Stress-strain state analysis of the leading car body of DPKr-2 diesel train under action of design and operational loads

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Abstract. Purpose. Provision of strength and durability of the main structural element of DPKr-2 diesel train - the leading car body. **Methodology.** A spatial solid-state 3-D model of the body is built and durability calculations are carried out concerning action of loads stipulated by regulatory documents operating in Ukraine. In particular, the following main estimated modes are considered: mode 1 – a notional safety mode which takes into account the possibility of considerable longitudinal forces arising during shunting movements, transportation and accidental collision; mode 2 – an operational mode which takes into account forces acting on a train during acceleration to constructional speed, coasting or braking from this speed while passing a curve. **Results.** Based on the results of theoretical and experimental studies a conclusion has been made that the leading car body construction of DPKr-2 diesel train meets the requirements of regulatory documents regarding strength and durability. **Practical relevance.** A complex of calculation and experimental work concerning assessment of stress-strain state of the leading car body of DPKr-2 diesel train under action of design and operational loads allowed the creation of construction which meets not only operational requirements but also strength and durability ones.

1. Introduction

Diesel trains are one of the main kinds of rolling stock which is successfully exploited in many countries of the world for suburban and interregional passenger transportation on unelectrified sections of railways. One of such latest developments of the national producer is DPKr-2 diesel train designed and manufactured at Kryukovsky Railway Car Building Works.

DPKr-2 diesel train consists of three railcars: 2 leading cars of model 63-7083 and one intermediate car of model 63-7084 (Fig. 1).

The main technical characteristics of DPKr-2 diesel train are given in Table 1.

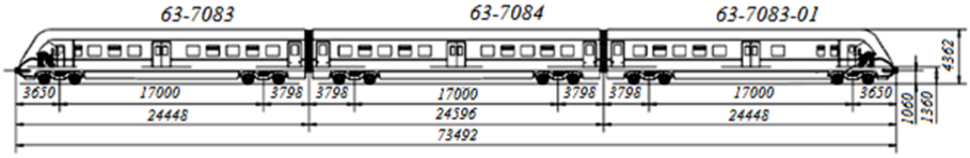

Fig. 1. Scheme of DPKr-2 diesel train

Table 1. Main characteristics of DPKr-2 diesel train.

Parameter, dimensionality	Standard for a car
Track width, mm	1520
Car gauge according to GOST 9238	T
Car framework, mm - leading car, model 63-7083 - intermediate car, model 63-7084	 17000 17000
Car width, mm	3500
Car height, mm	4400
Height of automatic hitch axis from the top of rails, mm	1060 ± 20
Car length along the hitch axes: - leading, mm - trailer, mm	 24596 24596
Passenger capacity/number of seats, pc:	637/289
Car tare-weight, t: car of model 63-7083 car of model 63-7084	 63,5 61,2
Maximum static pressure of a wheelset on the rails, tf: - leading car - intermediate car	 20 20
Engine unit capacity, kW	3x390
Maximum operating speed, km/h	140
Length of turnover section, km	up to 1000
Height of boarding platforms from the top of rail, mm millimeters	high – 1100 low - 200
Amount of fuel in every car, l	1000

To provide operation reliability and safety of DPKr-2 diesel train, specialists of Dnipro National University of

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Railway Transport and PJSC "Kryukovsky Railway Car Building Works" have conducted a complex of theoretical and experimental studies, in course of which the conformity of diesel train construction to the requirements of regulatory documents operating in Ukraine [1-2] and the requirements of statement of work has been checked. One of the main kinds of studies mentioned above was the assessment of strength, including fatigue strength, of the main load-bearing elements of DPKr-2 diesel train – frames of body and bogies.

The complex of calculation and experimental work of stress-strain assessment of the bogie frames of DPKr-2 diesel train under action of design and operational loads is outlined in work [3]. General issues related to design, manufacturing and putting into operation of new types of bogie frames of self-propelled rolling stock in the countries of the European Union are presented in works [4-7].

Quite a big number of works, e.g. [7-13], are devoted to the issues of theoretical and experimental research of strength and durability of welded car bodies, but none of them uses legal framework for multiple unit rolling stock operating in Ukraine.

2. Research methodology

To assess the strength of railway rolling stock, including self-propelled one, a legal framework based on fundamental research in the field of material fatigue is used in Ukraine and abroad. However, criteria for this assessment differ qualitatively. In particular, in Ukraine the fatigue strength assessment is carried out using fatigue safety factor [1-2] which should not exceed the normative value. In EU countries the fatigue strength assessment is carried out upon allowable stresses, which, in turn, are determined using ultimate stress charts [14-15]. In work [16] a comparison of the regulatory documents mentioned above is conducted which leads to the conclusion about good convergence of results obtained with regard to standards applicable in Ukraine and EU countries.

Strength assessment, including fatigue strength one, of DPKr-2 diesel train leading car was conducted according to the requirements [1] in two steps:

– theoretical studies aimed at choosing parameters of main load-bearing elements of the body and establishing installation positions of measuring devices during tests;

– experimental studies (static strength tests, navigation strength tests and collision tests) aimed at determining actual parameters characterizing the construction strength.

While dimensioning a diesel train car the ANSYS Workbench [17-18] package of applications (PA) is used which is characterized by a high degree of strength calculation automation at the stage of project-related research. This PA permits any combination of static pressures and allows for stress state at the elastic stage of both the whole car body construction and its separate nodes to be analyzed with a different degree of detailing.

An estimated 3-D model of the leading car body designed with the help of the ANSYS package of applications (PA) is presented in (Fig. 2). The model contains 1071131 elements and 1646383 nodes.

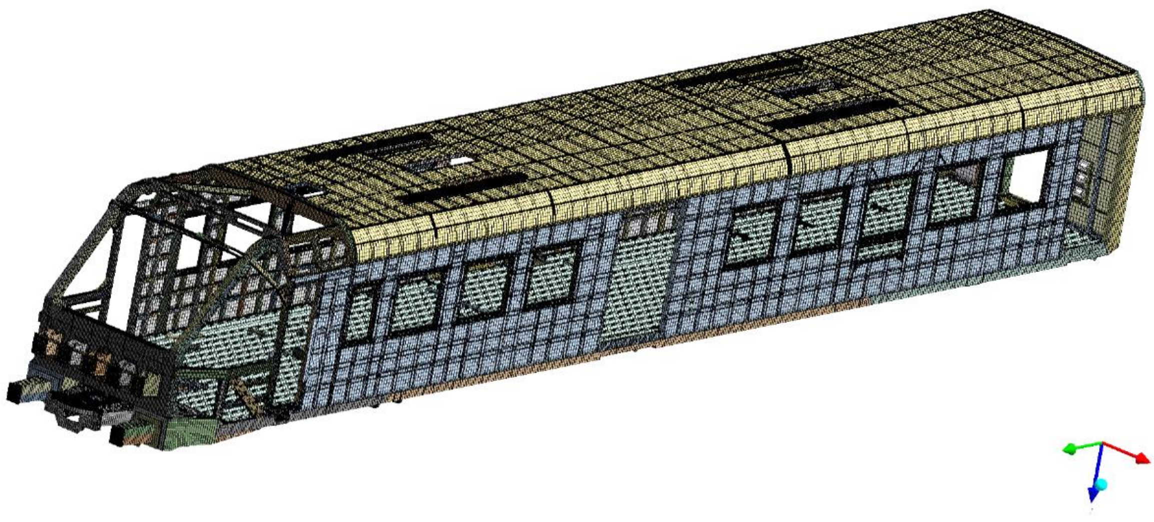

Fig. 2. Estimated 3-D model of the leading car body of DPKr-2 diesel train

Separately, the above given estimated scheme of the body is presented by a set of substructures integrated into a general estimated scheme. This approach allowed an independent preparation and adjustment of input data to be made for each substructure. After that system assembly and task solution can be performed. While designing the finite-element model of the body, flat quadrangular and triangular finite elements were used and an assumption was introduced that the construction material works in the elastic stage of deformation and has permanent characteristics – modulus of elasticity $E = 2,0 \cdot 10^5$ Mpa and Poisson's ratio $\mu = 0,3$ [19]. Car resting on bogie is presented in the estimated scheme by introduction of kinematic links into nodes which correspond to the support.

Car strength, according to [1], is calculated for 2 main estimated modes:

Mode 1 – a notional safety mode. This mode takes into account the possibility of considerable longitudinal forces arising during shunting movements, transportation and accidental collision;

Mode 2 – an operational mode which takes into account forces acting on a train during acceleration to constructional speed, coasting or braking from this speed while passing a curve.

During calculation for mode 1 the following main forces were applied to the estimated model:

– normative longitudinal compressive force of 1500 kN acting along automatic hitch axes;

– gross gravitational force of the body of 699 kN, in this case gravitational forces of equipment elements were applied at the points of their attachment to the body framework.

During calculation for mode 2:

– normative longitudinal tensile force of 800 kN;

– longitudinal inertia forces acting on separate nodes and elements which were identified by multiplying their mass by acceleration of the body;

– gross gravitational force of the body of 699 kN;

– vertical dynamic force which was identified by multiplying gross gravitational force of the body by the normative value of vertical dynamics ratio in the second stage of hanging which equals 0.2;

– centrifugal inertia force of the body proceeding from undamped acceleration while moving around a curve which equals 0,7 m/s^2.

Strength assessment for mode 1 was carried out upon allowable stresses, for mode 2 – upon allowable stresses and fatigue safety factor. Allowable stresses for estimated modes 1 and 2 are given in table 5.1 of standards [1].

To determine fatigue safety factor n the following proportion was used:

$$n = \frac{\sigma_{-1}}{k\sigma_v + \psi\sigma_m}, \quad (1)$$

where σ_{-1} – endurance limit of a standard sample in the symmetrical cycle of loading which was chosen depending on the steel grade using table 5.2 of standards [1];

σ_m – average stress of a cycle which was determined in every structural element under action of gross vertical static load;

σ_v – amplitude of dynamic stresses which was identified from the proportion $\sigma_v = k_d\sigma_m$, where k_d – vertical dynamics ratio in the second stage of suspension. On the basis of dynamic calculation results [20] of a diesel train $k_d < 0{,}1$. Normative (maximum permissible) value of vertical dynamics ratio is 0,2. Therefore during calculation the maximum value of $k_d = 0{,}2$ was accepted;

ψ – a coefficient reflecting the sensitivity of a metal to cycle asymmetry (if $\sigma_m > 0$ $\psi = 0{,}3$, if $\sigma_m < 0$ $\psi = 0$);

k – effective coefficient reflecting endurance reduction of a detail in relation to endurance limit of a standard sample.

Coefficient k was determined from the proportion:

$$k = \beta_k \frac{k_1 k_2}{\gamma m}, \quad (2)$$

where β_k – effective coefficient of stress concentration was accepted as equal to 1;

k_1 – coefficient reflecting material heterogeneity of the detail, for rolling $k_1 = 1{,}1$;

k_2 – coefficient reflecting the influence of inner stresses in the detail depending on detail size $k_2 = 1{,}0...1{,}2$;

γ – coefficient reflecting the detail sizes which was determined according to the graph given in figure 3,5 of standards [1];

m – coefficient reflecting the surface state of a detail, for rolling $m = 0{,}8$.

According to requirements [1], fatigue safety factor must be not less than normative value -2.

Based on conclusions from the analysis of calculation results for modes 1 and 2, installation positions of measuring devices during static strength tests, navigation strength tests and collision tests were established.

3. Research results

Figure 3 illustrates fields of equivalent (according to the Mises-Hencky theory) stresses in the structure of the leading car body of DPKr-2 diesel train as well as nodes in which there are maximum stresses under action of loads corresponding to estimated mode 1.

Table 2 presents allowable stress values and maximum stresses obtained as a result of calculation for estimated mode 1.

The presented results show that under loads simulating accidental collision and shunting movements maximum stresses in the most loaded elements of the body construction do not exceed allowable values, i.e. strength in estimated mode 1 is ensured.

Figure 4 illustrates fields of equivalent (according to the Mises-Hencky theory) stresses in the structure of the leading car body of DPKr-2 diesel train as well as nodes in which there are maximum stresses under action of loads corresponding to estimated mode 2.

Table 3 presents allowable stress values, maximum stresses and fatigue safety factors obtained as a result of calculation.

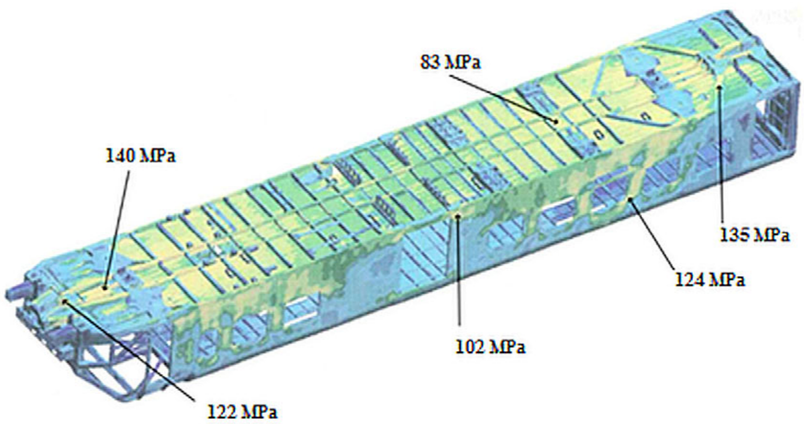

Fig. 3. Stress state of the structure of the leading car body of DPKr-2 diesel train under action of loads corresponding to estimated mode 1 (view from below)

Table 2. Maximum stresses in the main structural elements of the body under action of loads corresponding to estimated mode 1.

Structural element of the body	Steel grade	Allowable stresses, mPa	Equivalent stresses, mPa
Underframe			
Spine beam (head part)	325-09Г2С	292	122
Centre bearer	295-09Г2С	265	140
End girder	345-09Г2С	327	93
Cantilever unit diagonals	345-09Г2С	327	135
"Power pack" mount beams	345-09Г2С	327	85
Side wall			
Window opening vertical struts	08X18H10	194	127
Doorway vertical struts	08X18H10	194	102
Lower door beam	08X18H10	194	88
Cab framework			
Cab door step	345-09Г2С	327	95
Doorway pillar	345-09Г2С	327	83
Roof			
Longitudinal beam	08X18H10	194	39
Cross-beam	08X18H10	194	37
Air conditioner support	08X18H10	194	42

Note to table 2. Low alloy steel 09G2S is an analogue of European steel DIN 16Mn6, stainless steel 08X18H10 – European steel DIN 1.4301.

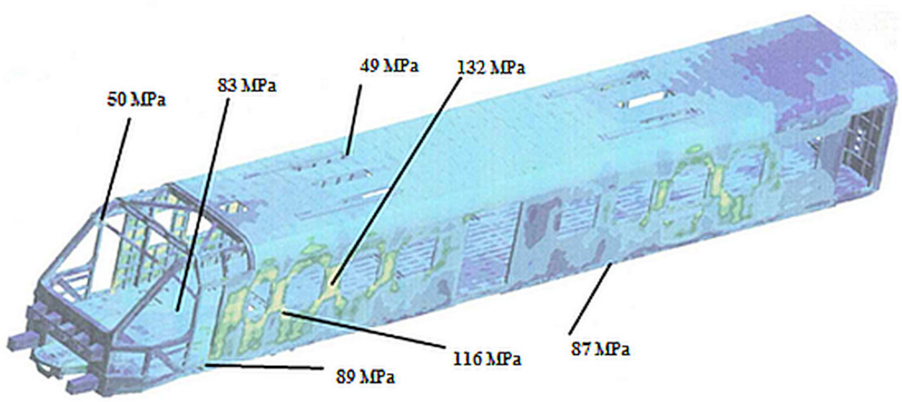

Fig. 4. Stress state of the structure of the leading car body of DPKr-2 diesel train under action of loads corresponding to estimated mode 2.

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Table 3. Maximum stresses in the main structural elements of the body and fatigue safety factors under action of loads corresponding to estimated mode 2.

Structural element of the body	Steel grade	Allowable stresses, mPa	Equivalent stresses, mPa	*n*
Underframe				
Spine beam (head part)	325-09Г2С	205	103	3,1
Centre bearer	295-09Г2С	195	83	3,6
Side rail (the middle of the wagon)	325-09Г2С	205	62	5,1
“Power pack” mount beams	345-09Г2С	220	92	3,6
Stair mechanism cross-beam	345-09Г2С	220	80	4,1
Side wall				
Vertical strut	08X18H10	138	112	2,6
Strut under window	08X18H10	138	96	3,0
Upper window opening beam	08X18H10	138	76	3,6
Lower window opening beam	08X18H10	138	87	3,3
Cab framework				
Cab door step	345-09Г2С	220	89	3,7
Inclined beam of the cab	345-09Г2С	220	50	5,7
Roof				
Longitudinal beam	08X18H10	138	36	7,9
Air conditioner support	08X18H10	138	49	5,8

The analysis of stress state of the leading car body shows that maximum stresses in the most loaded elements of body construction do not exceed allowable values and fatigue safety factor is significantly higher than the normative value 2.

Based on the results of theoretical studies described above, a strain gauge layout chart has been developed for the purpose of conducting static strength tests, navigation strength tests and collision tests. Figures 5-7 illustrate examples of strain gauge layout during the testing mentioned above.

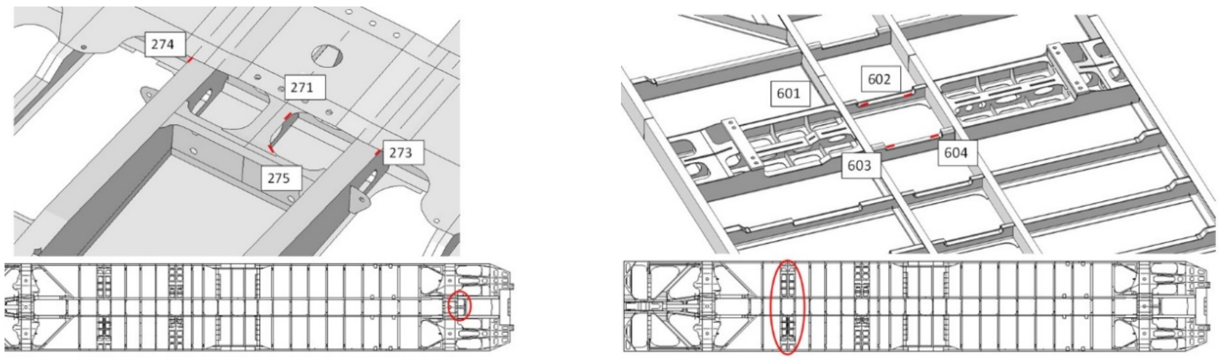

Fig. 5. Strain gauge layout on the underframe

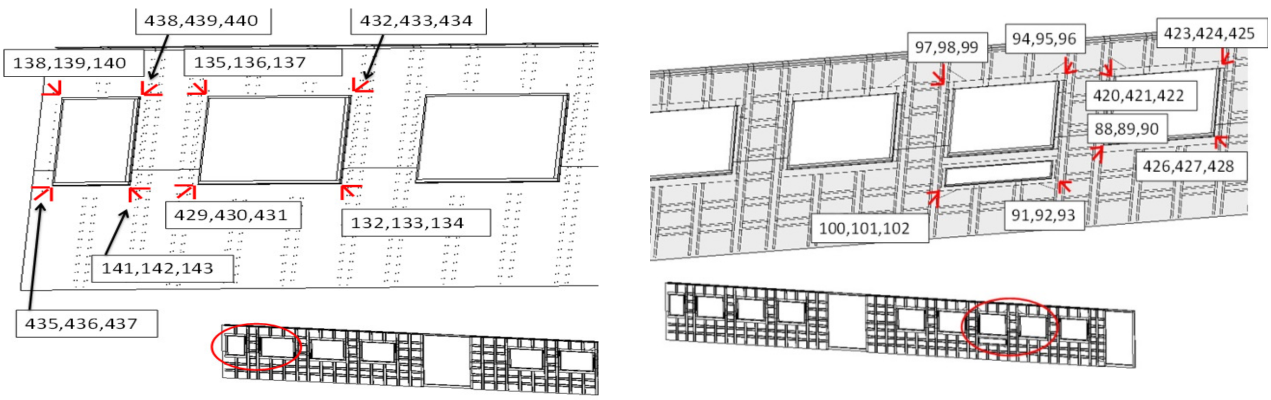

Fig. 6. Strain gauge layout on the side walls

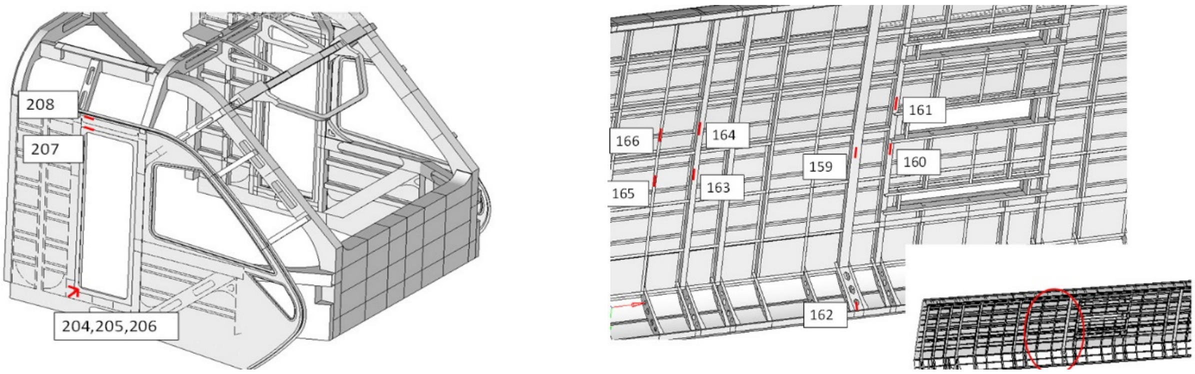

Fig. 7. Strain gauge layout on the cab framework and roof

The analysis of static strength testing and navigation strength testing results showed that the minimum value of fatigue safety factor occurs in the area of power unit fastening to the underframe and equals 3.7 (point 252, Fig. 5).

According to the collision testing results, the most loaded is the junction area of spine and longitudinal beams where stresses reached the values of 210 mPa (points 271, 275, Fig. 5) with the force of impact of 1750 kN.

On the basis of theoretical and experimental research results it was concluded that the construction of the leading car body of DPKr-2 diesel train meets the requirements of regulatory documents against the criteria of strength including fatigue one.

4. Scientific novelty and practical relevance

1. For the first time a spatial finite-element model of a diesel train body of a new generation is built and calculation of strength under action of standard loads is made.
2. An estimated scheme of the body is presented by a set of substructures integrated into a general estimated scheme. This modular approach made it possible to make an independent preparation and adjustment of input data for each substructure and after that perform the system assembly and task solution.
3. Modular approach to the estimated scheme design makes it possible to use it for the strength assessment of the body of diesel trains of new generations changing only the structural elements that are subject to upgrading.

Conclusions

The complex of calculation and experimental work on stress-strain state assessment of the leading car body frame of DPKr-2 diesel train under action of design and operational loads made it possible to create a construction that meets both operational standards and strength and durability requirements.

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