

STATIC ANALYSIS OF TIPPING SUPERSTRUCTURE OF SINGLE-AXLE TRACTOR TRAILER

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Abstract. Agriculture still belongs to the important parts of industry. Modern agriculture cannot do effectively and economically without state-of-art machines. They are usually the most often towed by a tractor and, in principle, they have the form of a trailer. A tipping trailer is still the most common type of trailers. It has very universal use. The big advantage of a tipping trailer is the possibility to unload it without another handling machine (cranes, diggers etc.). If a company wants to introduce a new product to the market to compete in tough competition, the product must fulfil quite strict criteria not only from the workshop processing and design point of view. It must mainly meet the requirements and criteria from the reliability, safety and long-term operation point of view. This article brings results of the research, which is intended to design a single-axle tipping tractor trailer. The trailer consists of two main parts, a frame and a superstructure. Both parts of the trailer must undergo strength analyses under determined loading conditions. While the results of strength analyses of the frame were already presented in the previous event, this work shows an overview of the strength analysis of the tipping superstructure of the trailer. The structure has been analysed under static loads and dynamical effects have been taken into account by means of the dynamic coefficient. The task has been performed by application of the finite element method. Three load cases have been chosen, namely, driving of the trailer on an even road, side tipping and back tipping. The strength analyses have shown, that for the first load case, the maximal stress value is of 255 MPa, for the second case it is of 206 MPa and for the third case it is of 225 MPa. The results have shown that the designed structure of the tipping superstructure is able to withstand the given loads and it can be used in practice.

Keywords: trailer, tipper, tractor, analysis.

Introduction

Agriculture is a very important part of countries' economics. It does not do without transport machines. Tractors and their accessories belong to them. Trailers are a standard and inseparable transport mean, which allow to transport goods of many kinds. In agriculture, they use trailers of various dimension and weight categories depending on individual needs. Single-axle trailers up to three- even four-axle trailers are used, either with a simple axle or with steering axles allowing to improve the steering properties of the entire tractor and trailer combination [1-3].

There are several producers of tractor trailers. Basically, the main structure of tractor trailers comes from a standard scheme, i.e. a trailer's frame consists of main longitudinal supporting beams, which are supplemented by lateral beams [4-6]. It leads to the frame structure known as a so-called ladder frame. Such a technical solution of a trailer frame is able to withstand bending loads caused by the load weight. Additional structural components help improve torsion resistance, when a trailer moves in heavy off-road conditions. There is also a special structure of a trailer frame, which uses a back-bone frame and independently suspended wheels. It comes from a back-bone frame of a lorry [7]. The main advantage of such technical solution is the great resistance against torsion loads in rough terrain conditions and a modular concept. On the other hand, this type of a frame structure is not very wide-spread in agricultural industry.

Generally, a single-axle trailer is a transport mean with a lower total weight, which has application in smaller farms for transport of material for shorter distances, has better steering properties in smaller spaces. A three-sides tipping trailer appears to be the most versatile type of trailers. In principle, it can be used for transporting almost all kind of goods, such as bulk materials, solid products, straw bales, wood (in a suitable form), palletized material and others [8]. The only exception is liquid products.

The objective of this research is a static analysis of a superstructure frame of such three-side tipping single-axle tractor trailer. It is a continuation of the research activities with this trailer, which has been presented in the previous event. As a frame, both of the chassis and the superstructure, is very important and the main supporting part of the trailer, it must be carefully designed and verified in terms of stresses distribution in a structure. The design has to meet given criteria [9-13] to avoid serious damages during

its long-term operation in heavy off-road operational conditions [14; 15]. The other efforts have been to identify and reveal, whether the calculation will show a similar tendency of the designed structure to be the most loaded in some locations, which are typical for the trailer frame and trailer superstructure frame. There are mainly welded joints, in which the structure of material is changed and affected by the welding process [14; 16-18]. Other components are some parts of the superstructure frame, in which it is supported by a hydraulic cylinder during the tipping process. Finally, some parts of the trailer chassis can be mentioned, which are loaded by stochastic loads during driving [19-23].

Materials and methods

The research of the individual loading cases requires to analyse the main structural units of the designed trailer (Figure 1). The main investigated parts of the trailer are the trailer frame and the superstructure frame (Figure 2). Just these two frames are the most important, because they are loaded by individual loads and related to force reactions in full. Both structural units have been exposed to loading. When a trailer moves on a road, the dynamical coefficient δ_D expresses the dynamical effect, which appears due to road irregularities [19; 23; 24] and other additional influences related with driving [25-29].

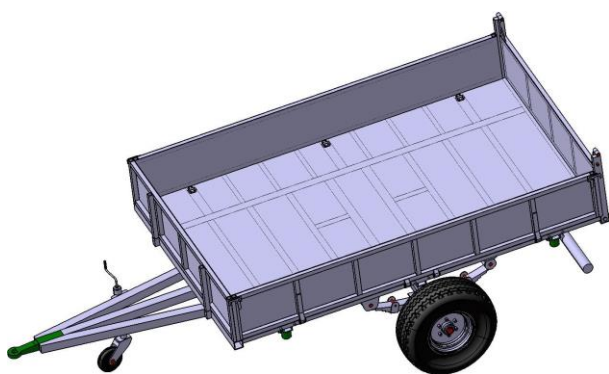


Fig. 1. CAD model of the designed single-axle tractor trailer

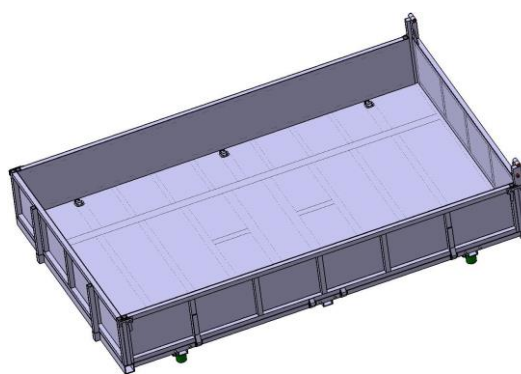


Fig. 2. CAD model of the analysed superstructure

The basic parameters of the designed trailer (including the analysed superstructure), which are important from the static analysis point of view, are listed in Table 1.

Table 1

Parameters of the designed single-axle tractor trailer

Curb weight, kg	Payload, kg	Total weight, kg	Maximal speed, km·h ⁻¹	Dynamical coefficient δ_D
1 500	3 000	4 500	40	1.5

There are the load cases described below. Analysis of the stress distributions in the trailer frame due to the loads for three various load cases have been performed and the results are presented in [30]. Hence, this research brings details of analysing a superstructure frame. It is the strength analysis. The strength analysis has been carried out by means of the finite element method (FEM) with the help of the Ansys modular software [31-34]. This software allows to perform required analyses and ensures wanted cooperation with the used CAD software Catia [35; 36]. The main objective is to identify the distribution of stress in the frame structure, which is generated due to acting of individual loads.

The analysed tipping superstructure is shown in Figure 3. The superstructure frame is a product, which is made of steel EN S355J0. This material has the yield of strength of $R_e = 355$ MPa. The ultimate strength of $R_m = 470-630$ MPa [37].

The main bearing elements are two longitudinal squared profiles with dimensions 70 mm x 70 mm x 5 mm. These profiles are connected and the ends by additional two profiles with the same shape and dimensions, which are oriented transversely. This main structure is supplemented by several other additional longitudinal and lateral profiles also with squared cross-section, but with smaller dimensions, namely 35 mm x 35 mm x 3 mm. The middle part of the superstructure frame is

strengthened by lateral profiles and between them, the U160 profile is welded. Here, a semi-sphere flange (I) is located for mounting of a hydraulic cylinder pivot (tipping functionality). Side, or end parts of the superstructure include semi-sphere elements (II). The entire superstructure will rest only on two side semi-sphere elements and the middle flange while side tipping or on two rear semi-sphere elements and the middle flange while back tipping. A loading area of the tipping superstructure is covered by a steel sheet metal with the thickness of 3 mm.

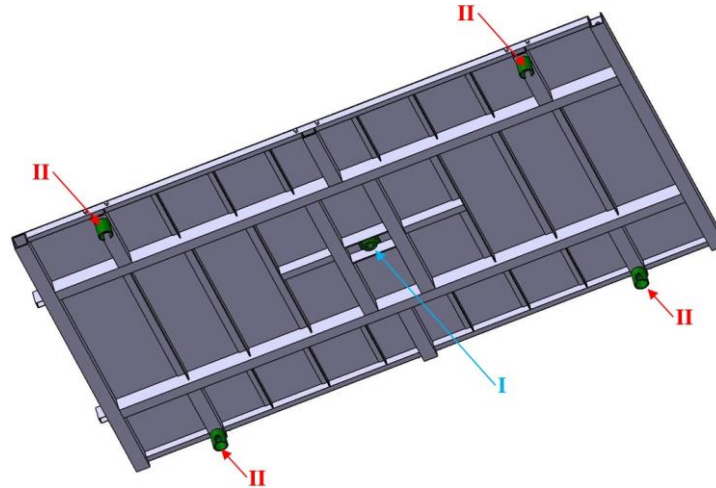


Fig. 3. Superstructure frame, a bottom view

The basis of the static analysis is the generation of the model geometry and determination of individual joints by the given elements of the model. The quadratic hexahedral elements have been defined in the FE mesh with the element size of 10 mm. The created FE mesh in the superstructure as well as its part is shown in Figure 4.

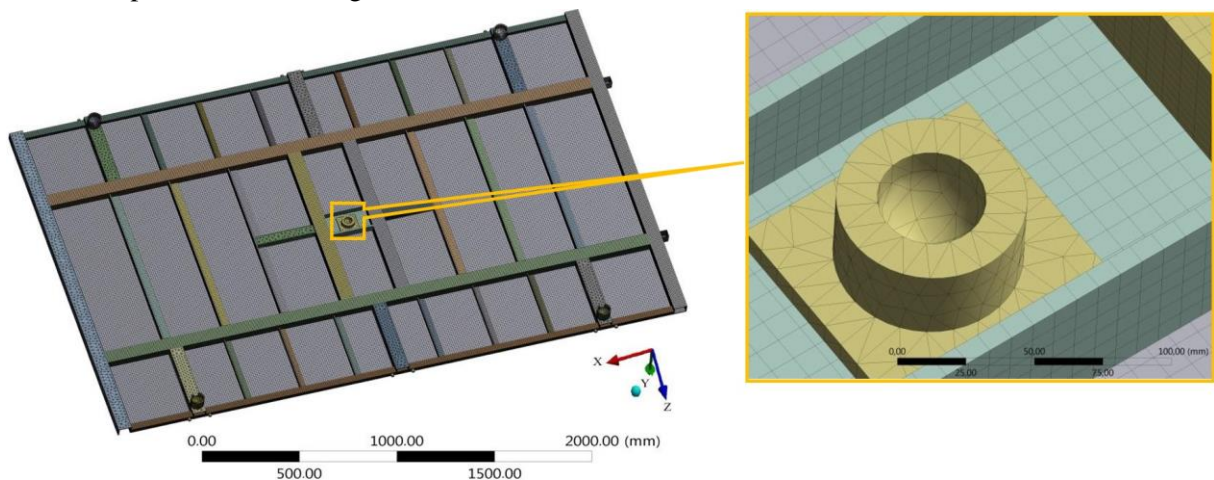


Fig. 4. A FEM mesh created in the superstructure and its part

Defining of boundary conditions depends on the given load case, which is investigated. There have been considered three loading cases, namely, the load on a straight road, the load while back tipping and finally the load while side tipping.

The first load case is for driving on a straight road (Figure 5). The superstructure rests on four semi-sphere elements located on the superstructure sides. Therefore, degrees of freedom are defined in these locations (Figure 6).

The load for the first load case F_{1st} is calculated by formula (1) as follows:

$$F_{1st} = m \cdot g \cdot \delta_D, \quad (1)$$

where m – weight on the superstructure, kg;
 g – gravitational acceleration, $m \cdot s^{-1}$;
 δ_D – dynamical coefficient.

Substituting the known values, i.e. $m = 3\ 000\ \text{kg}$, $g = 9.81\ \text{m}\cdot\text{s}^{-1}$ and $\delta_D = 1.5$, we get the load of $F_{1st} = 44\ 145\ \text{N}$.

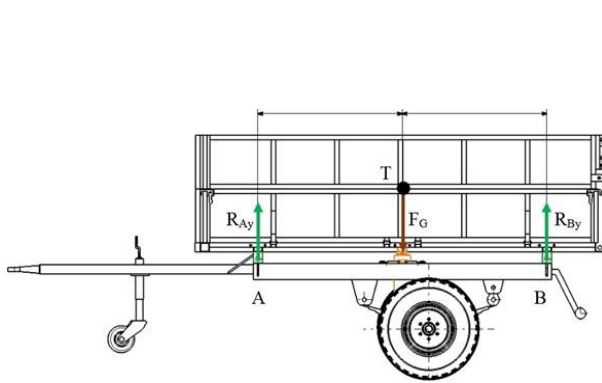


Fig. 5. Forces and reactions for the first load case

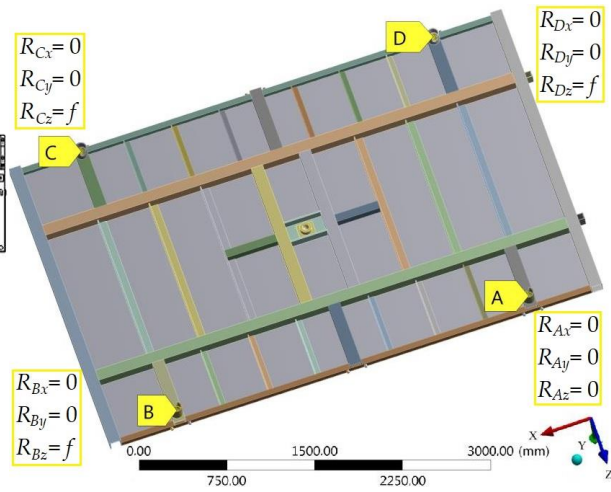


Fig. 6. Degrees of freedom for the first load case

The second load case is while side tipping. For this, the superstructure rests on the middle flange and on the side semi-sphere elements (Figure 7). Degrees of freedom are defined in the described locations (Figure 8), at which it does not matter, if we consider the right-side tipping or left-side tipping.

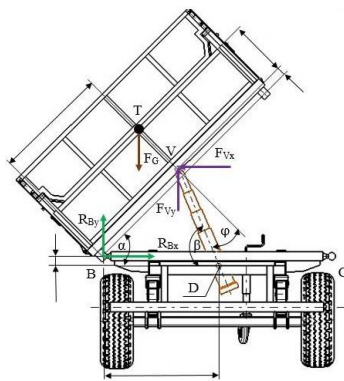


Fig. 7. Forces and reactions for the second load case

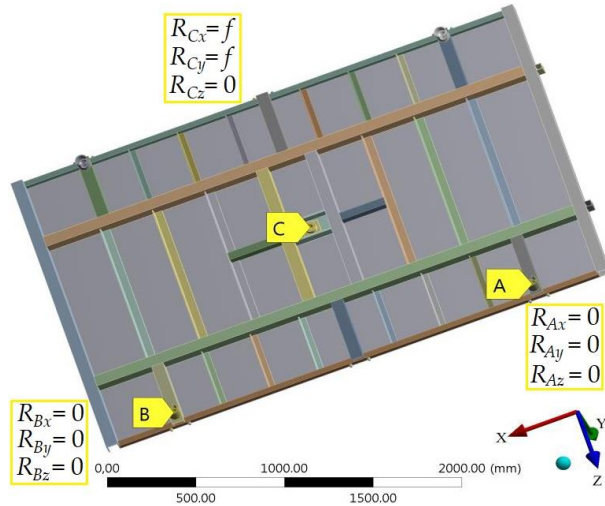


Fig. 8. Degrees of freedom for the second load case

It is due to the symmetrical design of the superstructure. It has to be noticed that Figure 7 shows an illustrative situation. However, the most unfavourable loading case is for the moment, when the superstructure begins to lift, i.e. for the very small tipping angle α ($\alpha = 1^\circ$). As the tipping is forbidden during driving, the dynamic coefficient δ_D is not considered and formula (2) serves for calculation of the load for the second load case F_{2nd} :

$$F_{2nd} = m \cdot g \quad (2)$$

Hence, the value is $F_{2nd} = 29\ 430\ \text{N}$.

The last load case (the third load case) is a situation, when the superstructure tilts back (Figure 9). The superstructure rests on two rear side semi-sphere elements and on the middle flange (Figure 10). Figure 10 shows the definition of the degrees of freedom. Similarly to the previous case, Figure 9 also represents an illustrative situation.

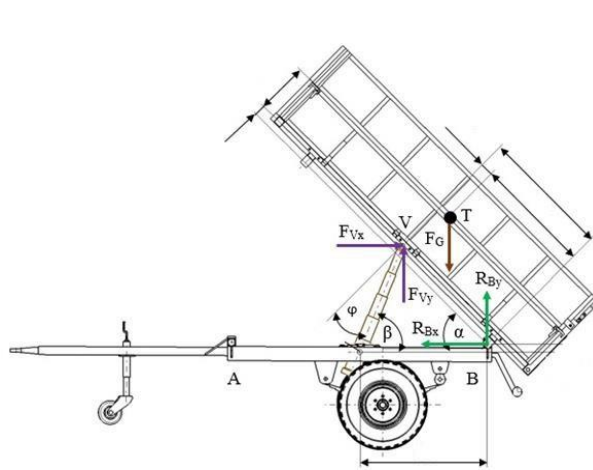


Fig. 9. Forces and reactions for the third load case

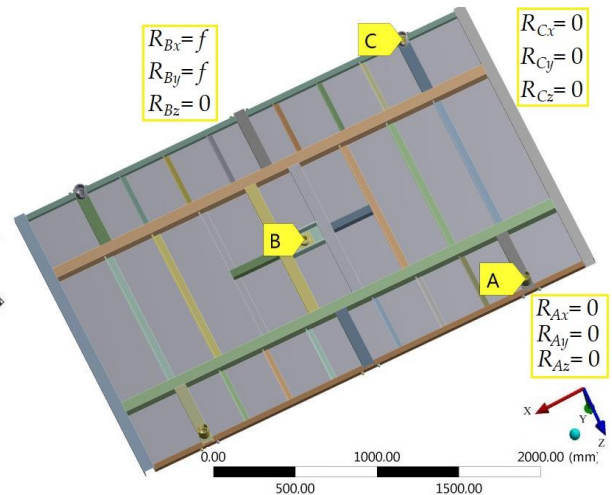


Fig. 10. Degrees of freedom for the third load case

It means that the most unfavourable loading case is also for the moment, when the superstructure begins to lift and the tipping angle is $\alpha = 1^\circ$. The dynamic coefficient δ_D is again not considered. Formula (3) gives calculation of the load for the third load case F_{3rd} :

$$F_{3rd} = m \cdot g . \quad (3)$$

Thus, the load is the same as for the second load case, namely of $F_{3rd} = 29\,430\text{ N}$.

Results and discussion

This section contains results of the strength analyses of the superstructure for individual load cases described above.

Figure 11 shows the distribution of the stresses in the structure for the first load case. It can be concluded that the maximal reduced stress (von Mises stress) is concentrated in the area, where the longitudinal side profiles (with the dimensions of 35 mm x 35 mm x 3 mm) are connected with the lateral profiles (with the dimensions of 70 mm x 70 mm x 5 mm). It can be seen in detail in Figure 11. A couple of longitudinal profiles is the most loaded in the centre part. Numerical values have revealed that the maximal permissible stresses are not exceeded and the structure meets the strength conditions for the first load case.

Results of the strength analysis for the second load case are depicted in Figure 12. After the strength analyses, it is obvious that the centre part of the superstructure belongs to the most load structural part of the superstructure. A hydraulic cylinder is considered to be mounted in this location. Higher values of the reduced stresses (von Mises stresses) are caused by the connection of smaller longitudinal profiles (50 mm x 50 mm x 5 mm) with lateral supporting profiles (70 mm x 70 mm x 5 mm).

This is shown in detail in Figure 12. These strength analyses have shown that also the load of the second load case does not lead to exceeding the permissible stress of the used material.

The numerical analyses of the superstructure for the third load case have led to the distribution of stress in the structure, which is shown in Figure 13.

As it can be seen, side tipping causes the greatest reduced stress (von Mises stress) in the centre part of the superstructure frame, where a hydraulic cylinder is mounted and also in the location of the main longitudinal profiles. Also, for this load case, the maximal permissible values for the stresses in the structure have not been exceeded. The reached results of the strength analyses of the superstructure frame for the individual load cases have shown that the main supporting profiles of the frame are loaded mainly in the centre part of the superstructure, where the hydraulic cylinder is mounted. These stresses are within the permissible stress values. The local stress values exceeded can be neglected, because it is only caused by the numerical errors during calculation and it is only located in very small locations of the superstructure for individual load cases.

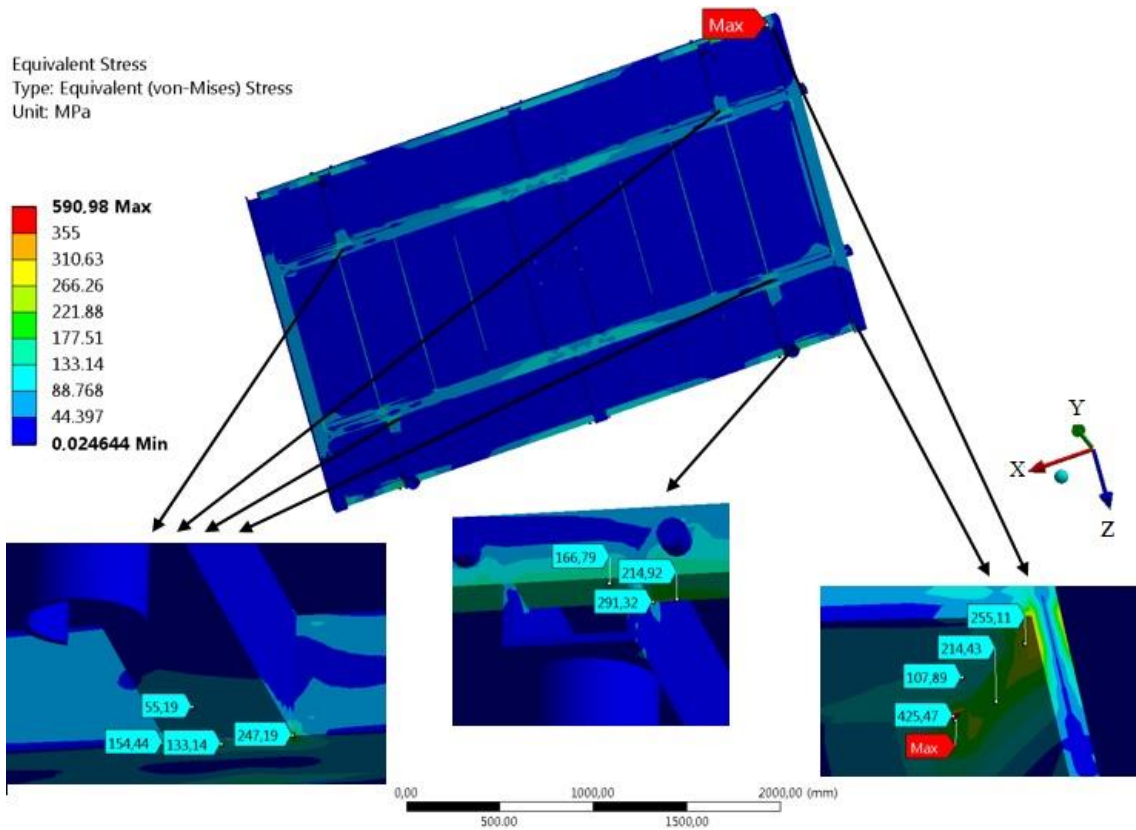


Fig. 11. Graphical view of von Mises stress distribution in the superstructure for the first load case

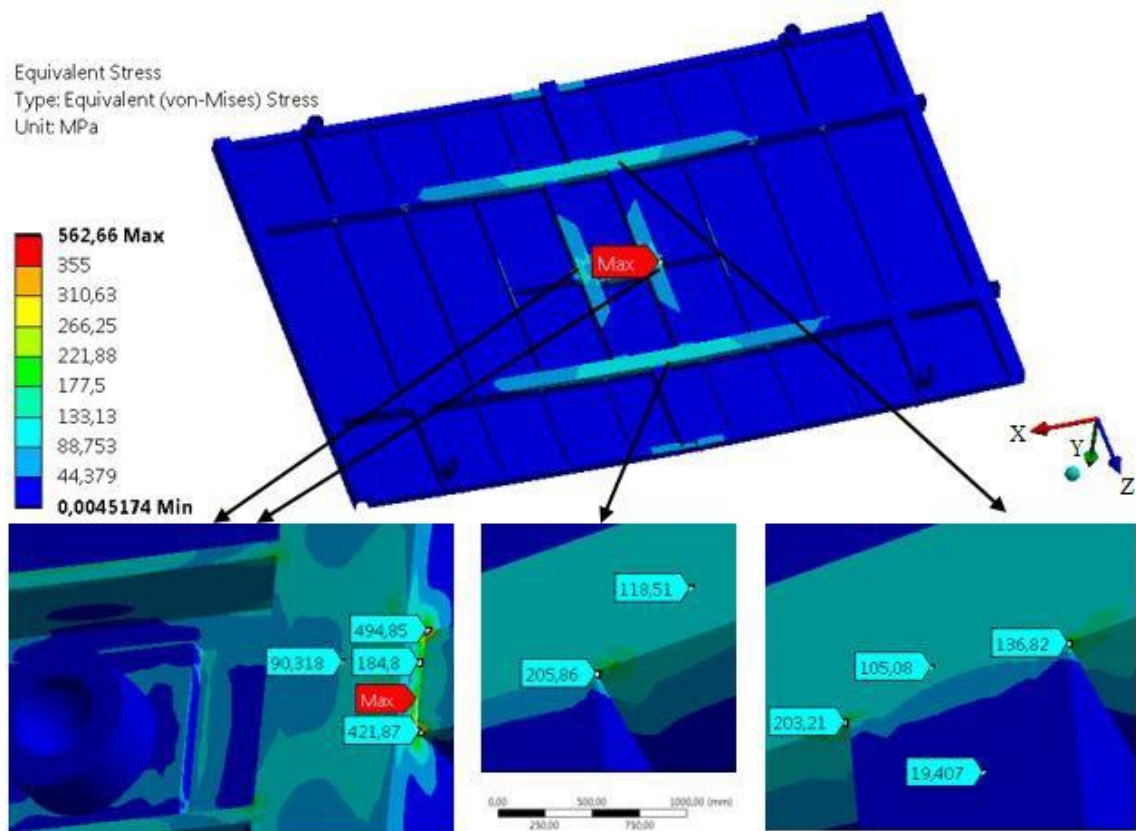


Fig. 12. Graphical view of von Mises stress distribution in the superstructure for the second load case

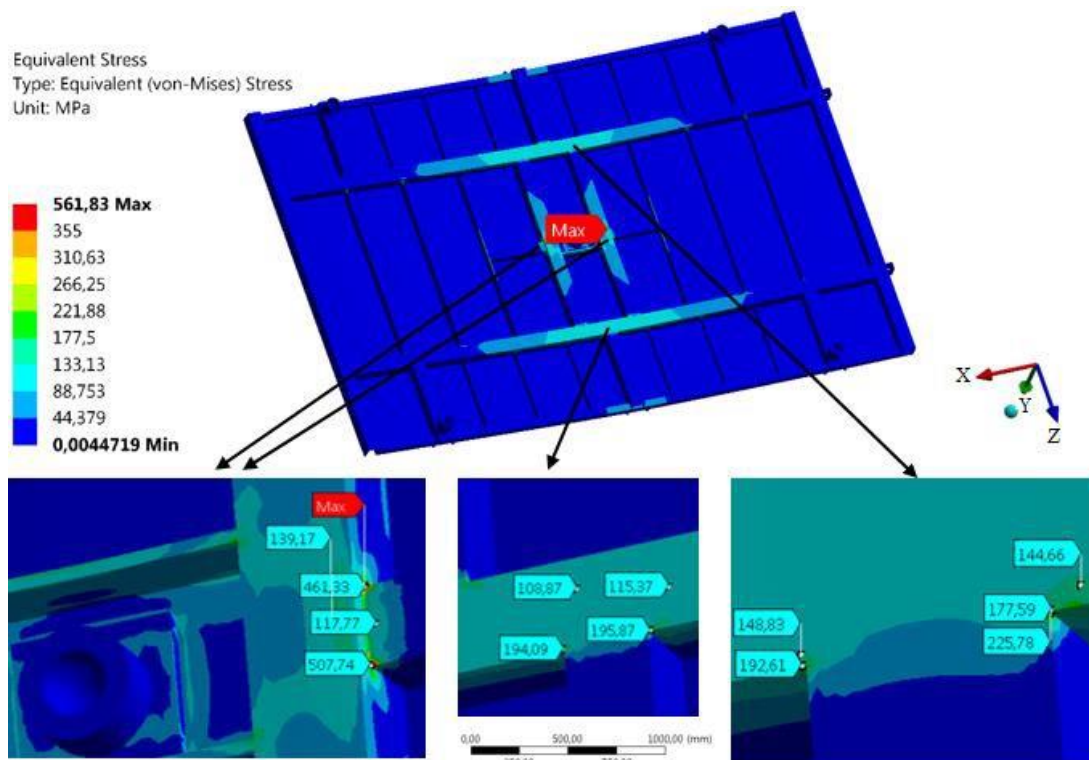


Fig. 13. Graphical view of von Mises stress distribution in the superstructure for the third load case

Conclusions

1. A superstructure for a single-axle tractor trailer has been designed together with the trailer itself.
2. The designed superstructure is intended to be used as a universal three-side tipping superstructure for transportation of various kinds of goods.
3. The paper presents the static analyses of the superstructure frame and the overall structure for three load cases, which represent the main kinds of load appearing during the trailer operation.
4. The numerical calculations have revealed the most loaded locations of the superstructure frame for individual load cases. The particular values of the maximal stresses for individual load cases are as following: for the first load case (on an even road) of 255 MPa, for the second load case (side tipping) of the 206 MPa and for the third load case (back tipping) of the 225 MPa.
5. The results of the static analyses have shown that the trailer's superstructure meets the given requirements in terms of the prescribed limits.

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Author contributions:

Conceptualization, J.D., M.B., S.S and J.K.; methodology, J.D., E.M. and J.K.; software, J.D., R.M. and J.K.; validation, M.B., R.F. and E.M.; formal analysis, J.D., R.M. and J.K.; investigation, M.B., E.M. and J.K.; data curation, J.D. and J.K.; writing – original draft preparation, J.D. and J.K.; writing – review and editing, R.M. and S.S.; visualization, J.K.; project administration, J.D. and M.B.; funding acquisition, J.D. All authors have read and agreed to the published version of the manuscript.

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