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Innovative stress analysis and machine learning forecasting for semi-trailer truck body durability

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Abstract: This article presents an in-depth analysis of the stress-deformation state (SDS) in the bottom structure of a semi-trailer truck body. Engineering analysis was conducted utilizing the SolidWorks software, focusing on a comprehensive CAD model of the semi-trailer truck body. The study explored variations in SDS parameters resulting from alterations in the geometric parameters of the body bottom elements. The research investigated alterations in static stress and displacement relative to changes in the proportions of the cross-section of the channel while maintaining fixed geometric dimensions of the workpiece, thickness of the workpiece, and the material of the body bottom. Graphical representations were generated to illustrate the variations in static stress, displacement, and safety margin concerning the thickness of the shelf and channel. Additionally, dependencies were derived that correlate static stresses in the channel with the thickness of the channel wall and the thickness of the body bottom sheet. The study results were compiled and summarized, offering valuable insights into the stress-deformation state of the semi-trailer truck body's bottom. Furthermore, machine learning techniques, specifically the RandomForest algorithm, were implemented in a Python environment to predict changes in

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static stress based on various factors. The model's predictions were validated by comparing predicted static stress values with actual values on a test sample. These findings facilitate efficient selection of appropriately sized elements by predicting static stress values, employing the RandomForest machine learning algorithm.

Keywords: transport, energy resources, semi-trailer truck body, static stress, static displacement, CAD model, algorithm, machine learning

1. Introduction

Trucks are widely used to transport all types of goods both within the country and internationally. Numerous methods of their classification make it possible to highlight the main parameters of vehicles, thanks to which the best option for the safe transportation of goods by road is selected (Ukraine State Statistic Service, n.d.).

Trucks differ in a large number of parameters and design features. Types of cars and truck bodies are a primary factor in their classification. Truck body types also determine the consumer purpose of each type of truck. The types of truck bodies are one of the decisive factors in favor of a specific type of vehicle for planning the process of cargo delivery by vehicle.

In the automobile industry, truck chassis are designed according to design standards, but bodies made by various manufacturers are designed without reference to a standard design. These bodies are manufactured according to their load capacity, and there is no standardization of the design regarding engine vibration and dynamic characteristics. Truck bodies manufactured without design standards are dangerous in terms of dynamic performance. Under such dynamic excitations, the body tends to vibrate at a specific frequency since the operating speed range of the truck engine is from 900 to 3000 rpm. It has been found that the natural frequency of vibration of the truck body structure coincides with the frequency of the external excitation caused by the engine, a phenomenon known as resonance. A sharp increase in deflection leads to excessive deflections and the destruction of the truck body structure (Gotmare & Gandhe, 2016).

When designing a truck body, several factors must be considered. Vehicles and related structures mainly worked on the design to increase strength, reduce weight and improve configurations (Mushtaque & Gangwani, 2016). The concept of beams of uniform strength has been used to reduce stress concentration. Accordingly, modifications are required so that the optimized model has better stress distribution and much less weight than the conventional model (Krishna, Reddy, Venugopal & Ravi, 2017).

In trucks, the body is the structural part intended for transporting goods. The body of the truck can be:

- universal for general purposes;
- specialized (for transporting special cargo);
- unique (technological installations where the cargo chassis serves to deliver the technological installation to the workplace).

The truck's design depends on its layout, the used materials and the body manufacturing technology. Socio-economic factors mainly influence the development of the truck design, and the emergence of a new design, in turn, forces the search for new technological techniques and materials (Krishna et al., 2017; Lyashuk et al., 2023).

Trailers are widely used to increase the efficiency of cargo transportation. Trailers belong to vehicles but are not equipped with an engine and are often used as part of a road train. Isothermal, tipper, flatbed, semi-trailers, etc., are distinguished by their purpose (Tson, 2016).

Semi-trailers are a subtype of trailers that rest on the tractor's front part and are connected to it by a fifth-wheel coupling mechanism. In case of a tractor breakdown, replacing the vehicle and avoiding overloading is possible. They have a high carrying capacity and the ability to transport long loads.

Regardless of the kind and type of cargo transport unit, semi-trailer bodies are classified according to their purpose: all-metal, flatbed, semi-trailers, refrigerators, isothermal, dump trucks, tanks, low-frame trawlers and platforms.

All-metal bodies of semi-trailers differ from other types of bodies by the presence of a strong frame and metal walls, which significantly increases the strength of the body and ensures the preservation of cargo during transportation.

The durability and maximum operational safety of semi-trailer bodies is primarily influenced by their steel elements' strength, reliability and durability. All components of the semi-trailer body must have a maximum margin of resistance to the influence of any external factors (Vinjavarapu, Koteswararao & Narayana, 2012; Garud & Pandey, 2018).

The main elements that perceive a large part of the load during the transportation of goods are the components of the body frame, which are most often made in the form of thin-walled elements of various cross-sections (Figure 1).

Figure 1: The appearance of the body bottom

Therefore, the given article aims to study the influence of the geometric parameters of the elements of the body bottom on its stress-strain state and predict the change in static stress and simultaneously increase strength, reduce weight and extend the service life.

2. Problem solving

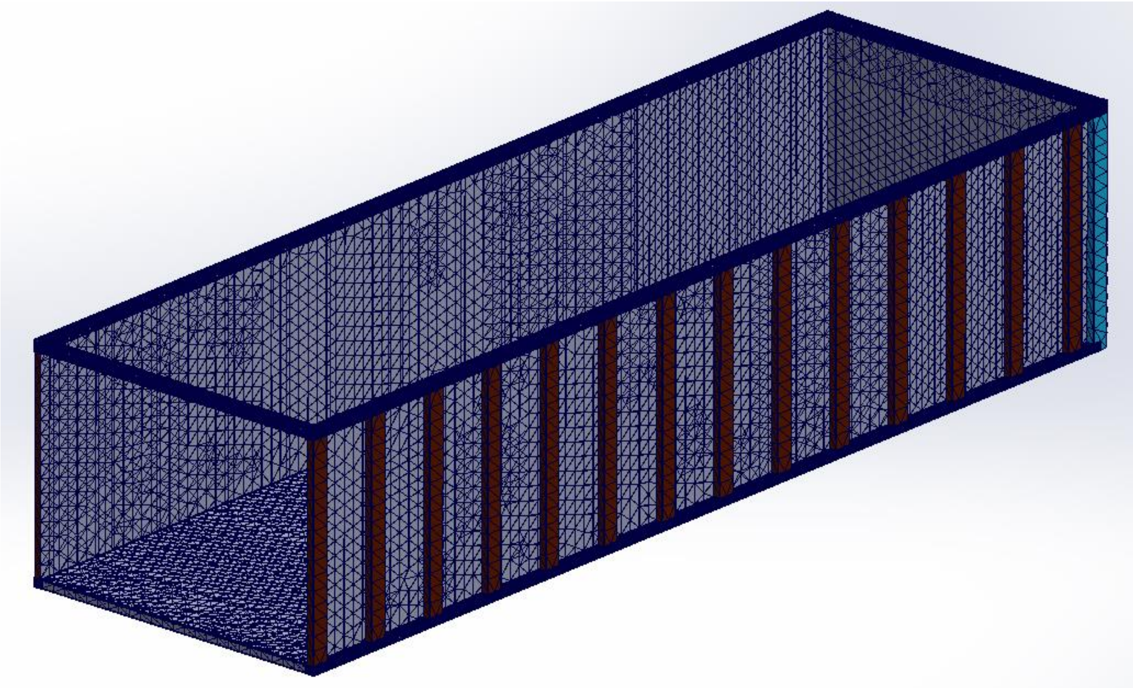
Channels have been used during studying the stress-deformation state (SDS) of the body of a semi-trailer truck. They have been made by bending blanks in the form of strips cut from steel sheets with side dimensions of 2500x1250 mm and thicknesses from 3 mm to 5 mm. The optimal width of cutting a blank from such a sheet is assumed to be 1250/5 = 250 mm. The width of the channel shelf is 55 mm. For various combinations of these parameters, the current value of the channel wall height was calculated, assuming a fixed width of the workpiece of 250 mm (Ramacharan & Prashanth, 2015). All combinations of channel sizes are given in Table 1.

Table 1: The dimensions of the channels used in the study

Channel wall thickness T_{shv}, mm	**Shelf width b, mm**	**Height h, mm**	**R, mm**	**L, mm**
3	55	151,0	3,75	2340
4	55	153,0	3,75	2340
5	55	155,4	3,75	2340

To carry out the SDS study of the truck body, a CAD model of the body was created using the SolidWorks three-dimensional modelling system, taking into account the dimensions of the channels from the Table. 1. For the body model, a mesh of finite elements with a global size of 30 mm and a tolerance of 1.5 mm was built (Figure 2).

Figure 2: Mesh of finite elements on a truck body model



The conditions for securing the body and applying an external load are shown in Figure 3. A transverse force P = 200 kN is applied to the sheet covering of the body bottom. The material of the body bottom elements is St 3 steel according to GOST 380-88 (yield strength σ_T = 206.81 MPa, strength limit σ_B = 517.02 MPa) (Lyashuk, 2023; Nayak & Sambaiah, 2012; Kumar, Jithendra & Kumar, 2013).

Figure 3: Conditions of attachment and application of load in the CAD model of the truck body

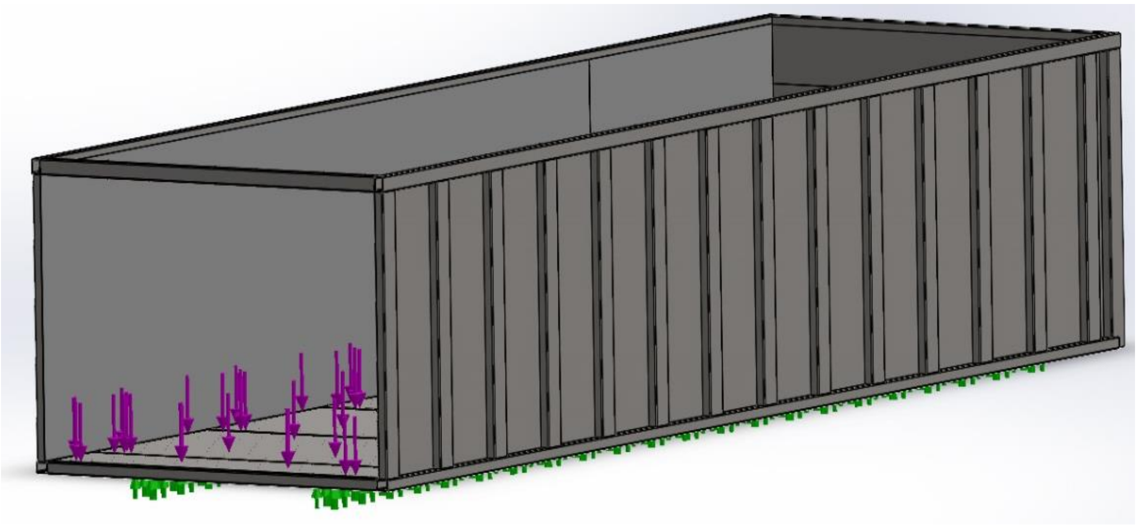
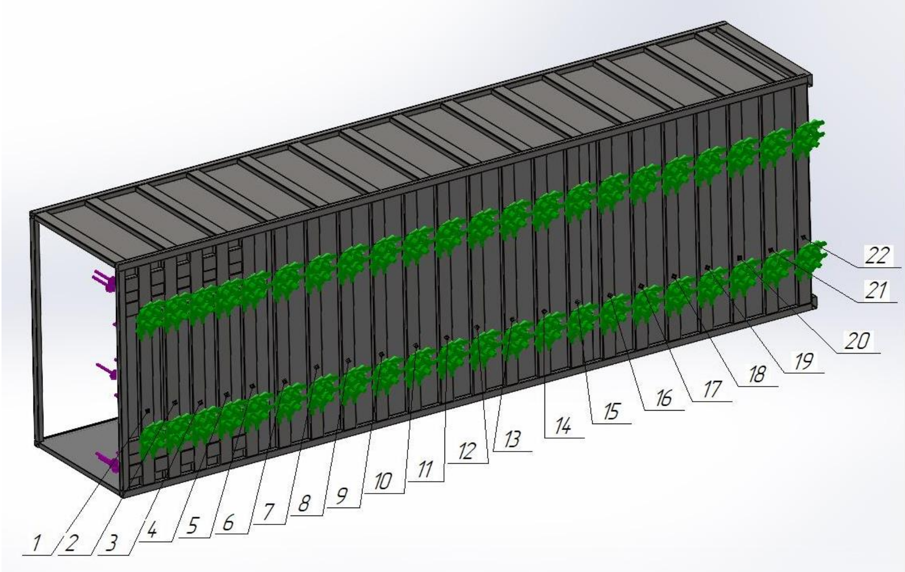


Figure 4 shows the placement of channels on the bottom of the truck body (with serial numbers from 1 to 22).

Figure 4: Schematic of placement of channels on the bottom of the truck body



The SDS analysis of the truck body bottom model was carried out using the Simulation engineering analysis module of the Solidworks software complex. The results of the SDS study with parameters 3<t_{shv} <5 (mm) and 3< $t_{l.dna}$ <5 (mm) are shown in Figure 5 – 20. The summarized results of the research are presented in the Table 2 and Table 3.

Table 2: Results of the study of static stresses acting on the elements of the bottom of the truck body, MPa

Position of the channel,	Channel wall thickness, t_{shv} =3 mm Bottom sheet thickness ($t_{l.dna}$), mm			Channel wall thickness, t_{shv} =4 mm Bottom sheet thickness ($t_{l.dna}$), mm			Channel wall thickness, t_{shv} =5 mm Bottom sheet thickness ($t_{l.dna}$), mm		
	3	4	5	3	4	5	3	4	5
1	53,83	52,30	49,98	35,70	34,29	32,85	26,57	25,38	24,47
2	29,33	27,92	27,34	21,65	20,40	19,62	16,88	15,67	14,87
3	26,38	25,34	24,62	18,60	17,72	17,16	14,97	13,55	13,05
4	25,45	24,57	23,89	18,14	17,31	16,80	14,50	13,21	12,77
5	27,32	27,10	26,53	19,41	18,47	18,00	14,54	14,23	13,72
6	26,58	26,03	25,59	18,94	18,28	17,91	14,35	13,82	13,50
7	26,73	26,32	25,96	19,16	18,54	18,08	14,50	14,11	13,70
8	26,90	26,74	26,47	19,50	18,67	18,20	14,83	14,27	13,89
9	27,95	27,21	26,89	20,01	19,00	18,63	15,14	14,51	14,08
10	27,77	27,28	26,99	19,96	19,19	18,73	15,10	14,63	14,25
11	28,34	27,74	27,39	20,18	19,40	18,84	15,50	14,85	14,40
12	28,82	28,00	27,53	21,56	20,25	19,68	15,96	15,63	15,01
13	29,06	28,53	28,08	20,78	19,54	19,40	15,79	15,18	14,73
14	29,57	29,07	28,50	21,18	20,19	19,55	16,00	15,42	14,95
15	30,37	29,92	29,27	22,16	20,87	20,25	16,36	16,26	15,43
16	31,10	30,22	29,48	21,65	20,76	20,20	16,48	15,79	15,30
17	31,51	30,56	29,98	22,17	21,16	20,42	17,03	16,20	15,66
18	32,54	31,59	30,84	22,64	21,55	20,81	17,08	16,60	15,94
19	33,91	32,46	31,68	23,27	22,12	21,43	17,76	17,00	16,38
20	34,34	32,88	32,04	23,72	22,58	21,76	18,09	17,44	16,75
21	34,57	33,35	32,49	23,83	22,80	22,05	18,27	17,19	16,58
22	30,57	29,58	28,61	19,87	19,41	18,76	14,86	14,48	14,14

Table 3: The results of the study of the maximum static movements of the bottom of the truck body

Channel wall thickness, mm	Bottom sheet thickness, mm	Value, mm
t=3	t=3	0,22
	t=4	0,18
	t=5	0,16
t=4	t=3	0,17
	t=4	0,15
	t=5	0,13
t=5	t=3	0,14
	t=4	0,12
	t=5	0,11

Figure 5: Static stress acting on channel #1 (t_{shv}=3 mm, $t_{l.dna}$ =3, σ_T=206,8 MPa)

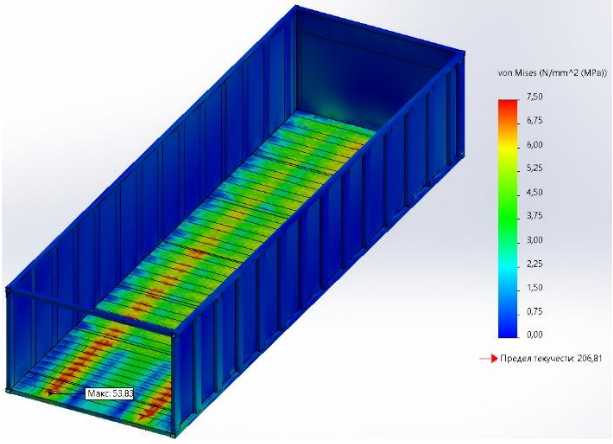


Figure 6: Maximum static displacement (t_{shv}=3 mm, $t_{l.dna}$ =3)

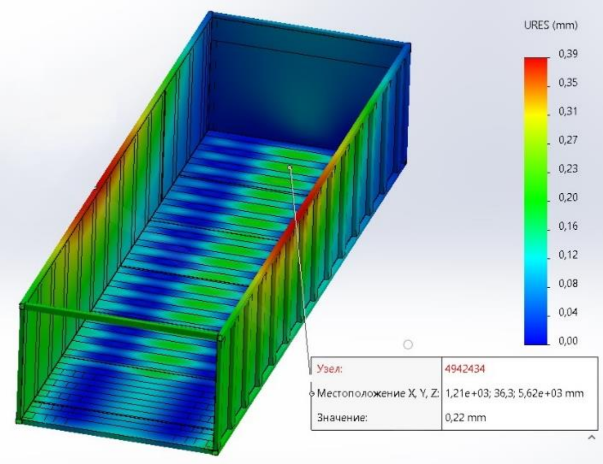


Figure 7: Static stress acting on channel #1 (t_{shv}=3 mm, $t_{l.dna}$ =4, σ_T=206,8 MPa)

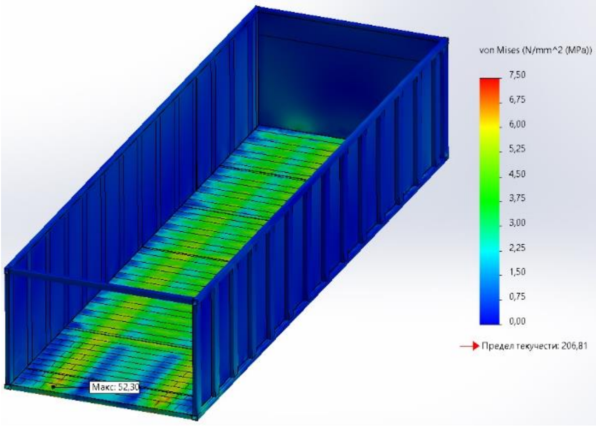


Figure 8: Maximum static displacement (t_{shv}=3 mm, $t_{l.dna}$ =4)

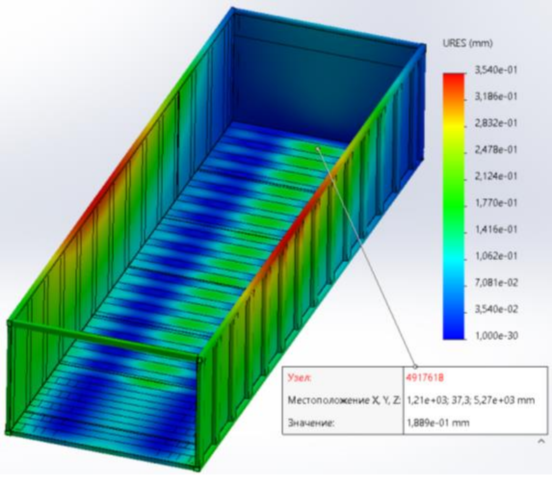


Figure 9: Static stress acting on channel #1 (t_{shv}=3 mm, $t_{l.dna}$ =5, σ_T=206,8 MPa)

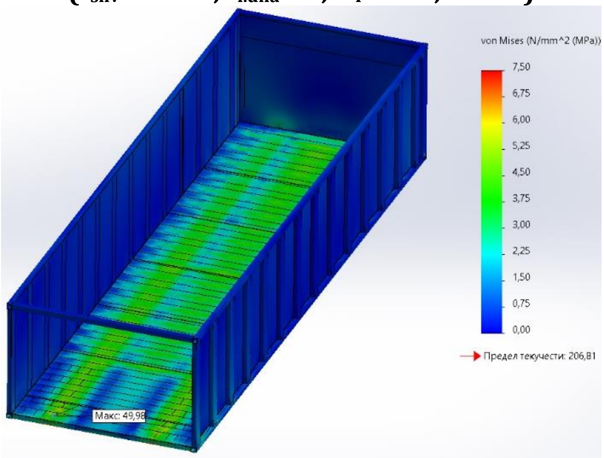


Figure 10: Maximum static displacement (t_{shv}=3 mm, $t_{l.dna}$ =5)

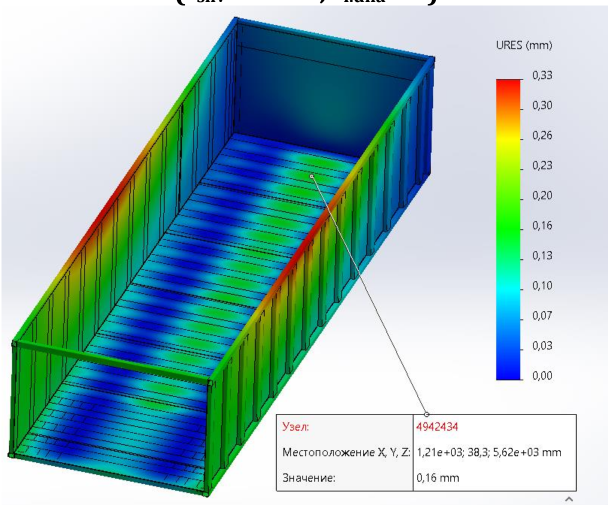


Figure 11: Static stress acting on channel #1 (t_{shv}=4 mm, $t_{l.dna}$=3, σ_T=206,8 MPa)

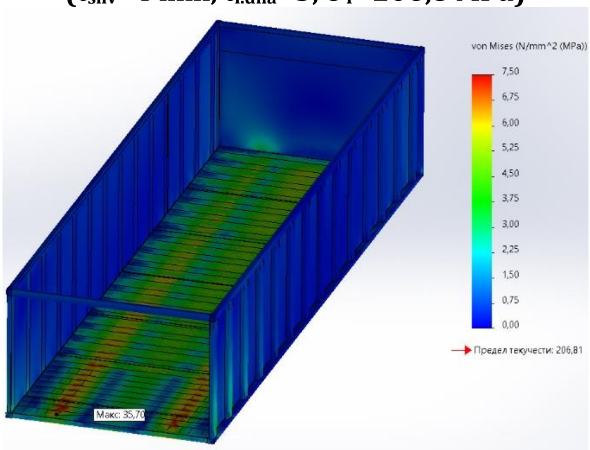


Figure 12: Maximum static displacement (t_{shv}=4 mm, $t_{l.dna}$=3)

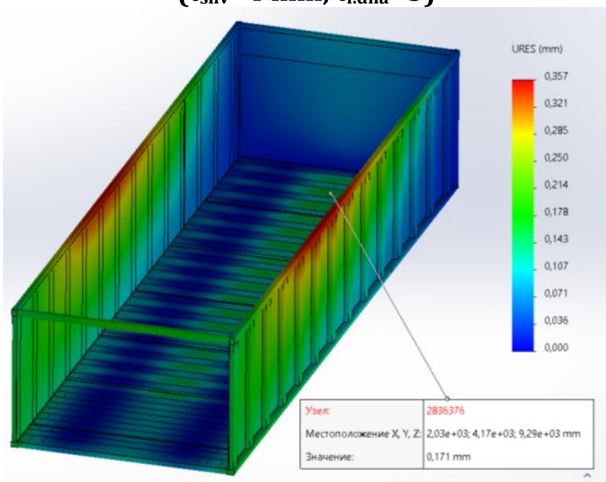


Figure 12: Static stress acting on channel #1 (t_{shv}=4 mm, $t_{l.dna}$=4, σ_T=206,8 MPa)

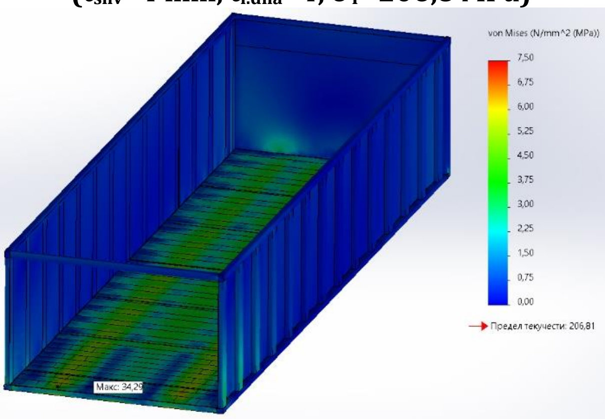


Figure 13: Maximum static displacement (t_{shv}=4 mm, $t_{l.dna}$=4)

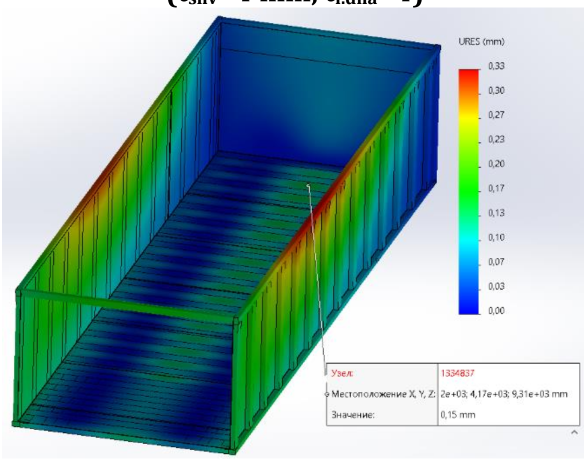


Figure 14: Static stress acting on channel #1 (t_{shv}=4 mm, $t_{l.dna}$=5, σ_T=206,8 MPa)

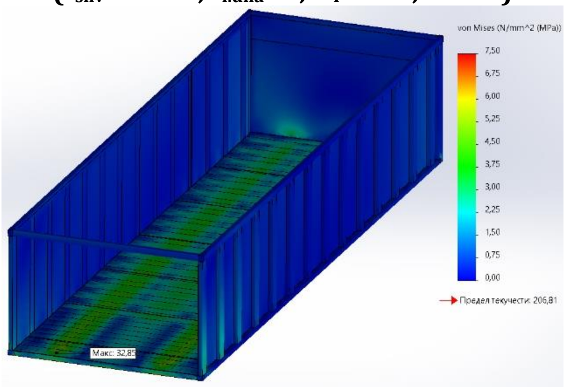


Figure 15: Maximum static displacement (t_{shv}=4 mm, $t_{l.dna}$=5)

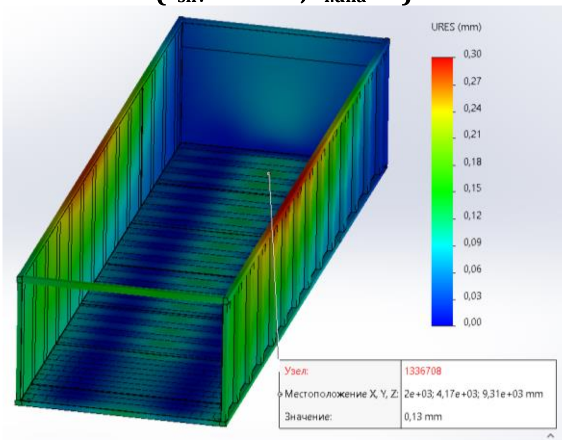


Figure 16: Static stress acting on channel #1 (t_{shv}=5 mm, $t_{l.dna}$=3, σ_T=206,8 MPa)

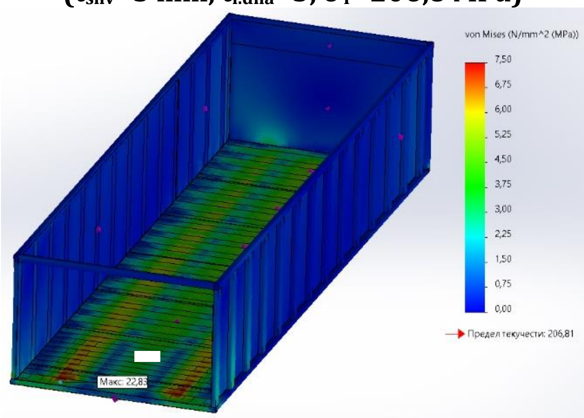


Figure 17: Maximum static displacement (t_{shv}=5 mm, $t_{l.dna}$=3)

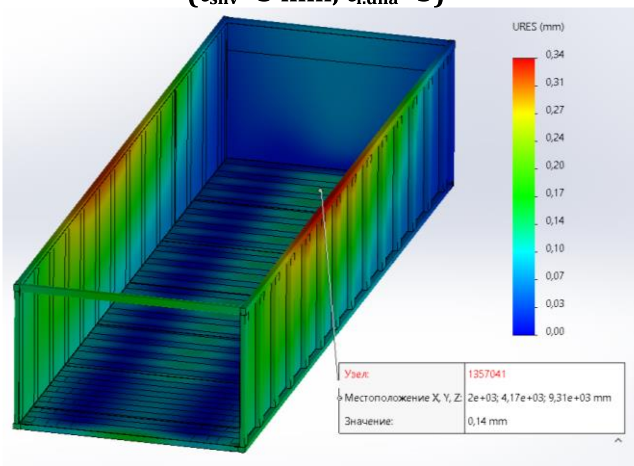


Figure 18: Static stress acting on channel #1 (t_{shv}=5 mm, $t_{l.dna}$=4, σ_T=206,8 MPa)

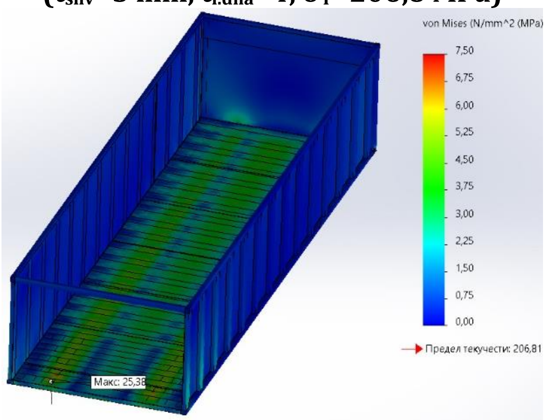


Figure 19: Maximum static displacement (t_{shv}=5 mm, $t_{l.dna}$=4)

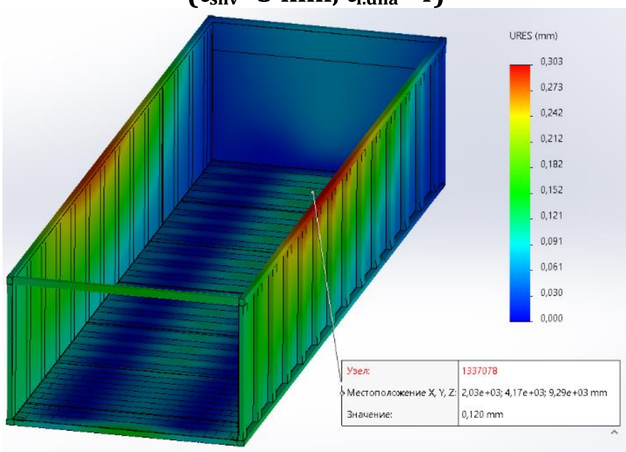


Figure 20: Static stress acting on channel #1 (t_{shv}=4 mm, $t_{l.dna}$=4, σ_T=206,8 MPa)

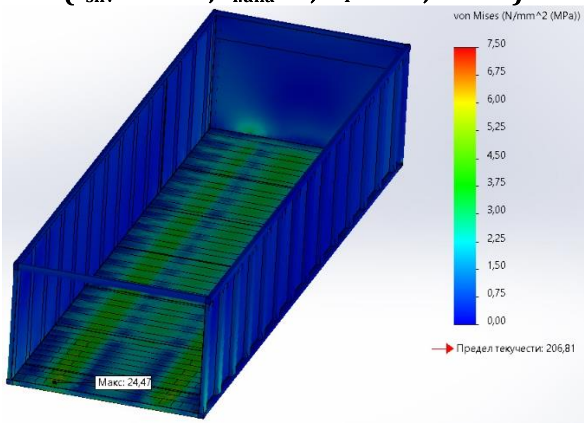
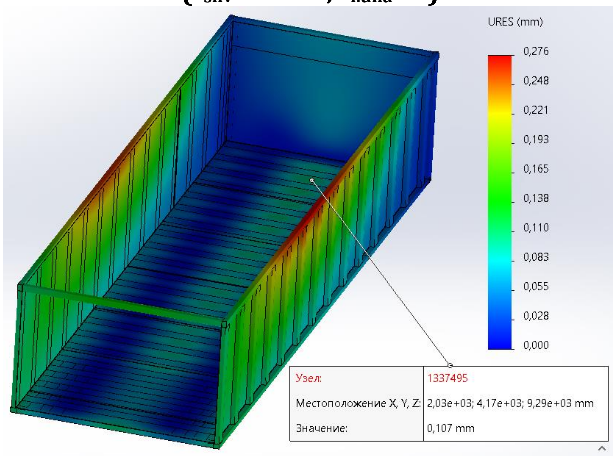


Figure 21: Maximum static displacement (t_{shv}=4 mm, $t_{l.dna}$=4)



Based on the results of the SDS study of the truck body bottom, graphical dependences of static stress and static displacement on the thickness of the channel wall (t_{shv}) and the thickness of the bottom sheet ($t_{l.dna}$) have been constructed (Figure 22 and 23). Equations of trend lines of changes in these parameters have been obtained.

Figure 22: Static stress in channels depending on the thickness of the wall of the channel and the thickness of the bottom sheet (t_{shv}=3-5 mm, $t_{l.dna}$=3-5, σ_T=206,8 MPa)

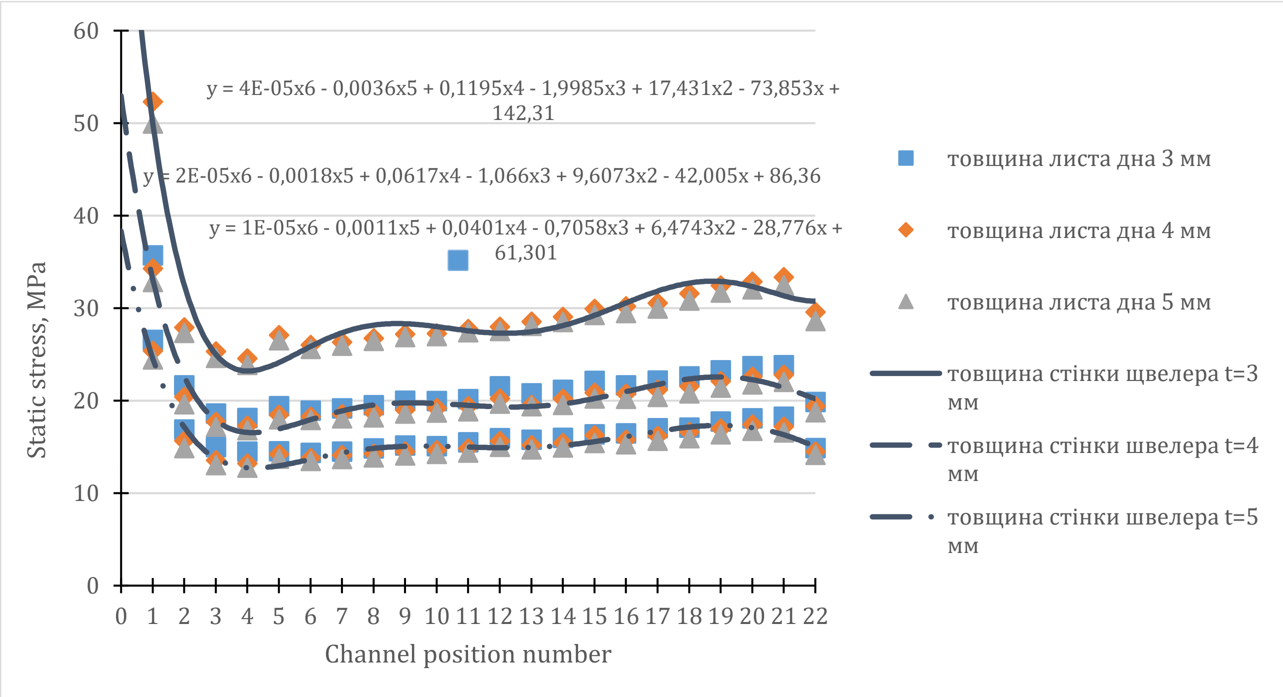
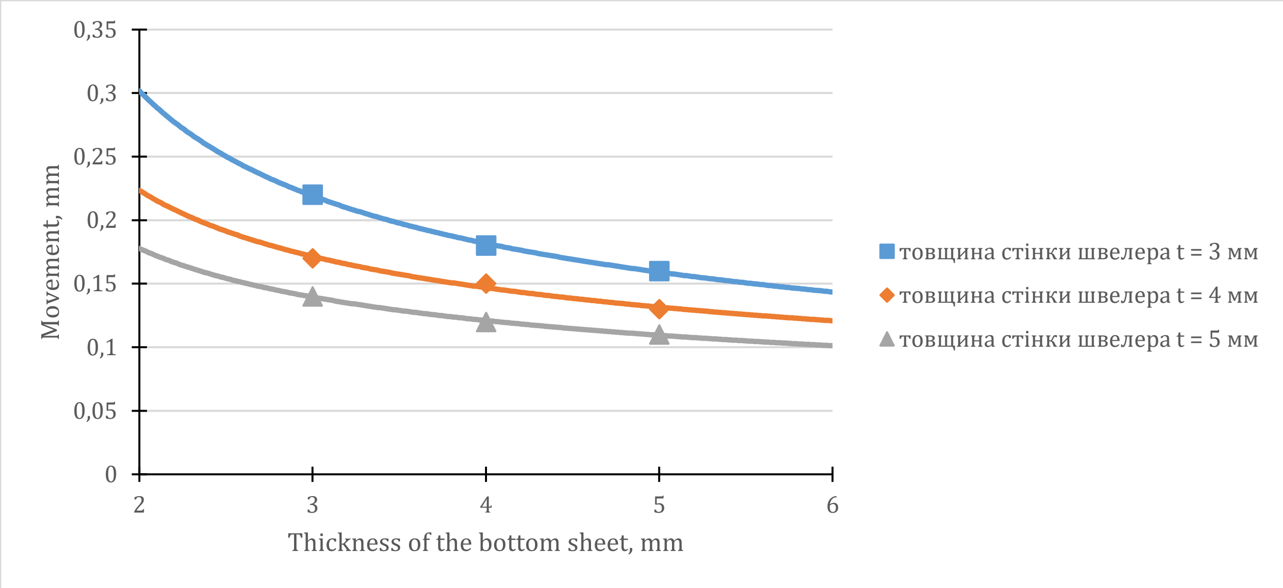


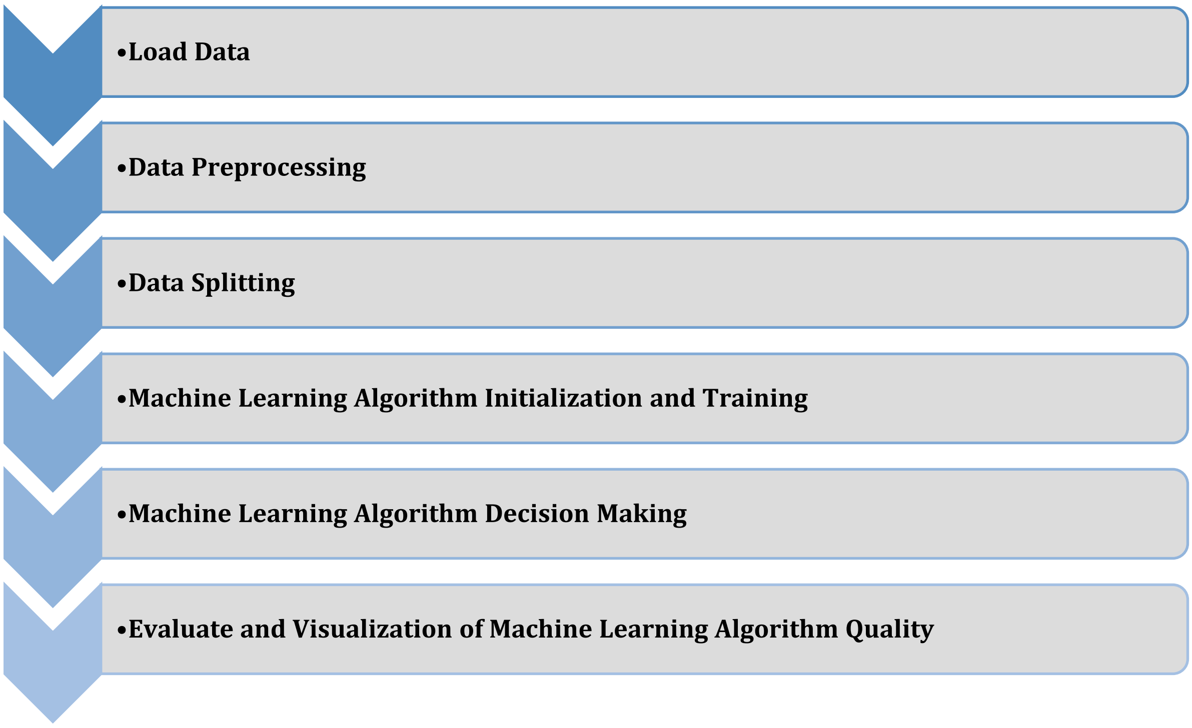
Figure 23: Maximum static displacements depending on the thickness of the channel wall and the thickness of the bottom sheet (t_{shv}=3-5 mm, $t_{l.dna}$=3-5, σ_T=206,8 MPa)



In order to generalize the results of the study of the VAT of the bottom of the truck body in the Python environment based on the RandomForest machine learning algorithm, the problem of predicting the change in static stress (factor Y1) depending on the factors has been solved: X1 (t_{shv}), X2 ($t_{l.dna}$), X3 (channel position number). At the same time, the static stress was used as the predicted (target) variable Y1, and the factors X1 (t_{shv}), X2 ($t_{l.dna}$), X3 (channel position number) have been used as input data to implement the RandomForest algorithm (Czech, 2013; Czech & Mikulski, 2014).

The algorithm and program for solving the forecasting problem are as follows.

Figure 24: Algorithm block diagram (machine learning pipeline)



Algorithm block diagram (machine learning pipeline):

1) Load Data: read data from the file;

2) Data Preprocessing: divide the variables into input data and output data;
3) Data Splitting: divide the data into training and test samples in the ratio of 80% and 20%;
4) Machine Learning Algorithm Initialization and Training: RandomForest algorithm initialization and training for regression problem based on training sample;
5) Machine Learning Algorithm Decision Making: prediction using pre-trained RandomForest algorithm on test sample;
6) Evaluate and Visualization of Machine Learning Algorithm Quality: evaluate and visualize RandomForest algorithm quality based on test sample (calculation of mean absolute percentage error for regression problem; visual perception of the quality based on the dependence of actual values on predicted values).

1. **Import the Python environment libraries.**

```
import pandas as pd
import numpy as np
from sklearn.ensemble import RandomForestRegressor
from sklearn.model_selection import train_test_split
import matplotlib.pyplot as plt
```

2. **Read the input data from the file.**

```
df = pd.read_excel(r"C:\Users\Oleg\Desktop\Ljashuk\input_data.xlsx", sheet_name=0)
del df[0]
```

3. **Divide the variables into input data (factors: X1 (t_{shv}), X2 ($t_{l.dna}$), X3 (channel position number)) and output (target variable Y1 (static stress))**

```
y = df['Y1'].values
del df['Y1']
x = df.copy().values
```

4. **Divide the data into training and test samples in the 80% and 20% ratio.**

```
x_train, x_test, y_train, Y1 = train_test_split(x, y, test_size=0.2)
```

5. **Train and test the RandomForest algorithm**

```
rf = RandomForestRegressor() #Initialization
rf.fit(x_train, y_train) #Training
Prediction = rf.predict(x_test) #Prediction
```

6. **Calculate the average value of the relative error of the static stress forecast on the test sample using the formula:**

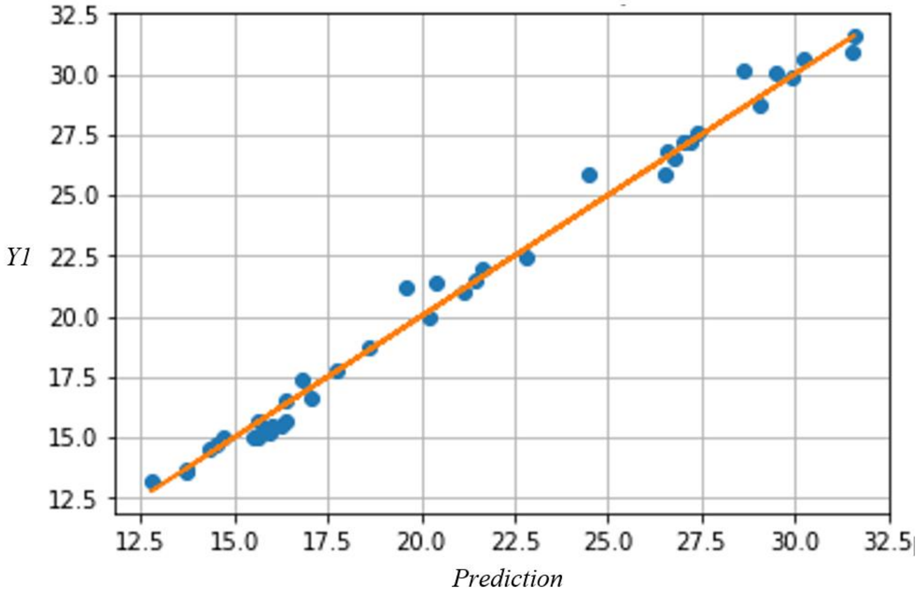
$$\delta_{mean} = \frac{1}{40}\sum_{i=1}^{40}\left|\frac{Y1_i - Prediction_i}{Y1_i}\right| \cdot 100\% \approx 2{,}9\%$$

```
mape = 100*np.mean(np.abs((Prediction-Y1)/Y1)) #Calculation of Mean Absolute Percentage Error
```

7. **For a visual perception of forecasting quality, the dependence of actual values on predicted values of static stress is visualized (Figure 24).**

```
fig, ax = plt.subplots()
ax.plot(Y1, Prediction, 'o')
ax.plot(Y1,Y1)
ax.set(xlabel='Y1', ylabel='Prediction')
ax.grid()
plt.show()
```

Figure 24: Visualization of the dependence of actual values on predicted values of static stress (abscissa axis – actual values of static stress (Y1), ordinate axis – predicted values of static stress (Prediction) based on RandomForest machine learning algorithm)



8. The results of testing the RandomForest algorithm are recorded in a variable (Table 4).
x_test, Y1, Prediction = pd.DataFrame(x_test), pd.DataFrame(Y1), pd.DataFrame(Prediction)
df_output = pd.concat([x_test, Y1, Prediction], axis=1)
df_output.columns = ["X1", "X2", "X3", "Y1", "Prediction"]

Table 4: Values of factors (X1, X2, X3), exact (Y1) and predicted (Prediction) values of static stress on the test sample

X1	X2	X3	Y1	Prediction	X1	X2	X3	Y1	Prediction
5	4	15	16,26	15,5197	3	5	22	28,61	30,1245
5	3	7	14,5	14,6911	5	5	5	13,72	13,6127
5	3	17	17,03	16,6154	5	5	13	14,73	15,0322
5	5	4	12,77	13,2191	3	5	11	27,39	27,5492
5	5	1	24,47	25,8468	3	5	5	26,53	25,8537
4	4	21	22,8	22,4564	4	4	17	21,16	21,023
3	4	8	26,74	26,4939	5	3	6	14,35	14,533
5	5	17	15,66	15,7161	5	3	14	16	15,4397
3	4	15	29,92	29,8939	5	3	12	15,96	15,1525
3	3	6	26,58	26,822	5	3	13	15,79	15,2552
3	5	16	29,48	30,0647	4	4	3	17,72	17,764
4	5	2	19,62	21,1905	3	3	17	31,51	30,9129
3	3	13	29,06	28,74	5	3	11	15,5	15,0497
4	5	9	18,63	18,7026	3	5	10	26,99	27,2024
4	3	16	21,65	21,9138	3	4	18	31,59	31,5321
4	5	4	16,8	17,3559	5	5	19	16,38	16,4946
3	4	16	30,22	30,6633	5	5	7	13,7	13,6889
5	3	15	16,36	15,6721	4	5	19	21,43	21,5273
4	4	2	20,4	21,3403	3	4	9	27,21	27,1884
4	4	14	20,19	19,9692	5	4	12	15,63	15,0252

The obtained results can have several economic effects both for manufacturers of car trailers and for their consumers.

First, the results can be used to improve the design of the semi-trailer by understanding the stress distribution and the dependence of the stress and strain levels on the thickness and width of the chassis elements. This can lead to more efficient and safer structures, potentially reducing costs associated with accidents and maintenance.

Second, the ability to quickly select the appropriate chassis element size using machine learning algorithms can increase the speed and accuracy of manufacturing processes, potentially reducing manufacturing costs.

Third, CAD modelling and machine learning algorithms can help reduce the amount of waste in the manufacturing process by more accurately predicting the materials needed for production.

Finally, the ability to more accurately predict load levels and select appropriate chassis components can improve the safety and durability of a semi-trailer truck, potentially reducing breakdown and maintenance costs over the vehicle's life.

Let us dwell in more detail on the economic effects for manufacturers. First, let us estimate the cost of producing a trailer in Ukraine measuring 2.5×8×1.8 meters (36 cubic meters), made of 3 mm metal. The costs will be:

Materials:

- Metal 3 mm - 120 sq.m (2,5 m*8 m2) - 24 sheets – $40-50 per sheet – $960-1200;
- Metal 2 mm (for floor) - 20 sq.m - 4 sheets - $30-40 per sheet – $120-160;
- Round pipe for the base - approximately 20-25 metres - $2-3 per meter – $40-75;

Equipment and tools

- Exes with enlarged diameter - $150-200 per item – $300-400;
- suspension on springs – $300-400;
- brakes – $150-200;
- tires – $100-150 per item – $400-600;
- set of headlights – $50-100

Labor and services:

- Metal cutting - $1-2 per linear meter – $120-240;
- bending and welding - $50-100 per working hour – $2000-4000;
- coloration – $500-800.

So, the total costs for producing a Ukrainian-made 3 mm metal cargo trailer can range from $4,250 to $7,135, depending on the selected materials and equipment, the amount and complexity of the work, and the amount of administrative and sales costs.

If machine learning algorithms are used in the production process of a cargo trailer to predict the value of static stress in trailer materials and components, it can reduce production costs by 10-15%. That is, to reduce the cost of production of a cargo trailer to $ 3800 - 6420.

It should be noted that in the early days, the use of machine learning algorithms will increase the costs of implementing such systems and the purchase of the necessary equipment and software for their operation. However, in the future, such a system will help identify possible problems with materials or components at the production stage, reducing the number of defects and reducing costs for repair or replacement of parts after sale.

In addition, predicting the value of static stress can help select the optimal materials and components that will provide the required strength and durability of the trailer, reducing maintenance and repair costs in the future.

Therefore, the use of machine learning algorithms to predict the value of static stress can positively affect the production costs of a cargo trailer by reducing the number of scraps and reducing the costs of repair and maintenance in the future.

The further prospects of this study

In order to obtain a complete picture of the stress-deformed state of the semi-trailer body, it is planned to conduct the following studies:

– the influence of the number of body side stiffeners, taking into account their geometrical parameters (shape and dimensions of the cross-section, material thickness);

– the effect of placement of body side stiffeners at different angles relative to the bottom of the body;

– the effect of changing the body side height on its load;

– the influence of the number of jumpers, taking into account their geometric parameters (shape and dimensions of the cross-section);

– the influence of the geometric parameters of the side cladding (flat and corrugated (of different shapes));

– the influence of the width, thickness and angle of inclination of the installation of the skirts between the bottom and the side of the body from the inside.

In addition to modelling the stress-deformed state of the body in the static formulation of the problem, it is also advisable to investigate its dynamic load when the angle of placement of the body relative to the horizon changes when unloading materials.

Conclusions

The stress-deformation state (SDS) analysis of the bottom channels of a truck semi-trailer body, utilizing a developed CAD model, has enabled a thorough investigation into stress distribution within the body bottom elements. This analysis established essential dependencies, shedding light on the relationship between stress levels, deformations in the body bottom channels, and their respective thickness and shelf width. Moreover, it facilitated the identification of the most critical bottom elements concerning the bearing capacity of the truck semi-trailer body.

Significantly, our findings indicate that the primary influencing factors on static stress are the thickness of the strip (t) and the width of the shelf (b), with the height of the channel (h) exerting a comparatively lesser impact. The specified parameter ranges for the factors were determined as follows: $3 < t < 5$ (mm); $50 < b < 60$ (mm); $140 < h < 160$ (mm).

These research outcomes serve as a foundational framework for informed engineering decisions aimed at enhancing the design of the truck semi-trailer body bottom. Additionally, they provide a practical tool for expedited channel selection, predicting static stress values based on the implementation of the RandomForest machine learning algorithm.

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Conflicts of Interest

The authors declare no conflict of interest.

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