Analysis of some problems in the theoretical wagon strength studies due to the imperfection of the European legislation

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Abstract. In this paper the strength calculations of a flat wagon are presented. These calculations are carried out in accordance with European standards, but in practice, often, calculations and tests are carried out by a shortened procedure not in accordance with the standards. On the other hand, the procedures prescribed in the standards do not always cover all aspects of the actual operating conditions. Based on the satisfactory results of the calculations, the notified body often admits the wagon into service. Under real working conditions it is established that the structural integrity of the wagon underframe is impaired due to loads not clearly reflected in the standard and are therefore not taken into account either in the calculations or when the wagon is admitted into service. Some activities have been done in order to reinforce the problem areas and a repeated extended strength analysis has been carried out with the loads not described in the normative documents. Subsequently, after the reinforcing measures had been taken, the wagon was admitted back into operation. A proposal for specification of such problems in the European standard EN 12663-2: 2010 is given.

1. Introduction

The strength calculations of the wagons and their components, such as the underframe, wagon body, bogies, axles, wheels, etc. are carried out according to methodologies and calculation procedures regulated in the relevant European standards, Technical Specifications for Interoperability (TSIs) and/or UIC leaflets. Today, to a large extent, these normative documents cover the calculation methods, but most of these methods after processing have been adapted in European standards. For example, in TSI - Rolling Stock Freight Wagons [1] have mainly left over general requirements for wagon structures. Prior to the introduction of a wagon in operation, whether new or modified, the strength calculations must be made. The new wagon structures or their components shall then be tested. For wagons, 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 and associated equipment such as: roof, side and front walls, doors, stanchions, fasteners and other equipment. It provides data on materials, identifies their use, and presents principles and methods that are used to validate the structure by strength analysis and testing.

In practice, calculations and tests are often carried out in shortened procedure that is not in accordance with the standard. Usually this is due to the client's desire or it is approved by the notified body. On the other hand, the procedures prescribed in the standards do not always cover all aspects of the actual operating conditions. In this particular case, this concerns the impact of additional equipment - the stanchions - on the underframe strength of the wagon series Smnpn 194. In EN 12663-2: 2010, load
cases for strength calculations and strength requirements on wagon underframe and on stanchions and their fastenings are clearly described. But nowhere is exactly stated that the impact of stanchion load on the wagon underframe should be taken into account. The first part of the paper presents the subject of the study - a flat also wagon equipped with stanchions, as well as the results of the stress-strain analysis of the wagon underframe and the side stanchions. Based on the results of these calculations and other validation documents, the notified body has commissioned the wagon into operation. In the course of the operation, it is established that the structural integrity of the wagon underframe is impaired due to loads not taken into account either in the calculations or when the wagon is admitted into service as they are not specified in the standard. These problems occur in the areas of stanchions connections with the wagon underframe and are described in the second part of the paper. Once problems and their causes have been identified, measures have been taken to reinforce the problematic areas. This would not have happened if the standard specified that it was also necessary to check the impact of the equipment on the underframe strength. It should be noted that during testing the stanchions are tested as a standalone object subjected to the regulated loads and not in a combination with wagon underframe [7].

2. Subject of the study and initial results
The subject of the study is a wagon series Smrps 194, which is a modification of the wagon series Smnps 193. The three-dimensional wagon model is shown in Figure 1.

![Figure 1. Three-dimensional model of wagon series Smnps 194.](image)

The main parameters of the wagon are: gauge G1, number of axles 4, axle load 22.5 tons, payload capacity about 68 tons, own weight 22 tons, base 11.7 m, wagon length without buffers 15.5 m. The underframe of the wagon is made of steel S355J2 according to EN 10025. The theoretical studies are made by the finite element method. The software product SolidWorks is used for calculations. For the strength analysis spatial computational models were developed by using 3D solids elements. The approximation of the solution has been examined, with the optimized model being made up of 344 495 notches and 177 678 finite elements. The maximum size of the finite elements is 80 mm and the minimum (in the zones with expressed stress concentrators) is 10 mm.

2.1. Load cases
In accordance with international standards, each newly designed or modified wagon is object of theoretical (by calculation) and each newly designed wagon is object of 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). Additionally, three load cases (SLC) as defined in subsection 7.10 of European standard EN 12663-2:2010 [2] are applied to high strength stanchions. An overview of all load cases is shown in Table 1.

**Table 1. Load cases applied to wagon construction.**

| Load case | Description |
|-----------|-------------|
| HLC 1     | Compressive force at buffer axis height 2000 kN (Table 2 of [2]) |
| HLC 2     | Compressive force 50 mm below buffer centre line 1500 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 30t distributed on area with width 2 m and length a-a = 1.3 m |
| VLC 2     | Vertical load 39t distributed on area with width 2 m and length b-b = 5.0 m |
| VLC 3     | Vertical load 60t distributed on area with width 2 m and length c-c = 7.8 m |
| VLC 4     | Vertical load 68t distributed on area with width 2 m and length d-d = 9.4 m |
| VLC 5     | Vertical load 68t distributed on area with width 2 m and length e-e = 11.7 m |
| VLC 6     | Vertical load 68t distributed on area with width 2 m and length f-f = 13.5 m |
| VLC 7     | Vertical load 30t distributed on whole width of wagon and length a-a = 1.3 m |
| VLC 8     | Vertical load 39t distributed on whole width of wagon and length b-b = 5.0 m |
| VLC 9     | Vertical load 60t distributed on whole width of wagon and length c-c = 7.8 m |
| VLC 10    | Vertical load 68t distributed on whole width of wagon and length d-d = 9.4 m |
| VLC 11    | Vertical load 68t distributed on whole width of wagon and length e-e = 11.7 m |
| VLC 12    | Vertical load 68t distributed on whole width of wagon and length f-f = 13.5 m |
| LLC 1     | Lifting at one end of the vehicle with most unfavourable vertical load (Table 7 of [2]) |
| LLC 2     | Lifting the whole vehicle at 4 lifting positions with most unfavourable vertical load (Table 8 of [2]) |
| LLC 3     | Lifting the whole vehicle at 4 lifting positions with one lifting point displaced 10 mm vertically with most unfavourable vertical load (Table 8 of [2]) |
| CHLC 1    | Compressive force at buffer axis height 2000 kN and most unfavourable vertical load |
| CHLC 2    | Compressive force 50 mm below buffer centre line 1500 kN and most unfavourable vertical load |
| CHLC 3    | Compressive force at buffer axis height 2000 kN and vertical load from own mass |
| CHLC 4    | Tensile force at coupler axis level 1500 kN and most unfavourable vertical load |
| CHLC 5    | Tensile force at coupler axis level 1500 kN and vertical load from own mass |
| SLC 1     | Force of 35 kN at 500 mm acting from inside the wagon from the centre of the borehole (Subsection 7.10. of [2]) |
| SLC 2     | Moment of 42 kNm in transverse direction (Subsection 7.10. of [2]) |
| SLC 3     | Moment of 15 kNm in longitudinal direction (Subsection 7.10. of [2]) |
Methods for the application of loads from HLC, VLC, LLC and CHLC load cases groups are described in detail in [4, 5, 6]. The loads acting on the stanchions (SLC group load cases) are applied in accordance with customer requirements. The stanchions used fully correspond to those of the prototype wagon - Smns 193. They underwent experimental testing by the Bulgarian National Research Institute for Transport (NRTI) in 2013 and were approved by the notified body. The loads and the methodology as used in the tests are the same as applied in the calculation model [7]. Loads for the SLC1, SLC2 and SLC3 load cases are applied as shown in Figures 2, 3 and 4, respectively. The displacements are limited to the three bolts connecting the stanchions to the wagon underframe.

![Figure 2](image1.png)  **Figure 2.** Load application for load case SLC 1.

![Figure 3](image2.png)  **Figure 3.** Load application for load case SLC 2.

![Figure 4](image3.png)  **Figure 4.** Load application for load case SLC 3.

### 2.2. Initial calculation results

The study on static strength of wagon underframe and side stanchions (load cases from Table 1) was conducted in accordance with the data in subsection 2.1. The strength evaluation of the wagon underframe and side stanchions is made using the security factors $S$ as given in equation (1):

$$S = \frac{\sigma_{\text{lim}}}{\sigma_{\text{Mises}}} \geq 1.0$$  \hspace{1cm} (1)

where $\sigma_{\text{lim}}$ is the yield limit of the material. For steel S355J2 the parameter is $Re = 355$ MPa. The stress $\sigma_{\text{Mises}}$ represents the maximum stress received under the corresponding load case.

After conducting the strength analysis, the following conclusions are defined:

- For all tested load cases, the resulting stresses are lower than permissible stresses.
- There are a small number of load cases in which the stresses are close to the permissible stresses, but they are lower. They are characterized by the following features: they have a
pronounced local character and there is a very rapid decrease of the values with an increased distance from the analyzed zone.

- The overall stress level is relatively low, which is a guarantee of high strength and reliability of the wagon.
- The wagon underframe and side stanchions are dimensioned correctly with respect to static load cases.

The results of the strength analysis of the wagon underframe and the side stanchions and the above conclusions have provided grounds for the notified body to admit the wagon series Smnps 194 into service.

3. Analysis of problem areas

Two years after the wagon was taken into service, it was found out that deformations in the connection zone between side stanchions and the wagon underframe were unacceptable. Particularly great distortion of the structural strength of the underframe is noted in the side stanchion connections with the side sill in the area of the weld connecting the two vertical side sill sheets. This area is shown in Figure 5.

![Figure 5. Deformation area at the side sill.](image)

After analysis of the problem zones it was found that the deformations were due to the pressure applied by the stanchion transmitted through its fastening on the wagon underframe at the side sill. The strength analysis of the connection between the stanchion fastening and the wagon underframe has not been requested by the customer and the notified body, due to the fact that the on prototype
wagon series Smns 193 any strength problems have not be identified. Also this is not exactly specified in EN 12663-2:2010.

In order to determine the cause for deformations in the problem zone, it was analyzed by modeling the impact of the load from stanchion fastening on the underframe. Figure 6 shows the simulation model of the connection, and figure 7 shows the load application on the stanchions fitted on the underframe.

![Figure 6. Model of the stanchion fastening.](image1)

![Figure 7. Load application on stanchions fitted to the wagon underframe.](image2)

The stress results obtained in the most unfavorable load case SLC 2 are shown in figure 8. Those stresses do not occur in the connection itself or in the stanchion, namely they occur in the side sill of the underframe.

![Figure 8. Calculated stress results for load case SLC 2.](image3)

Extreme stress values are: - 353,943 MPa and +268,615 MPa. They are very close to the stress values (-337 MPa) registered in the wagon partial tests conducted in Germany by DAkkS Laboratory. Considering that the maximum stress is obtained in the weld area (permissible stresses are $\sigma_{\text{lim}}=355/1.1=323$ MPa) and the minimum stresses are in parent material (permissible stresses are $\sigma_{\text{lim}}=355$ MPa), then the safety factors are:

$$s_{\text{max}}=355/353.943=1.003$$

$$s_{\text{min}}=323/268.615=1.202.$$ (2)
Equations (2) show that the safety factors are higher than 1, but with minimal increase in load force (e.g. due to impact in the stanchion during loading and unloading operations) deformations in side sill may occur. The analysis shows that it is necessary to propose appropriate measures for reinforcement of areas in which the stanchions are connected to the wagon’s side sill.

4. Reinforcement measures and results from extended calculations

Following the analysis made in section 3, it is clear that the stanchion fastenings should be subject to constructive changes as they could cause deformations in the side sills. The authors of the calculations propose to reinforce the problem zone as shown in figure 9. In figure 9 can be seen that the reinforced fastening has a larger contact area with the vertical web of the side sill. In this way, the pressure load from the stanchion acting on the underframe is redistributed more evenly over a larger area. This leads to a reduction of the maximum stresses in the problem area to 315.8 MPa, which is below the permissible 355 MPa. The maximum stresses are displaced from the underframe side sill to the stanchion body, as shown in figure 10.

Figure 9. New fastening of the side stanchion.

Figure 10. Maximal stresses in side stanchion for load case SLC2.
5. Conclusion
When carrying out theoretical and experimental strength studies of wagon structures, it is often the case that they are carried out by a shortened procedure, which is not in full accordance with the regulations in the relevant standards. This is usually due to the fact that a given wagon component is already realized in another similar construction and has not shown insufficient strength. However, the calculation procedures prescribed in the standards do not always cover all the possible impacts of individual wagon components on the overall construction. This report show how this can result in a mismatch with real operating conditions and that the consequences can lead to higher costs, even though all aspects of the calculation procedures prescribed in the normative documents are respected. It follows from this that the tests and theoretical studies of wagon strength prescribed in the normative documents should be expanded or more clearly formulated in order to approximate as much as possible to the real conditions. In this way is it possible to avoid problems similar to those described in this report.

Regarding this study, the authors propose in EN 12663-2: 2010 to add a text "the strength analysis of the side stanchions with the prescribed loads should be carried out by taking into account their impact on the wagon underframe”.

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