

$f_1(R) = 1.6$ for $R < -1.0$;
$f_1(R) = -0.4R + 1.2$ for $-1.0 \le R \le 0.5$;
$f_1(R) = 1.0$ for $R > 0.5$.

The factor $f_2(N)$ takes into account the limited fatigue. In the range of $10^4 < N < 10^8$ cycles, $f_2(N)$ according to [7] (Figure 2) is determined by the dependence:

$$f_2(N) = \left(\frac{C}{N}\right)^{\frac{1}{m}},$$

where N is the life of welded joint; $C = 2\cdot10^6$, $m = 3$ at $10^4 < N < 10^7$ cycles; $C = 5.8\cdot10^6$, $m = 5$ at $10^7 < N <$ $< 10^8$ cycles.

The correction for the thickness of the adjacent element in which a fatigue crack arises, $f_3(\delta) = 1.0$ if the thickness is $\delta < 25$ mm. At higher thicknesses:

$$f_3(\delta) = \left(\frac{25}{\delta}\right)^{0.3}.$$

Table 2. Comparison of amplitudes of permissible stresses and calculated maximum stresses in different zones of structure of side frame in accordance with the acting Standards [6] and Recommendations of IIW [7]

Area of structure of side frame	Standards [6]		IIW [7]	Calculation/ measurement
	Coefficient of reduction of endurance limit $\overline{K}_\sigma$	Maximum permissible amplitude of stresses max(σ_a), MPa	Permissible amplitude of stresses [σ_a], MPa (γ_M = 1.0/1.4)	Maximum value of main stresses σ_a, MPa
1. Main material in the zone R55 of axial hole	1.5	150	–	81
2. Longitudinal fillet welded joint of the side wall and the supporting surface of the springs	3.0	78	40/50	56
3. Transverse fillet welded joint of support in the thrust hole	3.0	78	40/50	37
4. Longitudinal fillet joint in the area R55 of the thrust hole	3.0	78	40/50	53
5. Cross butt welded joint of the side wall	4.7	51	44/56	33

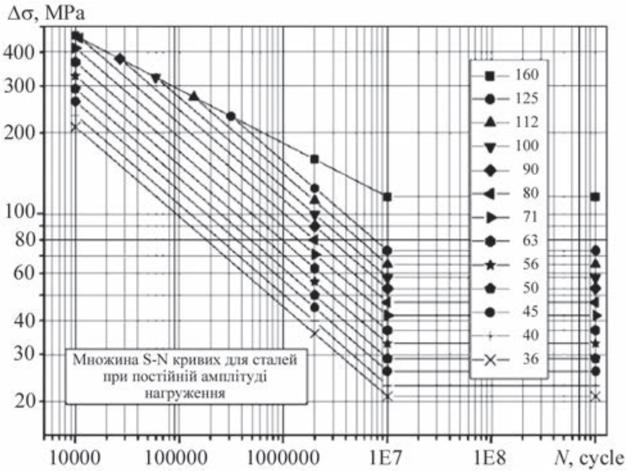

Figure 3. Generalized Weller curves for different classes of *FAT* welded joints (material — steel) for normal rated stresses at $N < 10^9$ cycles [7]

For the considered joints of the structure of the side frame with a thickness of elements of up to 25 mm $f_3(\delta) = 1.0$ can be taken.

The factor $f_4(T)$ takes into account the operating temperature T of the joint service. According to [7] at $T < 100$ °C, $f_4(T) = 1.0$ can be taken.

When setting the value of the safety factor γ_M, it is necessary to take into account that *FAT* is recommended based on 0.95 of nondestruction probability (experimental data). Therefore, in [7] it is recommended to choose γ_M within the range of 1.0–1.4. Moreover, the value of the safety factor $\gamma_M = 1.4$ corresponds to the case when a threat to human life exists.

The load spectrum for the calculation of fatigue resistance is determined by the coefficient of vertical dynamics and the probability of movement in the range of speeds to the design speed (120 km/h).

Taking into account the abovementioned, for the considered evaluation areas of the structure of the side frame (zones of welded joints) at regular load the dependence (5) can be represented as:

$$[\Delta\sigma] = \frac{FAT}{\gamma_M}\left(\frac{C}{N}\right)^{\frac{1}{m}}. \tag{6}$$

Accordingly, the fatigue limit $[N]$ at a regular load with a range $\Delta\sigma$ is expressed as follows:

$$[N] = C\left(\frac{FAT}{\Delta\sigma\gamma_M}\right)^m. \tag{7}$$

Taking into account the load spectrum of ten regular cycles according to the Standards (Table 1), the life N_{spec} is determined by linear summation of damageability (Palmgren–Miner method):

$$\sum_{j=1}^{10}\frac{n_j}{N_j} \le 1, \tag{8}$$

where n_j is the number of j-cycles with a range $\Delta\sigma$; N_j is the ultimate life at a regular load with a range $\Delta\sigma_j$ for the spectrum element. The value of N_j is determined by the formula:

$$N_j = C\left(\frac{FAT}{\Delta\sigma_j\gamma_M}\right)^m. \tag{9}$$

Table 2 summarizes the permissible stress amplitudes (fatigue strength) in accordance with the Standards [6] and recommendations of IIW [7] in different zones of welded structure of the side frame, taking into account the specified [6] load spectrum based on 10^7 cycles during long-term operation. The comparison shows the insufficient conservatism of the Standards during evaluation of the fatigue strength of welded joints.

Also Table 2 represents calculated values of maximum stresses in different areas of the side frame due to the action of maximum design forces on a bogie with an axial load of 23.5 ts. The carried out calculations (Table 2, items 2, 4) show that in order to provide a sufficient level of fatigue strength in the most dangerous zones of welded structure of the side frame, it is advisable to use a general heat treatment for residual stress relaxation and impact ultrasonic treatment along the fusion line of longitudinal fillet welds.

It is important that designing of the welded side frame was also performed taking into account the technological capabilities of assembly and welding of all its parts, providing high demands on the quality and load-carrying capacity of the product. For this purpose, a minimum number of welded joints, especially transverse joints was used and they were placed in the least loaded areas, providing a complete penetration of all welded joints and, if possible, performing double-side welding with edge preparation. Technological instructions for assembly and welding of the side frame were developed, as well as corresponding specialized equipment was designed that provides the accuracy of assembling structural elements and low levels of residual deformations, performance of high quality welding, additional treatment and nondestructive testing of the most dangerous regions of welded joints, reducing overall labour costs and time for manufacture of the product.

Two experimental specimens were manufactured (Figure 4) and accelerated fatigue tests (Figure 5) were carried out according to the requirements of standards existing in Ukraine [9].

The results of fatigue tests showed that in the specimen of the welded side frame No.1 after $N_{i\_mp} = 8.8$ mln cycles of vertical load (amplitude $P_{ai} = 245$ kN = 25 ts, a constant average load cycle $P_m = 363$ kN = 37 ts), the first macrocrack was formed in the base metal on the side wall between the lower belt and the spring supporting surface. During the continuation of regular loads, the crack was slowly propagated in the lower belt and almost was not propagated on the spring supporting surface. At 11.6 mln cycles in the zone of a transverse welded joint of the side wall, the second macrocrack was formed, which led to the fracture at N_{i_p} = 13 mln cycles (Figure 5, *b*). The opening of both cracks were performed. Visual analysis of the surface of the first crack did not reveal welding defects, all welded joints were produced with a complete penetration (Figure 5, *c*). The analysis also revealed that the second crack was formed as a result of a defect of discontinuity, namely a partial penetration of the transverse welded joint (Figure 5, *d*). In the specimen No.2, after N_{i_mp} = 5.0 mln cycles, a macrocrack formed in the axial opening in the zone of radius blend R55 after N_{i_p} = 5.4 mln cycles the fracture occurred. Visual analysis of the fracture revealed that the crack was formed in the zone of longitudinal fillet joint, but welding defects were not revealed (Figure 6).

Figure 4. Equipment for assembly and welding of side frame structure (*a*) and two manufactured test specimens (*b*)

Figure 5. Test specimen No.1 of all-welded side frame during accelerated fatigue tests (*a*) and fracture in the area of transverse welded joint of side wall (*b*), fracture in the zone of a first crack (*c*) and in the fracture zone (*d*)

In general, the cyclic life of two test specimens of the welded side frame exceeded the cyclic life of cast frames by 2–4 times, even those strengthened by HMP technology under the same loading mode. At the same time, the established life of welded frames exceeds the calculated permissible number of cycles before fracture by ten times, which for the load 37 ± ± 25 ts for cast frames is $[N_c] = 0.345 \cdot 10^6$ (according to the data of investigations carried out by UkrNDI

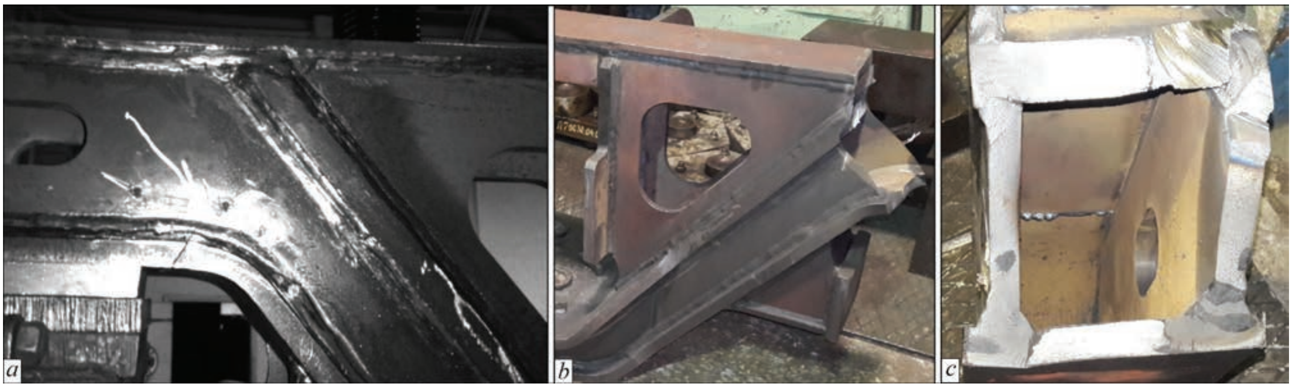

Figure 6. Fragment of fracture of test specimen No.2 of all-welded side frame after macrocrack formation during accelerated fatigue tests (*a*) and after fracture in the radius blend zone R55 of axial hole (*b*, *c*)

«Vagonobuduvannya», Kremenchug). It should be noted that the specimen of the welded side frame No. 1 showed a high value of relative survivability $Zh = (N_{i\_p} - N_{i\_mp})/N_{i\_p} = 0.32$, and according to the absolute value the survivability of the welded specimen exceeds several times the life of the standard cast frame (without additional strengthening treatments).

Thus, the high values of fatigue resistance of the structure of all-welded side frame of a freight car bogie with an axial load of 23.5 ts designed at PWI, which gives grounds to recommend this design for implementation on the railways of 1520 mm track.

Conclusions

1. The calculation of fatigue resistance of the structure of all-welded side frame of the freight car bogie of sheet rolled metal (09G2S steel) with an axial load of 23.5 ts designed at PWI was performed taking into account the specified load spectrum. As a criterion of fatigue fracture the origination of a fatigue macrocrack was considered. The maximum permissible stress amplitudes in different zones of the investigated frame were established in accordance with the standards acting in Ukraine and the recommendations of IIW. It is shown that designing of the side frame structures should be carried out according to the recommendations of IIW as they are more conservative.

2. It was proved that with the use of the developed technology and equipment it is possible to produce all-welded side frame of the railway car bogie with providing a high quality of welded joints and geometric shapes of products.

3. The fatigue test of two specimens of all-welded side frame at a load of 37 ± 25 ts was carried out. It was experimentally established that the cyclic life of welded frames is 2–4 times higher than the cyclic life of cast frames, even strengthened by the technology of high-frequency mechanical peening. In this case, the life of welded frames is ten times higher than the calculated number of cycles before fracture at a specified loading mode.

4. High values of fatigue resistance of the structure of all-welded side frame of the freight car bogie with an axial load of 23.5 ts designed at PWI give grounds to recommend this structure to be introduced at 1520 mm rail tracks.

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