Analysis of some issues in the theoretical studies of unloading flaps strength of wagon series Falns

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Abstract. The self-unloading wagons with saddle-shaped floor, known under the serial designation Falns, are equipped with unloading flaps contributing to the rapid mechanized unloading of the wagon. In general, the theoretical and experimental studies of such wagons are standardized in EN 12663-2: 2010. Unlike many other nodes, no specific conditions (load forces, application locations, supports, etc.) have been described in the standard in order to properly investigate the strength of unloading flaps. This leads to the use of various methods for determination of their strength, which on other hand can lead to their improper design. The report analyzes the current used methods for the investigation of the unloading flaps strength, as well as their advantages and disadvantages. It is recommended to develop a specific methodology, reflecting the specifics of the construction and its way of operation. In this way, unification in the investigation of the unloading flaps strength will be achieved, as well as avoiding of the oversizing or undersizing of these responsible nodes in the Falns series wagons.

1. Introduction

Wagons of the Falns series (figure 1) are specialized self-unloading wagons designed for the transport of bulk goods. Numerous varieties are exploited in the world practice, differing in their basic parameters: axle load, pivot distance, width, length, console length, useful volume, number of unloading flaps, etc.

The common ground between them is that the floor is not horizontal but is inclined at a certain angle to the horizontal plane, which contributes to the rapid unloading of the vehicle. Additionally, the process is favored by the presence of unloading side flaps, a mechanism for opening and closing the flaps and a mechanism for locking the flaps during loading and transport. Those mechanisms are operated with pneumatic cylinders and suitably designed lever systems.

The theoretical study of the strength of wagons of this type is carried out in accordance with EN 12663-2:2010 Railway applications. Structural requirements of railway vehicle bodies. Freight Wagons [1]. Figure 2 shows the calculation model for testing the strength of the wagon body. The full list of load cases is given in [2-5]. In the stress-strain analysis, the unloading flaps are not presented in the wagon calculation model.

The reason for this is that they are an auxiliary bearing element and are hinged to the wagon body. Here the hypothesis is that if the structure stands without any problems the regulated loads in the absence of the unloading flaps, a more favorable distribution of stresses, deformations and displacements will be found upon their presence. In practice, complying with the requirements of [1, 6-8], the unloading flap and the unloading and locking mechanisms may remain unanalysed.

This is the reason why the manufacturers (or initiators of the theoretical analysis) of such wagons explicitly require the calculation teams to perform a stress-strain analysis of the mentioned parts.
2. Methods for determination of the loads acting on flaps

Extensive analysis of the normative documents shows that there are no regulated methodologies for determination of the values of the loads, the positions of their application, the methods of evaluation, etc. needed for the analysis of the flaps strength. The issue is dealt with in a number of publications [9-16], most fully analyzed in [9]. The methods of Jansen HA, Kleyn, GK, Mazarskiy SM, Putyato AV, Rusinek R., Zenkov RL, as well as the Standards of Eurasian Economic Union 1996 [17], GOST 33211. 2014 [18] and the German engineer’s manual [19] were analysed. These publications offer different formulas for determining the pressure acting on the walls of the wagon (in this case, the wagon body). It has been found that the proposed functional dependencies are derived from the classic hydrostatic pressure formula. They mostly take into account the parameters of the repose angle, the angle of internal friction of the bulk load, the coefficient of friction between the bulk material and the wall studied, the angle of wall inclination, etc. and they allow simplifications (to alleviate the calculation process and avoid the demand for data specific to the material), which in practice lead to the use of the classic hydrostatic pressure formula. The proposed functional dependencies resulting in increased pressure values on the walls.

This is the reason in [19] to recommend following dependencies (equations (1) and (2)) to be used when analysing the strength of bulk storage vessels (including the Falns series flaps):

\[ F = \frac{\rho g (h_1^2 - h_2^2)}{2 \sin \alpha} l; \]

\[ e = \frac{(h_1-h_2)(h_1+2h_2)}{3 \sin \alpha (h_1+h_2)^2}. \]

The variables used in both equations are (as illustrated in figure 3): \( F \) – the force acting on the wall; \( \rho \) – density of bulk good; \( g \) – gravity acceleration; \( h_1 \) – height of the vessel; \( h_2 \) – the height of the unstudied part of the vessel; \( \alpha \) – angle of inclination of the wall studied; \( l \) – length of the studied wall and \( e \) – point where the force \( F \) is applied.

3. Analysis of wagon’s Falns unloading flap

The theoretical strength analysis of similar wagons was done in some previous works of calculation team [2-5]. Strength analysis of flap is done using the Finite Element Method [20, 23] in SolidWorks Simulation [21, 22]. For this purpose, the calculation model shown in figure 4 was used. The object geometry is modelled with 3D finite elements.
The load is distributed unevenly over the entire surface of the flap. For this purpose, equation (3) is used at variable values of the distance $h_2z$ from $h_0$ – the height of the fixed part of the wagon wall to $h_1$ – the height of the movable (flap) and the fixed part of the wall, i.e.:

$$h_2z = h_0 \div h_1.$$  

(3)

The displacements are limited to the zones of the six hinges around which the valve rotates, two lateral hinges for the levers to open and close the flap and in the three zones of thumbs that lock the flap, as shown in figure 5.

The results of strength analysis are shown in figures 6 and 7.
The strength assessment is performed using permissible stresses in accordance to equation (4) [1, 7, 8, 24]:

$$\sigma_c \leq \sigma_{lim}, \quad \text{(4)}$$

where $\sigma_c$ is calculated stress and $\sigma_{lim}$ is permissible stress. The permissible stresses $\sigma_{lim}$ depend on material used and analysed area. For steel S355J2 permissible stresses are 355 MPa for parent material and 323 MPa for parent metal in immediate vicinity to weld. The maximal stress value is 321.9 MPa and is obtained in the weld area. This value is very close to the permissible value and is characterised with safety factor as given in equation (5):

$$S = \frac{\sigma_{lim}}{\sigma_c} = 1.0034 > 1.0. \quad \text{(5)}$$

According to [1, 7] equation (5) allows the flap to be commissioned.

4. Additional calculations and test analysis of wagon’s Falns flap

The minimal fulfillment of a condition in equation (5) has provoked the authors to continue the flap research in order to improve the calculation model by reflecting the design features, the modes of operation of the object, its behavior during operation. For this purpose, real observations were made of 80 Falns series wagons operating across Europe for more than 3 months. They serve for transporting powdered material, calcium carbonate CaCO₃, with a grain diameter of 0.1 to 5 mm. The following more important conclusions were made:

- The wagon as a whole (calculations done by the same team of authors) does not show any indications of insufficient strength. It is convenient for service. The mechanisms for opening and closing the flaps and for locking them operate flawlessly.
- Flaps are designed and manufactured to a high level. There is no spilling of the material transported.
- When the flaps are unlocked (without using the opening mechanism) there is also no spilling of the loaded material.
- No plastic deformations have been observed on the flap bottom sealing profile (position 2 in figure 8).
- The middle locking pin of the flap (figure 5, middle lower profile support) does not contact the lower profile both during the movement and when unloading. This is confirmed by the undamaged layer of paint on both elements.

The last four conclusions are extremely important as they show that, in the absence of locking, the flap seals seamlessly the wagon’s cargo space and thus prevents leakage of the load.

![Figure 8. Flap bottom sealing profile.](image1)

![Figure 9. Schematic diagram of the contact between the wagon floor and the bottom flap profile.](image2)
This is assured as follows: Constructively, the bottom profile (position 1 of figure 8) is designed with a certain curvature. In this case, the bending arrow is 15 mm (figure 9). When the flap locking mechanism is actuated, the bottom profile travels the free distance to the floor, touches its convex part to the floor and, under the action of the applied forces, elastically deforms until contact is made across the entire floor line. Elastic deformations occur in both the sheet metal and the sealing profile 2 in figure 8. Deformations are elastic, which is confirmed by the observations made.

The described principle of flap closing operation required correction of the test method to maximize the simulation to the actual flap operation. For this purpose, the stress-strain analysis is done through the “Non-linear task” module, with contact between the floor and the valve. The results of the calculations are given in figure 10. In this case, the calculation model and boundary conditions are preserved the same as in the initial study.

**Figure 10.** Distribution of stresses in the flap when calculated with “Non-linear task”.

The analysis of the data from figures 6 and 10 allows the following conclusions to be made:
1. The stress distribution in the flap for the two calculation methods is similar.
2. When using the “Non-Linear Task” Module with Floor/Flap contact the maximum stresses are 342.73 MPa recorded in the upper end hinges of the flap. The stresses in the bottom area of the flap increase by an average of 21%. The stresses in the connections between the bottom profile and the vertical columns of the flap increase by 16.2% in the middle and by 43% in the intermediate columns adjacent to them. This is particularly worrying as these are welding zones and the allowable stresses are 323 MPa.

These data make it possible to conclude that the stress-strain analysis should be done through the “Non-linear task” module with floor-to-flap contact.

5. **Analysis of the need for correction of methods for theoretical determination of the pressure on Falns series wagons**

The conclusions from the Falns series wagon observations unambiguously showed that the flaps reliably seal the interior space, no gaps are detected when the locking thumbs are released, the middle locking pin does not contact the bottom profile of the flap during movement and unloading. These facts make it possible to assess the pressure-determining method used on the wagon flaps. For this purpose, the following hypothesis is formulated: The bulk load does not overcome the forces of elastic deformation of the bottom profile of the flap, the sealing profile 2 of figure 8 and the floor sheet. Consequently, the assessment of the working pressure can be carried out according to the following procedure:
In the model shown in figure 5 the three displacement constraints of the bottom profile should be removed. This corresponds to the state “released locking thumbs”.

The flap shall be loaded in the manner described in chapter 2.

The displacements are determined theoretically for the flap in the state “released locking thumbs”.

If the flap displacements obtained are smaller than the bending arrow of the flap bottom profile (figure 9), the pressure is determined fairly accurately. Otherwise, it is necessary to adjust the pressure calculation methodology. The suggested hypothesis was tested in accordance with the methodology described. The results of the study are shown in figure 11.

Figure 11. Distribution of displacements in the flap for state “released locking thumbs”.

Their analysis showed that the maximum displacement in the center of the flap was 54.61 mm. This indicates that when the locking thumbs are released, the bulk material should begin to flow through the gap between the flap and the floor. In experimental observations this was not found. Therefore, the displacements obtained under the theoretically imposed load do not correspond to real displacements during operation. The conclusion of the hypothesis is that there is significantly less pressure on the flaps and walls of the wagon. Therefore, the determination of the load with equations (1) and (2) results in substantially higher values. Similar findings have been made in [9], where it has been found that the forces applied in analysis of the walls of different series of wagons give rise to stresses which are about 2.5 times greater than the permissible.

As a sign of correctness, it should be noted that the proposed hypothesis is based on the complex application of theoretical and experimental studies. It can not be used alone at the design stage. It is possible to apply at the earliest after wagon prototype has been made and an test is conducted. This allows to see to what extent the theoretical values for Falns wagon flaps loading differ from actual.

6. Conclusions and recommendations
Summarizing the overall work on this study, the following main conclusions can be drawn:

- A comprehensive theoretical and experimental study of the flaps of a special wagon Falns was carried out.
- It is proven that if there is a pre-curvature in the bottom profile of the flap, the theoretical strength tests should be done through the “Nonlinear Task” module with floor-to-flap contact. This leads to a more accurate determination of the stresses in the subject and can prevent the occurrence of strength problems during operation.
- A hypothesis and a methodology for assessing the coincidence of flap loading forces obtained theoretically with those occurring during operation are proposed.
After applying the hypothesis and the accompanying methodology, it has been found that for the particular object under consideration the theoretically determined flap loading forces are significantly higher than those acting on it during operation.

The conclusions made unequivocally suggest that it is expedient to develop a new methodology for determining Falns wagon flap loading forces to be used correctly in the stress-strain analysis of these objects.

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