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PhD Thesis Summary

Studiu privind sporirea capacității de transport a unui vagon descoperit, cu pereți înalți

Study of increasing the load capacity of an open high-walls wagon

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Bucharest – 2020

CONTENT

INTRODUCTION

The paper “Study on increasing the transport capacity of an open wagon, with high walls” presents the analysis of the structure strength of an open wagon, with high walls, Eaos series, aiming to increase the transport capacity of the vehicle. In this regard, the following steps have been taken:

- research has been carried out in the field, in order to establish the development trends of this type of vehicle;
- the geometric model of the main vehicle that was the basis of the study was made, through the ANSYS numerical analysis software;
- the numerical analysis of the realized model was performed, following the state of stress and displacements in the vehicle structure, as a result of the application of standardized loads. The main areas of interest on the entire structure of the wagon have been established;
- using the results obtained in the previous step, experimental analysis were performed by the resistive electrical tensometry method, using a special test rig;
- the model was validated starting from the obtained experimental results;
- experimental and numerical buffing analysis of the the vehicle structure were performed, following the strains evolution occurred in the vehicle structure;
- new constructive solutions were established to increase the transport capacity of the vehicle and numerical analysis were performed in which the stress evolution and the displacements evolution were followed, as a result of the application of standardized loads.

1. THE TOPICALITY OF THE THESIS SUBJECT

Starting from the European development trend of the rail freight transport system and implicitly in our country, finding solutions to increase the transport capacity is absolutely necessary for the efficiency of rail freight transport.

Currently there is a limited series (from a constructive point of view) of this type of wagon, the transport capacity being low, below the maximum limit of 22.5 tons per axle.

Given the high costs required to develop a new project, the improvement of existing rail vehicles is an optimal solution for streamlining freight rail transport.

Following the parks of freight wagons in Romania, it can be easily observed that the vehicles have a high degree of wear and aging (due to erosion, aging of the material, plastic displacements etc.) [2], these being in use for many years now.

The activity of designing new railway vehicles is almost non-existent in Romania, this being almost replaced by the repair and modernization activity of vehicles whose structure is already aged.

The topicality of the thesis is given by the presentation of viable, new variants of open high walls railway vehicles, which could represent a solution for the renewal of the freight wagon fleet. Also, following the general trend in the field of rail freight transport, the new structural solutions presented in the paper offer the advantage of increasing the transported loads.

1. THE IMPORTANCE OF THE THESIS SUBJECT

Freight rail transport occupies an important place in society, offering a multitude of advantages, such as: high transport volume, low energy consumption, speed, safety, zero CO_2 emissions in most cases, etc.

In order to improve the quality of rail freight transport, it is necessary to use new vehicles that meet a number of conditions, as follows:

a. Transport safety;

Railway vehicles must ensure full safety in the transport activity, by fulfilling all the conditions regarding the strength, braking, dynamic rolling behavior, noise, etc. The use of vehicles that do not comply with these minimum conditions of transport safety, or the use of aged vehicles that no longer offer safety, may lead to unwanted events, such as material loss or loss of human lives.

In the railway transport field, freight rail vehicles have a peculiarity in comparison with the rest of the railway vehicles, in that they are designed to carry loads whose mass can be even three times the mass of the vehicle, which leads to a significant stress on the strength structure and a rapid aging of the steel, which can lead to undesirable consequences.

b. Transport of large loads;

Most of the uncovered high-walled freight rail vehicles running on Romanian railways are equipped with 20 tons axles, which means a total load equivalent to a mass of 80 tons when the wagon is loaded and is equipped with four axles. In Europe, the 22.5 tonnes load axles is widely used, which represents a significant increase of the total load up to 10 tonnes. It is obvious that a vehicle (with four axles) equipped with axles of 22.5 tons load, can carry about 10 tons more than a classic one with axles of 20 tons load.

As mentioned before, in order to make the rail freight system more efficient, it is necessary to replace the old technically limited railway vehicles with new ones capable of carrying much higher loads.

c. Good rolling behaviour;

During traffic, railway vehicles run on different sections of track, such as: straight-line sections without slope, straight-line sections with slope, large and small radius curve lines, twisted line sections etc. In all these situations, the vehicles must perform well, both empty and loaded.

To this end, in order to ensure safety requirements for rail traffic, rail freight vehicles must easily take over all road distortions and have flexibility to ensure smooth running, without the risk of derailment or overturning. The structures of railway vehicles, which have been in use for many years, can present defects that can endanger the safety of the rolling and the integrity of the transported goods, by producing undesirable events, such as derailment or overturning at low speed in curves with high elevation.

CH. 1 GENERAL ASPECTS REGARDING THE STRUCTURE OF CARGO WAGONS AND MEASURES TO INCREASE THEIR LOAD CAPACITY

This chapter presents general notions on the history of the rail transport system, the conventional system that characterizes this branch of transport, information on the characteristics of freight rail vehicles and their development trends.

Railway vehicles are characterized by their specific mode of travel on the track, through a set of wheels and the two rails. The wheels of railway vehicles fulfill the role of vehicle support, running and, unlike other means of transport, self-guidance. Thanks to the wheel-rail running system, which is made of metal, railway vehicles can support significantly higher masses compared to other types of transportation systems [5].

Also, the chapter presents the main characteristics of the studied wagon and the main parts of its structure.

Research in the field aims, as much as possible, to reduce the masses of the vehicles and increase the volume of goods transported, respectively the increase of maximum axle loads. Following this trend, the designers and manufacturers of railway vehicles are analyzing new solutions, through which to contribute to the increase of the transport quality [37].

Given the very high costs of designing and building a new vehicle capable to meet these requirements, the existing wagons are also being improved.

The current trend is to increase the transported loads, by increasing the axle load, the use of new materials and structures and simplifying, as much as possible, the constructive structure, within the safety limits of traffic. Regarding the open high walls railway vehicles (gondola wagons), different solutions have been applied in order to increase their transport capacity, by developing new projects.

In our country there is a limited number of open-walled wagons type (E-series wagons), whose axle load is below the maximum limit of 22.5 t, which means a lower transport capacity.

Starting from the main goal pursued in the development of open, high-walled freight rail vehicles, the last part of the chapter presents a series of new construction solutions developed in Europe, Russia and China.

CH. 2 MAIN OBJECTIVES AND STRUCTURE OF THE THESIS

2.1 THESIS OBJECTIVES

The study of increasing the transport capacity of an open high walls wagon, is based mainly on the current situation, in which is the fleet of freight wagons in Romania and the development trend that dominates the rail freight transport system in Europe and worldwide.

The main objective of the paper is to offer new constructive solutions, starting from the wagon structure of the Eaos series, which will ensure the transport of additional loads, compared to those borne by the initial structure.

A series of steps were followed to achieve the objective, as follows:

- Carrying out a study on the current state in the field of rail freight transport, especially on the type of vehicle studied and the characteristic trend of the development of these vehicles;
- Documentation regarding the structure of the open high walls wagon, realization of the geometric model of the vehicle structure and its analysis by the finite element method, using Ansys Mechanical software;
- Numerical analysis were performed in which loads were applied in accordance with the reference standards, loads identical to those applied in the railway vehicles structures tests performed on the test rig. During the simulation, the stress evolution and the displacements evolution of the structure were followed, which were used in order to establish the conditions for the next stage of the study;
- Based on the results obtained in the simulations and numerical analysis performed with finite elements, the points of interest on the entire structure of the wagon were established, points where strain gauges were applied, in order to verify the stress evolution and displacement evolution of the structure, using the special test rig of the Romanian Railway Authority (AFER).
- The results obtained on the test rig were compared with those obtained through finite element numerical analysis method and were subsequently used to calibrate the numerical model;
- Experimental and numerical verifications of the wagon structure in dynamic regime (buffing) were performed, respectively the buffer verification. The aim of these verifications was to compare the results obtained in the numerical analysis, for the calibrated model, with those obtained in the experimental verification;
- Based on the results obtained in the previous stages, the structural modification of the wagon was carried out, in order to deliver new, improved variants, which would ensure the transport of a higher quantity of cargo. Following these new modeling and numerical analysis, four constructive variants were offered, for which proper results were obtained in some cases and satisfactory in others.

2.2 THESIS STRUCTURE

The main objectives of the thesis are presented during seven chapters, to which an introductory part was added, the paper being written in accordance with the Regulations imposed by the POLITEHNICA University of Bucharest.

The seven chapters of the paper were structured as follows:

Chapter 1, entitled ***"General aspects of the structure of freight wagons and measures to increase their load capacity"***, presents general notions of the rail transport system history, notions of the rail transport system characteristics and new trends in this field of transport. Starting from the main purpose of the paper are presented the characteristics of the analyzed railway vehicle and a series of studies and current information on the development trends of railway vehicles of this type.

Chapter 2, entitled "***Objectives and organization of the thesis",*** presents the objectives of the thesis and how this paper is organized.

Chapter 3, entitled “***Modeling and study of freight railway vehicle structures by means of the finite element method”***, presents generalities regarding the finite element method, some aspects related to numerical modeling and calculation model and the results obtained after performing vehicle structure numerical analysis.

Chapter 4, entitled ***“Experimental results obtained on the test rig, for an open high walls wagon and validation of its virtual model***”, presents the experimental results obtained on a special test rig for testing the strength of railway vehicles, from Romanian Railway Authority laboratories and deals with the calibration stage of the numerical model, based on the results obtained experimentally and some comparative analysis.

Chapter 5, entitled ***“Experimental and numerical buffing analysis of an open high walls freight vehicle stucture***”, presents the experimentally and numerically results of the buffing tests behavior of the studied railway vehicle structure. The structure of the studied vehicle was dynamically tested at shock, in accordance with the requirements of the current standard.

Chapter 6, entitled “***New proposed structural variants and their numerical analysis***”, presents the personal contributions regarding the increase of the transport capacity of an open high walls wagon. During this chapter, a series of new constructive solutions are presented, which ensure a higher transport volume than the initial version of the vehicle.

The structural analysis of the vehicle was performed using the finite element method, using Ansys Mechanical software and based on the virtual model calibrated using the results obtained experimentally.

Chapter 7, entitled “***General conclusions, personal contributions and new research directions***”, contains three subchapters and presents the general conclusions of the thesis, information of personal contributions and future research directions in the studied field.

CH. 3 MODELING AND STUDY OF RAILWAY STRUCTURES THROUGH THE FINITE ELEMENT METHOD

In the railway field, the structure of vehicles must comply with international standards, in order to ensure the transport of significant mass goods, without endangering traffic safety. The railway vehicles structure is composed of standardized metal profiles, which make up an assembly called a chassis.

The chassis supports almost the entire transported load and all the forces that occur in the transport and handling processes of the vehicles.

The main objective of the railway vehicle structures design is to reduce, as much as possible, the masses of the vehicles, in order to optimize the transport process and reduce fuel and energy consumption.

This chapter presents the numerical analysis of an open high walls freight wagon using the finite element method, tested in static mode, in accordance with European reference documents.

The vehicle chosen (fig. 1) as a study model has the following characteristics:

Table 1.The main characteristics of the analyzed wagon [21]

Characteristic	Size
Gauge	1435 mm
Useful length of the body	12792 mm
Useful width of the body	2772 mm
Useful body height	1890 mm
Usable floor area	36 m^2
Useful volume of the body	68,4 m^3
Wagon mass	22 tons
Maximum axle load	20 tons
The wagon is suitable for passing over humps	yes

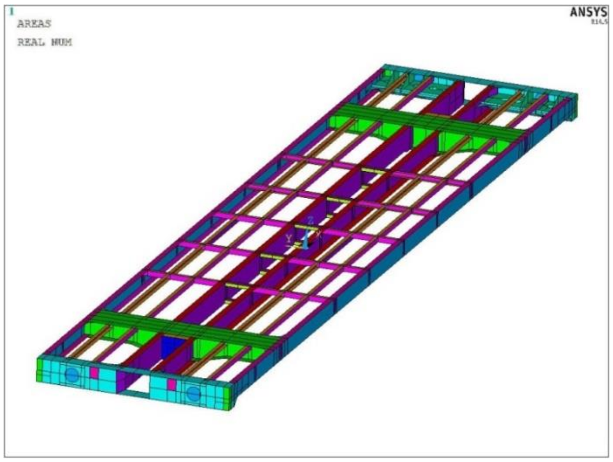
From a constructive point of view, the structure of the vehicle consists of: chassis, front walls and side walls. This type of vehicle is used to transport bulk goods (ore, coal, timber, scrap metal etc.) or palletized, weather-resistant goods.

The geometric construction of the wagon has symmetry, both to the longitudinal axis and to the transverse axis of the vehicle.

Fig.1 Wagon would be Eaos

Therefore, only a quarter of the vehicle was modeled, and with the help of the "reflect" command, the entire model was made. The Ansys 14.5 program was used to create the virtual model of the vehicle. In the analysis performed on the vehicle, the bogies and the loading/unloading doors were not modeled, as they were not part of the whole strength elements of the structure.

The geometric model of the wagon was made and its main structural elements were presented, as can be seen in figure 2.



a. Chassis

b. Pillars and belt

Fig. 2 Structural elements of the studied vehicle

The load cases will simulate the test conditions of the strength structure for this type of freight wagon, according to the standard SR EN 12663-2: 2010 [49].

In the case of freight rail vehicles structure testing, the folowing tests are performed:

- Compressive force at buffer level test (CT);
- Compressive force at coupler attachment test (AC);
- Compressive force below buffer test (CT50);
- Compressive force applied diagonally at buffer level test (CD);
- Tensile force at coupler attachment test (TA);
- Operating load test (SV);
- Compressive force at buffer level, under the action of the operating load (CTSV);
- Compressive force at coupler attachment, under the action of the operating load (CASV);
- Tensile force at coupler attachment, under the action of the operating load (TASV) [61].

All these tests aim at simulating the behavior of the vehicle structure in accordance with the actual operating cases.

Starting from the initial data, through which, from a dimensional point of view, the model was expressed in [mm], after the application of forces in [N] will result displacements in [mm] and stresses in [MPa].

The vehicle is made of S355 steel. For S355 steel, according to tables 18 and 19 of SR EN 12663-2: 2010, the stress limits for tests with horizontal forces and combined loads has the following values [61]:

- for non welded areas:

$$\sigma_{aH} = R_{p0,2} = 355 \ N/mm^2 \tag{1}$$

- for welded areas:

$$\sigma_{aH} = \frac{R_{p0,2}}{1{,}1} = 323 \ N/mm^2 \tag{2}$$

Further on it is presented, as an example, the case of compressive force at buffer level, under the action of the operating load, one of the most important analyzed load case.

The compressive force at buffer level, under the action of the operating load, simulates the real case in which the vehicle is loaded at maximum capacity (58 t) and a compressive force (2000 kN) acts on it, in the buffers area [61].

The schematization of the forces is presented in figure 3, and the obtained results are presented in figures 4 - 6.

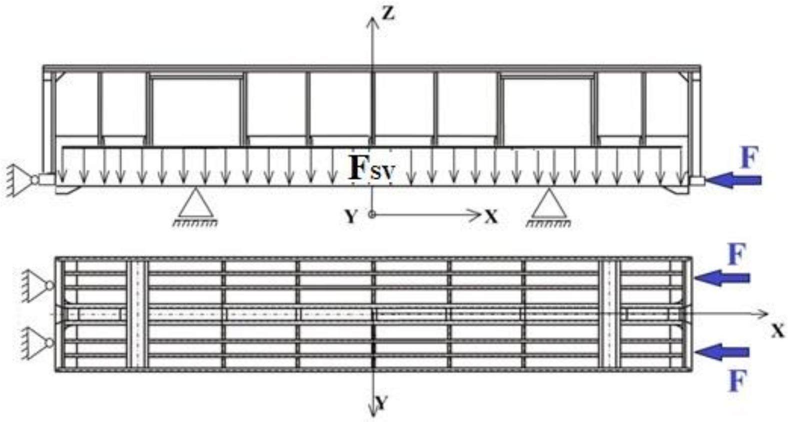


Fig. 3 Compressive force at buffer level, under the action of the operating load schematization

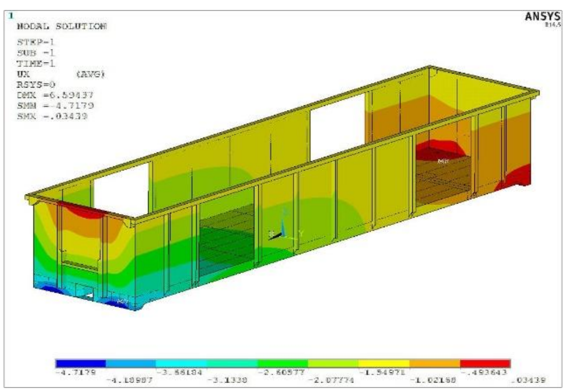


Fig. 4 Longitudinal displacements

Fig. 5 Vertical displacements

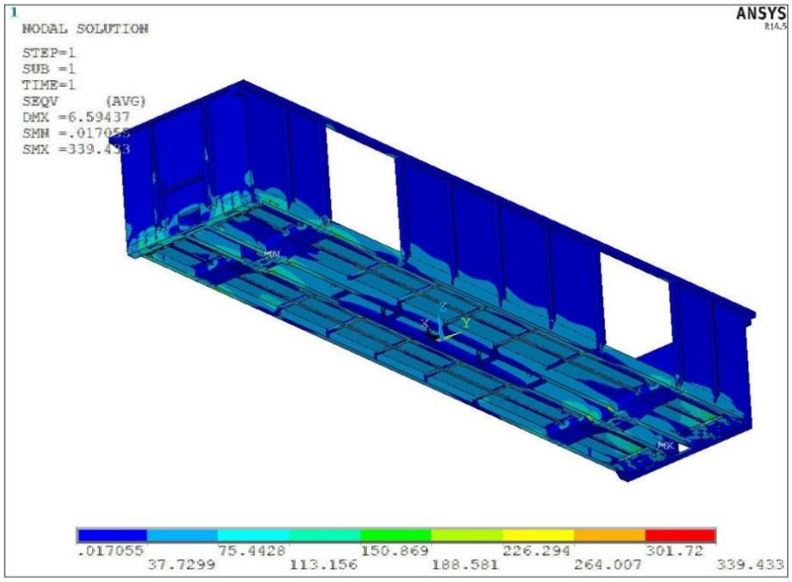


Fig. 6 von Mises stress

Except for the singularities that appeared in the area of application of the force, in this load case the maximum stress value was approximately 220-240 MPa, as it can be seen in figure 6. The maximum displacements registered values of approximately 6, 5 mm in the vertical direction.

The main objective of the finite element simulations, presented in this chapter of the thesis, was to determine the stress evolution and the displacement evolution in the vehicle structure.

The simulations aimed to reproduce the actual load cases defined in the reference standard for freight rail vehicles, cases which reflect the phenomena that occur in the running and handling of railway vehicles.

Given the results obtained and following the paper objective, that of increasing the transported load, the variant of trying to modify the studied vehicle structure can be considered, by replacing certain metal profiles or by reducing the thickness of the structural elements, where this is possible, without affecting the rail traffic safety and the integrity of the transported goods.

In order to validate the results obtained from the simulations, they will be compared with the results obtained on the test rig using resistive electrical tensometry, on a Eaos wagon.

Table 2 shows the maximum values of von Mises stress and the maximum values of displacements (in the direction of the longitudinal axis Ox or in the direction of the vertical axis Oz), followed during the numerical analysis of the vehicle structure by the finite element method.

It is observed that the von Mises stress has the highest value in the case of compressive force at buffer level, under the action of the operating load, while the extreme displacements occur in the case of tensile force at coupler attachment.

Table 2 Centralized numerical simulation results

Test	**Force / Load applied**	**Von Mises stress [MPa]**	**Maximum displacements (Ox direction or Oz direction) [mm]**
Compressive force at buffer level	2000 kN 1000 kN/buffer	200	4,4
Compressive force at coupler attachment	2000 kN	120	3
Tensile force at coupler attachment	1500 kN	150	10
Operating load	569 kN	100	4,5
Compressive force at buffer level, under the action of SV	2000 kN + 569 kN	240	6,5
Compressive force at coupler attachment, under the action of SV	2000 kN + 569 kN	220	6,4
Tensile force at coupler attachment, under the action of vertical load	1500 kN + 569 kN	200	9,8

The main stress appeared in the area of the front cross beams, in the areas of application of forces, being transmitted further to the central longitudinal beam and to the side longitudinal beams. At the body level, the stress presents low values in all load cases presented above.
This demonstrates that most of the loads acting on the structure are taken over by the chassis.

CH. 4 EXPERIMENTAL RESULTS OBTAINED ON THE TEST RIG FOR AN OPEN WAGON WITH HIGH WALLS AND VALIDATION OF ITS VIRTUAL MODEL

The railway transport activity is a very complex one and of a special importance all over the world. The railway transport activity requires the observance of some requirements, which have become more and more strict and complex, with the passing of the years and as a result of the technological development.

Railway vehicles must meet some requirements related to the safety of transport activities. Thus, the newly designed vehicles go through a series of tests to confirm compliance with the requirements. The test of the railway vehicles structure is one of the most important, without which a railway vehicle cannot be considered suitable for circulation.

The tests of the railway vehicles structure are carried out in specialized laboratories, properly equipped to meet all the requirements of the reference standards. In our country, the Romanian Railway Authority (AFER) has a test rig of this type, which, by the method of resistive electric tensometry, determines whether the structure of a railway vehicle meets the necessary conditions for operation [59], [60].

According to SR EN 12663-2: 2010 standard, freight rail vehicles are subjected to horizontal force tests, vertical load tests and combined load tests.

During the experimental verifications on the test rig, the method of resistive electrical tensometry was used, a method of determining the structures stresses, by measuring the strains from the surface of the bodies subjected to some loads.

If the studied stress is one of simple stretching or compression and is characterized by an elastic strain of the material, thus subjecting to Hooke's law, the corresponding normal stress can be determined with the relation [64]:

$$\sigma = E \cdot \varepsilon \tag{3}$$

where:

- *σ [MPa] is the normal stress;*
- *ε is the strain;*
- *E [MPa] is the Young's modulus of the material [64].*

The tests performed by resistive electric tensometry on the structure of the analyzed wagon were carried out on the "tensometry test rig" inside the Romanian Railway Authority - AFER, Bucharest [70].

Tensometric materials (transducers, adhesives, accelerators, etc.) manufactured by Hottinger from Germany were used to perform the measurements:

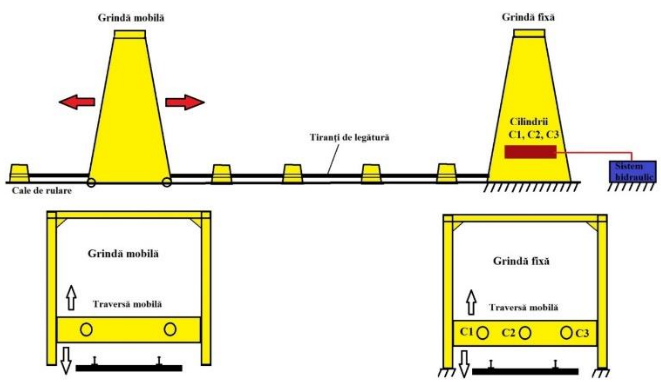


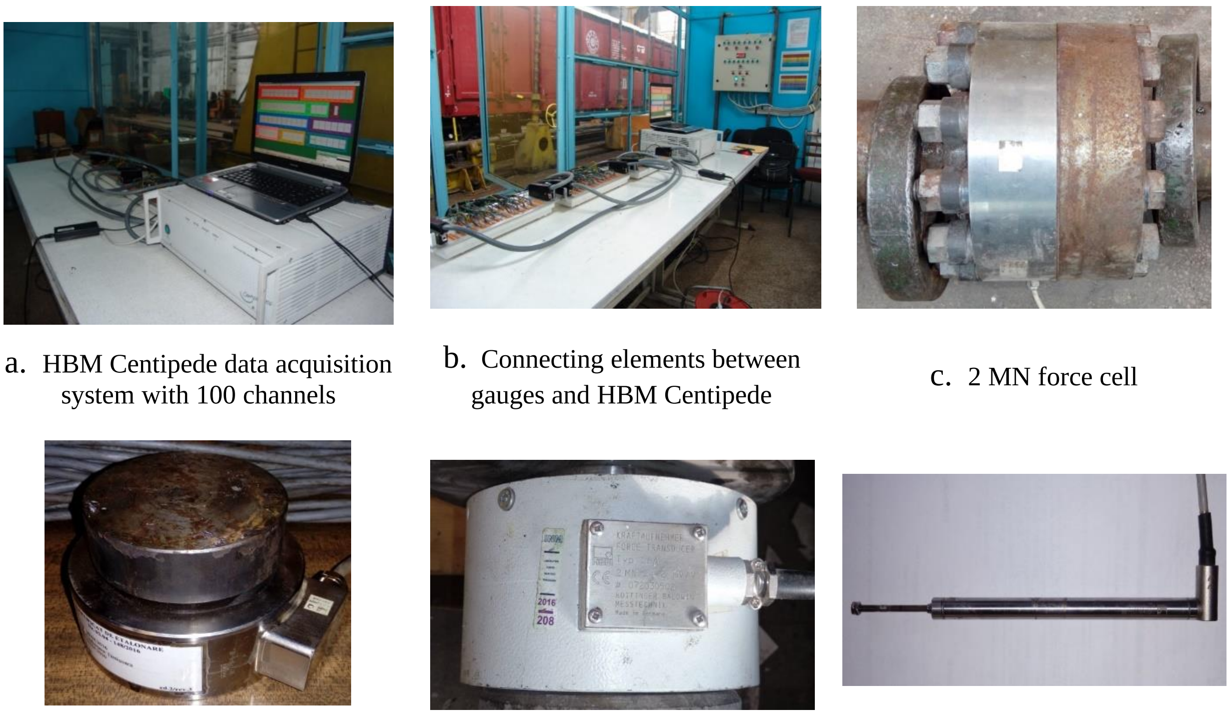
Fig. 7 Test rig for railway vehicles structure tests

- ➢ strain gauges 1-LY11-6 / 120, with electrical resistance R = 120 Ω ± 0,35 % and constant k = 2,07 ± 1%;
- ➢ strain gauges (tensometric rosettes) 10/120 RY 41, with electrical resistance R = 120 Ω ± 0,2 % and constant k = 2,0 ± 1%;
- ➢ quick adhesive Z70;
- ➢ accelerator type BCY01 for adhesive Z70 [73], [74].

The devices and measuring instruments used in the tests are presented in table no. 3 and in figure 8 [75], [76].

Table 3 Measuring tests chain - measurement accuracy

Crit.no.	Measuring device	Measurement precision
1	Hottinger tensometric system, Centipede with 100 channels	±1 μm/m
2	Hottinger K 3608 calibrator	±1 μm/m
3	Software Catman 4.5	-
4	Displacement transducers	Class 1
5	2 MN force cells (compression)	Class 1
6	2 MN force cell (compression - traction)	Class 1
7	200 kN force cells (compression)	Class 1



a. HBM Centipede data acquisition system with 100 channels

b. Connecting elements between gauges and HBM Centipede

c. 2 MN force cell

d. 200 kN force cell

e. 200 kN force cell

f. Displacement transducer

Fig.8 Measuring devices used

Preparing railway vehicles for the tests performed on their structure is a laborious and time-consuming operation. This preparation involves the following steps:

- Position the vehicle on the test rig and disassemble the buffers and conection elements;
- The main points for applying the strain gauges are established;
- Surface preparation operations are performed and the strain gauges are glued at the established points;
- Connect the cables between strain gauges and measuring equipment used for tests;
- Configure the test rig for each test case.

Following the finite element numerical analysis performed, 55 measuring points were established (fig. 9), most of them being found at the chassis level [59], [61].

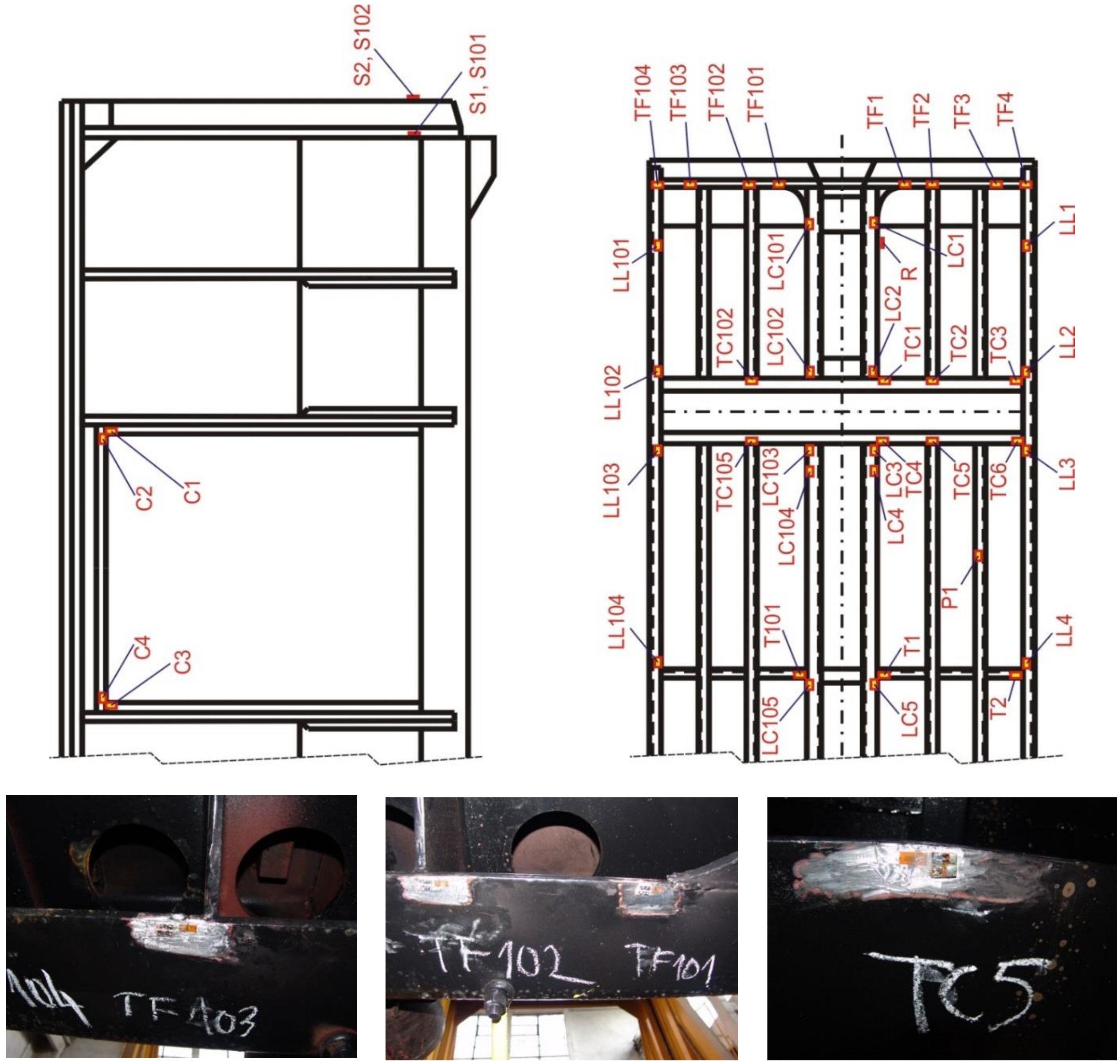


Fig. 9 Location of gauges on the vehicle structure

Strain gauges were applied in the longitudinal axis of the structural elements of the vehicle, where the strains have the highest values, and the stresses were determined based on the strains measured, using the relation (3).

The following table shows the main results obtained for the load cases in which the highest stress values were obtained.

Table 4 The main experimental results

Crit. No.	Measuring point	Test	Result [MPa]
1	LC3	CA	51
2	LC4	CA	128
3	LC5	CA	66
4	LL4	CA	64
5	LL5	CA	49
6	C2	CA	44
7	TF1	CT	48
8	TF2	CT	51
9	TF4	CT	157
10	LC1	CT	-218
11	LC4	CT	-92
12	S2	CT	68
13	R	CT	102
14	LC2	SV	-64
15	LC3	SV	-40
16	LC4	SV	-90
17	LL104	SV	-85
18	T1	SV	-141
19	C2	SV	-77
20	C3	SV	85
21	TF102	CT+SV	107
22	TF4	CT+SV	149
23	LC1	CT+SV	-230
24	LC102	CT+SV	-138
25	LC4	CT+SV	-182
26	LL103	CT+SV	-101
27	T1	CT+SV	-123
26	R	CT+SV	129

After the completion of the experimental verifications, the obtained results were centralized and analyzed, in order to modify the numerical model, so that the results of the numerical simulations are very close to the experimental results [60].

To determine the stress evolution on the virtual model, in the areas where the strain gauges were applied on the vehicle structure, the following steps were performed [60].

- the areas in which the strain gauges were applied on the vehicle structure during the rig tests were identified;
- using the numerical model, the positioning of the finite elements related to the locations where the measurement points were applied on the structure of the real model was identified and the stress results were extracted according to the measuring direction of the transducer;
- the results on each element were analyzed, for the correct determination of the stress in the respective area, as can be seen in figure 10 and in figure 11.

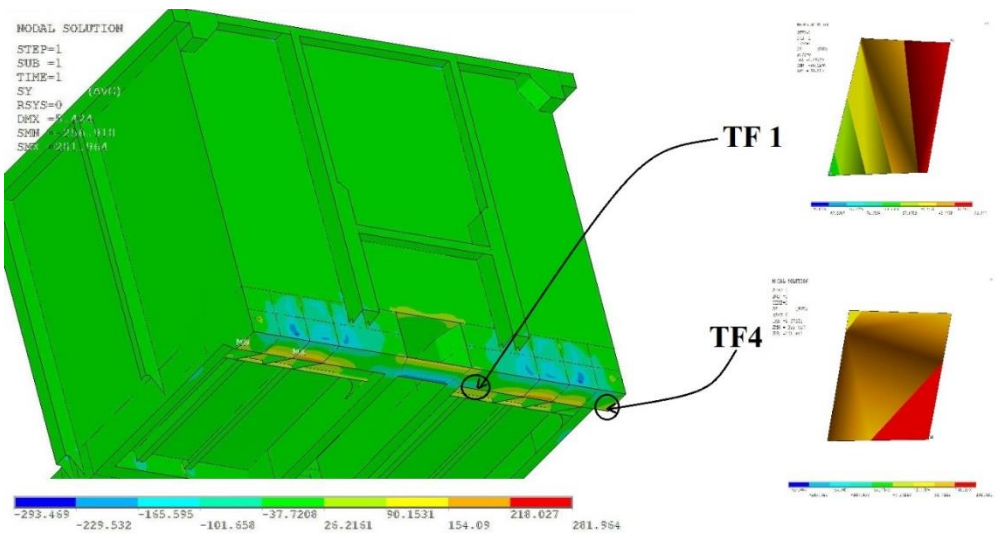


Fig. 10 Elements selection and plotting (CT test)

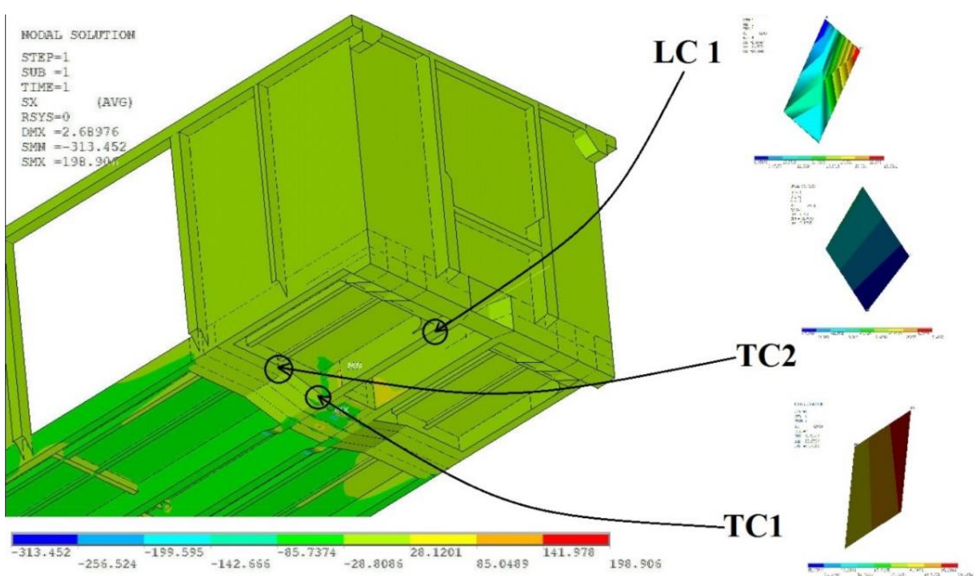


Fig. 11 Elements selection and plotting (CA test)

Table 5 presents the results obtained by the two methods.

Table 5 Main results MEF-Experimental

Crit. No.	Measuring point	Obtained values			
		Test	Experimental [MPa]	MEF [MPa]	Error [%]
1	LC3	CA	51	50	2
2	LC4	CA	128	130	2
3	LC5	CA	66	61	8
4	LL4	CA	64	61	5
5	LL5	CA	49	40	18
6	C2	CA	44	37	16
7	TF1	CT	48	54	11
8	TF2	CT	51	60	15
9	TF4	CT	157	168	7
10	LC1	CT	-218	-194	11
11	LC4	CT	-92	-105	14
12	S2	CT	68	59	13
13	R	CT	102	93	9
14	LC2	SV	-64	-60	6
15	LC3	SV	-40	-37	8
16	LC4	SV	-90	-75	17
17	LL104	SV	-85	-78	8
18	T1	SV	-141	-137	3
19	C2	SV	-77	-69	10
20	C3	SV	85	78	8
21	TF102	CT+SV	107	110	3
22	TF4	CT+SV	149	139	7
23	LC1	CT+SV	-230	-226	2
24	LC102	CT+SV	-138	-139	1
25	LC4	CT+SV	-182	-174	4
26	LL103	CT+SV	-101	-121	10
27	T1	CT+SV	-123	-124	1
26	R	CT+SV	129	136	5

Following the comparative analysis of the numerical and experimental results, it can be considered that the calculation model of the studied wagon is a correct one, considering the small differences between the results obtained on the two ways, except for a few measurement points, where the errors are slightly higher.

CH. 5 EXPERIMENTAL AND NUMERICAL BUFFING ANALYSIS OF THE OF AN OPEN WAGON WITH HIGH WALLS STRUCTURE

5.1 BUFFING TEST WITH EMPTY AND LOADED WAGON

The handling of freight rail vehicles is carried out in order to compile trainsets, on types of wagons, depending on the type of transported goods, respectively for their transport between the loading and unloading points.

In most cases, the handling of freight wagons is done at low speed, in order to avoid the occurrence of shocks, which could endanger their integrity and the transported goods [81], [82].

In some cases, when railway vehicles are maneuvered over the sorting hump, the vehicles collide with each other, generating shocks that are transmitted on to their structure.
Buffing tests of rail vehicles shall be carried out in order to determine the behavior of the structure and to analyze the influence of the carried load on it as a result of the application of instantaneous forces similar to those arising from the handling of wagons over the hump. [81], [82].

The buffing test consists of launching a ram wagon at a set speed (using a motor railway vehicle), which bumps into the tested vehicle, which is stationary, with all the measuring equipment mounted on its structure [81], [82].

The buffing test shall be carried out on the ramp track of the AFER Railway Testing Center, or in any railway triage equipped with a sorting hump, by specialized personnel, using measuring equipment that meets the requirements of the European standards. Figure 12 shows the positioning of the vehicles used in the buffing test [81], [82].

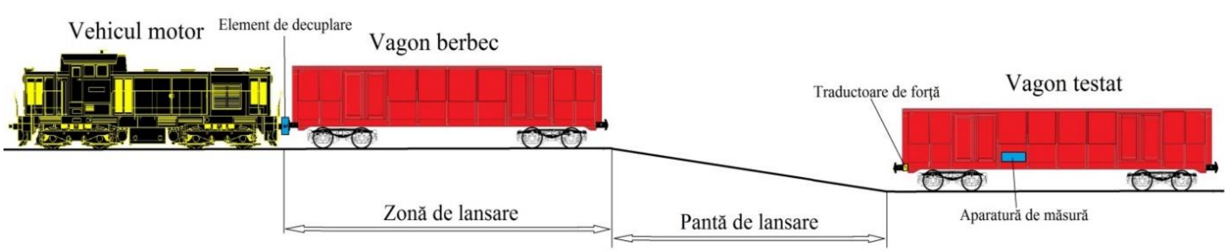


Fig. 12 Schematization of the buffing test

For the buffing tests, the following equipments were used:

- acquisition system for measuring strains and forces behind the buffers;
- force cells for measuring buffering forces;
- speed measuring device;
- strain gauges for determining the stresses that arise in the tested structures;
- displacement transducers for measuring the stroke of the collision elements.

To perform the buffing tests of the vehicle structure, 16 measuring points have been established.

Figure 13 shows the positioning of strain gauges, abbreviated TER, on the vehicle structure. The tests on the empty wagon were aimed to determining the behavior of the vehicle structure and verifying the interaction between the vehicle and the bogies. According to the reference standard, the force acting on the vehicle buffers shall not exceed the value of 1500 kN / buffer or the maximum speed of 12 km / h [61], [81].

The results obtained for the buffing tests with the empty wagon (max. values) are presented in table 6.

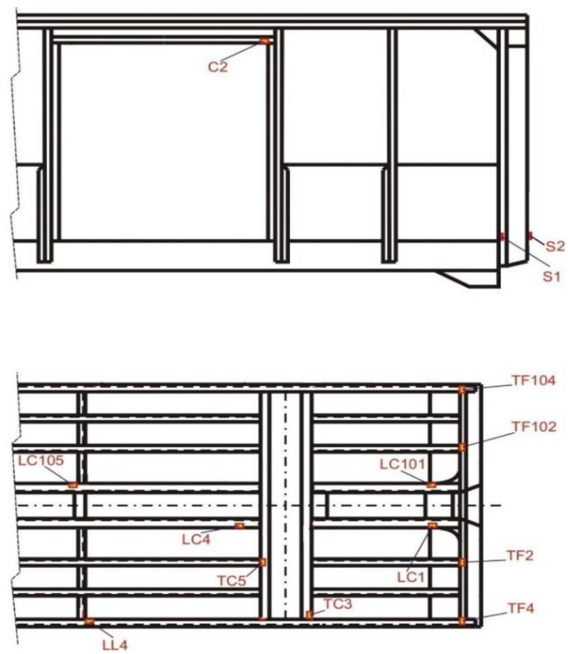


Fig. 13 Positioning of strain gauges on the tested vehicle structure

Table 6 Experimental results obtained for the empty wagon buffing test

Buffing test no.			**1**	**2**	**3**	**4**	**5**	**6**	**7**
v [km/h]			**5,65**	**7,2**	**8,82**	**9,52**	**10,26**	**10,47**	**12,97**
Measuring points	TF2	µm/m	-62	-90	-114	-129	-148	-171	-195
	TF102		-190	-229	-295	-338	-381	-386	-552
	TF4		262	300	390	438	486	495	667
	TF104		224	262	348	395	448	467	629
	LC1		281	352	519	610	710	743	1010
	LC101		286	324	410	457	510	533	700
	LC4		-171	-205	-271	-310	-348	-362	-519
	LC105		-129	-152	-205	-238	-267	-271	-357
	TC3		-19	-33	-38	-48	-52	-52	-71
	TC5		-76	-95	-133	-157	-167	-171	-181
	LL4		-148	-176	-233	-271	-305	-310	-395
	LL105		-195	-205	-276	-295	-324	-333	-486
	S1		-62	-71	-90	-105	-110	-114	-186
	S2		-129	-157	-233	-271	-295	-295	-424
	R1		-229	-267	-362	-414	-471	-490	-652
	C2		-52	-76	-81	-95	-100	-105	-176

During the tests with the empty wagon, no damage was caused to the wagon subassemblies, which remained in working order and no visible displacements of the structure occurred.

In the case of the test with the wagon loaded, the tested vehicle was loaded with crushed stone, which is used in the light of the railway, to simulate the mass transported. As it is an open wagon with high walls, the use of broken stone to simulate the mass of the load is the best solution, because the whole load was evenly distributed and there was no risk of moving it during the tests. The results are presented in Table 7.

Table 7 Results obtained in the buffer test with the wagon loaded

Buffers/ Buffer no.	**Prelim.**	**5**		**15**		**25**		**35**		**40**	
1 Speed [km / h]		**12.24**		**12.37**		**12.2**		**12**		**11.43**	
Average speed [2]) [km / h]		**12.05**									
Measuring point	εp[3])	**σ [MPa]**	**ε**	**σ [MPa]**	**ε**	**σ [MPa]**	**ε**	**σ [MPa]**	**ε**	**σ [MPa]**	**ε**
TF2	-117	-115	-548	-77	-367	-84	-400	-76	-362	-89	-424
TF102	-185	-175	-833	-186	-886	-166	-790	-180	-857	-170	-810
TF4	-194	-174	-829	-188	-895	-168	-800	-182	-867	-177	-843
TF104	-177	-157	-748	-171	-814	-149	-710	-160	-762	-147	-700
LC1	287	267	1271	297	1414	268	1276	284	1352	267	1271
LC101	185	176	838	194	924	181	862	188	895	178	848
LC4	-165	-149	-710	-157	-748	-140	-667	-154	-733	-140	-667
LC105	-123	-111	-529	-120	-571	-102	-486	-117	-557	-107	-510
TC3	76	58	276	55	262	41	195	59	281	49	233
TC5	-83	-61	-290	-68	-324	-63	-300	-66	-314	-68	-324
LL4	-167	-120	-571	-131	-624	-112	-533	-127	-605	-117	-557
LL105	-178	-160	-762	-166	-790	-164	-781	-165	-786	-165	-786
S1	-253	-221	-1052	-235	-1119	-262	-1248	-230	-1095	-255	-1214
S2	-205	-198	-943	-217	-1033	-235	-1119	-207	-986	-246	-1171
R1	-118	-176	-838	-144	-686	-142	-676	-156	-743	-152	-724
C2	-103	-161	-767	-176	-838	-175	-833	-179	-852	-185	-881

During and after the end of the impact tests with the loaded wagon, no damage to the wagon subassemblies occurred, they remained in working order and no visible strains of the vehicle structure occurred [81], [82].

1) The values in this line are the speed values for buffing test no. 5, 15,…, 40

1) The value on this line represents the average speed for the 40 buffers

1) ε_p represents the value of the cumulative residual strains for the preliminary buffing tests

5.2 FINITE ELEMENT BUFFING NUMERICAL ANALYSIS

The buffing test simulations with the empty wagon were performed in non-linear static mode, on the entire structure of the vehicle, using finite elements with 35 mm size, using the Ansys software. Through the non-linear static analysis aimed at the static reproduction of the buffing test of the wagon structure, studying the stresses evolution and displacements evolution after the application of overloads in the buffers area, its value being established starting from the size of the maximum forces recorded in the tests (of about 745 KN / buffer, measured with load cells) and considering the value of the impact multiplier 2,017, obtained for v = 12.97 km / h and δst = 10 mm.

Thus, the most unfavorable case was chosen, being applied a force of 3000 kN (1500 kN / buffer) in the two areas where the buffers are mounted, at one end of the wagon, and at the opposite end constraints were applied [86]. Constraints were also applied in the bogie cross beam areas.

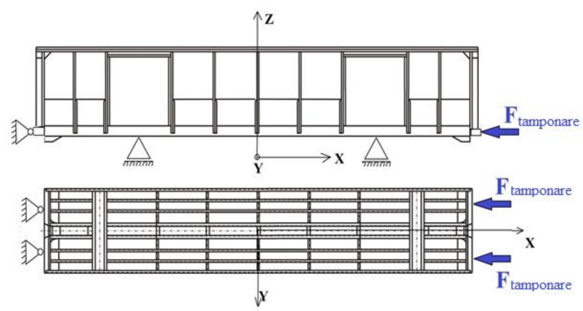


Fig. 14 Buffing test with the empty wagon -schematization of forces and constraints

Figure 15 shows the von Mises stress map, recorded in case of the buffing simulation with the empty wagon. Based on the stresses obtained in the numerical simulations, the strains were calculated using relation (3) and were compared with those obtained experimentally.

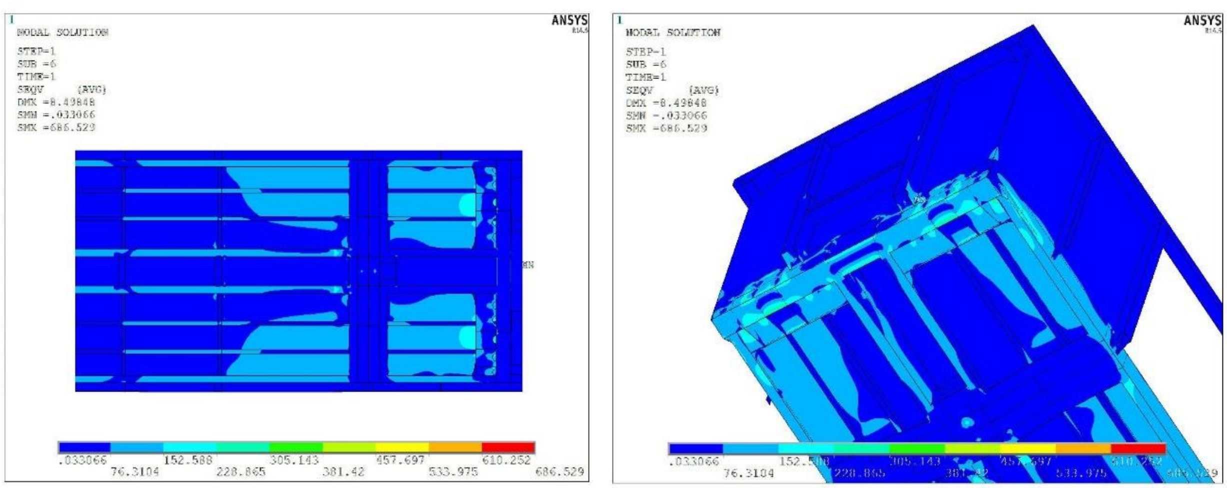


Fig. 15 von Mises stress - buffing test with empty wagon

To determine the stress evolution on the virtual model, in the areas where the strain gauges were applied to the vehicle structure, the next steps were followed:

- ➢ the areas in which the strain gauges were applied on the vehicle structure during the experimental tests were identified;
- ➢ the finite elements on the structure of the virtual model were selected and the stress results were printed in the direction corresponding to the application of the buffing force on the structure, for each element corresponding to the area where a strain gauge was applied on the real vehicle structure. The experimental / MEF results are presented in table 8.

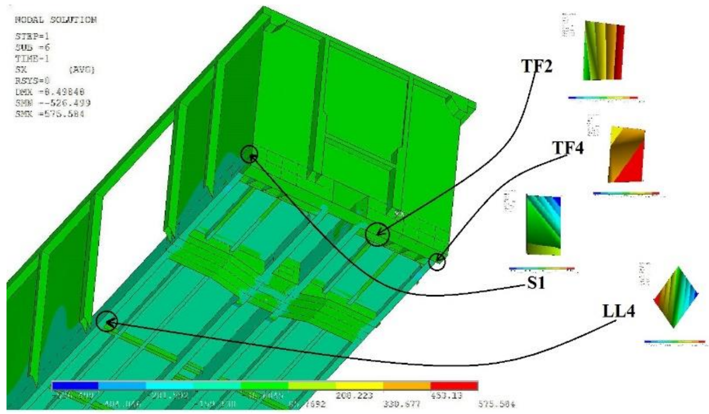


Fig. 16
How to select the elements corresponding to the positions of the transducers (buffering with the empty wagon)

Table 8 ***Experimental results / MEF shock test with empty wagon***

	TER	Values obtained experimentally Ɛ [µm/m]	Values obtained by the MEF method Ɛ [µm/m]
Measuring point	TF2	-195	-243
	TF102	-552	-667
	TF4	667	629
	TF104	629	667
	LC1	1010	876
	LC101	700	676
	LC4	-519	-524
	LC105	-357	-405
	TC3	-71	-43
	TC5	-181	-219
	LL4	-395	-395
	LL105	-486	-438
	S1	-186	-195
	S2	-424	-362
	R1	-652	-562
	C2	-176	-119

The differences between the experimentally results and those obtained by the finite element method are due to measurement uncertainties, possible strain gauges gluing errors on the vehicle structure, but also other causes specific to the experimental procedure used.

The same procedure was followed for the buffing test with the loaded wagon, the results obtained being presented in table 9.

Table 9 ***Experimental/MEF buffing test results with loaded wagon***

	Straing gauge	**Experimental strain results Ɛ [μm / m]**	**MEF strain results Ɛ [μm / m]**
Measuring point	TF2	-400	-414
	TF102	-790	-862
	TF4	-800	-781
	TF104	-710	-733
	LC1	1276	1181
	LC101	862	890
	LC4	-667	-676
	LC105	-486	-429
	TC3	195	295
	TC5	-300	-305
	LL4	-533	-500
	LL105	-781	-767
	S1	-1248	-1248
	S2	-1119	-1214
	R1	-724	-790
	C2	-881	-757

As mentioned in the previous cases, some of the results showed slightly different values, due to the used measurement tests method, the different way of working of the two buffers of the wagon etc.

The main objectives of the buffing tests of the vehicle structure were to determine the strains ε, as a result of the application of shock loads. The loads applied to the structure have been established in accordance with the reference standards and reproduce the operation and shock handling cases of railway vehicles.

In order to determine the strains appeared in the structure, 16 measuring points were established, most of them being found in the chassis area, a structural component that takes over most of the stresses that appear on the vehicle, when it is handled over the sorting hump. The results obtained in both cases have close values in most measuring points, with a few exceptions, where the larger differences are explained by the different behavior of the wagon structure (due to structural asymmetries), in the tests case.

CH. 6 NEW PROPOSED STRUCTURAL VARIANTS AND THEIR NUMERICAL STRUCTURAL ANALYSIS

Railway vehicles have a great advantage in that they differ from the rest of the transportation vehicles, namely the very low forward resistance, given by the low contact between the wheel and the rail [5].

For this reason, the rail transport system is currently considered the most efficient mass transport system. Freight rail vehicles must ensure a series of requirements, among which we remind: transport safety, high speeds, low transport and maintenance costs etc.

Starting from the current trends in rail freight transport, the main objective of the paper was focused on the study of the strength structure of an open freight high walls wagon, to increase its transport capacity, while complying with all traffic safety requirements. .

To this end, numerical and experimental studies have been carried out, using methods currently used in the design and verification of railway vehicles, prior to their manufacture and entry into service.

Starting from the numerical model developed through Ansys software and validated based on experimental results obtained from static and dynamic tests, dimensional changes were made to the structure of the studied vehicle, in order to meet the objective of the work, respectively, increase the transport capacity.

The study focused on determining the stress evolution and displacement evolution for the new structures, in order to verify the fulfillment of the minimum safety requirements of the railway traffic. The analysis of the structures focused on the structure loads of the initial model, where results registered the highest stress values [59], namely:

- compressive force at buffer level;
- compressive force at coupler attachment;
- compressive force at buffer level, under the action of the operating load;
- tensile force at coupler attachment, under the action of the operating load.

Analysis were performed for four new constructive solutions, which are presented below.

6.1 VARIANT OF THE MODIFIED STRUCTURE BY INCREASING THE USEFUL LENGTH OF THE VEHICLE BODY

Following studies on the vehicle structure, using the finite element method [59], low values of mechanical stress were recorded in the middle area of the vehicle, the main stresses being found in the end areas of the wagon, where the forces act directly on structure.

This leads to the conclusion that changing the useful length of the wagon body can be a viable solution to increase the transport capacity, without exceeding the stresses and displacements, while meeting the safety requirements of rail traffic.

Figure 17 shows schematically the variant of the modified body by extending the structure by 1271 mm (the length between two pillars of the side walls, in the middle area of the vehicle).

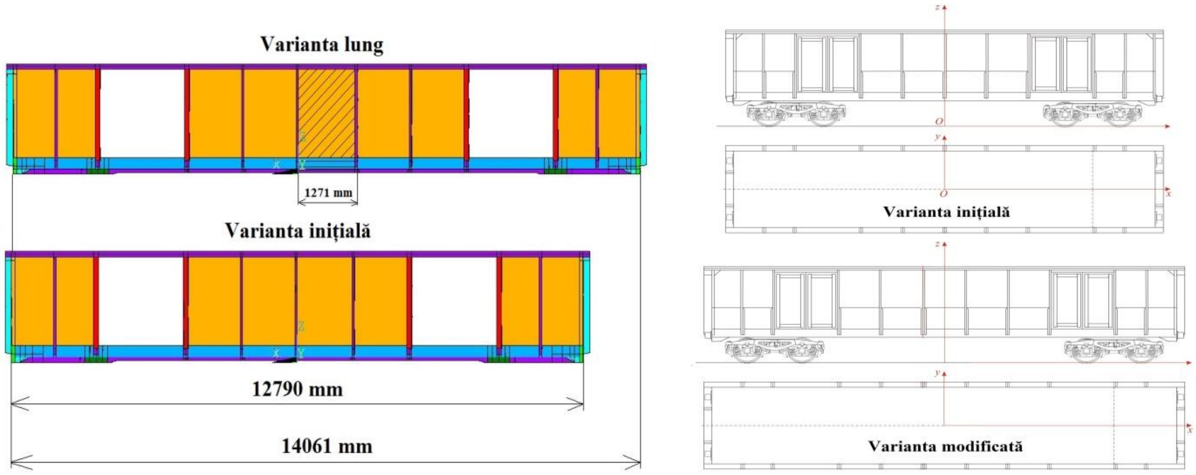


Fig. 17 Geometric model of the new structure by changing the length - comparative presentation with the initial model

Table 10 The main features of the wagon - the initial version / extended body version

Crit. No	Characteristic	Initial variant with 20 t axles	Variant of the extended body with 22.5 t axles
1	Vehicle body mass (without doors) [t]	9,3	10,02
2	Vehicle mass [t]	22	22,72
3	Vehicle body volume [m^3]	68,4	74
4	Transport capacity [t]	58	67,28

6.2 VARIANT OF THE MODIFIED STRUCTURE BY INCREASING THE USEFUL HEIGHT OF THE BODY

Starting from the same results that formed the basis of the analysis of the structure presented above (point 6.1), the modification of the useful volume of the vehicle body, in order to increase the transport capacity, can also be achieved by extending the side and front walls in the direction of the Oz axis, respectively on the height of the vehicle.

Modifying the useful height of the wagon body (fig. 18) can be another viable solution to increase the transport capacity, without exceeding the stresses, with the fulfillment of the safety requirements of the railway traffic.

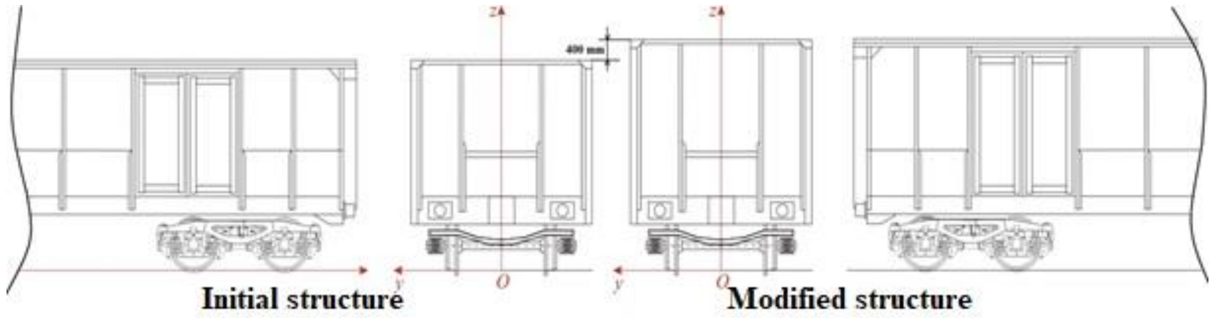


Fig. 18 Geometric model of the new structure by changing the height - comparative presentation with the initial model and overall presentation

The main advantage of changing the height of the body, by extending the side walls and front walls by 400 mm (value determined after performing calculations to determine the useful volume of the body), is the increase of the useful volume of the body from 68.4 m3, to 82.4 m3. The disadvantage of adding the structural segment is the increase of the body mass by approximately 0.5 t, respectively the modification of the vehicle weight from 22 tons to 22.51 tons.

Table 11 The main features of the wagon - the initial version / the new version

Crit. No.	Characteristic	The initial variant axles 20 t	Raised body variant and axles of 22.5 t
1	Vehicle body mass (without doors) [t]	9,3	9,8
2	Vehicle mass [t]	22	22,51
3	Vehicle body volume [m^3]	68,4	82,4
4	Transport capacity [t]	58	67,5

In this case, the transport capacity of the vehicle increases significantly compared to the original version. The increase in the mass of the vehicle is insignificant compared to the increase in the useful volume of the body, which ensures the increase of the transported masses by about 10 tons.

6.3 VARIANT OF THE STRUCTURE MODIFIED BY JOINTS – THE VEHICLE CONSISTED OF TWO UNITS, WITH COMMON BOGIE IN THE MEDIAN AREA

Analyzing the variants presented above, it can be seen that the new structures ensure a significant increase in the transport characteristics of the vehicle. Given the current trend of increasing the mass transported, specific to rail freight, meeting the requirements of this century involves the creation and implementation of new solutions.

Such a solution can also be the option that will be presented below (figure 19 ant table 12).

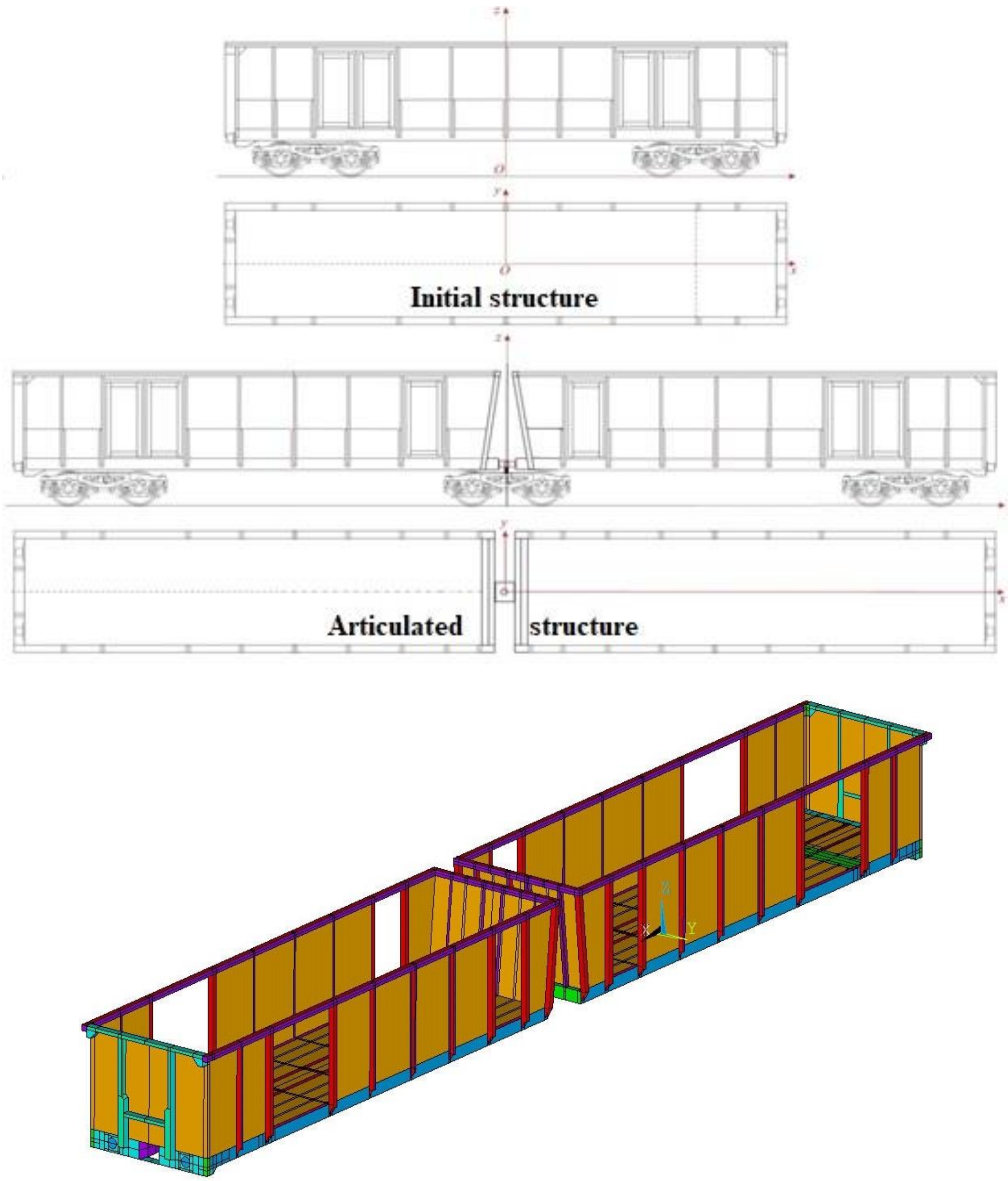


Fig. 19 The geometric model of the new structure by articulating two units

Table 12 The main features of the wagon - the initial version / articulated version

Crit. No	Characteristic	The initial version axles 20 t	Articulated variant axles 22.5 t
1	Vehicle body mass (without doors) [t]	9,3	15,94
2	Vehicle mass [t]	22	34,5
3	Vehicle body volume [m^3]	68,4	115,2
4	Transport capacity [t]	58	100,5

The new vehicle offers the advantage of increasing the useful transport volume and implicitly the transported mass, the transport capacity experiencing an almost double increase, compared to the initial variant. The length of the units has been reduced, compared to the original structure, in order to use a single bogie in the middle area, which provides a number of advantages in terms of execution and maintenance costs.

Thus, a vehicle composed of two identical units was obtained, connected through a coupling, which is part of their structure, its total length being equivalent to the length of two open wagons, with high walls, Eaos series.

6.4 VARIANT OF THE STRUCTURE WITH COMPOSITE MATERIAL WALLS

Analyzing the propagation stress (obtained in the structural study by the finite element method and in stand tests) in the structure of the original vehicle, it can be easily seen that the values of stresses obtained at the body level are relatively small [59], which may lead to the idea that, in order to reduce the mass of the vehicle, it is possible to opt for the option of removing the steel sheet covering the wall structure and replacing it with lighter materials, such as composite materials (figure 20) [87], [88], [89], [90], [91], [92].

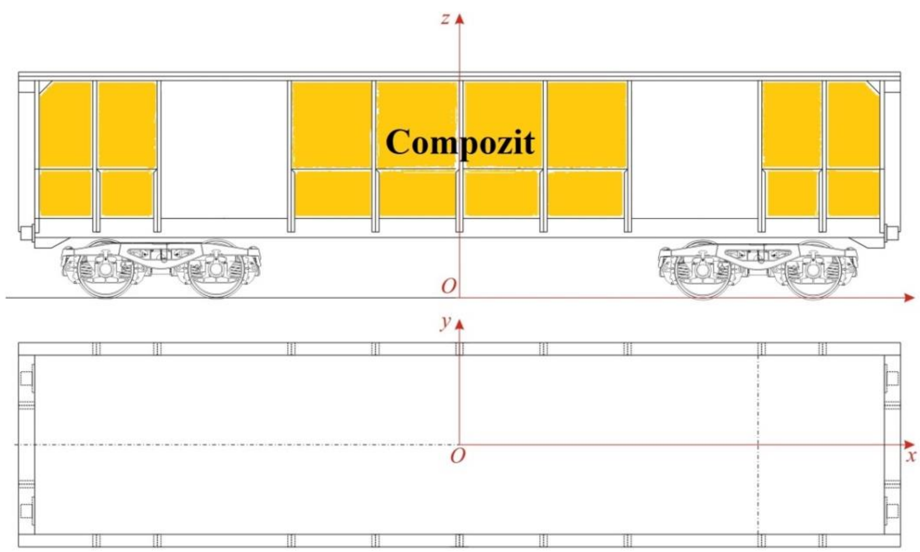


Fig. 20 Composite walls structural

In order to verify this theory, a numerical structural analysis was performed on the vehicle, without the sheet covering the walls. The analysis followed the evolution of mechanical stresses for the entire structure of the wagon.

In order to reduce the mass of the vehicle, the steel wall was removed and a numerical analysis of the vehicle structure was performed, using the finite element method. For this analysis, the most unfavorable case of loading the vehicle structure was chosen, respectively compressive force at buffer level, under the action of the operating load, the result being presented in figure 21.

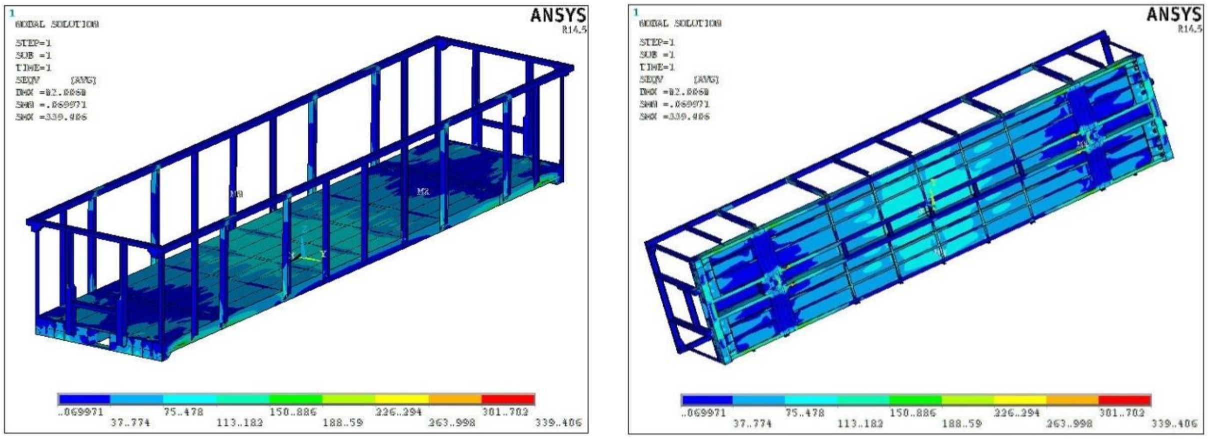


Fig. 21 von Mises stresses for the structure without steel wall plate

Table 13 The mass evolution of steel walls 5 mm / composite 5 mm, 10 mm, 15 mm

Crit. No.	**Tile thickness[Mm]**		**Mass of tiles coverings the wall - steel [Kg]**		**Mass of tiles covering the walls - composite [Kg]**	
1	Steel	Composite	With doors	Without doors	With doors	Without doors
2	5	5	803.63	1345.92	157.01	262.97
3		10			314.04	525.94
4		15			471.05	788.92

Performing a simple calculation results in a total surface area of the wagon of 20,606 m^2, without doors, and a total area of 34,511 m^2 with doors. Table 13 shows the evolution of the mass of the walls depending on the material used and its thickness.

Figure 22 shows (for example) the stress map for the case of the wagon walls, made of composite material with a thickness of 10 mm.

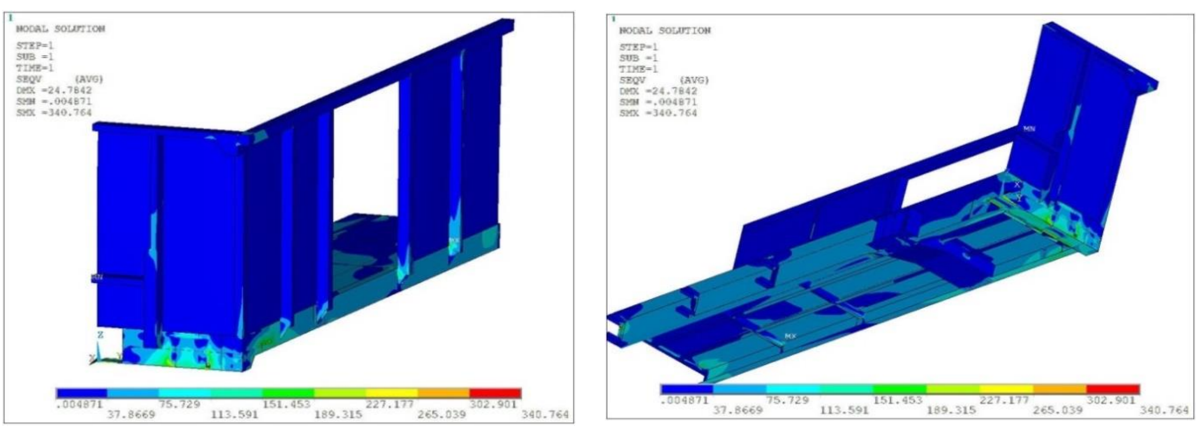


Fig. 22 Structure with 10 mm thick composite walls - von Mises stress

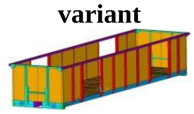
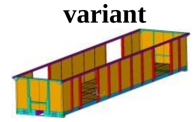
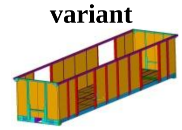
In the case of 10 mm thick panels, the total mass of the vehicle decreases by 820 kg compared to the initial mass of the vehicle.

Below are the main results obtained in the case of numerical analysis of the first three proposed structural variants (table 14 and table 15).

Table 14 ***The main features of the new structural variants / initial variant***

Crit. No.	**Characteristic**	**Initial variant with 20 t axles**	**Articulated variant with axles 22.5 t**	**Long variant with axles 22.5 t**	**The tall variant with axles 22.5 t**
1	Vehicle body mass (without doors) [t]	9,3	15,94	10,02	9,8
2	Vehicle mass [t]	22	34,5	22,72	22,51
3	Vehicle body volume [m^3]	68,4	115,2	74	82,4
4	Transport capacity [t]	58	100,5	67,28	67,49

Table 15 S*tress/displacements results new structural variants and the initial variant*

Test	**Registered unit**	**Structure in the initial variant** 	**Structure in the extended variant** 	**Structure in the raised variant** 	**Structure in the articulated variant** 
compression in the axis of the coupling	stress σ_{max} [MPa]	162	170	156	148
	Displacement in the direction of the *Ox* axis	2,5	2,92	2,62	2,97
	Displacement in the direction of the *Oz* axis	3,08	4,38	3,34	3,97
compression on buffers + vertical load	Stress σ_{max} [MPa]	278	288	279	273
	Displacement in the direction of the *Ox* axis	4,71	5,22	5,07	4,83
	Displacement in the direction of the *Oz* axis	6,37	6,01	8	5,08
Traction in the coupling axis + vertical load	Stress σ_{max} [MPa]	215	247	220	207
	Displacement in the direction of the *Ox* axis	3,04	3,42	2,9	3,03
	Displacement in the direction of the *Oz* axis	9,76	15,43	11,06	10,46

The results of the finite element analysis showed that all four new variants are viable, while complying with the requirements of the standards on the structure tests of railway vehicles.

CH.7 GENERAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

7.1 GENERAL CONCLUSIONS

Rail freight can be considered the most efficient mass land transport system, due to the advantages induced by the large volume of transport and the low costs of energy or fuel consumption. The wheel-rail system ensures a specific rolling resistance almost ten times lower than in the case of freight transport road vehicles, due to the reduced contact between the wheel and the rail.

In order to achieve an efficient and safe transport, the railway vehicles must ensure a series of requirements, among which we remind: full transport safety, high traffic speeds, low transport and maintenance costs, reliability, satisfaction of the requirements in the field, etc.

Before being put into service or after major repairs, railway vehicles must be safety checked, both statically and dynamically.

Any new railway vehicle can only enter the test phase if it is considered fit from the point of view of the structure strength.

In order to improve the quality of rail freight transport in our country, but also in Europe, new projects are needed, in order to replace old vehicles and to bring the rail freight system back to the forefront of land transport systems.

Starting from this idea, the paper presented the study of an open, high-walled freight railway vehicle, on which modifications were made, in order to increase its transport capacity.

The vehicle that formed the basis of this study is an open wagon, with high walls, with side loading/unloading doors. This type of vehicle is one of the most popular wagons used for transporting bulk or palletized, weather-resistant goods, such as: ore, coal, wood (logs or processed wood), scrap metal etc.

Freight wagons are the most stressed railway vehicles, carrying goods whose mass can be up to three or even four times the mass of the vehicle itself. This leads to very high stresses in the the vehicle structures, especially when it is in the composition of a train, and the forces that are transmitted into the body of the train amplify the forces caused by the transported load.

The wagon presented at the base of this study has a relatively simple construction, being made, for the most part, of standardized metal profiles, made of S355 type steel.

Following the numerical analysis of the wagon structure (presented in Chapter Three), carried out by the finite element method, using the Ansys Mechanical software, the stress evolution and displacements evolution determined as a result of the application of longitudinal, vertical and combined loads was determined, in accordance with the reference documents defining the method of verifying the structure of goods vehicles.

The next stage of the work consisted in the experimentally analysis of the structure, by the resistive electrical tensometry method, using a special test rig.

The results obtained experimentally were compared with those obtained numerically and were used to validate the virtual model, used further in the study.

As the wagon is suitable for maneuvering over the sorting hump, an additional set of checks, both experimental and numerical, was performed to verify the behavior of the vehicle when applying shock loads.

The results obtained numerically are close to those obtained experimentally, which shows that the finite element method provides good results.

As mentioned during the paper, the studied wagon is equipped with axles that support a maximum mass of twenty tons each, which means a maximum mass of eighty tons, minus the wagon mass, amounting to twenty-two tonnes, resulting in a maximum transported mass of fifty-eight tonnes.

The increase of the transported mass can be done through two variants:

1. Reducing the mass of the wagon;

In this case, reducing the mass of the wagon involves reducing the thickness of the material from which the structural elements are made, which could lead to very high structure stresses and, as mentioned, to a premature aging of the entire structure.

2. Increasing the useful volume of the body;

Increasing the useful transport volume of the vehicle body requires structural changes that lead to an increase in the mass of the vehicle and, in this case, there is a need to use axles that support larger masses. In our country and at European level, the maximum value of the mass allowed on the axle is 22.5 tons.

Four new structural variants were proposed in the paper, these registering stress values below the maximum allowable limits, and can be considered viable variants to increase the transport capacity.

7.2 PERSONAL CONTRIBUTIONS

The research activity in the field of freight railway vehicles is almost non-existent in our country, and this can be easily seen, following the trainsets, which seem completely outdated.

Achieving the objectives proposed in this study required the completion of complex stages of research and through this, the paper brings a number of contributions, of which I mention:

- ➢ performing a numerical analysis of the structure of the studied vehicle, by the finite element method, which resulted in the determination of the stress and displacement evolution of the studied structure, following the application of standardized longitudinal and vertical loads;
- ➢ performing the static experimental analysis of the vehicle structure, by the method of resistive electric tensometry, using a special test rig, in order to determine the stress and displacement evolution arising from the application of standardized loads;
- ➢ validation of the numerical model, using the results obtained by the method of resistive electrical tensometry, obtained on the test rig;

- ➢ performing dynamic experimental analysis on the vehicle structure, following the application of longitudinal shock loads, using the method of resistive electrical tensometry, in order to measure the strains occurred at the level of the wagon structure;
- ➢ performing the dynamic numerical analysis of the vehicle structure shock load and comparing the results with those obtained experimentally;
- ➢ providing four new constructive solutions, which ensure the increase of the transport capacity of the analyzed wagon.

7.3 FUTURE RESEARCH DIRECTIONS

Starting from the basic idea of this study, which focused on offering new constructive solutions, in order to increase the transport capacity of a freight railway vehicle, the theme of the paper can be easily directed to the analysis of other constructive solutions or to the analysis of other types of freight railway vehicles.

At the same time, using the finite element method [109], which has proven to be an effective solution for the analysis of railway structures, it is possible to study, on a large scale, the structures of railway vehicles in use, to identify possible areas with problems, areas where analysis of rupture and fatigue may be necessary.

In the case of the new structural solutions presented, analysis and simulations can be performed to determine the dynamic rolling behavior and to perform the brake calculations, necessary to provide a complete design.

Also, a more detailed analysis of the possibility of using composite materials in the structure of railway wagons is needed [110], [111], [112].

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