FE numerical tests of railway wagon for intermodal transport according to PN-EU standards

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Abstract. A special wagon, presented in the paper, can be used for intermodal transport of various types of vehicles. It enables transport of vehicles of 36 tons mass and height of 4m on the GB1 clearance height. An innovative wagon is equipped with a frame-support with marginal parts mounted on standard biaxial bogies and the central part lowered with a rotatable loading platform. The rotating part of wagon acts as a kind of platform, allowing truck to move through it during load/unload. During railway operation, this rotating platform is to become an integrated part of the wagon; the tailboards of the rotating part will be connected to the over-bogie part with the special locks. A unique concept of the wagon structure forced a design approach which was rather unusual for the rail industry. Since the design team aimed at very challenging demands of GB1 envelope and usage of standard bogies, the layout of the wagon had to be thoroughly examined in terms of its overall stiffness. Every major design change had to be simulated in order to accurately predict its influence on the whole wagon structure. FE analysis was used for numerical tests of such a wagon structure in different configurations. The calculations were carried out on the basis of PN-EN standards. Selected results of numerical tests of the prototype version of a such wagon for intermodal transports were presented in the paper.

Key words: prototype railway wagon for intermodal transport, FE methodology of numerical tests, analysis of the wagon strength and dynamics simulations according to PN-EU standards.

1. Introduction

A prototype railway wagon for intermodal transport [1–6] is a subject of consideration. The special wagon allows quick and convenient loading/unloading of vehicles and containers (without cranes), no platform infrastructure is required, instead of hardened, flat, surface; no need for hubs, terminals or special logistics; each wagon can be operated separately. An innovative wagon is equipped with a frame-support with marginal parts mounted on standard biaxial bogies and the central part lowered with a rotatable loading platform (Fig. 1).
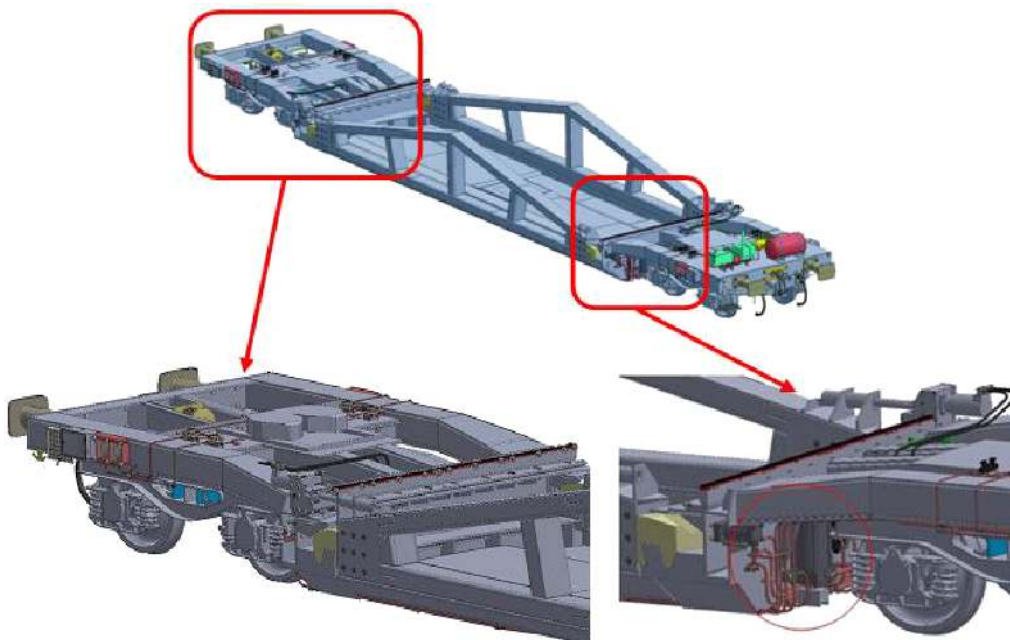

Fig. 1. Prototype wagon for intermodal transport – different views

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The rotating part of wagon acts as a kind of platform, allowing truck to move through it during load/unload. During railway operation, this rotating platform is to become an integrated part of the wagon; the tailboards of the rotating part will be connected to the over-bogie part with the special locks. Motion of the rotatable platform and the locks are hydraulically controlled. At the ends of the rotating part of the wagon body, there will be located rolls enabling its moving on the railway platform and simultaneously constituting a support of the rotating platform in the process of loading/unloading. The rotatable platform of the wagon enables an independent entry of the set of tractor/towing vehicle and semitrailer from the one side and exit from the other side (the arterial body of the wagon). During loading, in order to stabilize the platform, a bottom plate of the wagon frame will be supported on the heads of rails on the additional, hydraulically controlled, supports.

The main design goal was to develop a wagon solution which would allow for easy load/unload procedure without extensive railway infrastructure changes. A non-standard layout of the innovative wagon forced a revised approach to the design process. Instead of analyzing an almost finally developed, validated in terms of technology, structure (usual approach), numerical simulations had to be included as an immanent part of the design process. Every major design change had to be simulated in order to accurately predict its influence on the whole wagon structure. It should be stressed out that such an approach (mainly multibody [7] and FE analysis [3, 4, 8]), although time consuming, was the only way to access information how design changes would affect wagon mechanics. Without this knowledge, design of the new wagon would not be possible. The developed methodology of examination of such a wagon structure enables its implementation both at the stage of the design and during tests on already exploited or renovated constructions. The object of the paper comprises selected problems of numerical analysis of strength of a constructional solution for a wagon with a rotating platform subject to the influence of standard loads. The calculations were carried out on the basis of PN-EN 12663 standard. There are discussed the results of numerical tests of the prototype version of the wagon for intermodal transports.

2. FE methodology of numerical analysis

A very popular, as well as effective and also accurate, method of studies on compound constructions is the method consisted in combining experimental and numerical studies. Design offices develop numerical models of new constructions as well as conduct strength analyses. Additionally, strength experimental studies of such a construction or its subsystems are carried out. On the basis of the results of experimental studies, it is possible to verify both a numerical model of the developed construction and the applied calculation method. In case of convergence of the results of both tests, the correctness of the numerical model and the calculation method is verified. The properly developed discrete model can be used

for more complicated and complex strength calculations or for modification of the already developed and verified construction.

Numerical studies are mainly used for the strength testing at the stage of the construction work, if a prototype for experimental tests has not been built yet. Static and dynamic FE analysis of the prototype intermodal wagon was developed and discussed in the paper. For this purpose, discrete models of main components of the prototype wagon: the frame-stand and cooperating with its rotational load platform as well as a FE model of the complete wagon on the section of rail were built.

In static FE tests on the developed numerical model of a wagon with nonlinearities resulted from the contact phenomena and clearances, the analyses were conducted with the use of an iterative calculation algorithm. The algorithm in question is based on the Newton-Raphson scheme [9] and allows the analysis of the systems with a variable stiffness matrix resulting from the equilibrium state determined by equation $Q = f(q)$, where Q represents the vector of external forces and q is a value of displacement corresponding to it.

In the dynamic tests on the developed numerical model with nonlinearities resulted from material models and the contact phenomena, the analyses were conducted with the use of the Lagrange-Finite Element methodology [9], an explicit code and calculation algorithms [7, 8, 10, 11].

Equations of a dynamic problem in time domain are solved by central difference integration. Explicit codes are relatively more efficient for problems with the following characteristics:

a) Short duration – the computational cost increases linearly with a time problem, however, simultaneously, a small time problem needs a lot of time integration steps.

b) Large number or extent of nonlinearities – the computational cost remains the same, while, for an implicit method, CPU time increases exponentially.

c) Large problem size – the computational cost increases linearly with a size problem. CPU time increases when number of elements is doubled.

In Explicit solution [11]:

- The time step size is usually set by the requirements to maintain stability of the central difference integration. The stability limit can be approximated by the smallest transient time of the wave to cross the smallest element.
- The stability limit is defined in terms of (1):

$$\Delta t \leq \frac{2}{\omega_{\max}} \left(\sqrt{1 + \xi^2} - \xi \right), \tag{1}$$

where $\omega_{\max}$ – the highest eigenvalue in the system, ξ – a fraction of critical damping in the highest mode.

Damping can be introduced by bulk viscosity pressure of viscoelastic material behavior or other means.

Courant Criterion [11] was used in numerical simulation as well. The time step used with this criterion must be smaller than the smallest natural period of the mesh used in numerical models. Let us imagine doing an eigenvalue analysis with

the same mesh and extracting every possible mode. The time step must be smaller than the period associated with the highest natural frequency given. The mode shape associated with this eigenvalue is typically one grid point oscillating on the stiffness of the elements to which it is attached. The time step used with this criterion depends on the smallest element dimension, L (2).

$$\Delta t = SL/c, \tag{2}$$

where c is the speed of sound through the element material. For 1-D elements it is defined with the relation (3):

$$c = \sqrt{E/\rho}, \tag{3}$$

where E – Young's Modulus, ρ – density, S is the time step Scale Factor (< 1), thus for Explicit integration it is (4).

$$\Delta t \leq L/c. \tag{4}$$

Explicit FE methodology [11] used in numerical tests is characterized by:

- Small time step,
- There are no big matrices or matrix inversion due to using a diagonal matrix (lumped mass),
- Robust solution procedure even for a high degree of non-linearities.

3. Deformable models of the wagon in a prototype version

The elaboration presents a geometrical model of a railway platform wagon in a version constructed based on working documentation. There were introduced some simplifications aiming at adjusting it for numerical analysis of strain and stress of fundamental subsystems of the complete wagon system. The simplification consisted in complete removal of the following elements:

- hydraulic system,
- pneumatic system,
- all bundles of cables and wires,
- buffer elements.

Figure 2 presents a 3D model, ultimately simplified in a solid form, with a rotatable platform in a surface form (all elements of the construction have been changed to the surfaces, except rotatable nodes and two parts of locks-hooks).

Two different versions of FE deformable models were carried out: for static and dynamic tests, respectively. The deformable numerical FE model of a complete wagon for static tests, presented in this part of the paper – Fig. 3, has been built based on a geometrical model of a prototype wagon – Fig. 2.

Due to the size and complexity of the model, it was decided to apply a half of the rotatable platform in the initial stage of model calculations. 359050 finite elements (layer and solid) have been used to map the railway wagon.

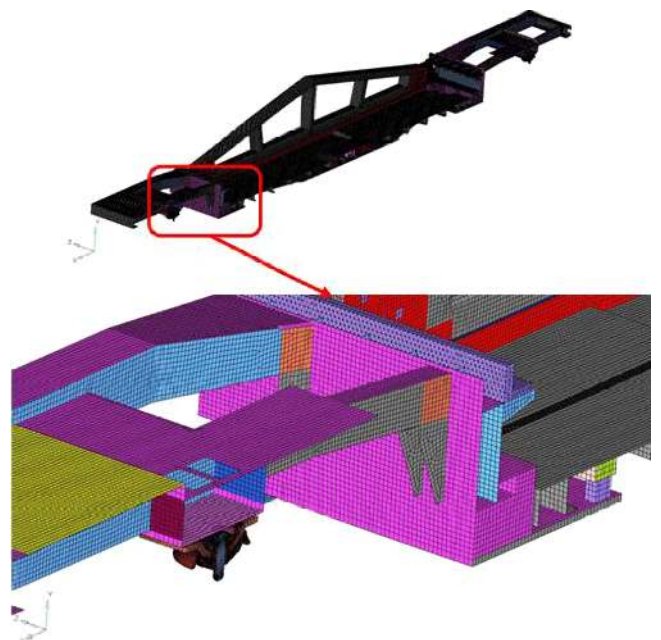Fig. 2. Simplified 3D geometrical model – a view with a cross-section of a rotatable platform

Fig. 3. Numerical FE model of a half of the loading platform and a fragmentary view of its over-bogie part of the wagon frame

Due to cooperation of the wagon elements, it was necessary to consider contact interaction with friction on locks and other subassemblies. Friction coefficient was assumed as 0.2. Due to applied simplifications and taking into consideration rail bogies, a special modelling of boundary conditions was required. Therefore, supporting the structure on the bogie elements and on the springs of suitable stiffness was taken into consideration in the model (Fig. 4). The wagon was loaded with forces resulted from interaction of a semitrailer of 40 tones mass and with gravitational load with a standard coefficient of 1.95.

A numerical model of a complete wagon for dynamic tests has also been built based on working documentation of a 3D prototype wagon (Figs. 5 and 6). The model has been developed in HyperMesh application [12] with preferences for dynamic simulations with the use of LS-Dyna code [11].
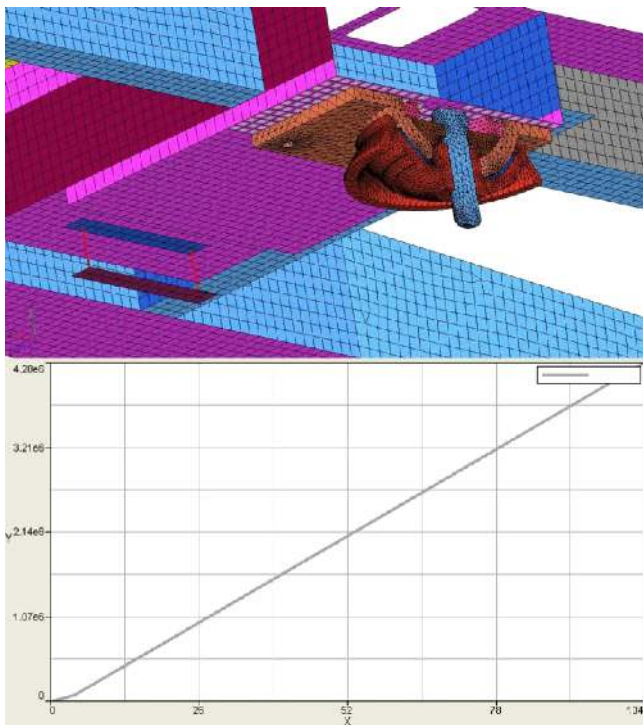
Fig. 4. Model of the king-pin joining the bogie with the frame in a bottom view and a graph of spring stiffness (N/mm) assumed in the numerical model
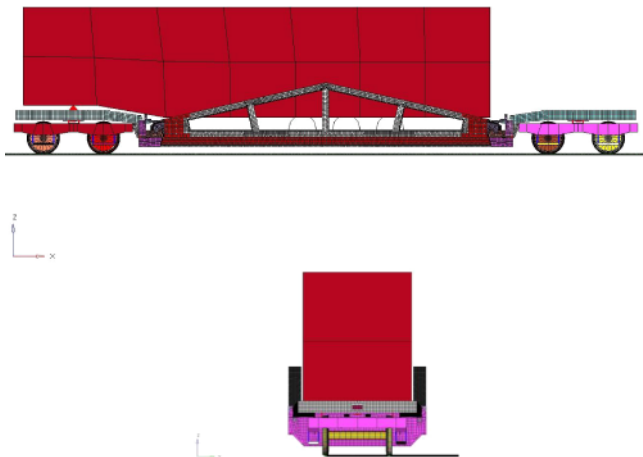

Fig. 5. FE model of a complete wagon in a prototype version and a part of rails system for dynamic FE analyses and a front view of the wagon model

In a FEM numerical model of a complete prototype wagon for dynamic tests, all fundamental subsystems of the designed construction have been mapped. It is composed of railway bogies of Y25 type, a frame, a rotatable platform, a saddle and locks. The model considers all contacts described in details in a model for static tests. With the use of suitably defined constraints, a joint of the semitrailer with the wagon through a saddle, the same as for trucks, was mapped in the model. A selected point of the semitrailer was joined with the wagon by means of additional special elements MPC. A possibility of suitable rotations has been assured (spherical constraint). A standardised [13] curved section of the railway track (Fig. 6), on which the wagon is supposed to move during dynamic simulations, was defined. In the presented model, similarly as in the case of a model for static tests, the additional devices such as: buffers, trimming mechanism (for controlling a position of frame wagon), hydraulic actuators, hydraulic cables, pneumatic cables were not taken into account. However, the dynamic model takes into consideration additional masses coming from omitted elements of the installation and the above mentioned additional equipment of the wagon. A deformable numerical model of a complete wagon designed for dynamic tests includes 194898 nodes and 166091 finite elements.
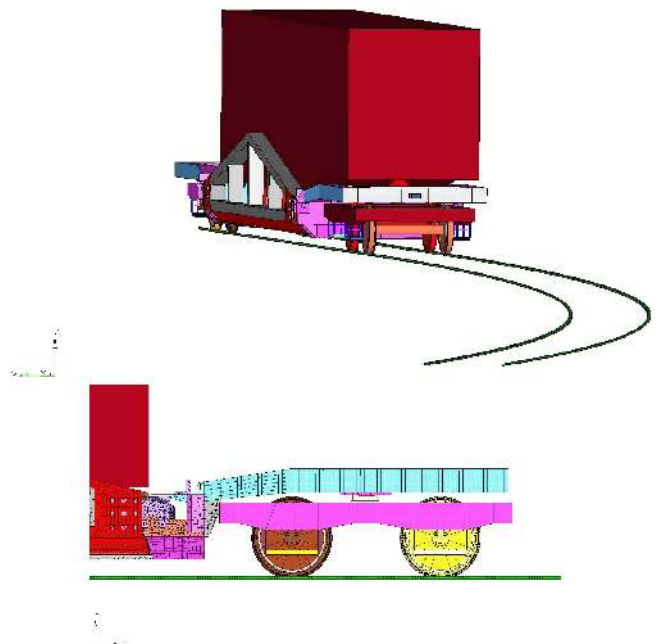

Fig. 6. FE model of a complete wagon along with a model of a semitrailer in a prototype version for dynamic analyses – a diagonal view of the wagon and a fragmentary view of an over-bogie part model

4. Static numerical tests of a set of major components of the prototype wagon

In numerical analyses of a set of major components of the prototype wagon for transport of truck semitrailers, the research procedures developed based on standard EN 12663:2000 [14] were applied. To demonstrate appropriate static strength of construction, the following cases of load were tested repeatedly:

- Compression force of 2 MN at the level of buffers,
- Compression force of 1.5 MN at 50 mm below the level of buffers,
- Tensile force of 1 MN in the area of the coupler,
- Maximum service load of $1.95 \times g \times$ (mass of wagon + mass of load),

- Compression force of 2 MN and vertical loads,
- Compression force of 1.5 MN at 50 mm below the level of buffers and vertical loads,
- Compression force of 2 MN and minimum vertical load (without the load),
- Tensile force of 1 MN in the area of the coupler and vertical load,
- Tensile force of 1 MN and minimum vertical load (without the load).

Based on the calculations, it was proved that, in the prototype version of the wagon, no permanent deformations or fractures of the construction as whole, or of any of its element, took place under operations of loads. The standard points out that in the case of determining the level of strains for plastic materials, the phenomenon of local concentration of strains cannot be taken into consideration. The areas of local plastic deformations connected with concentration of strains, however, should be sufficiently small so that after removing the load there were no significant deformations left. In the case of evaluation of the construction only on the basis of calculations,

the following safety coefficients (5) are applied:

$$\frac{R_e}{\sigma_c} \geq S_1, \tag{5}$$

where $S_1 = 1.15$, R_e – yield stress, σ_c – design stress.

Additionally, in the case of tensile, safety coefficients is expressed by (6):

$$\frac{R_m}{\sigma_c} \geq S_2, \tag{6}$$

where $S_2 = 1.5$, R_m – tensile strength, σ_c – design stress.

Local instability in the form of the elastic buckling is allowed under the condition of existence of alternative ways of transmitting the loads and when the criterion of field stress is satisfied. To verify the construction tendency to lose its stability, displacements of a selected point in the over-bogie part of the frame in the function of a parameter describing an increase of the load have been tested. Figures 7, 8 and 9 demonstrate the results of the selected cases of FE static analysis of a complete frame wagon cooperating with the rotatable loading platform.
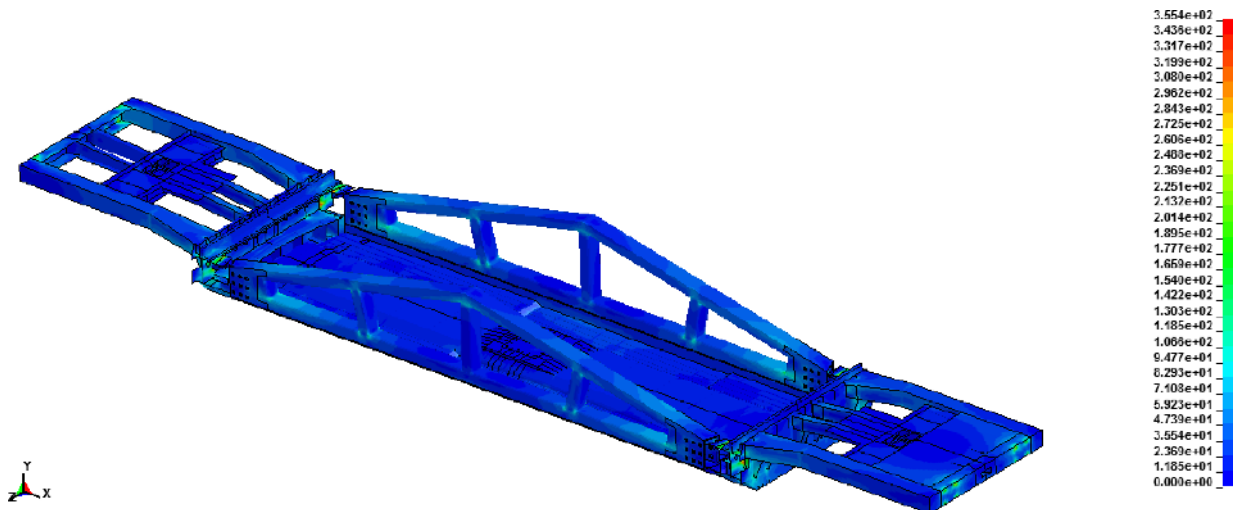

Fig. 7. Map of HMH equivalent stresses ($\sigma_{R\,\max} = 355$ MPa) – a case of load with compression force of 1.2 MN at the level of buffers
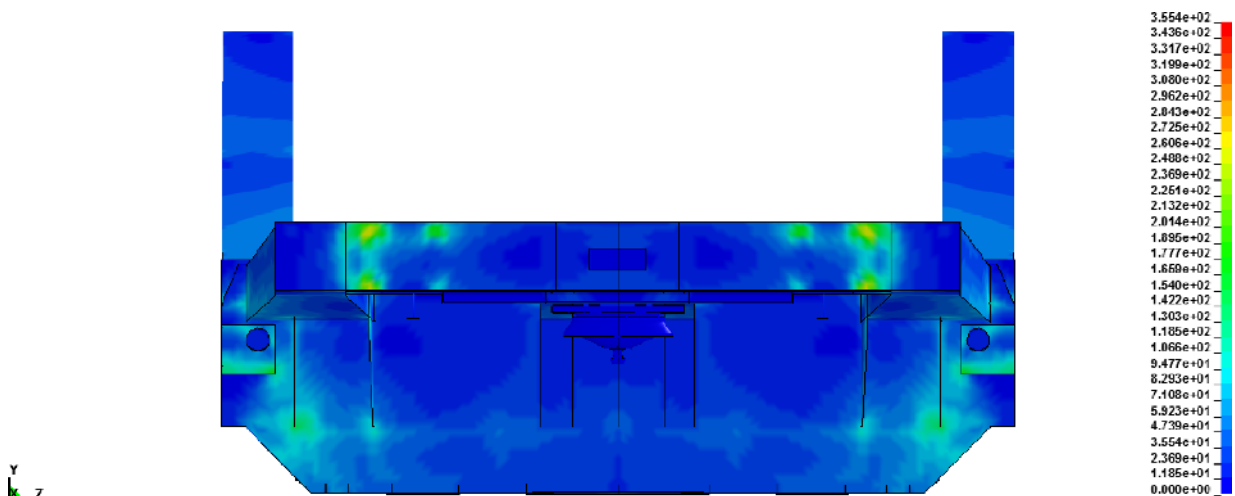

Fig. 8. Map of HMH equivalent stresses in the front view of the wagon ($\sigma_{R\,\max} = 355$ MPa) – a case of load with compression force of 1.2 MN at the level of buffers
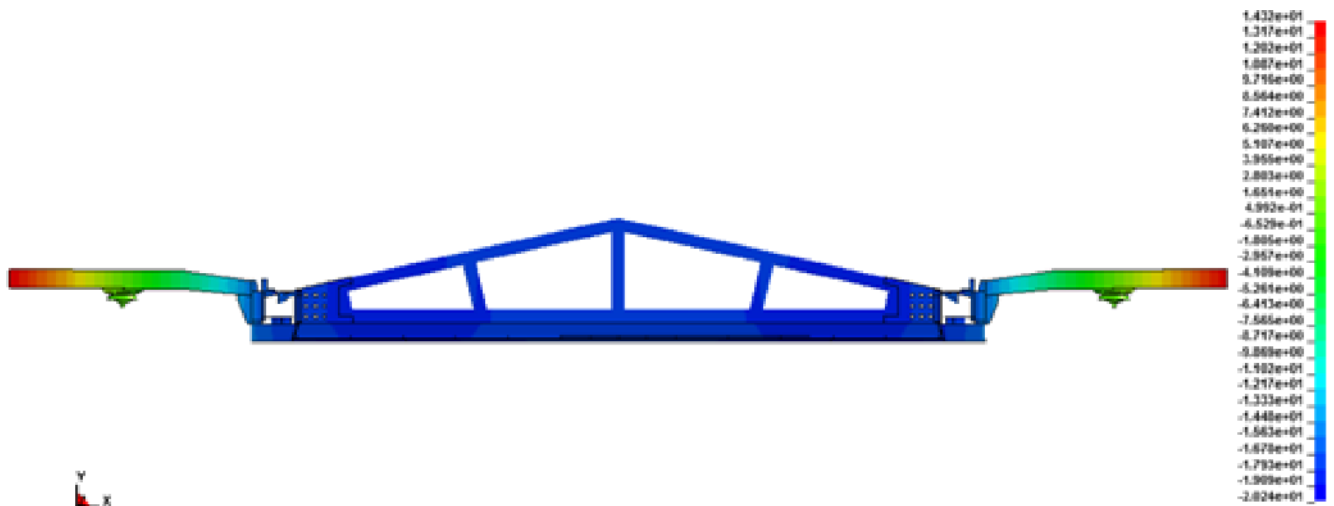
Fig. 9. Map of vertical displacements $V_{Y\max} = 14$ mm, $V_{Y\min} = -20$ mm

Table 1
Comparison of selected results from different cases of numerical analysis (prototype wagon)

Case of numerical analysis	Max. vertical displacements [mm]	Max. horizontal displacements [mm]	Max. H-M-H stresses [MPa]	Safety coefficient S_1 (min = 1)	Safety coefficient S_2 (min = 1.5)
Compression force of 1200 kN (level of buffers)	−20.2	−12.4	355.4	0.99	1.51
Compression force of 1200 kN (level of couplers)	−8.7	−14.3	426.6	1.07	1.63
Tensile force of 1000 kN (level of couplers)	20.3	15.2	417.8	1.08	1.6
Tensile force of 1000 kN (level of couplers and vertical loads)	−17.2	5.4	216.5	1.01	1.72

On the basis of the conducted examinations, it can be concluded that the highest values of contact stresses occur in the small areas of mounting of the buckles connecting the tailboards of the moving platform with the over-bogie part of the wagon support. Based on the conducted static analyses, it can be verified that the proposed conception can meet the standard criteria included in PN-EN standard [14].

A comparison of selected results from different cases of numerical analysis according to PN-EN standard loads [14] is presented in Table 1.

S1 factors determined outside the connectors are in some cases smaller than the minimum values recommended in PN-EU standards. This means that the possibility of the occurrence of local plastic zones. However, this state is acceptable because, as indicated in the standard entries, 'in the case of determining the stress level of the plastic materials of the local stress concentration phenomenon cannot be taken into account'.

Similarly, coefficients S2 determined outside the joint of main locks are in several cases smaller than those recommended by the PN-EU standards. However, the standards also indicate, that safety factors may be reduced if the calculations are so detailed that they assure high identification of areas of a critical design factor. H-M-H stresses are smaller than the limit values and there is no risk of destruction of the structure in each considered variant of research.

5. Selected results of FE analysis of the complete prototype construction

Due to an expected character of work of the wagon under design, it was verified that proper mapping of the construction work is possible only when all subsystems are subject to analysis at the same time, taking into account boundary conditions resulting from their cooperation and different variants of loads, with a special focus on the most demanding verification criteria of a railway construction resulting from standards EN-PN [13, 14].

Strength analysis of a prototype version of a constructional solution of a wagon with a rotatable platform was carried out according to standard EN-PN 12663 [14]. There were implemented multivariant tests taking into caonsideration individual standard loads, including the most limiting ones, for a tested wagon, i.e., compression with force of 2MN at the level of buffers, tensile with force of 1MN and maximum service loads.

Based on previous investigations [15], it was decided that a dimensioning variant for the tested construction is the case of maximum service loads [10] described with a formula (7)

$$1.95 \times g \times (m1 + m2), \qquad (7)$$

where $m1$ – mass of wagon ready to work, $m2$ – allowed mass of load, g – gravitational acceleration.

The following assumptions adopted in the dynamic analysis presented in the work:

- FE models of the complete wagon and models of subassemblies (discussed in Chapter 2) were used,
- set of load was defined as the weight of the empty wagon and the weight of the trailer load scaled so that it corresponds to the static load according to formula (7),
- wagon moves along a straight railway track with a constant

minimal value of speed equal to 0.01 m/s,

- dynamic interaction effects in this variant of simulation are negligible small (quasi-static case).

Figure 10 and 11 present maps of HMH reduced stresses obtained in the variant of numerical analysis of the frame of the wagon with a rotatable platform in a prototype version subject to loading, as in the limiting standard case with overloading of 1.95 g [15].
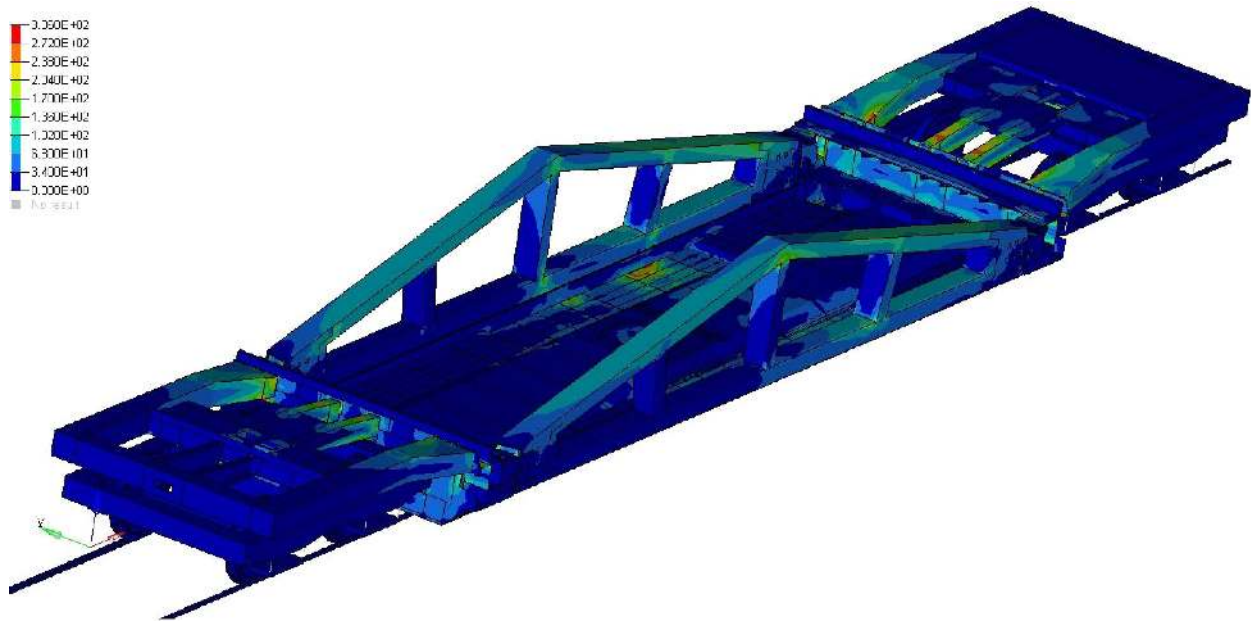

Fig. 10. Map of H-M-H equivalent stresses in the variant of numerical analysis of a complete wagon with the case of maximum service loads ($\sigma_{R\,\max} = 306$ MPa)
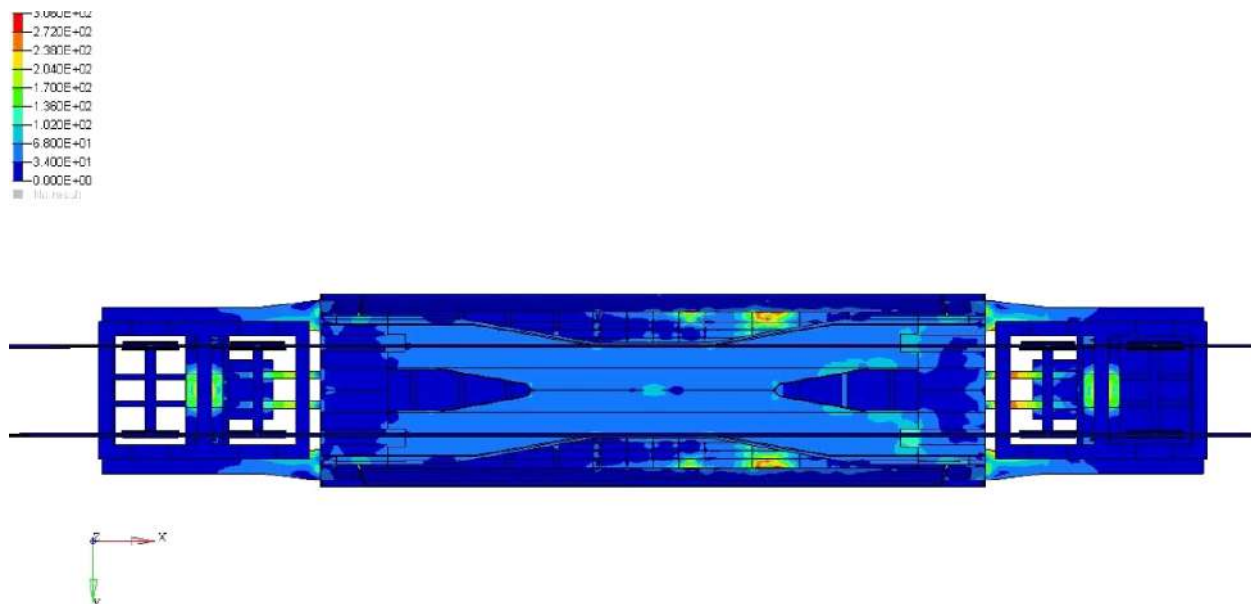

Fig. 11. View of the bottom of complete wagon with a map of H-M-H equivalent stresses in the case of maximum service loads a ($\sigma_{R\,\max} = 306$ MPa)
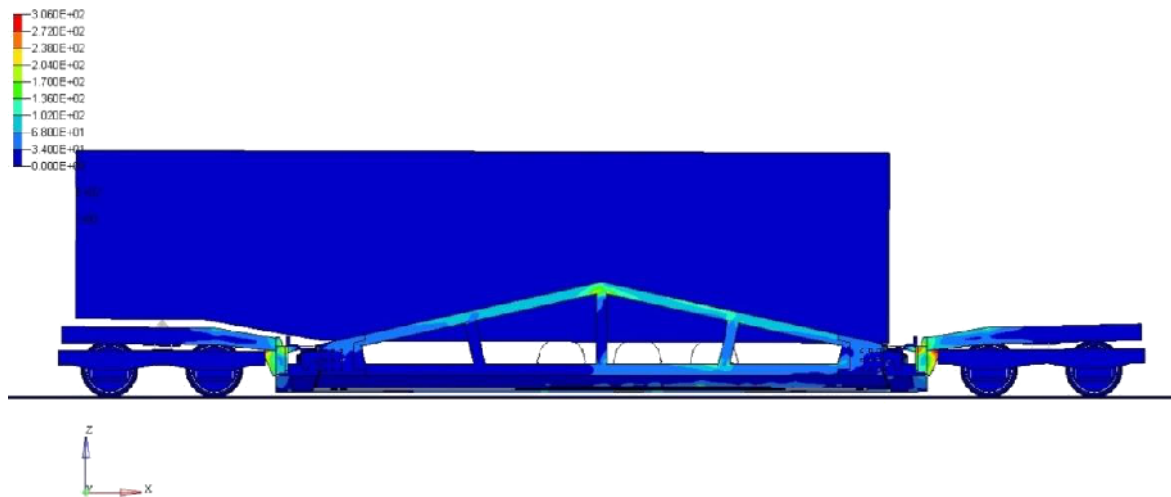
Fig. 12. View of complete wagon and semitrailer with a map of H-M-H equivalent stresses in the case of maximum service loads a ($\sigma_{R\,\mathrm{max}} = 306$ MPa)

Analogous analyses were carried out for different constructional configurations, developed within the frameworks of constructional works, of a special wagon [15]. Figure 10 presents a map of H-M-H equivalent stresses obtained in the variant of numerical analysis of a complete wagon with a rotatable platform and railway bogies in the prototype version subject to tests as previously. Maximum equivalent stresses, in this case, were limited to $\sigma_{R\,\mathrm{max}} = 306$ MPa.

The most significant contact stresses occurs in a small areas of fastening the locks joining the tailboards of the moving platform with an over-bogies part of the wagon frame and in the area of joining the over-bogie part with a lowered floor of the wagon frame (Fig. 11).

Maximum equivalent stresses, according to H-M-H hypothesis, in this variant of analysis of a complete wagon with a semitrailer of the maximum mass (Fig. 12), obtain the value of 306 MPa in a small areas of joints of the over-bogies part of the wagon frame with the loading platform [15], therefore the proposed construction of the wagon can work safely. The selected results of dynamic and static analysis, which mapped the maximum operating load variant – described in equation (1) were compared. The maximum values of displacements and H-M-H stresses received from the numerical tests differed by less than 1%.

A comparison of the results of static and dynamic analysis confirms the correctness of the FE models of the complete wagon with the railway track. The results of the comparison confirm the possibility of using the models for testing the prototype wagon during the motion simulations with different boundary-initial conditions.

6. Conclusions

Within the framework of the design works intending to meet constructional assumptions and assumed technical requirements, there were carried out necessary design calculations, verification and model tests and numerous multivariant numerical simulations [15–17].

Due to a non-linear character of the mapped cooperation of wagon subsystems, including contact phenomena, to perform the strength calculations in the range of static and dynamic [15–17], MSC.Nastram, MSC.Marc and LS-Dyna applications [11, 12], specialized for analysis of big structures taking into consideration non-linear procedures in the geometric and physical range, were chosen.

At each stage of the design, information concerning identification of strains concentration areas in the tested system and indication of places requiring strengthening is an important conclusion derived from the performed analyses. An important criterion of the construction evaluation is also the wagon maximum deflection. Therefore, in the wagon strength tests, there was assumed the methodology of numerical verifications not only for the final version of the construction, but also after all modifications of the construction influencing directly the stiffness of a complete wagon. The main aim of the numerical investigations, applied at each stage of the conducted constructional works, is, therefore, verification of possibilities of satisfying the main assumptions for the wagon construction and indication of directions of further design works.

Based on the conducted tests, it was verified that the proposed constructional concept meets the standard criteria included in PN-EN 12663 [14]. They resulted in selection of standard elements of the system or proposition of original parts of the considered subsystems, there was verified the accuracy of their operation in the system and, subsequently, after verification with the use of suitably selected simulations CAE and stand tests [3, 4, 15–17], there was proposed a working project of the modified functional mechanism of the platform and a working project of a prototype version of the loading platform along with 3D documentation of the developed constructional solutions.

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