Researches in the field of the bearing structure of tank wagon

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Abstract: - The paper deals with one of the (studied) possibilities of connecting and attaching the chassis to the tank. The adopted constructive and technological solution answers to the requirements imposed through the international regulations by the UIC. The paper also presents the determination of the resistance of the studied technical solution using the finite element method and its ratification through experimental trials considering a static stress regime. The comparison of the theoretical determinations to the experimental ones leads to a positive assessment of the accuracy and veracity of the determination method as well as the safety of using the constructive solution into operation. Moreover, the paper brings forward a theoretical as well as an experimental study of the resistance of the attachment (frame) tank-chassis to the dynamic stress due to the collision shock. The theoretical determinations of the resistance, using the finite element method for the cushioning action of the buffers, have constituted the fundamental information for choosing the verified dangerous sections. The paper also brings forward collision trials and the conclusions imposed by the experimental study.

Key-Words : bearing structure, relative deformation, pressure.

1 Introduction

Designing, building, promoting and operating a railway vehicle follows a complex process which applies to the strict rules and concepts of applied mechanics. Consequently a scientifically well established trajectory is adopted attached therefore to a series of precise norms which are imperiously necessary:

1. The establishment of a set of technical norms comprising the technical characteristics as well as the resulted economical and environmental impact.
2. The theoretical study on the adopted constructive and technical solutions, as well as finishing the technical characteristics for building a vehicle.
3. The design phase outmatched by a series of researches following to establish a series of solutions to be comprised in the design of the prototype which will be ratified by the experimental research.
4. The experimental research which follows a schedule comprising the possibilities in which the vehicle may react during operation considering the resistance of their bearing structure, the safety and dynamic while running.
5. Modifying the design and consequently the prototype following the implications of the researching programme as well as trials and the rerun of the experimental research until it is finalized. The finalisation of the vehicle supposes that all the initially proposed requirements be respected.

The paper makes reference to the design phase of the prototype of the tank wagon together with the confirmations offered by the experimental study regarding the resistance of the bearing structures.

The experimental study, using static trials, of the resistance of the bearing structure is compulsorily continued through dynamic trials of repeated shock for the determination of the life span related to the random stress acting on operational vehicles.

The paper proposes to follow the modality in which theoretical and an experimental researches are made in order to finally lead to a correct appreciation of the technical, technological and constructive solutions adopted for the studied case, therefore the resistance in exploitation.

2 Theoretical verification calculation using the finite element method

The finite element method (FEM) is a procedure to approximately solve a series of differential equations, in given limited conditions, describing physical phenomena from various fields. Obtaining a number of exact solutions for the differential equations describing physical phenomena in given limited conditions supposes the simplification of the model until the integration of the differential equations is realisable.

The steps required for a linearly static analysis to be carried out with the help of the MSC/NASTRAN software are realising the model, applying the loads and limit conditions, solving the problem as well as visualising the results.

A 3D model of the geometry of the wagon was realised in the design phase, model which was afterwards introduced in the MSC Nastran software and adapted the specific requirements for three-dimensional analysis with the finite element. Both the individual components as well as the components have been interconnected in order to obtain a sequential geometry of the model. The resulted geometry has been discretised.

Due to the fact that the structure of the wagon is made of thin metal plates, the finite element bi-dimensional analysis uses plate type elements. The thickness of the elements of the discretisation was chosen to be between 10 and 70 mm in order for acceptable values shall result in stress concentrators.

Taking into consideration that the structure of the wagon is symmetrical and the applied stress is symmetrical as well, the calculation considers only a quarter or a half of the entire structure.

The calculations were made for a tank wagon with the following characteristics:

The weight of the empty wagon
- m_c = 27000 kg;
- Maximum load m_2 = 63000 kg;
- Admissible load per axle $2Q_0$ = 22500 kg;
- Wheelbase a = 10820 mm;
- The external diameter of the tank without insulation D = 2700mm.

The properties necessary for the static analysis, corresponding to steel, are – the longitudinal elasticity model (Young's module), E = 210000 [Mpa]; mass density ρ = 7850 kg/m^3 and the coefficient of transversal contraction (Poisson's) ν = 0.3.

The chassis and the attachment device are made of St52 DIN 17100 with $R_{p0,2}$=355 N/mm^2 and the flow limit for the material of the tank, as the tank is equipped with an exterior heating installation welded on it, having the maximum calculation temperature of +190^o, the flow limit at 190a 190^{o}C obtained through interpolation is $R_{p0,2}$=229 N/mm^2.

The objective of the static analysis is to determine the relative deformations respectively von Mises stress [N/mm^2] of the structure of the wagon considering the loading conditions imposed by the ERRI B12 Rp17. The simulated stresses which the vehicle underwent and the results obtained are presented in figures 1 to 4. The simulated stress which the vehicle underwent for the loads SV63t+CT2x1MN are the ones presented in figures 5 to 7.

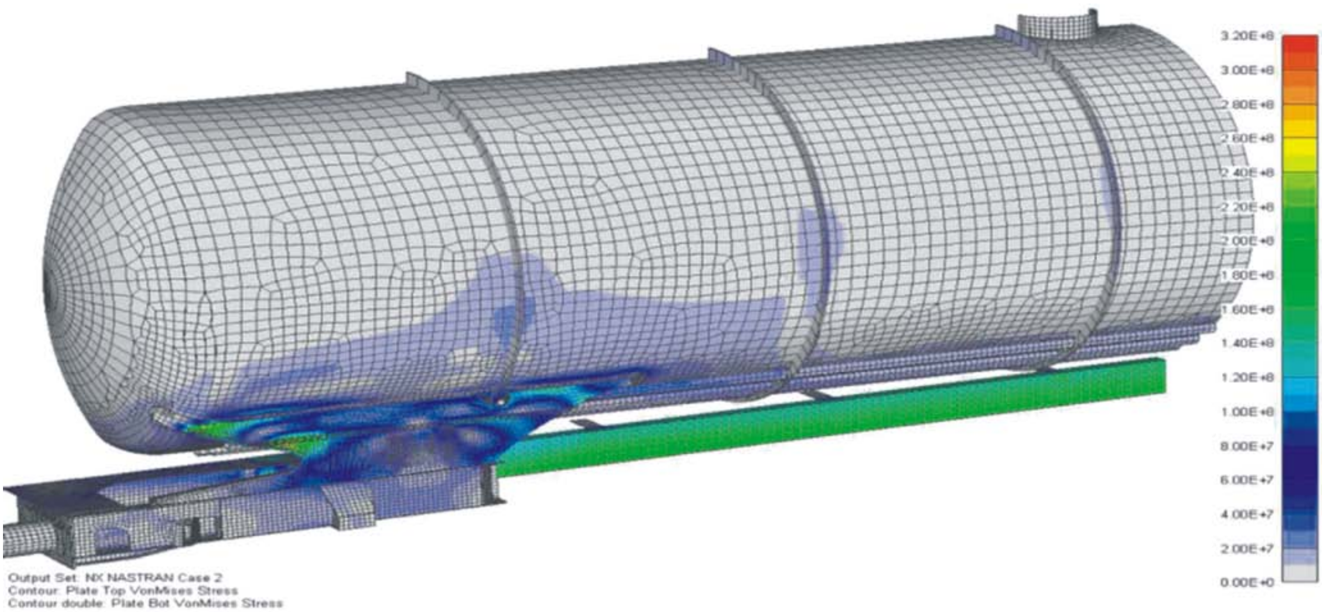

Fig.1 Central compression – CA 2MN – equivalent von Mises stress [N/m^2]

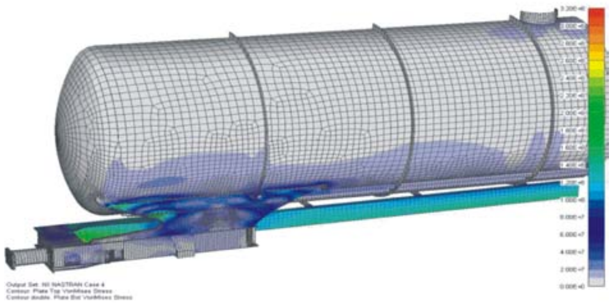

Fig.2 Traction TA T1,5MN – equivalent von Mises stress [N/m2]

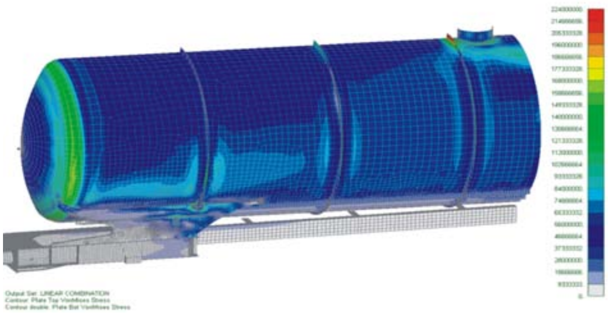

Fig.3 Pressure 1gx63000kg+p 3bar – SV63P3bar – equivalent von Mises stress [N/m^2]

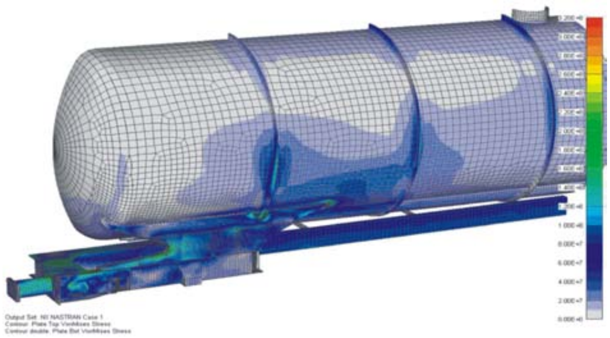

Fig.4 Buffer compression + vertical stress [SV63+CT2x1MN] – equivalent von Mises stress [N/m^2]

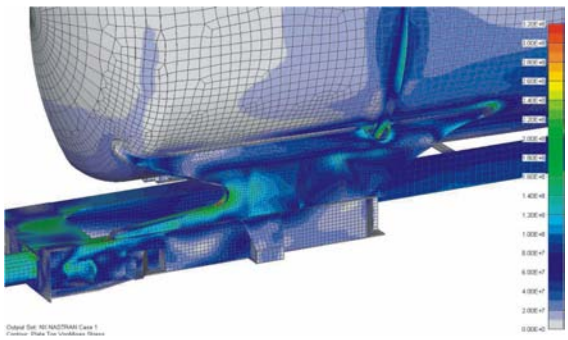

Fig.5 Equivalent von Mises stress [N/m^2]

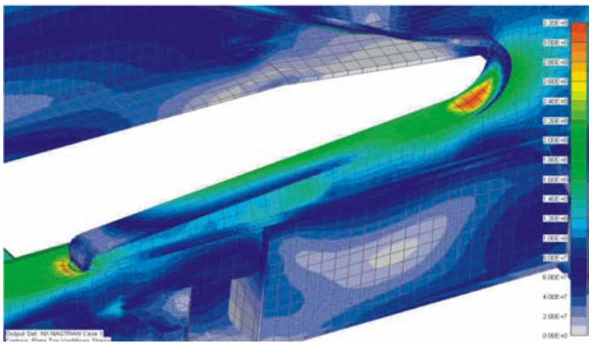

Fig.6 Equivalent von Mises stress [N/m^2]

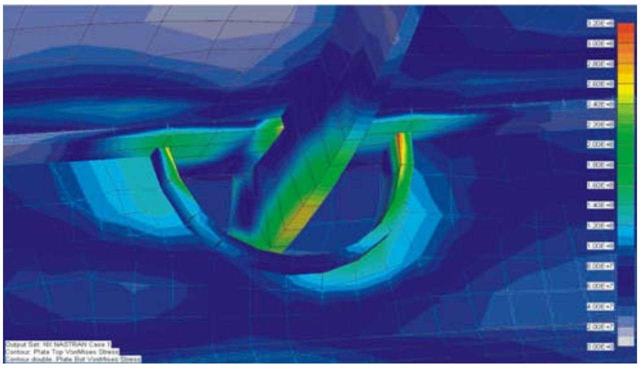

Fig.7 Equivalent von Mises stress [N/m^2]

3 Static experimental determinations

Analysing the theoretical results obtained through calculations, the areas and sections the most dangerous considering the resistance to static stress stimulating the operational stress have been detected, according to ERRI B12 Rp17. Therefore, a number of 20 linear transducers and 15 three way transducers (marked with R hereinafter) were installed on the structure of the tank and its attachment to the chassis. They are resistive electrical transducers their purpose being that of determining the relative deformations, respectively tensions (in an elastic field). The location of the transducers is presented in the diagram in figure 8.

The following trials were made on a specialised test bench fitted with measuring, recording, and experimental data processing devices:

- Axial compression with an applied force of 2MN (CA 2MN);
- Axial traction with an applied force of 1.5MN (TA T1,5MN);
- 3bar pressure in the presence of vertical load SV=63000 kg (SV63P3bar);
- Buffer cushioning with an applied force of F=2x1MN (1 MN on each buffer) in the presence of vertical load SV=63000kg (SV63+CT2x1MN).

The electric resistive tensometry method is a high accuracy method.

The results of the experimental determinations are presented in:

- Table 1 – the stress values for the unidirectional transducers (linear) expressed in N/mm^2;
- Table 2 – the value of von Mises stress calculated considering the determination of the main stresses σ_1 and σ_2 based on the experimental three way relative deformations.

$$\sigma_e = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} \qquad (1)$$

Table 1

Transducer/ Trial	CA 2MN	TA T1.5MN	SV63P3bar	[SV63+CT2x1 MN]
	N/mm^2	N/mm^2	N/mm^2	N/mm^2
101	-65	-6	-16	-334
102	-42	-20	-21	-298
0102	-51	-9	-18	-282
103	129	-109	12	12
104	100	-81	20	29
105	20	-7	23	44
106	12	-26	9	-55
107	1	-2	8	-4
108	-103	105	19	-92
109	-127	130	30	-216
110	-3	2	2	-5
111	-78	63	33	-121
112	-38	40	28	-59
113	3	-1	-71	7
114	9	-6	89	14
115	-269	288	30	-203
116	-296	283	-29	-236
117	6	-41	0	-347
0117	7	-38	2	-301

Table 2

Transducer/Trial	CA 2MN	TA T1.5MN	SV63P3bar	[SV63+CT2x1 MN]
R1	28.5	28.2	12.1	64.6
0R1	27.1	23.5	15.7	51.7
R2	54.9	68.6	21.5	87.3
R3	108.9	90.3	70.0	175.0
0R3	119.0	92.7	58.9	174.8
R4	155.3	164.7	47.3	206.0
R5	277.2	295.4	48.4	291.1
R6	201.2	171.7	42.1	68.3
R7	147.0	134.8	19.0	39.0
R8	24.7	19.9	98.3	15.5
R9	6.8	4.7	70.6	3.3
R10	6.2	3.7	28.4	13.1
R11	42.3	28.8	33.8	72.4
R12	33.7	23.7	152.0	123.0
R13	54.0	39.2	16.1	117.4

In order to carry out the experimental study in complete accordance to the danger areas discovered through theoretical determination and the results of experimental trials in a static regime 9 linear transducers and 5 tensometry transducers were used according to the location diagram presented in figure 8.

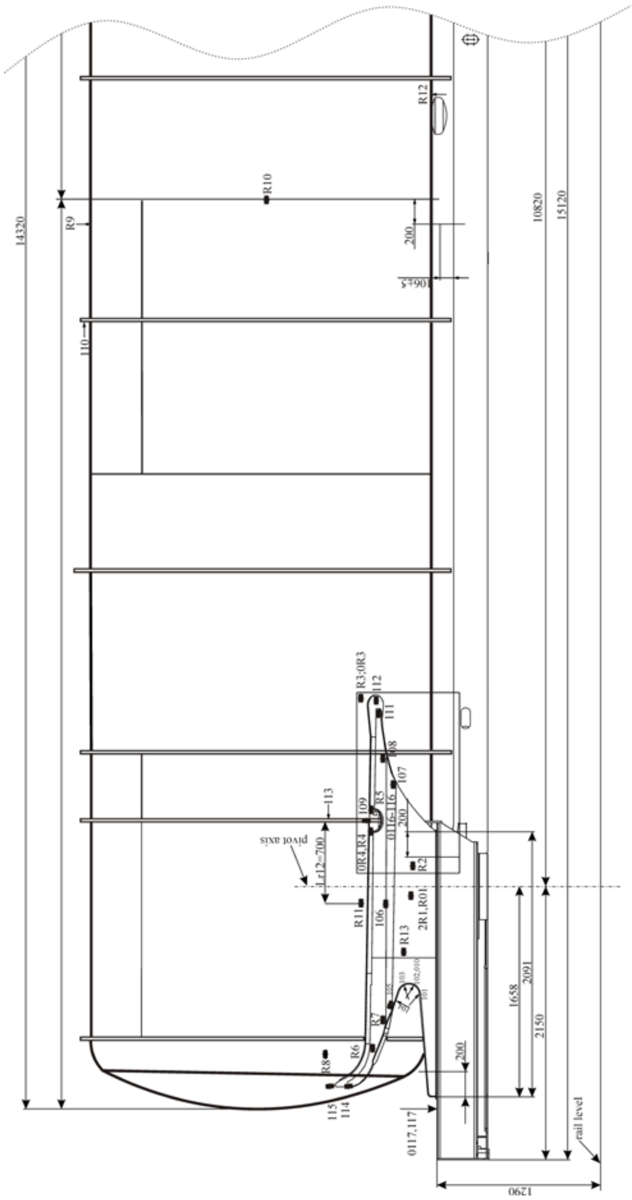

Fig.8 Transducers' location

4 Dynamic experimental determinations at the shock resulted during collision

4.1 The presentation of the collision study

The collision trials for the experimental determination of the elastic dynamic characteristics of shock isolators were carried out using the collision bench of the Researches and Trial Laboratory (ICPV Arad SA, Romania).

The collision bench, specially built and set up is presented in figure 9.

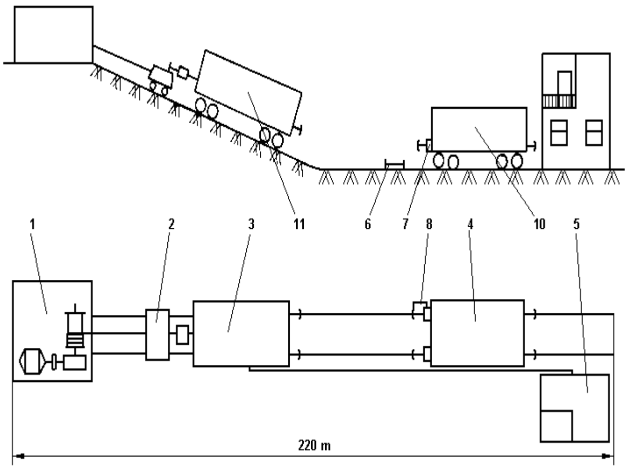

Fig.9 Collision bench
1 - pulley; 2 – triggering cart; 3 – colliding wagon; 4 – collided wagon; 5 – bench building; 6 – speed transducer; 7 – force transducer; 8 – movement transducer; 9 – connecting cables; 10, 11 – acceleration transducers.

The bench is composed of two important parts:

- an 80 m long slope, with an 8‰ angle of tilt, required for launching the colliding wagon with speeds comprised between (1 ... 30) km/h, depending on the level the wagon will be raised on the launching ramp. The 8‰ angle of tilt ensures the accuracy concerning the repeatability of the values of the collision speeds obtained for the same starting level of the colliding wagon;
- the landing section of approximately 100 m is followed by a slight alignment ramp of 90 m. The collision of the vehicles practically takes place on this landing section, where it exists a concrete platform for different uses.

The bench is equipped with the following:

- pulley 1, which ensures, with a power cable, the hauling of the connection triggering cart and the colliding wagon;
- triggering cart 2, foreseen with a self triggering mechanism allowing for the wagon to be launched from the desired level;
- a two level specially designed building with the required functions. The controller room is found on the second floor of the building, approximately 6 meters high, from where the collision process is observed. The room offers great visibility of the entire bench, especially of the platform where the collision takes place, existing therefore the possibility of continuous audio communication between the controller room, the pulley, and the collision platform;
- connection cables between the transducers installed either on the colliding wagon or on the collided wagon and the existent connection plug which continues with the circuits to the controller room;
- transducers, i.e. measuring, recording and processing devices, figure 10.

Collision trials are carried out by launching the colliding wagon from the ramp at different speeds, depending on the reached level, followed by the collision, in the landing section, with the collided motionless and non-braked wagon.

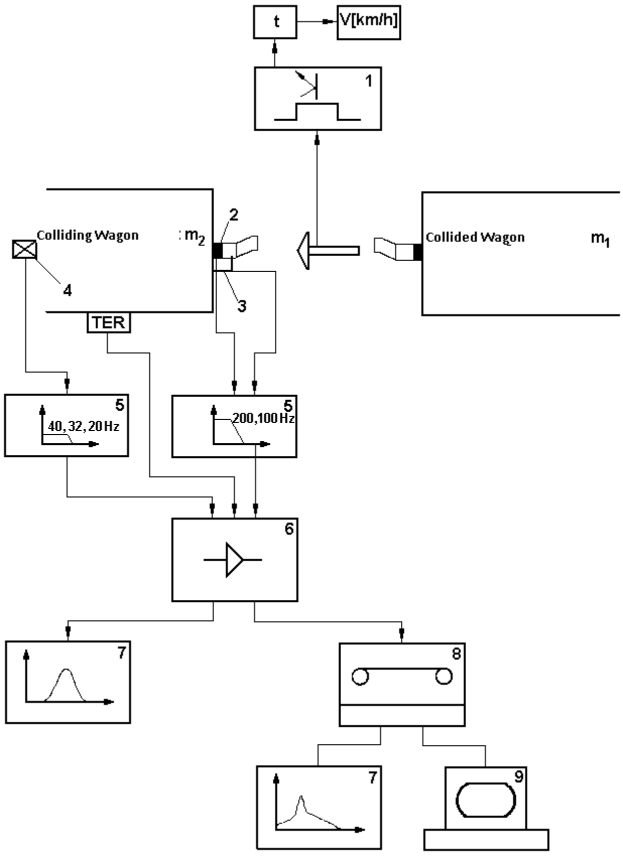

Fig.10 Transducers, i.e. experimental data measuring, recording and processing
1 – speedometer; 2 – force transducer; 3 – movement transducer; 4 – acceleration transducer; TER – resistive tensometric transducer; 5 – low frequency filters; 6 – measure amplifier; 7 – ultraviolet rays recorder; 8 – magnetic recorder; 9 – computer.

All the researched parameters are measured and recorded during the collision process:

- forces F1, respectively F2 transferred through the buffers;
- contractions of buffers D1, respectively D2;
- acceleration given to the collided wagon a2.

These parameters were recorded during the collision process of two wagons equipped with category B buffers, each wagon weighing 80t, at a collision speed of v = 12.7 km/h. It is important to highlight that the forces transferred through collision and the acceleration of the wagon is cancelled in the moment considered in the research, i.e. , moment previous to moment t2 during which the value of the contractions of the buffers is equal to zero.

It is observed that, in any collision scenario, the force transferred to the two vehicles may be appreciated to be the same, and the acceleration differs in proportion to the masses of vehicles m2 /m1. If vehicles are equipped with the same shock isolators, the contractions of the isolators are identical.

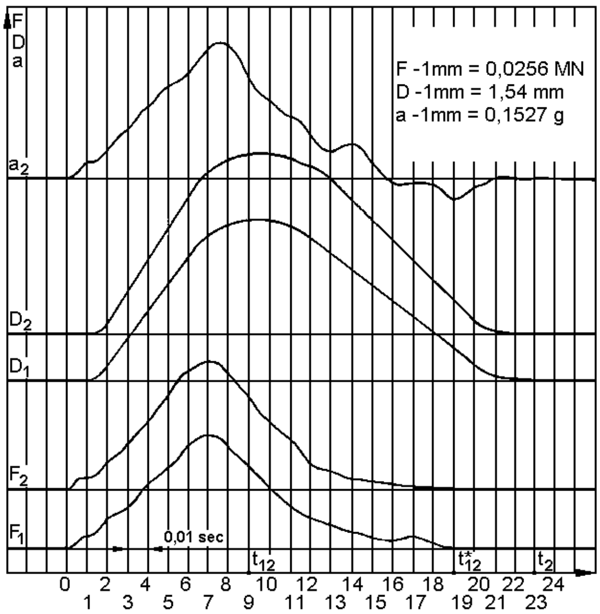

Fig.11 Experimental diagram of the time variations of forces F1, F2 transferred through the buffers, the contractions of the D1 and D2 buffers and the acceleration of the collided wagon

4.2. The expression of the transferred force during generalised collision

The effect of the shock of the collision if the transfer of forces and accelerations which may determine unwanted consequences on the resistance structures, equipments, passengers, and transported goods by the rail vehicles.

In order to decrease the transferred forces and accelerations and, consequently, the unwanted effects of shock, rail vehicles are equipped with shock isolators. The capacity of shock isolators to store the potential deformation energy, emphasises factor 2β, which directly influences the forces and acceleration transferred to the vehicles as well as the level of potential energy $(1 - 2\beta)$ Ep which rests with the vehicles, respectively to the effects occurring following the collision shock. Consequently, there is the tendency, while designing and building rail vehicles, to increase the storage capacity of potential energy of shock isolators in order to decrease the level of the forces and accelerations transferred to the rail vehicles during collisions.

The theoretical expressions of the transferred force, previously presented, may be used only if the rail vehicles are equipped with shock isolators which have a linear variation between force and contraction.

Rail vehicles may be equipped with shock isolators the elastic elements of which have a non-linear variation between force and contraction.

The coefficient of plenitude is therefore defined, for the shock isolators for any type of variation function of contraction, representing the relation between the potential energy of deformation stored and the product between the maximum transferred force and the maximum contraction of the shock isolator.

Considering two colliding vehicles equipped with different types shock isolators the coefficient of plenitude is the following:

- for the shock isolators of the colliding vehicle:

$$p_1 = \frac{W_{e1}^*}{F_{max} f_1} \qquad (2)$$

- for the chock isolators of the collided vehicle:

$$p_2 = \frac{W_{e2}^*}{F_{max} f_2} \qquad (3)$$

where

- W_{e1}^*, W_{e2}^* - the potential deformation energy of the shock isolators of the colliding vehicle, respectively the collided one;

- f_1, f_2 – the maximum contraction of the shock isolators of the colliding vehicle, respectively the collided one.

It has been considered that the buffers of a vehicle present the same potential deformation energy stored as well as the same contraction.

The following defines the conventional K_T rigidity of the buffer, respectively the one of the central coupling shock absorbent K_C , as being the relation between the maximum transferred force and the maximum contraction of the shock isolator at a colliding speed v:

- for the shock isolators of the colliding vehicle:

$$K_{T1} = \frac{F_{max}/2}{f_1}\ ; \qquad K_{C1} = \frac{F_{max}}{f_1} \tag{4}$$

- for the shock isolators of the collided vehicle:

$$K_{T2} = \frac{F_{max}/2}{f_2}\ ; \qquad K_{C2} = \frac{F_{max}}{f_2}\ . \tag{5}$$

Replacing f_1 and f_2 of (4), respectively (5), in relations (2) respectively (3), the expressions of the potential deformation energy stored by the buffers is obtained:

- the colliding vehicle:

$$W^*_{e1} = \frac{F^2_{max}}{2\,K_{T1}} p_1 = \frac{F^2_{max}}{K_{C1}} p_1 \tag{6}$$

- the collided vehicle:

$$W^*_{e2} = \frac{F^2_{max}}{2\,K_{T2}} p_2 = \frac{F^2_{max}}{K_{C2}} p_2 \tag{7}$$

The specific energetic factors β_1 and β_2 of the colliding vehicle, respectively the collided one are:

$$\beta_1 = \frac{W^*_{e1}}{E_p}\ ; \qquad \beta_2 = \frac{W^*_{e2}}{E_p} \tag{8}$$

Using relations (6), (7) and (8), it results

$$\begin{aligned}(\beta_1+\beta_2)\ E_p &= \frac{F^2_{max}}{2}\left(\frac{p_1}{K_{T1}} + \frac{p_2}{K_{T2}}\right) = \\ &= F^2_{max}\ \left(\frac{p_1}{K_{C1}} + \frac{p_2}{K_{C2}}\right)\end{aligned} \tag{9}$$

Replacing the expression of potential energy E_p (2), the relation of the maximum force transferred to the buffers while the collision of buffer equipped vehicles

$$F_{max} = (v_1 - v_2)\ \sqrt{\frac{m_1 m_2 \cdot (\beta_1+\beta_2)\cdot K_{T1}\ K_{T2}}{(m_1+m_2)\cdot(p_1 K_{T1} + p_2 K_{T2})}} \tag{10}$$

Considering the collision of two vehicles of the same type, having $m_1 = m_2 = m$, $K_{T1} = K_{T2} = K_{T1}$, $p_1 = p_2 = p$, and $\beta_1 = \beta_2 = \beta$, the expression of the transferred force becomes

$$F_{max} = (v_1 - v_2)\ \sqrt{\frac{m}{4}\ 2\ \beta\ \frac{K_T}{p}} \tag{11}$$

Considering the collision of vehicles equipped with a central coupling, the expression of the force transferred results from relation (9) as being

$$F_{max} = (v_1 - v_2)\ \sqrt{\frac{m_1 m_2 \cdot (\beta_1+\beta_2)\cdot K_{C1} K_{C2}}{2(m_1+m_2)\cdot(p_1 K_{C1} + p_2 K_{C2})}} \tag{12}$$

Considering the collision of two vehicles having the same type, having $m_1 = m_2 = m$, $K_{C1} = K_{C2} = K_C$, $p_1 = p_2 = p$, and $\beta_1 = \beta_2 = \beta$, the expression of the force transferred becomes

$$F_{max} = (v_1 - v_2)\ \sqrt{\frac{m}{2}\ 2\ \beta\ \frac{K_C}{p}} \tag{13}$$

The established expressions may be used to determine the force during the collision of the vehicles equipped with shock isolators the elastic elements of which may be of any type of variation, both linear as well as non-linear.

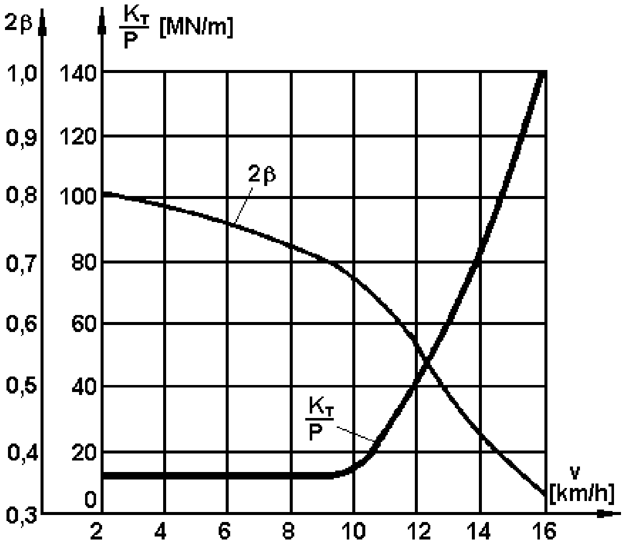

Fig.12 Variation diagram of the 2β factor and of the K_T/p parameter, for a collision of two wagons equipped with category a buffers with elastic elements composed of RINGFEDER rings

4.3 Experimental research carried out

In order to carry out the experimental study in complete accordance to the danger areas discovered through theoretical determination and the results of experimental trials in a static regime 9 linear transducers and 5 tensometry transducers were used according to the location diagram presented in figure 8 [10], [11].

Collision trials were made on a specialised bench by launching the buffer wagon, with a weight of 80t, which collided with the tank wagon, with the weight of 90t. Category A buffers are installed on both vehicles applying to the norms of European Railways, UIC 526-1 [7], [8].

The following parameters were determined during the trials:

- v [km/h] – the speed of the buffer wagon;
- F_1 [kN] and F_2 [kN] – the forces transmitted during the impact;
- D_1 [mm] respectively D_2 [mm] – the contractions of the buffers of the buffered wagon;
- Acc1 [g] – the acceleration of the buffered wagon;
- Linear transducers stresses σ [N/mm^2] and von Mises stressed [N/mm^2] with rotary transducers marked with R hereinafter.

For the linear transducer 116 respectively the 118 one, the values in italic and bold presented in the tables with the experimental researches, represent relative deformations experimentally determined expressed in [μm/m].

Collision trials consisted of two phases:

1. Preliminary trials made at increasing collision speed, namely from 6.71÷12.01 km/h in order to discover the most stressed areas. The results of these trials are presented in tables 3 and 4.

Table 3

TER	SV	Speed [km/h]									
		6.71	7.39	8.5	9.02	9.02	9.16	10.3	11.04	11.2	12.01
101	-6	-106	-112	-122	-118	-110	-116	-120	-148	-172	-258
0101	-7	-114	-124	-124	-120	-134	-142	-146	-176	-194	-286
102	-9	-108	-114	-122	-126	-122	-116	-126	-144	-148	-228
103	-9	20	27	31	32	35	35	39	50	52	94
104	-4	26	32	36	40	39	40	44	52	57	92
105	4	18	21	24	25	25	27	28	29	30	44
116	-97	-224	-226	-274	-286	-295	-319	-323	-339	***-1664***	***-2028***
118	69	182	193	220	245	252	278	280	297	301	***1734***
117	-4	-62	-77	-74	-77	-75	-79	-80	-93	-100	-170
0117	-2	-60	-68	-74	-75	-78	-79	-81	-90	-94	-167
F1 [kN]		339	370	435	457	463	465	532	596	602	1224
F2 [kN]		421	458	522	544	542	551	620	681	687	1158
D1 [mm]		58	64	74	78.5	79	80	90	97	98	105
D2 [mm]		57	63	73	77.5	78	79	89	96	97	104
Acc1 [g]		1.87	2.16	2.35	2.61	2.61	2.66	3.19	3.46	3.46	6.32

Table 4

Speed [km/h]	6.41	7.43	8.59	9.5	10.4	11.04	12.02
Rotary							
R1	48	50	53	54	57	60	73
R3	72	77	94	112	114	116	174
R4	191	209	234	241	256	281	372
R5	157	166	178	185	192	206	265
R11	97	103	109	121	124	122	140

2. Endurance trials at an approximate speed of 12 km/h, a series of 40 collision shocks. The results of these trials are presented in tables 5 and 6.

Table 5

Speed [km/h]		11.92	11.92	12.04	12.03	Residual	11.92	Residual
TER	S.V.	Buffer 1	Buffer 10	Buffer 20	Buffer 30	[‰]	Buffer 40	[‰]
101	-6	-258	-266	-280	-278	0.07	-274	0.07
102	-9	-193	-194	-243	-240	0.19	-221	0.19
103	-9	66	40	52	60	0.02	53	0.02
104	-4	124	111	95	93	0.06	88	0.06
116	-97	***-1501***	***-1883***	***-2021***	***-1996***	***0.3***	***-1891***	***0.3***
118	69	***1707***	***1859***	***2058***	***1961***	***0.27***	***1961***	***0.27***
117	-4	-203	-217	-266	-252	0.02	-231	0.02
F1 [kN]		1266	1214	1273	1208		1234	
F2 [kN]		1234	1159	1231	1110		1156	
Acc [g]		6.5	6.3	6.6	6.3		6.3	

Table 6

Buffer no.	1	10	20	30	Residual	40	Residual
Speed [km/h]	11.92	11.92	12.04	12.03	[‰]	11.92	[‰]
R3	222	217	221	210	0.07	215	0.07
R4	393	394	379	395	0.3	386	0.3
R5	240	215	181	183	0.13	172	0.13

Figures 13, 14 and 15 present parameters F_1, F_2, and the acceleration Acc1 of collision. Figure 16 presents an area of the studied stress concentrator area.

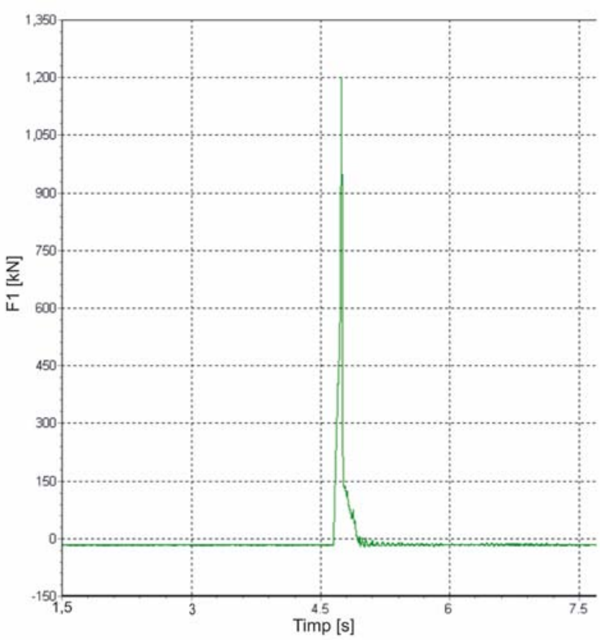

Fig.13 The variation of force F1 depending on time for the collision process – loaded wagon

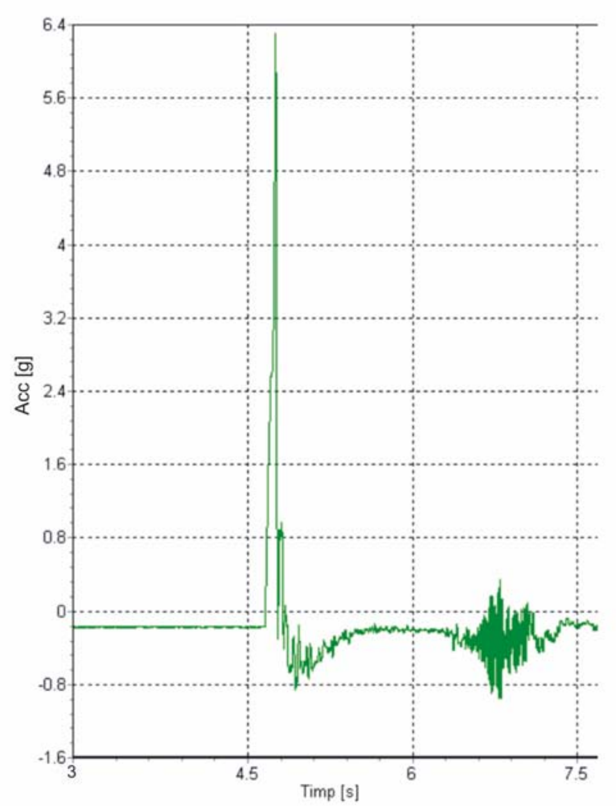

Fig.15 The variation of acceleration Acc depending on time for the collision process – loaded wagon

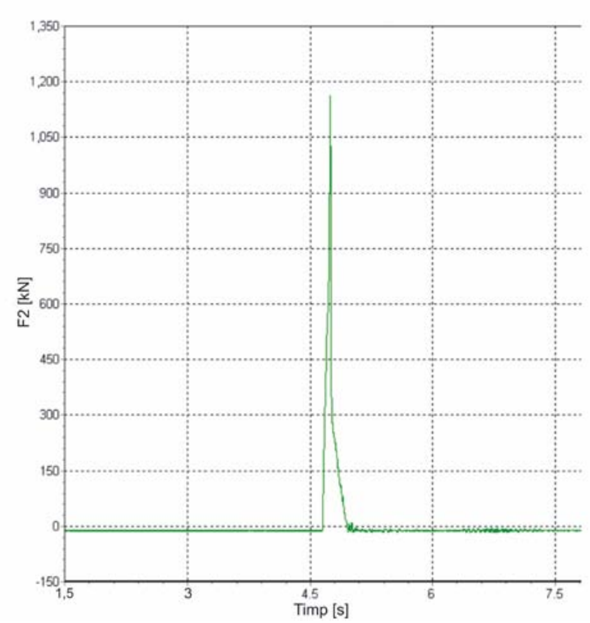

Fig.14 The variation of force F2 depending on the time of the collision process – loaded wagon

Fig. 11 The variation of acceleration Acc depending on time for the collision process – loaded wagon

5 Conclusions

It has been observed that the stress values obtained theoretically are in accordance with the values obtained experimentally. Moreover, experimental results confirm the dangerous areas of the bearing structure of the vehicle.

The determination using the finite element method offers extremely useful information regarding the investigation of the experimental research. The later one has the function of giving a verdict in its different phases concerning the resistance of the bearing surface of a rail vehicle.

The following conclusions may be drawn from the presented study:

1. The theoretical determination using the finite element method is a support and offerts important information regarding the dangerous areas (the most stressed areas) which need to be experimentally investigated.

2. Shock trials through collision confirms the positive response of the studied structure to exploitation stress as in all the measured spots of the relative deformation respectively of stress permanent deformations were not recorded to exceed $2^{o}/_{oo}$ according to B12 Rp17 ed. 8.

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