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Comparative analysis of the results of theoretical and experimental studies of freight wagon Sdggmrss-twin

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Abstract. This paper presents a comparative analysis based on the results from static strength calculation of wagon body, series Sdggmrss-twin, and on the results from the real wagon test. The verification of results from calculations and tests and their comparison was mandatory for client's commissioning of the wagon by notified body. Calculations based on the finite elements method were carried out in the Department of Railway Engineering at Technical University of Sofia. Experimental studies on real wagon construction were conducted at the facilities of Bulgarian National Transport Research Institute by testing team from Laboratory of rail vehicles at University of Belgrade. It was found that the obtained static stress results are similar, which proves that the proposed models are appropriate and they can help to solve a wide range of issues, for example those related to lightweight design of railway vehicles.

1. Introduction

The strength calculations and real tests of the freight wagons underframe and wagon body have to be carried out in accordance to procedures regulated in the relevant European standards, Technical Specifications for Interoperability – Freight Wagons (WAG TSI [1]) and/or UIC leaflets. Before the new freight wagon is allowed for operation, the strength calculations and real tests are mandatory. If new freight wagon structure passes both strength calculations and tests, notified body allows the commissioning of the wagon based on positive results. If there is a large discrepancy in results from both procedures, notified body can order either new calculations or tests or both. This causes loss of time and money, but also loss of confidence in calculation or testing teams by the wagon manufacturer. That's why the verification of results from calculations and tests and their comparison is important for the client and is mandatory for commissioning. On other hand, this is also very important for calculation teams, because they can prove precision and reliability of their models, as well as the appropriateness of calculation method and the level of their know-how. If the know-how of calculation team is not on enough high level, chances for future orders are small. This is valid also for the testing crew. Based on similar results from calculations and tests and in case of relatively low stresses, wagon structure could be built up from thinner profiles and beams. This helps to reduce the own weight of the wagon and to increase the maximum payload.

   Chapter 2 of this paper describes the object of the study, load cases applied on the wagon structure and the properties of calculation model and methods. Testing and measuring equipment, testing and

measuring methods and some specific features regarding tests are the subject of chapter 3. Chapter 4 presents the results from calculations and tests as well as their analysis. Paper ends with conclusions.

2. Object of the study and calculation model

The object of the study is a wagon series Sdggmrss-Twin, manufactured by Bulgarian wagon manufacturer KOLOWAG Plc. Sdggmrss-Twin is articulated wagon with two underframes that differ among themselves only in a small area of articulation. This wagon is designed for transportation of containers and semitrailers and is defined in category F-II (vehicles restricted in hump and loose shunting). The three-dimensional wagon model (section 2) is shown in figure 1.
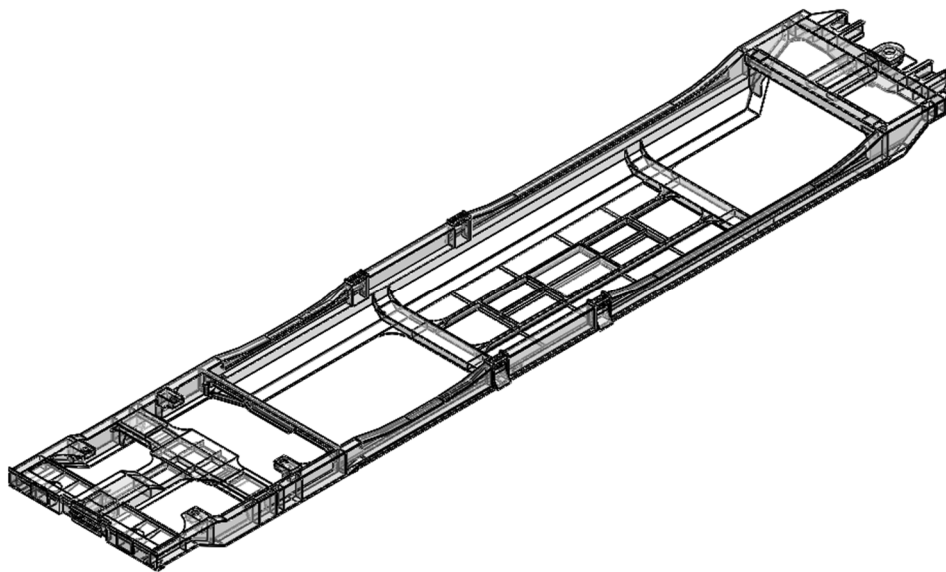
Figure 1. Three-dimensional model of wagon series Sdggmrss-Twin.

The main parameters of the wagon are: gauge G1, number of axles 6, axle load 22.5 t, payload capacity about 101 t, own weight 34 t, wagon length without buffers 33 m. The underframe of the wagon is made of steel S355J2 according to European standard EN 10025.
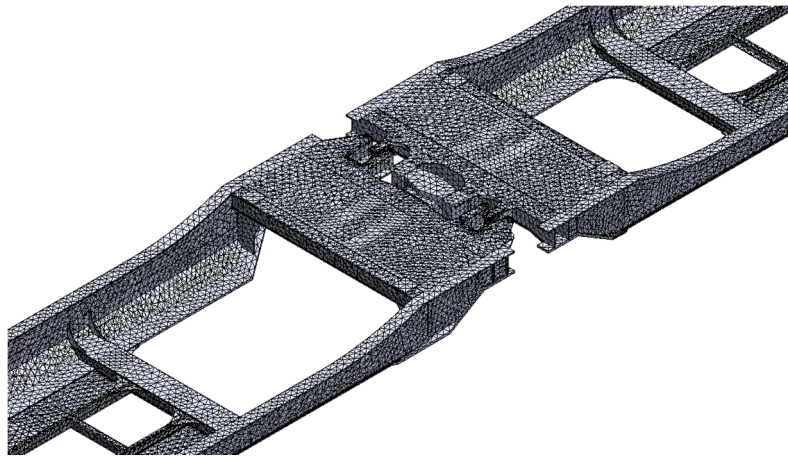
2.1. Calculation model

Strength calculations of the wagon are made by the finite element method. The software product SolidWorks is used for calculations. For the purposes of strength analysis, spatial computational models were developed by using 3D solid elements.

The models were optimized by analysing the approximation of the calculations. Optimized model is made up of 561722 notches and 289763 finite elements. The finite elements mesh is shown in figure 2. The maximum size of the finite elements is 80 mm and the minimum size (in the zones with expressed stress concentrators) is 10 mm.

2.2. Load cases

In accordance with international standards, each newly designed wagon is object of theoretical (by calculation) and experimental studies in order to determine stresses and deformations. Load cases and conditions are specified in European standard EN 12663-2:2010 [2], TSI subsystem "Rolling stock – Freight wagons" [1] and leaflet 577 [3] of the International Union of Railways (UIC). According to documents cited, loads are divided into the following groups: longitudinal static loads (HLC), vertical static loads (VLC), exceptional static loads (LLC) and superposition of static loads (CHLC). An overview of all load cases is shown in table 1. Methods for the application of loads from HLC, VLC, LLC and CHLC load cases groups are described in detail in [4-10] and for articulated wagons in [11].

Figure 2. The finite elements mesh used in calculation model.

Table 1. Load cases applied to wagon construction.

Load case	Description
HLC 1	Compressive force at buffer axis height 1200 kN (table 2 of [2])
HLC 2	Compressive force 50 mm below buffer centre line 900 kN (table 3 of [2])
HLC 3	Compressive force applied diagonally at buffer level 400 kN (table 4 of [2])
HLC 4	Tensile force at coupler axis level 1500 kN (table 5 of [2])
VLC 1	Vertical load from weight of 2×20 ft. containers 1,3 g ($m_1 + m_3$)
VLC 2	Vertical load from weight of 40 ft. container 1,3 g ($m_1 + m_3$)
VLC 3	Vertical load from weight of 45 ft. container 1,3 g ($m_1 + m_3$)
VLC 4	Vertical load from weight of semitrailer 1,3 g ($m_1 + m_3$)
LLC 1	Lifting at one end of the vehicle (table 7 of [2])
LLC 2	Lifting the whole vehicle at 8 lifting positions (table 8 of [2])
LLC 3a	Lifting the whole vehicle at 8 lifting positions with one lifting point displaced 10 mm vertically (table 8 of [2]) – at wagon end
LLC 3b	Lifting the whole vehicle at 8 lifting positions with one lifting point displaced 10 mm vertically (table 8 of [2]) – in the middle of wagon
CHLC 1	Compressive force at buffer axis height 1200 kN combined with most unfavourable vertical load
CHLC 2	Compressive force 50 mm below buffer centre line 900 kN combined with most unfavourable vertical load
CHLC 3	Compressive force at buffer axis height 1200 kN combined with vertical load from own mass
CHLC 4	Tensile force at coupler axis level 1500 kN combined with most unfavourable vertical load
CHLC 5	Tensile force at coupler axis level 1500 kN combined with vertical load from own mass

For freight wagon's underframe and body, the methodologies and procedures for strength analysis and testing are defined in the European standard EN 12663-2: 2010 - Railway applications - Structural requirements of railway vehicle bodies - Part 2: Freight wagons [2]. In addition to the load cases it also defines the minimum requirements for wagon body strength, materials, permissible stresses and displacements and presents principles and methods that are used to validate the structure by strength analysis and testing.

The strength evaluation of the wagon underframe (acceptance criteria) is made using the safety factors S as given in equation (1):

$$S = \frac{\sigma_{\lim}}{\sigma_{Mises}} \geq 1.0, \tag{1}$$

where $\sigma_{\lim}$ is the permissible stress. For steel S355J2 the parameter $\sigma_{\lim} = R_e$ (yield limit of the material) = 355 MPa for parent material and $\sigma_{\lim} = R_e/1.1 = 323$ MPa for immediate vicinity of welds. The stress σ_{Mises} represents the maximum stress received under the corresponding load case.

3. Testing and measuring procedure and equipment

Current European regulations [1] and standards [2] require strength tests for every new rail vehicle structure. The first part of the test consists of a static strength test, which is dealt with in this document. The second part of the strength test includes buffing impact tests. Structural problems during operation may require additional strength testing under actual operating conditions [12].

The static strength test of the Sdggmrss wagon prototype was performed in the hall of the Bulgarian National institute for transport research (NIIT) in Sofia and in accordance with the "Program for static strength test of Sdggmrs-twin wagon carbody" which is previously approved by the manufacturer and Notified body.

As already mentioned above, the wagon has two carbodies that differ among themselves only in a small area of articulation. In order to include articulation influence, for the test was chosen one carbody and head part of the other carbody, resting on two bogies as shown in figure 3. In order to reduce lowering of the carbody during loading, the carbody was resting on two bogies with blocked suspension. The test was performed on the test rig (figure 4) with adjustable configuration. Different load cases according to the test program, i.e. application of the appropriate compression or tension forces as well as different combinations of vertical forces was provided by using hydraulic cylinders and auxiliary tools.
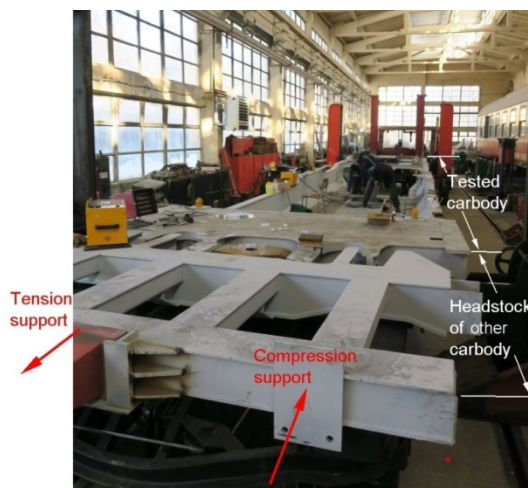
Figure 3. Arrangement of carbodies during the test.

Figure 4. Test rig overview.

Strain gauges were applied in the points according to test program. The positions of one part of those points were determined based on the locations of highest stresses obtained during the calculations. Other part of strain gauges is placed in some standard positions on wagon underframe, as well on the positions, for which the testing team proposed to be important based on their experience and know-how. Figure 5 shows example of applying the strain gauges on the testing object. Strain gauges were covered with glue for protection against mechanical damage as shown in figure 6.

The following quantities were measured:

- local strains ε_i, μm/m of the testing object and derived stresses σ_i, N/mm^2;
- forces for the vertical load application resulting from vertical cylinders pressures p_i;
- forces F_i, kN used for horizontal loads application;
- deflections f_i, mm of the superstructure under different load cases.

In order to measure all measuring quantities measuring chain presented schematically in figure 7 was used. Data acquisition system (DAQ), consisting of four Quantum X MX840A, one Quantum MX1615 and two SPIDER8 systems, was able simultaneously to record all signals of measuring quantities (strain gauges, forces and displacements). Readings of both DAQ systems were timely

synchronized, which was simply because of the static character of the test. Quantum X was connected via Ethernet connection to the PC. For the data acquisition and analysis the HBM CatmanEasy AP software was used. SPIDER8 was connected via USB-LPT adapter to the PC. For the data acquisition and analysis the HBM CatmanExpress software was used. The stress measurements were performed using 34 resistance strain gauges and 2 rosettes 0/45/90° with nominal resistance of 120 Ω and length of the measuring grid of 6 mm.

Figure 5. Applying the strain gauges on the testing object.

Figure 6. Protected strain gauge.
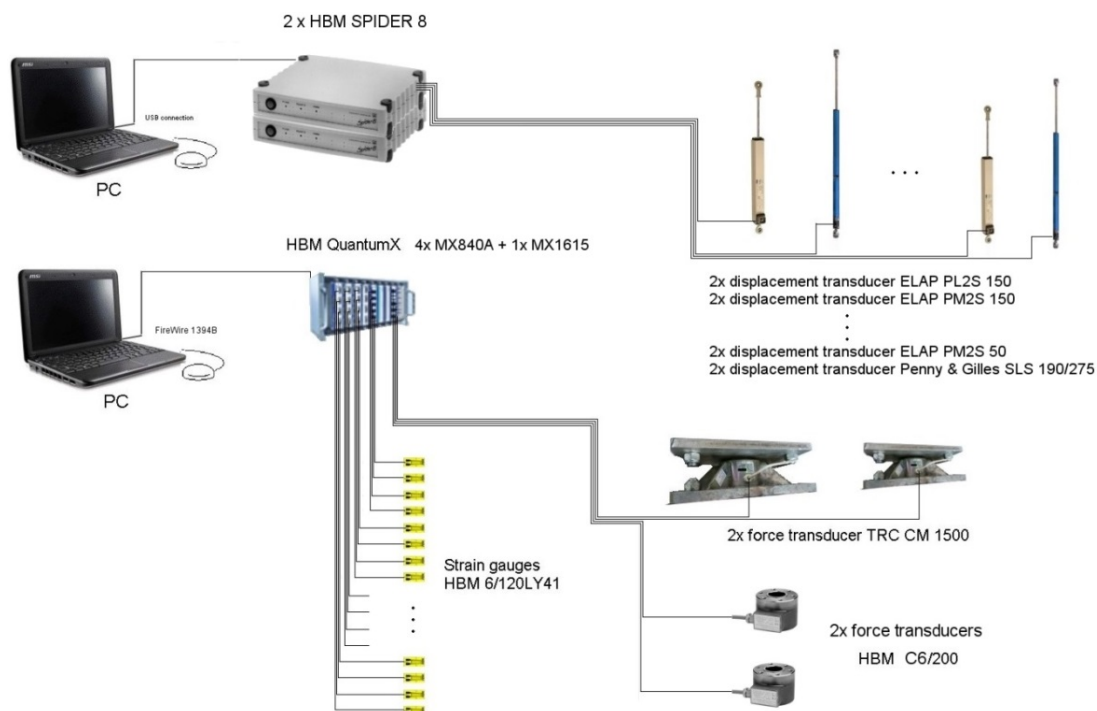
Figure 7. Measurement chain.

Longitudinal forces were measured using two force transducers CM1500. Vertical forces were measured at one hydraulic cylinder in each cylinder group connected in parallel using load cells HBM C6. Eight displacement transducers were used for measurement of carbody vertical deflections on each longitudinal beam (dz1 to dz4 on one side and dz5 to dz8 on the other side). Four displacement

transducers were used for measurement of the longitudinal displacement of the both main longitudinal beams (dx1 to dx4). From eight displacement transducers used for vertical deflection measurements, two of them on each longitudinal wagon side are in the vertical plane of the supporting points on bogies. They are used to define referent straight line relative to which the deflections in the middle of the wagon and on the wagon end are determined. Horizontal displacement transducers were used for measurement of the main longitudinal beams change in length under compression and tension load.

4. Analysis of results from calculations and tests and their comparison

The discrepancies between the calculated and measured stress values arise for various reasons:

- geometrical idealization and simplifications of the calculation model;
- numerical calculation errors;
- mesh size, mesh adaptation to object geometry;
- characteristics of finite elements used;
- boundary conditions fidelity;
- tolerances in real material characteristics (R_{eH}, E, etc.);
- geometrical imperfections of the real structure. For example tolerances of profile and sheet thicknesses and shapes, not ideal symmetry of the real (especially welded) structure etc.;
- residual stresses from manufacturing (after welding, bending of sheets etc.);
- measurement uncertainty which includes among others strain gauge gluing imperfections, strain gauge tolerances, errors of positioning and aligning of strain gauges, measurement equipment accuracy etc.;
- averaging along measurement base of strain gauge;
- tolerances in the force introduction (intensities, symmetry, accuracy of the force application area etc.).

Relevant standards [2] prescribe that in order to stabilize the residual stresses due to manufacturing, before proceeding with the recording of the stresses, for all static tests preliminary loading shall be carried out. Preliminary loads are applied in stages, up to the stipulated maximum loads and after removal of the loads, the strains are considered to be zero. After applying the loads a second time up to the maximum value, the measurement should be considered as decisive.

The data used in the analysis is excerpted from reports of calculations and tests performed. It summarizes only the results registered in the strain gauges, which were recommended by calculation team to be used in the tests. It should be noted that the results obtained in calculation have been refined; taking into account the stresses at exactly the same points at which the strain gauges were positioned in the test. Only the so-called "clear" load cases have been taken into account, i.e. only the load cases for which the stress values were measured directly, without additional mathematical processing of the results, such as superposition, application of strength hypotheses for calculation of the equivalent stresses etc. Such load cases are: HLC2, HLC4, HLC6, HLC8, VLC2, VLC8 and LLC1 (table 1). The purpose of the above-mentioned features is to use the most accurate information possible to objectively assess the contrasting juxtaposition of results from calculations and tests. Namely for this reason, the comparative analysis was carried out according to criterion σ_1, which is actually measured by strain gauges in the wagon tests. Only the stress values for the positions where the highest stresses during the tests were registered are compared. The comparison of results obtained in calculation and tests for load cases mentioned above for some strain gauges is given in table 2. In table 2 abbreviation T stands for "Test" and C for "Calculation". All values are given in N/mm^2.

The analysis of the data from table 2 shows that there is a good match of the results for the stresses obtained in calculations and tests. Largest differences in measured and calculated stress values can be observed for resistant strain gauges Rosette 1 and Rosette 2 particularly for load case LLC 1. The discrepancies mentioned above can be explained visually in figures 8 and 9.

As it can be seen in the figure 8, maximal stress values are calculated in parent metal in the bending area of large metal sheet, divided in this way in vertical and horizontal sills with small bending radius

between. It should be noted, that the calculated values of stress are valid for whole finite element independent on its size and present actually the average stress value. This means, that the average stress value is same e.g. for point at distance 1 mm from the edge and for point at 30 mm from the edge. In figure 9 the position of two corresponding measuring strain gauge rosettes is shown. Distance between them is 36 mm. This is because it is almost impossible to place the rosette so close to the edge because of restrictions for placing the strain gauges. This area between bended vertical side sill and horizontal plate also causes structural changes in the material because of bending during the manufacturing of the wagon and presents significant stress notch.

However, in this load case and for all tested load cases, the resulting stress values are lower than permissible.

Table 2. Comparison of results from calculations and tests.

Strain gauge	No.	1	2	4	14	15	19	Rossette 1	Rossette 2
HLC 1	T	−124.2						66.2	67.0
	C	−117.8						48.3	58.0
HLC 2	T		−157.6						
	C		−145.3						
HLC 3	T		−50.7						
	C		−53.9						
HLC 4	T				−121.0				
	C				−122.8				
VLC 1	T			−223.3					
	C			−193.5					
VLC 4	T						−92.2		
	C						−105.8		
LLC 1	T					−120.1		190.9	197.6
	C					−95.4		259.7	276.9
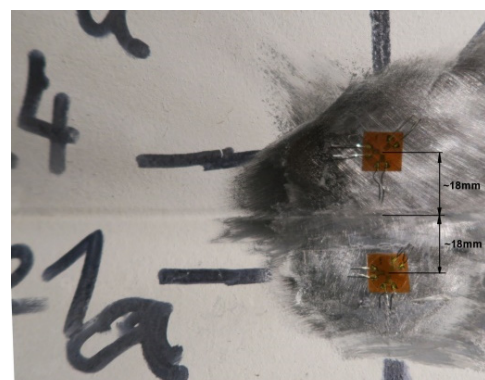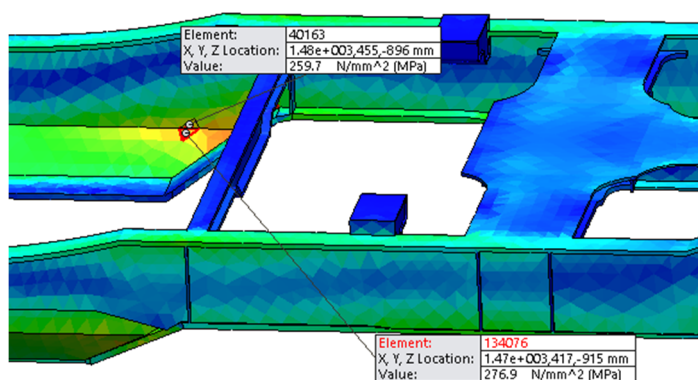
Figure 8. Calculated stress results for load case LLC 1.

Figure 9. Position of strain gauge rosettes.

5. Conclusion

Summarizing the overall work on this study, it can be concluded that very good match of the results for the stresses obtained by calculation and those of the wagon test is present. This allows calculation models to be used for research and optimization of similar objects with similar construction. The performed tests show that the wagon withstands all prescribed loads without exceeding the permissible stresses and displacements. The developed models for static strength analysis of the articulated wagon series Sdggmrss-Twin structure can be used to optimize areas with considerably lower stresses. This will lead to a considerable reduction of the wagon's own mass and an increase in its load capacity.

Acknowledgements

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