Modelling of the electric locomotion DS3 working

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Abstract. The purpose of the work is to evaluate the spatial distribution of the rigidity of the carrier frame and the body of the Ukrainian electric locomotive DC3 as a single system during operation and repair. The research was carried out on the basis of the finite element method with the application of design and computing complex SCAD for Windows. The numerical model of the electric locomotive was built, tested and then used to identify the causes and providing guidance on solving some specific operational questions. They are included, for example, the possibility of eliminating the body skew when jacking up on jacks and jamming the door as a result. The researches showed that the structure of the electric locomotive DS3 in general has a rather high spatial rigidity, both in transverse and longitudinal directions, and on torsion. However, for some practical repair tasks there is not enough for that rigidity. It was recommended to increase the thickness of the shell of its body up to 4 mm or the roof up to 8 mm, which leads to an increasing in the total mass of the machine by about 2,5 and 3,5 tons, respectively.

1 Problem statement

In the late 90's of the twentieth century, in Ukraine, at the premises of the Dnipro Electric Locomotive Building Plant (DELBP), the development of the constructional part of the new mainline cargo and passenger electric locomotive of alternative current – fig.1 was launched. 1. At the same time, Siemens Corporation partook in the constructional design of the electrical section of the car. The first 18 pilot electric locomotives were manufactured during 2002 – 2008 and put into operation at the Southwest Railway (place of registration – Kyiv-Passenger depot). It was planned that the car will be used on international routes as a new generation of modern electric locomotives additionally intended for the markets of China and India.

Structurally, the engine is a one-section 17 m long locomotive with a nominal weight of 90 t designated for a track of 1520 mm wide. Construction speed is 160 km/h.

Since 2008 the production of these cars has initially been slowed down and then completely suspended. According to various data, today there are only 3 engines, which are in satisfactory condition. Other engines are either decommissioned, mainly due to lack of spare parts, or under repair.

Along with the economic reasons associated with the global crisis of 2008 – 2010, some exploitation and maintenance issues of the engine in question have had no small share in this situation.

2 Analysis of recent research and publications

The constructional design of the electric locomotive DS3 was carried out in accordance with the norms [1], which at that time were, in fact, the only available norms that regulated the development of the supporting elements of electric locomotives. Concurrently, the constructional design was carried out on the basis of traditional approaches that were based on consideration of the electric locomotive as a system of solids [2], which together represented a mechanism. Without a doubt, such a simplified modeling of the engine required a great deal of ingenuity from constructional design engineers, since such models had far more assumptions than factual data. Therefore, to get a foresight about the actual work of an engine designed under such circumstances was possible only after its manufacturing on the basis of relevant testing.

Similar testing was carried out in 2003 by specialists of the branch research laboratory (BRL) of the dynamics and sustainability of the rolling stock of the Dnipro National University of Railway Transport named after academician V. Lazaryan. Their results were presented in a series of publications: static sustainability tests in the publication [3], dynamic sustainability tests – in the publication [4], and shock tests – in the publication [5].

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Fig.1. Mainline electric locomotive DS3.

The main conclusion, based on the review of these works, made by the authors, is that, in general, the electric locomotive DS3 meets the requirements of the norms. However, there are individual places in its construction that require additional attention and should either be reinforced or refined, since the load in them is too big. Separately maximum speeds for the motion of the electric locomotive DS3 in the curves of different radii [6], in railroad switches [7] were outlined, and joints, which needed improving, in particular, brake transmission were defined [8].

On the basis of the given recommendations the modernization and improvement of the constructional design of the electric locomotive DS3 was carried out, which increased the engine's operational reliability. remain the only alternative.

2.1 Unresolved issues

Exploitation of part of the experimental batch of DS3 electric locomotives during 2004 – 2007 revealed the necessity to carry out the engine's lifting on jacks during the work on maintenance and repair of the car. In this case, there was often a jamming of the superstructure's door, which complicated the carrying out of repair work.

In this regard, the question about the supporting capacity of the superstructure of the engine in the event of its possible uneven supporting arose. Such calculation is not provided for by norms [1]. In addition, it needed a qualitatively different approach that would allow taking into account the dispensation of rigidity in the supporting frame and the superstructure of the electric locomotive, under the condition of changing the nature of the engine's supporting.

The rapid development of computer technology in the beginning of the twenty-first century gave impetus to the development of qualitatively different approaches to the constructional design of mechanical-engineering in general, and locomotives in particular. Thus, one of the methods of building mechanics – The Method of Finite Elements – got widespread development (MFE) [9], and on the basis of which there were developed many software products for its computer implementation. One of these products is the project-computational complex SCAD for Windows, which has become very popular on the domestic market since approximately 2005 – 2007. Despite its construction orientation, it has successfully been applied in the machine-building industry as well [10].

In international practice, more versatile software products under MFE have been developed, such as ANSYS [11], NASTRAN [12], CosmosWorks [13], or SolidWorks [14]. They allowed for machine-building constructions to perform not only linear static analysis, but also nonlinear analysis [15], dynamic analysis [16], and sometimes even investigating the processes of destruction of material [17]. However, up to now, their cost in the market is very high, so powerful domestic software development, such as SCAD for Windows [18] or Lira for Windows [19], remain the only alternative.

2.2 Purpose of the research

The assessment of the spatial distribution of the rigidity of the supporting frame and the superstructure of the DS3 electric locomotion as a single system with the use of software products for the MFE implementation was identified as the main goal of the research carried out by the authors.

Moreover a number of following tasks were subsequently formulated and solved. Firstly, it was necessary to construct a numerical model of the electric locomotive, which would include appropriate boundary conditions and load for different modes of its operation.

Secondly, the created model had to be checked by comparing the results of calculations with experimental data. Thirdly, on the basis of the tested model of the engine, to evaluate the nature of the distribution of the rigidity of the engine and provide recommendations for repair and maintenance work, in particular with the use of jacks.

3 Main material presentation

To construct a finite-element model (FE-model) of the DS3 electric locomotive and to conduct further research of the engine's work on its basis, SCAD for Windows versions 11.1-11.3 was selected. Due to its construction orientation during the simulation, it became necessary to adapt this product in a certain way for the purpose of modeling machine-building constructions. The main methods of calculation, developed and tested by the author in this regard, are highlighted in his publication [10]. As a result, it was possible to accurately illustrate in the model both necessary boundary conditions in the course of engine's functioning in different operating modes, and the nature and location of load of sources that created static and dynamic impacts on the structure.

Designed by the authors the FE-model of the electric locomotive DS3 is presented in Fig. 2. It is a plate-core system and consists of about 50,000 elements, mainly of isoparametric type. The total number of joints reaches 40,000, which results in about 250,000 degrees of freedom.

The carrier beam of the electric locomotive frame and the elements of the carcass and the superstructure of the engine were modeled by core finite elements, for which the required cross section was set. Coating of the superstructure, cab and deck of the electric locomotives, as well as the interior floor, were modeled with lamellar finite elements of required thickness. For the simulation of the location of internal equipment, special "rigids" the rods of considerable rigidity and at the same time insignificant mass were used. With their help, it was possible to accurately place on the model the available masses from the elements of the equipment.

Numerical analysis and all necessary calculations were carried out in a physically and geometrically linear formulation. Thus, the first of the formulated research tasks was solved.

For the solution of the second task of research, a comparison of the results of calculations based on the FE model of the electric locomotive DS3 with the results of its experimental studies, which, as already noted above, were performed in 2003 by the specialists of the GNDL of the dynamics and sustainability of the rolling stock of the Dnipro National University of Railway Transport named after academician V. Lazaryan.

The comparison was performed for the most loaded and therefore the most dangerous first mode of the engine's functioning, which assumed the effect of the compressive force of 2500 kN. The scheme of placing of experimental sensors on the elements of the electric locomotive, together with their original designations taken during the experiment, according to the functioning [3] is shown in Fig. 3. The stress values at these points, obtained after processing data measurements of strain indicators, according to the results of the summary report, are given in Table. 1. Additionally, there are the strains obtained from the FE modeling. The error in the last column is computed in relation to the experimental values.

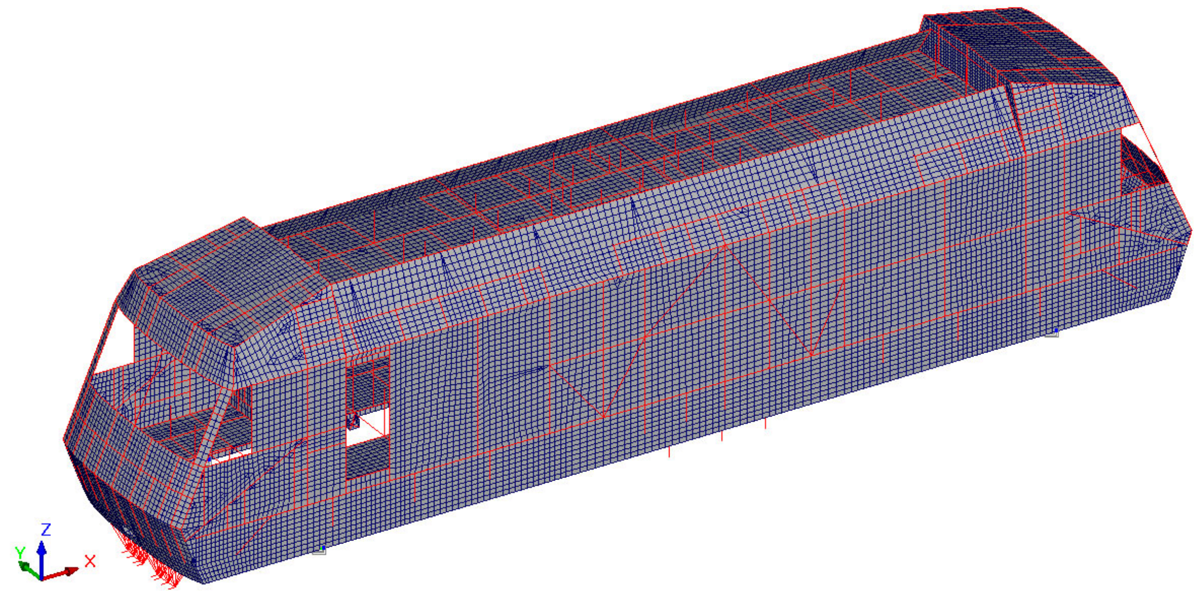
In general, the comparison of the results showed a fairly good level of commonality between numerical and experimental data. The average error was about 15%. However, at the point YP1 (highlighted in darker colors) the computational stress was significantly different from the experimental data. Unfortunately, we could not determine the reason for this deviation. Most likely it is connected with the fault of the sensor itself or its poor-quality connection to the elements of the construction. On the cross-bearer beams of the superstructure the stress values were generally low in absolute magnitude and slight deviations from them already give a high error. Therefore, for some sensors with a stress level below 10 MPa (limit of instrumental error) this error was not calculated.

It should also be noted that the FE-model was originally constructed only for the engine frame with a part of its coating. However, in contrast to the experimental data, the discrepancy was very significant and reached 2-3 times. Therefore, it was decided to modulate also the superstructure, the roof and the entire internal system of load bearing partitions (the final model is shown in Fig.2. The results obtained after this are shown in Table 1.

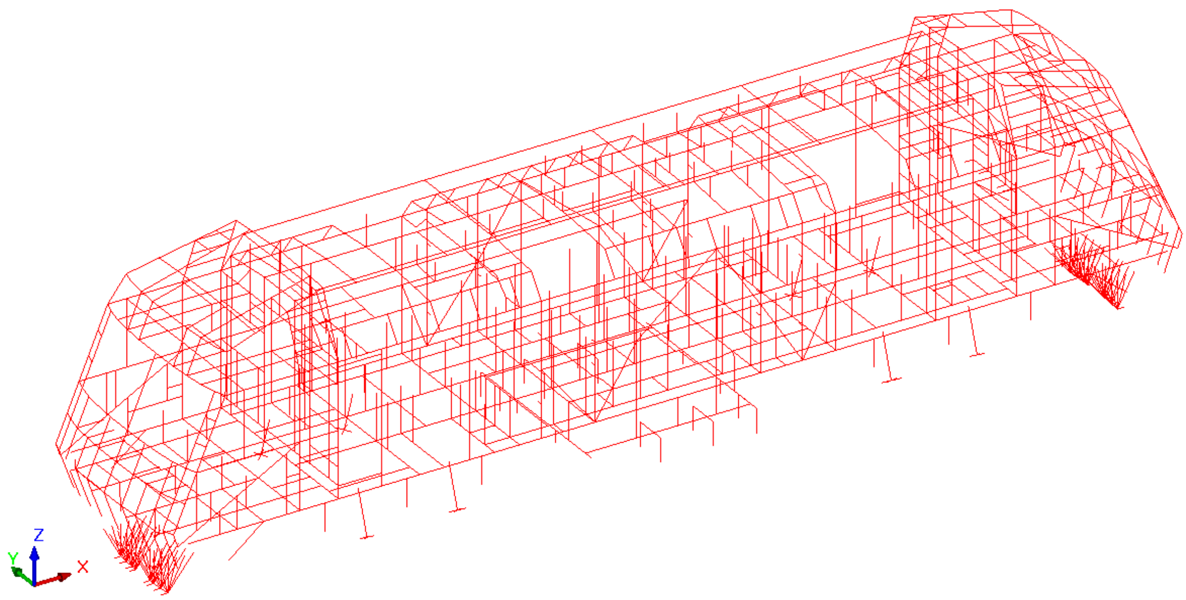
Thus, one of the interim conclusions of the research was the conclusion on the significant impact of the superstructure on the overall stress-strain state (SSS) of the electric locomotive structure and the necessity of its mandatory consideration in conjunction with the carriage frame.

The tried and tested FE model of the electric locomotive DS3 was further used to assess its deformed state when using jacks for repair work. Fig. 4 shows the scheme and markings of the points in which the assessing of movement of superstructure and doorways of the electric locomotive DS3 in different directions during the change of the points of support was performed. In Tables 2 and 3 there are the results obtained for different variants of the location of the supports.

From the analysis of the obtained data it was found that approximately equally unfavorable are the cases of leaning of the superstructure of the electric locomotive DS3 against both two and three diagonally placed supports. Moreover, the largest vertical deflections occur in the buffer beams and reach values of approximately 13 mm, which practically does not affect the angle of twisting of the superstructure of the electric locomotive and can be considered as relatively acceptable. However, moving the doorways at the same time reaches the value of approximately 7 mm, which practically leads to the jamming the doors. It should also be noted that the strain in the elements of the supporting frame and the superstructure of the engine did not exceed 50 MPa, which is a totally acceptable level.



a)



b)

Fig. 2. Numerical model of electric locomotive DS3: a – general view; b – rod frame of the model.

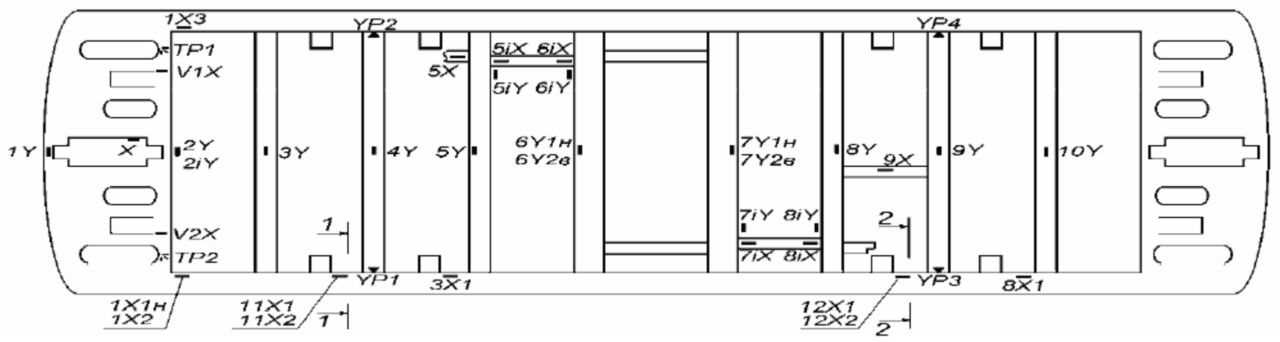


Fig. 3. Scheme of control sensors' placement.

After detecting this characteristic of the engine the developers offered several options for enhancement. It should be noted that all suggestions regarding the reinforcement of supporting structures of the electric locomotive DS3 encountered a constructive limitation of the weight of the engine in 90 tons, because the actual mass of the designed engine was already very close to it. There were even attempts to lower it due to the installation of hatchways in various elements of the engine. However, this did not add to the overall rigidity of the electric locomotive construction, but on the contrary, lowered it.

It should be noted that similar simulation of various variants of DS3 weight reduction was also carried out by the author of the publication using the project-computational complex SCAD for Windows.

In the result, as the main working decisions, two of the most effective options were selected – an increase of thickness of the superstructure's coating from 1.5 mm to 4 mm, or an increase of the thickness of the engine's roof's coating from 1.5 mm to 8 mm. According to numerical simulation, both options allow to increase the general rigidity of the electric locomotive superstructure and reduce deformation values by 15 – 25%. Under such conditions, the total weight of the engine increases in the first case by about 2,5 tons, and in the second by about 3,5 tons.

A corresponding change in the characteristics of the electric locomotive DS3 required additional special tests. However, due to the gradual curtailment of the production of this engine, such works were not carried out.

Table 1. Comparison of experimental and numerical data.

№	Sensor	Stress values, MPa		Error (%)
		Expe-riment	**FE-modeling**	
Main beams of the base frame of the carriage body				
1.	1X1	-185	-155 ÷ -230	-16 ÷ +24
2.	1X2	-77	-67	-13
3.	11X1	-116	-105 ÷ -125	-9 ÷ +8
4.	11X2	-85	-76	-11
5.	3X1	-157	-110 ÷ -120	-30 ÷ -24
6.	12X1	-108	-100 ÷ -120	-7 ÷ +11
7.	12X2	-69	-74	+7
8.	8X1	-123	-130 ÷ -135	+6 ÷ +10
9.	УП1	54	-25	-146
Cross-bearer beams of the base frame of the carriage body				
10.	3Y	0	+9	–
11.	4Y	-1	+16	–
12.	5Y	+3	+16	–
13.	5iY	+18	+16	-11
14.	5X	-9	-6	–
15.	5iX	-9	-7	–
16.	6Y1	+11	+13	+18
17.	6iY	-3	-6	–
18.	7iX	-13	-9	-31
19.	7iY	+10	+10	–
20.	8iX	-18	-7	-61
21.	8iY	+8	19	–
22.	9X	-48	-35	-27
Buffer beam				
23.	1Y	290	-225 ÷ -240	-22 ÷ -17
24.	2Y	103	+100 ÷ +115	-3 ÷ +12
25.	2iY	82	+100 ÷ +110	+22 ÷ +34
26.	B2X	14	+15	+7
27.	X	225	+150	-33
28.	Y	99	+100 ÷ +110	+1 ÷ +11

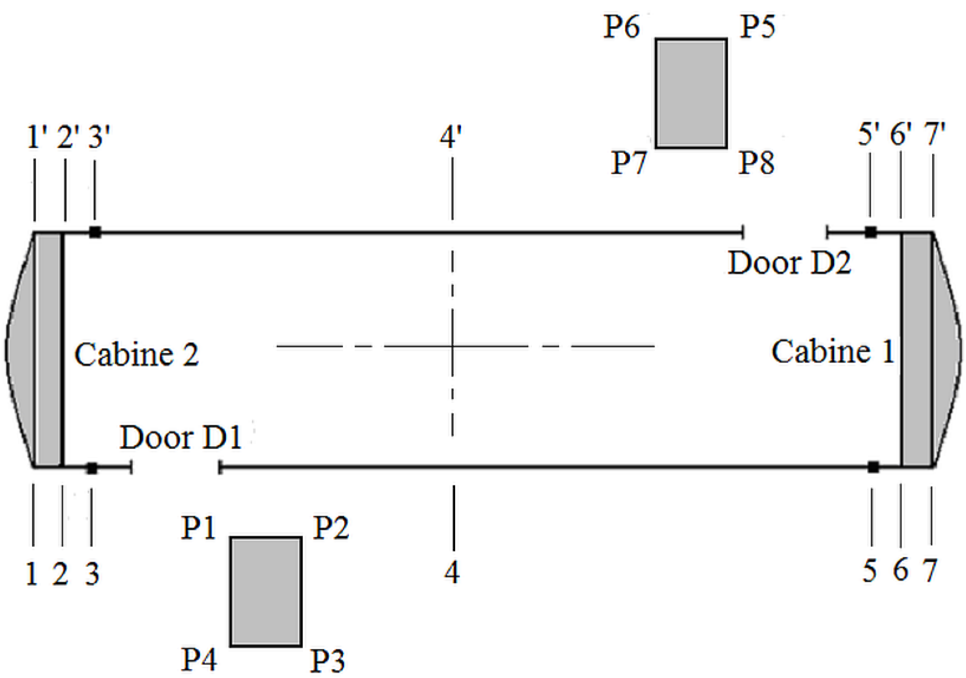


Fig. 4. Points for assessing the movement of the body and doorways of the electric locomotive DS3 while changing the points of support

Table 2. Deflection of the superstructure of the electric locomotive DS3.

Point	1 (1')	2 (2')	3 (3')	4 (4')	5 (5')	6 (6')	7 (7')
Coordinate	**0**	**1105**	**2080**	**7890**	**13700**	**14675**	**15780**
Supporting:							
4 points	-0,04 (-0,04)	-0,06 (-0,07)	-	-1,44 (-1,40)	-	-0,07 (-0,07)	-0,03 (-0,05)
3 points along the diagonal of the doors	-0,64 (-12,97)	-0,36 (-12,36)	0,00 (-11,66)	-1,58 (-7,59)	0,00 (0,00)	0,34 (0,46)	0,67 (1,10)
3 points diagonally without doors	0,62 (1,05)	0,31 (0,42)	0,00 (0,00)	-1,37 (-6,67)	0,00 (-10,98)	-0,36 (-11,64)	-0,59 (-12,22)
2 points along the diagonal of the doors	0,57 (-3,66)	0,20 (-3,70)	0,00 (-3,70)	-5,75 (-3,43)	-8,02 (0,00)	-8,43 (-0,11)	-8,75 (-0,10)
2 points diagonally without doors	-13,11 (-0,70)	-12,47 (-0,41)	-11,69 (0,00)	-7,07 (-1,03)	0,00 (0,64)	0,41 (0,99)	1,17 (1,34)

Table 3. Moving of the doorways of the electric locomotive DS3.

Supporting:	Moving	Door D1					Door D2				
		D1	D2	D3	D4	Δ	D1'	D2'	D3'	D4'	Δ
4 points	longitudinal	0,19	0,18	0,26	0,25	**0,08**	-0,19	-0,19	-0,27	-0,26	**0,08**
	transverse	0,15	0,18	0,12	0,13	**0,06**	1,61	1,65	1,68	1,63	**0,07**
	vertical	-0,33	-0,79	-0,66	-0,27	**0,52**	-0,33	-0,78	-0,64	-0,27	**0,51**
3 points along the diagonal of the doors	longitudinal	-0,55	-0,53	0,19	0,15	**0,70**	2,59	2,57	3,65	3,69	**1,12**
	transverse	9,59	8,76	3,02	3,53	**6,57**	-1,66	-0,74	-2,16	-2,71	**1,97**
	vertical	-0,44	-1,12	-0,84	-0,33	**0,79**	-0,97	-2,31	-2,03	-0,84	**1,47**
3 points diagonally without doors	longitudinal	0,87	0,84	0,33	0,34	**0,54**	-2,31	-2,29	-3,50	-3,51	**1,22**
	transverse	1,47	2,13	0,73	0,43	**1,70**	13,21	12,61	7,28	7,55	**5,93**
	vertical	-0,12	-0,40	-0,40	-0,13	**0,28**	-10,80	-10,42	-10,41	-10,81	**0,40**
2 points along the diagonal of the doors	longitudinal	1,34	1,36	0,84	0,80	**0,56**	4,17	4,15	3,99	4,03	**0,18**
	transverse	2,18	1,42	0,55	0,99	**1,63**	-7,95	-7,10	-3,61	-4,08	**4,34**
	vertical	-0,81	-1,96	-1,67	-0,69	**1,27**	-0,61	-1,49	-1,21	-0,49	**1,00**
2 points diagonally without doors	longitudinal	1,90	1,88	3,19	3,20	**1,32**	-0,59	-0,57	0,04	0,03	**0,56**
	transverse	-9,91	-9,40	-3,65	-3,79	**6,26**	-0,60	-1,05	0,71	0,82	**1,76**
	vertical	-11,55	-11,12	-11,12	-11,56	**0,44**	0,49	0,18	0,19	0,48	**0,31**

4 Conclusions

On the basis of the finite-element simulation of the mainline cargo and passenger electric locomotive of alternative current DS3 functioning, one should state the following:

1. The construction of the electric locomotive as a whole has a rather high spatial rigidity, both in transverse and longitudinal directions, and on torsion. This is confirmed by the conclusions made through a series of various tests by the specialists of the branch research laboratory (GNDL) of the dynamics and sustainability of the rolling stock of the Dnipro National University of Railway Transport named after academician V. Lazaryan.

2. In a number of situations related to the repair work of this engine, there is a need for lifting its superstructure on the jacks. Furthermore, even in the case of uneven lift on two diagonally placed supports, the spatial rigidity of the engine's body is sufficient to provide a suitable level of stress-strain state of the carrier frame and the superstructure of the electric locomotive. However, at the same time, there is a movement of the doorways, which is ample for superstructure doors jamming/

3. Elimination of this characteristic of the electric locomotive DS3 requires an increase in its superstructure's coating to 4 mm or the roof's coating to 8 mm, which leads to an increase in the total mass of the engine by about 2.5 and 3.5 tons, respectively. Taking into account the constructional limitation of the weight of the engine at 90 tons, as well as the need for special additional tests, such a reinforcement of the electric locomotive cannot be recommended as final.

4. Simulation with the help of FE-modeling, in particular on the basis of project-computational complex SCAD for Windows, can be used with high probability to simulate the operations of the electric stock structure of the railways s in general and electric locomotives in particular.

In concluding, the authors of the publication would like to express their sincere gratitude to the team of developers of project-computational complex SCAD for Windows, who kindly provided the authors at one time with the possibility of conducting scientific research and practical calculations – doctor of technical sciences. A.V. Perelmuter, candidate of technical sciences. A.M. Perelmuter, candidate of technical sciences V.S. Karpilovsky, Ye. Z. Kryksunov, O.M. Trofymchuk.

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