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FATIGUE RESISTANCE OF WELDED ELEMENTS OF FREIGHT CARS OF A NEW DESIGN MADE FROM STEELS OF S345 AND S390 STRENGTH GRADE

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The paper presents the results of experimental-calculation studies of fatigue resistance of full-scale samples of the bolster assembly and side wall rack sealing assembly of a gondola car of 12-4106-01 model. It is found that their operating life is determined by fatigue resistance of welded joints of structural elements of the assemblies. Their fatigue strength is equal from 12.1 MPa (side wall rack sealing assembly) up to 33.6 MPa (bolster assembly). Sections of fatigue cracks initiation, regularities of their propagation and fatigue limit of the structure were established. As shown by calculation of the car body stressed state, the fatigue limit values ensure operation for 34.1 and 57.0 years for the bolster assembly and side wall rack sealing assembly, respectively, before appearance of the fatigue crack. 9 Ref., 2 Tables, 8 Figures.

Keywords: *welded elements of freight cars, bolster assembly, side wall rack sealing assembly, fatigue resistance, stressed state*

The most damaged elements of gondola cars in operation are the assemblies of joining the elements of the frame and racks of the side walls. Reduction of loading of these assemblies creating the preconditions for extending the service life and reducing the cost of car repair is a priority in development of the new generation rolling stock. In this connection, PJSC «Dneprovagonmash» developed 12-4106-01 model of gondola car with side wall racks of a tubular design, which envisages increase of the strength of the latter. Figure 1 gives the general view of the assembly.

Strength characteristics of car elements were improved also due to application of steels of strength grades C345 (racks) and C390 (bolster assembly).

Owing to modification of the design and application of materials with improved strength characteristics, the specified service life was extended up to 32 years that should be confirmed by the results of the work on residual life assessment.

Such problems were earlier considered in papers [1–4]. The problem of investigation of fatigue strength of side wall rack sealing is considered for the first time in [4], and work [1] shows that the existing norms for fatigue strength assessment do not fully reflect the real service conditions and defines the ways of further development of calculation-experimental assessment of fatigue strength of freight car bodies. Works [2, 3] give the results of investigations of fatigue strength of side wall rack sealing with improved strength characteristics for gondola cars with axle loads of 23.5 and 25 tf.

Acad. V. Lazaryan Dnepropetrovsk National University of Railway Transport (DNURT), by the request of PJSC «Dneprovagonmash», performed a package of work on assessment of the residual life of assem-

Figure 1. Side wall rack sealing assembly (*1*) of a gondola car of 12-4106-01 model (*2*)

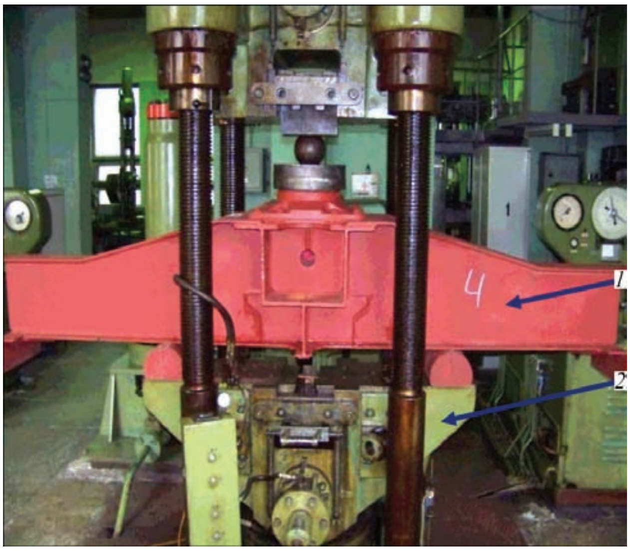

Figure 2. Sample of bolster assembly No.4 (*1*) in testing machine ZDM-200pu (*2*)

blies, including bench testing of full-scale samples of the gondola car for evaluation of the stress-strain state and fatigue resistance, as well as calculation-experimental assessment of the assembly residual life.

Service life of the assembly up to initiation of fatigue damage, in keeping with the acting normative documentation [5–8], is assessed by Palmgren–Miner hypothesis, in the assumption that the fatigue curve consists of two sections with values m_1 and $m_2 = 2m_1 – 1$, divided by point $N_0 = 10^7$ (number of basic cycles). Stresses $\sigma_{a,\,N}$, the structure fatigue limit, correspond to this point.

The objective of experimental research conducted at PWI consisted in revealing the structure sections with the worst fatigue resistance values and determination of the value of fatigue limit $\sigma_{a},\,_{N}$ for them. The sequence of experimental research performance is set forth in [9]. Because of the limited volume of experimental data, the fatigue curve was not plotted, assuming the value of index $m_1 = 3$ recommended in normative documentation [5].

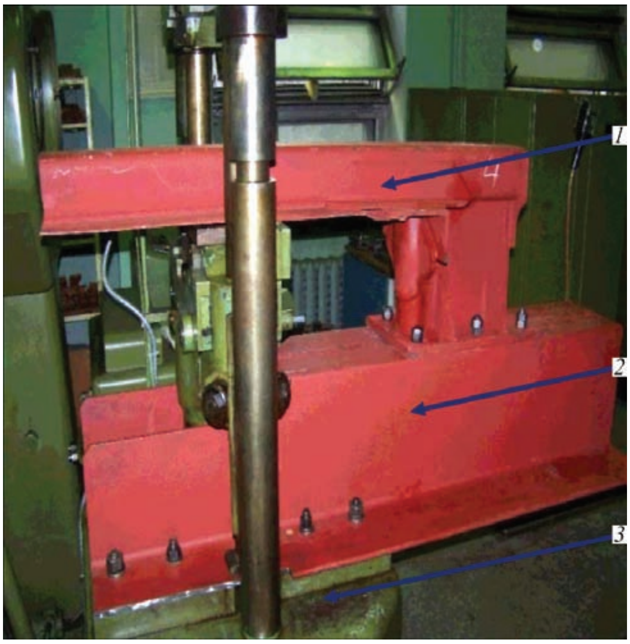

Figure 3. Sample of side wall rack sealing assembly No.4 (*1*) installed on a platform, (*2*) in testing machine ZDM-10pu (*3*)

Four full-scale samples of the bolster assembly and side wall rack sealing assembly each were prepared. Three samples of each kind were subjected to fatigue testing to fracture. Strain measurement was performed in the remaining sample for validation of finite-element models of the assemblies. Sample positioning in hydropulsating machines ZDM-200pu (bolster assembly) and ZDM-10pu (side wall rack sealing assembly) is shown in Figures 2, 3. Testing was conducted at sinusoidal alternating loading cycle. Maximum and minimum loads were set so that fracture (loss of load-carrying capacity) of the sample occurred under the conditions of elastic stress-strain state in the region of high-cycle fatigue (up to 5 mln loading cycles). As average cycle stresses are not taken into account in normative documentation [5, 7] at assessment of fatigue resistance, the values of loading cycle asymmetry (ratio of the smallest to the largest load) of the bolster assembly and side wall rack sealing assembly differed (were assigned proceeding from testing machine capabilities). Loading frequency of the bolster assembly and side wall rack sealing assembly was equal to 5.5 and 7.0 Hz, respectively, and was assigned proceeding from technical characteristics of ZDM-200pu and ZMD-10pu testing machines.

During testing, the number of loading cycles up to appearance of cracks, their location and size, as well as number of cycles to sample fracture were recorded.

As the process of fatigue crack initiation and propagation in all the three samples of the bolster assembly was identical, the kinetics of fatigue fracture of just bolster assembly No.4 is given below as an example. Sample of bolster assembly No.4 was tested at cyclic loading ($P_{\min} = 98.1$ kN and $P_{\max} = 883$ kN) with the frequency of 5.5 Hz. The distance between the supports was 1400 mm. The following was found at 797 thou cycles: crack at the top of the coverplate on the vertical plate near the center sill (crack T5) 20 mm long and crack between the vertical plate of the body bolster and web of Z-shaped center sill (crack T6) 25 mm long (Figure 4). After 1029 thou cycles a crack was found in the lower horizontal plate of the body bolster at the center sill I-beam (crack T7) 35 mm long. After operating for 1126 thou cycles of stress alternation, the length of crack T5 of 20 mm remained unchanged, crack T6 propagated up to 35 mm, and

Figure 4. Cracks in bolster assembly (sample No.4): *1* — crack T5; *2* — T6; *3* — T7; *4* — T8; *5* — T9 from crack T6 on the other side from center sill

T7 started propagating both in the vertical (along the bolster assembly side wall) up to 10 mm, and in the horizontal direction (along the lower chord) — up to 55 mm. At 1282 thou cycles T7 crack along the vertical propagated up to 40 mm, and along the horizontal — up to 90 mm. A new crack was also revealed between the center sill I-beam (crack T8) 55 mm long. After 1458 thou cycles, the length of crack T5 of 20 mm remained unchanged, T6 propagated in the base material of the vertical plate of body bolster up to 45 mm, T7 grew in the vertical direction up to 80 mm, and up to 130 mm in the horizontal direction, crack T8 grew up to 180 mm. After testing for 2346 thou cycles, a crack was found between the vertical plate of body bolster and web of Z–shaped center sill (crack T9) 50 mm long (from the opposite side of T6). After testing for 2815 thou cycles, the length of crack T5 was equal to 22 mm, T6 — 150 mm; T7 reached the length of 150 mm, both along the vertical and the horizontal, T8 — 180 mm, T9 — 120 mm. The process of active fracture of the bolster assembly started after 2971 thou loading cycles: crack T6 grew up to 250 mm, and crack T9 — up to 180 mm. At 2995 thou cycles crack T6 reached the length of 320 mm, and T9 was 300 mm), and at 3031 thou cycles the sample failed.

As the process of fatigue crack initiation and propagation was identical in all the three samples of side wall rack sealing, kinetics of fatigue fracture of just sealing of the rack of side wall No.4 is given below as an example. Sample of sealing of the rack of side wall No.4 was tested at cyclic loading ($P_{\min}$ = 41.2 kN and $P_{\max}$ = 68.7 kN) with the frequency of 7.0 Hz. At 325 thou loading cycles fatigue cracks T1 and T2 were found in the joint of the cross-beam (coverplate over the upper flange) with the lower chord 18 mm and 15 mm long, respectively, as well as crack T3 in the joint of the reinforcing angle bar and lower chord 10 mm long (Figure 5). Furtheron, at 931 thou loading cycles crack T1 grew up to 25 mm, T2 up to 50 mm, and length of crack T3 did not change. At 1550 thou loading cycles, coalescence of cracks T1 and T2 occurred, their total length being 110 mm, crack T3 grew up to 22 mm, and new fatigue cracks were found: T4 and T6 in the joint of the rack of side wall and lower chord (from two sides), of 10 and 38 mm length, re-

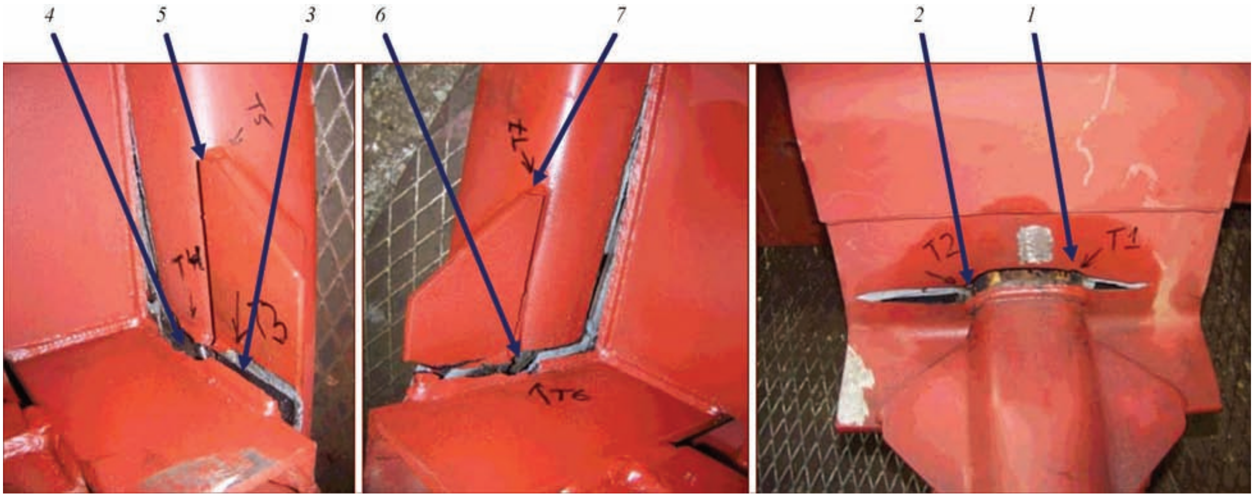

Figure 5. Cracks in the side wall rack sealing assembly (sample No.4): *1, 2* — in the joint of the cross-beam (coverplate over the upper flange) and the lower chord (cracks T1 and T2, respectively); *3* — in the joint of reinforcing angle bar of side wall rack and the lower chord (crack T3); *4, 6* — in the joint of side wall rack and lower chord (cracks T4 and T6, respectively); *5, 7* — on top of the reinforcing angle bar of side wall rack (cracks T5 and T7, respectively)

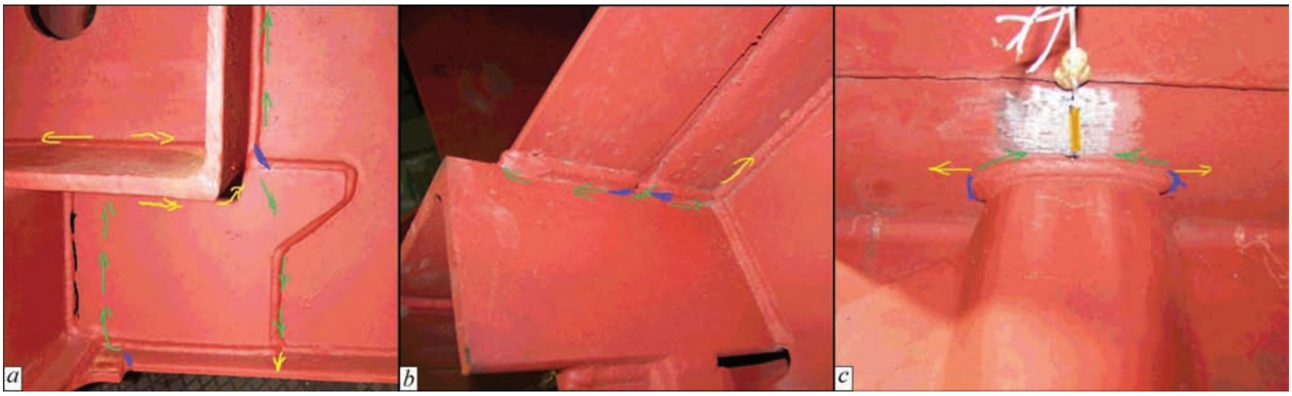

Figure 6. Crack propagation: *a* — in bolster assembly; *b, c* — in side wall rack sealing assembly

spectively; cracks T5 and T7 on top of the reinforcing angle bar of side wall rack of 7 and 10 mm length, respectively. After 2227 thou loading cycles, the length of crack T1 + T2 still was 110 mm, T3 crack grew up to 25 mm, T4 — up to 14 mm, T5 — up to 10 mm, T6 — up to 70 mm and T7 — up to 10 mm. At 2414 thou loading cycles, T1 + T2 crack propagated up to 120 mm, T3 crack merged with crack T4 (total length of 52 mm), T5 crack propagated up to 10 mm, T6 — up to 85 mm and T7 — up to 12 mm. After 2793 thou loading cycles, length of crack T1 + T2 still was 120 mm, crack T3 + T4 propagated up to 55 mm, T5 — up to 10 mm, T6 — up to 115 mm, and T7 — up to 15 mm. At 3351 thou loading cycles, crack T1 + T2 grew up to 125 mm, crack T3 + T4 — up to 66 mm, crack T5 — up to 10 mm, T6 — up to 130 mm and T7 — up to 15 mm. At 3872 thou loading cycles the sample failed.

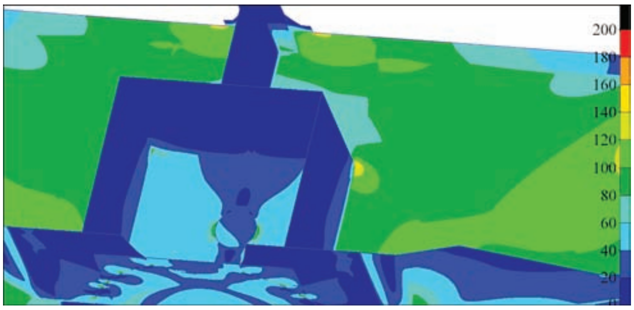

Figure 7. Stresses in bolster assembly from applied working load $P = 883$ kN, MPa

The generalized pattern of crack propagation and fracture is shown in Figure 6. Crack initiation sites are designated by blue marks. The cracks first propagate along the weld (green arrows). Having reached its boundary, they move over to the adjacent weld or to the base metal (yellows arrows). Black color in Figure 6, *a* shows a crack, which initiates at the initial testing stage, breaks the weld between the small I-beam of the center sill and bolster beam, and after that its propagation stops. It does not lead to loss of the sample load-carrying capacity. Further analysis was conducted for points of crack initiation (lower and upper blue marks in Figure 6). Table 1 gives the test results (cycle number to crack initiation and to sample fracture).

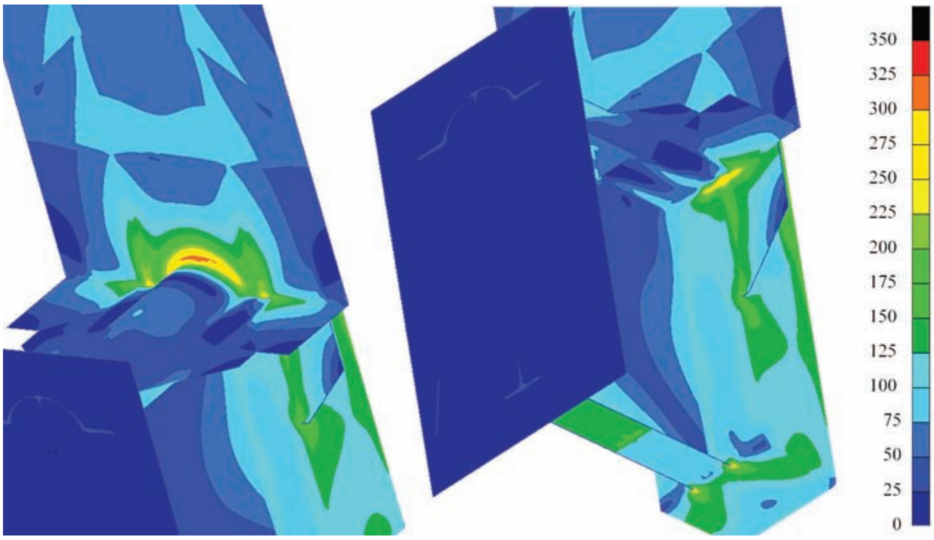

Figure 8. Stresses in side wall rack sealing assembly from applied working load $P = 68.73$ kN, MPa

Table 1. Results of fatigue testing of assemblies of a gondola car of 12-4106-01 model

Sample number	Loading cycle parameters, kN		Cyclic fatigue life, thou cycles	
	$P_{\max}$	$P_{\min}$	Up to crack initiation (point)	Up to sample fracture
Bolster assembly				
2	903	98.1	679 (1)	6432
			975 (2)	
3	903	98.1	771 (1)	3327
			1820 (2)	
4	883	98.1	1029 (1)	3031
			797 (2)	
Side wall rack sealing assembly				
1	68.7	41.2	284 (1)	5225
			1752 (2)	
3	68.7	41.2	139 (1)	2913
			877 (2)	
4	68.7	41.2	325 (1)	3872
			1550 (2)	

Obtained results enable evaluation of the fatigue limit by force $P_{a,N}$ (precise definition: proportion of samples broken by force $P_{a,N}$ during the number of basic cycles $N_0 = 10^7$, is equal to $1 - \alpha = 0.95$). Let P_j, N_j be the load and number of cycles to fracture for the j-th sample. To reduce the load to a basic number of cycles, we will use the «upper» part of the fatigue curve with index m_1, $\overline{P_j} = P_j (N_j / N_0)^{1/m_1}$. Based on [5, item 6.3.3.1] limit $P_{a,N}$ is equal to

$$P_{a,\,N} = \mathrm{M}[P] + Z_{1-\alpha}\sigma[P], \qquad (1)$$

where M[P], $\sigma[P]$ are the estimates of mathematical expectation and standard deviation; $Z_{1-\alpha}$ is the quantile of $1 - \alpha$ level for the normal distribution with zero mathematical expectation and unit variance.

Table 2. Fatigue limit values of welded joints of a gondola car of 12-4106-01 model

Points	Fatigue strength $\sigma_{a,\,N}$, MPa	
	Bolster assembly	Side wall rack sealing assembly
1	32.2	12.1
2	33.6	19.0

Fatigue limit (by stresses) $\sigma_{a,\,N}$ are the stresses due to the action of force $P_{a,\,N}$. Finite element models of the studied assemblies have been developed for their determination. Distribution of stresses from applied working loads in the samples is given in Figures 7, 8. Performed calculation confirms that stresses are maximum in the points, where cracks initiate (Figure 6, blue marks).

Strain measurement of samples was conducted to check the validity of modeling results. Stresses were measured in 15 points on the bolster assembly and in 8 points on the side wall rack sealing assembly, respectively.

Table 2 gives the experimentally established values of fatigue limit $\sigma_{a,\,N}$ of the studied assemblies. Minimum fatigue limit values for them are equal to 12.1 MPa (side wall rack sealing assembly), and 33.6 MPa (bolster assembly). Established values of fatigue limit, as shown by calculation of car body stressed state, guarantee operation up to initiation of a fatigue crack for 34.1 and 57.0 years for the boslter assembly and side wall rack sealing assembly, respectively.

Conclusions

1. Performed experimental-calculation studies of fatigue resistance of full-scale samples of the bolster assembly and side wall rack sealing assembly of a gondola car of 12-4106-01 model revealed that their

operating life depends on fatigue resistance of welded joints of assembly structural elements. Fatigue limit for them is equal from 12.1 MPa (side wall rack sealing assembly) up to 33.6 MPa (bolster assembly).

2. It is found that in the studied assemblies of gondola car of 12-4106-01 model the fatigue cracks initiate in two most stressed zones. The established values of fatigue limit, as shown by calculations of stressed state of the car body, guarantee operation up to initiation of the fatigue crack during 34.1 and 57.0 years for the bolster assembly and side wall rack sealing assembly, respectively.

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