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Tomasz MATYJA[1]

DETERMINING THE OPTIMAL NUMBER OF STRETCH FILM LAYERS FOR ENSURING PALLETIZED CARGO STABILITY: A SIMULATION STUDY

Summary. Numerical simulation tests were carried out to determine the influence of the characteristic features of a load unit (such as: weight, height, number of load layers, coefficient of friction between the layers) per number of wraps with stretch film necessary to ensure unit stability. Manufacturers of stretch film sometimes provide guidelines on how many layers of film should be used depending on the weight and height of the load. But they do not explain on the basis of which studies these values were determined. Performing simulations similar to those made in this work in laboratory conditions would be very expensive. The work attempts to determine such relationships by simulation methods. A developed by the author in his earlier works dynamic model of a layered cargo unit wrapped with stretch film was used. The study plan was to check 108 cases. On the basis of the collected data, an attempt was made to develop a mathematical formula that would allow to estimate the optimal number of foil wraps when certain parameters of the load unit are known. In the author's opinion such an estimate could reduce film consumption, which would have a positive impact on the environment.

Keywords: palletized cargo, stretch film, dynamic model, linear regression

[1] Faculty of Transport and Aviation Engineering, The Silesian University of Technology, Krasińskiego 8 Street, 40-019 Katowice, Poland. Email: tomasz.matyja@polsl.pl. ORCID: https://orcid.org/0000-0001-6364-619X

1. INTRODUCTION

Goods are commonly transported in the form of pallet loading units. A properly protected loading unit, secured against disintegration and excessive deformation, guarantees the safety of transport operations. During transport, the load is exposed to short-term pulses of inertia forces and vibrations, which may lead to the movements of packages forming a pallet unit relative to each other and relative to the pallet in the cargo space of the vehicle [3, 9, 15]. Under certain circumstances, this may lead to excessive deformation of the load unit, its disintegration or damage to the goods. The possible effect of such events is not only the loss of value of commercial goods, but also a danger in vehicle traffic.

A common and inexpensive method of securing a pallet load unit against excessive packaging movement is to wrap it with pre-stretched stretch film. The so-called stability (or stiffness) of the load unit [6] is primarily ensured by the containment force [2] obtained by appropriately pre-stretching the film. In addition, the stability is influenced by the friction forces and elastic forces appearing as a result of further stretching of the film in relation to the "sweet spot" [1, 11].

The more layers of film applied, the greater the load unit's stability. However, in the author's previous work it was shown, using methods of numerical simulation of the loading unit's dynamics [10], that there is a certain limit number of film wraps, beyond which no clear benefits are observed. Determining the optimal number of wraps is of utmost importance in reducing packaging costs and waste generated. Especially that the global consumption of stretch film can be calculated in millions of tons per year [7, 12, 16].

The literature includes attempts to use numerical methods to study the stability of the cargo [4]. The presented study conducted simulation tests to establish the relationship between the characteristic parameters of a load unit (weight, height, number of layers, friction coefficient) and the number of wraps with a stretch film necessary to ensure stability. During the tests, the model of a stratified loading unit developed by the author was used [10]. A Formula to estimate the optimal number of wraps, based on the cargo characteristics mentioned above, can reduce film consumption. In the case of road transport, the law [5] recommends carrying out experimental stability tests of the loading unit [8, 13]. Being able to pre-estimate the number of wraps could also limit the number of experimental tests performed.

2. SIMULATION MODEL OF A LOAD UNIT WRAPPED WITH STRETCH FILM

The simulation model of the dynamics of a layered load unit secured with a stretch film used in the research was described in detail in the author's work [10]. The model was implemented in the Matlab environment. The main features of the dynamic model are presented below in order to show both its possibilities and limitations.

It was assumed that the loading unit consists of a number of homogeneous layers, which are treated in the model as rigid bodies. The layers can only move in a direction parallel to the pallet surface. This greatly simplifies the equations of the model's motion (Fig. 1):

$$m_i \ddot{x}_i = -m_i a - F_i + F_{i+1} + R_i \quad , i = 1, \dots, N \ , F_{N+1} = 0 \tag{1}$$

where: m_i – the mass of the layer,

a – the acceleration of the global system (vehicle cargo space),

F_i – the friction force between layer *i* and *i-1*,

R_i – the resultant reaction (restoring) force of the stretch film acting on the layer (arising from the containment force and film tensions),
x_i – the displacement of the layer i relative to the global system.

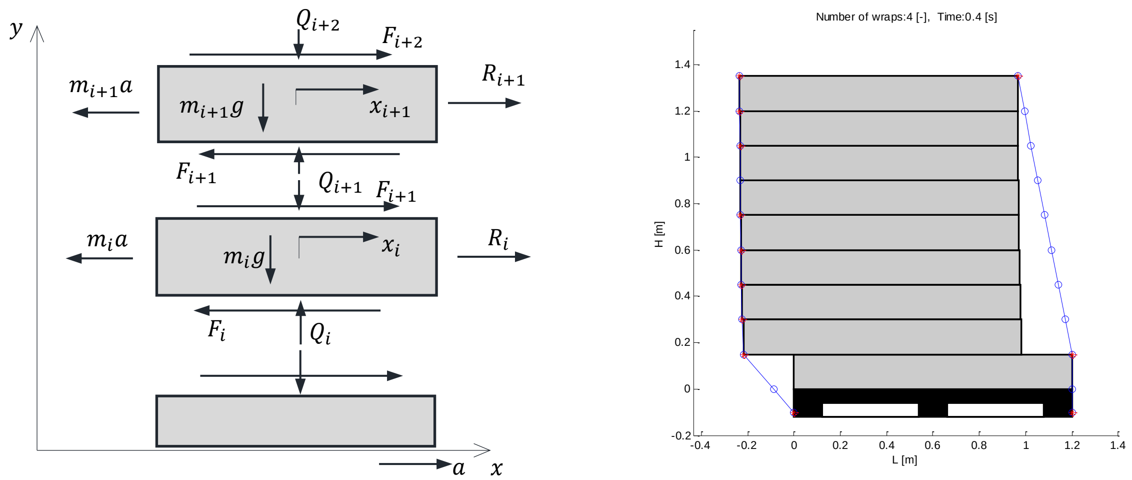

Fig. 1. Simulation model of a load unit [10]

In the case of very large displacements of layers, the stack may become unstable. Since the equations of motion do not take this effect into account, the algorithm automatically detects this condition and terminates the simulation. Loss of stack stability is equivalent to cargo instability in the sense of the norm EUMOS 50409.

In the dynamic model, a stick-slip friction model was implemented between the layers of the load and between the bottom layer and the pallet. In the case of slip, the Stribeck effect as well as kinetic and viscous friction were taken into account:

$$F_i^s(\Delta\dot{x}_i) = \sqrt{2e}\left(F_i^b - F_i^c\right)\exp\left[-\left(\frac{\Delta\dot{x}_i}{V_s}\right)^2\right]\frac{\Delta\dot{x}_i}{V_s} + F_i^c\tanh\left(\frac{\Delta\dot{x}_i}{V_c}\right) + f\Delta\dot{x}_i \tag{2}$$

where: $F_i^c = \mu_{ki} Q_i$ – kinetic friction force,
μ_{ki} – kinetic friction coefficient between layers "i" and "$i -$
1",
V_s – speed threshold of the Stribeck phenomenon,
V_c – Coulomb speed threshold,
f – viscous friction coefficient.

A special algorithm was developed to model the interaction of the stretch film with cargo layers depending on their displacement. The idea of the algorithm is to introduce checkpoints on the edges of the load unit. The algorithm works recursively and consists in successively span foil sections on the most protruding layers of the load. The edge of the foil is visible in the 2D model in the form of a polyline. This is a considerable simplification, since the side surface of the film actually curves. However, such a simplification is acceptable if the purpose of the simulation calculations is to assess the number of wraps with the stretch film necessary to ensure its stability, i.e., in the case of sufficiently small layer displacements [10].

By knowing the displacements of individual layers and their interaction with the foil, the value of the restoring forces can be determined. It is the result of the containment force (depending on the initial stretching of the film in the wrapping process) and the elastic forces resulting from the additional stretching of the film in the horizontal and vertical direction[2], as a result of the layers moving relative to the pallet surface. Part of the force from the horizontal tension of the film can be expressed by the formula (3):

$$R_i = 2n_0 H_i \left\{ \exp\left[\alpha\left(\frac{x_i - \min\limits_{i=1:N}(x_i)}{\Delta}\right)^2\right] - \exp\left[\alpha\left(\frac{\max\limits_{i=1:N}(x_i) - x_i}{\Delta}\right)^2\right]\right\} + \begin{cases} (n_p + n_{p+1} - n_0)H_p - (n_q + n_{q+1} - n_0)H_q, & \begin{cases} x_{Lp} = x_{Lp+1} = x_p = \min\limits_{j=1:N}(x_j) \\ x_{Rq} = x_{Rq+1} = x_q = \max\limits_{j=1:N}(x_j) \end{cases} \\ 0 & i \neq p \wedge i \neq q \end{cases} \quad (3)$$

where: H_i – layer height,
α – dimensionless containment force vanishing factor (e.g. $\alpha = ln\, 0.01$),
Δ – assumed distance of containment force disappearance (e.g. $\Delta = 0.02$ m),
n_0 – tension force obtained initially in the wrapping process (containment force/edge length),
$n_k = n_0 + k_H(x_{Rk} - x_{Lk} - L),\ k = p \vee q$ where $p, q \in \{1, \ldots, N\}$,
k_H – horizontal stiffness of the wrapped film [N/m],
$x_{Lk}(t), x_{Rk}(t)$ – coordinates of the foil control points on the left and right side,
L – pallet length.

Additionally, horizontal projections of forces caused by vertical tension of film will modify the values of the restoring forces. The vertical force[2] of film stretching per unit length on the left (same on the right) side of the loading unit can be calculated using pallet depth and the following formula:

$$t_{L(R)} = t_0 + k_V\left(\sum_{i=1}^{N} l_{L(R)i} - H\right) \quad (4)$$

where: t_0 – pre-tension of the film due to wrapping,
k_V – vertical film stiffness,
$l_{L(R)i}$ – distance between foil control points on the left (right) side,
H – load unit height.

Variable acceleration (e.g., during emergency braking) may act on the layers of the load unit. The simulation model allows, inter alia, to determine the maximum values of displacements in the elastic range and the maximum permanent displacements. This is information that can be used to assess the stability of a load unit (EUMOS 40509).

[2] In fact, this force is not exactly vertical. It results from the stretching of the foil in the direction that depends on the current arrangement of control points on the sides of the load unit (Fig. 1)

3. EXPERIMENT PLAN

Using the above-described dynamic model, simulation tests were carried out in order to determine the optimal (ensuring stability) number of stretch film wraps of different load units with respectively variable parameters. Four basic parameters of the load unit were modified: the coefficient of friction μ between the layers of the load and between the pallet and the lower layer (the same value was assumed), the total weight of the load M_t (without the weight of the pallet), the total height of the load H_t (without the height of the pallet), and the number of load layers N_l.

Three different values of the friction coefficient $\mu \in \{0.2; 0.25; 0.3\}$, three total weight values $M_t \in \{200; 600; 1000\}\,kg$, three different total heights $H_t \in \{0.8; 1.0; 1.2\}$, and four values for the number of layers of cargo $N_l \in \{6; 8; 10; 12\}$ were selected. The method of generating the individual cases is explained by the hierarchical tree in Figure 2. A total of 108 different cases were analysed.

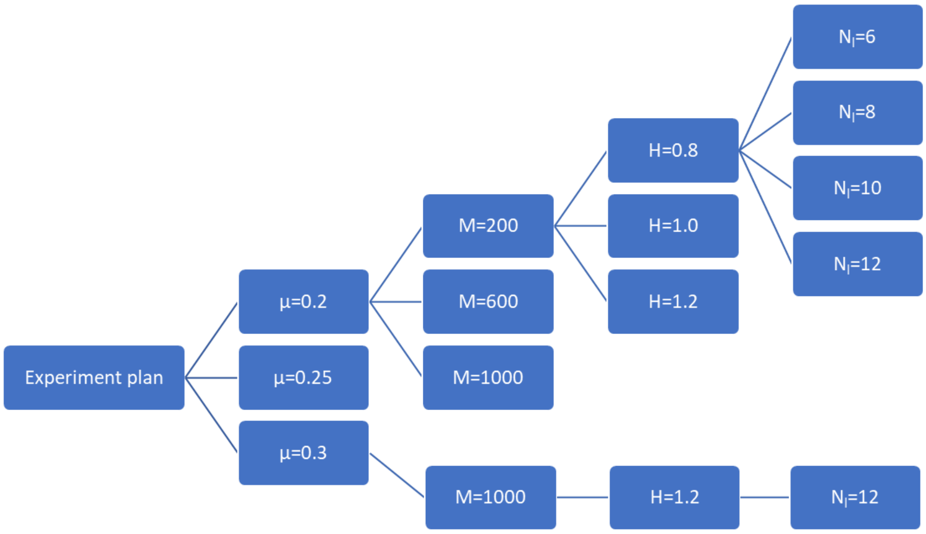

Fig. 2. Part of the hierarchical tree to generating experiment plan

The tensile properties of the stretch film remained the same in all tested cases. It was assumed that the containment (bonding) force of one foil layer per unit of height is $n_0 = 85$N/m. A 50% reduction in bonding force as a result of the relaxation phenomenon was taken into account. The value of this type of force can be easily determined experimentally by measuring the corner force [2, 14]. The stiffness, representing the elastic properties of the pre-stretched film, in the horizontal and vertical directions are equal 1.7N/m per one wrap. To ensure the stability of the load unit, the value of the containment force is crucial. For this reason, in the case of stretch films with different parameters, the obtained simulation results can be used to estimate the number of film wraps using the proportion rule:

$$N_l^* = N_l n_0^* / n_0 \tag{5}$$

The simulation tests were performed in accordance with the recommendations of the EUMOS50409 standard. Numerical tests simulating the braking of the loading unit were carried out. Such tests in real conditions are performed on specially adapted mobile platforms [8]. Recommended braking acceleration reached 0.8g and changed over time as shown in Fig. 3.

An algorithm was prepared in the Matlab environment that analysed individual cases selected for the experiment and automatically determined the minimum number of wraps necessary to obtain a stable load unit by an iterative method. A typical diagram of the displacements of the cargo layers during the simulated acceleration test is shown in Fig. 4. On its basis, it is possible to control extreme temporary elastic displacements and also the permanent displacements of the layers.

The algorithm checks four criteria that must be met simultaneously. The first three result directly from the EUMOS 40509 [6, 8] standard:

1. Elastic displacements must not exceed 10% of the load height.
2. In the case of a layered cargo, the relative displacements of the layers may not exceed 2% of the load height.
3. Permanent displacements must not exceed 5% of the load height. When the height of the load does not exceed 1200 mm, the limit is fixed at 60 mm. In addition, permanent displacements of the lower layers, located at a height of up to 200 mm, must not exceed 40 mm.

The fourth criterion checks whether the cargo layers remain at rest after the acceleration test. For this purpose, the algorithm compares the displacement values in 1.9 seconds and at the end of the test (Fig. 4). The differences should be close to zero.

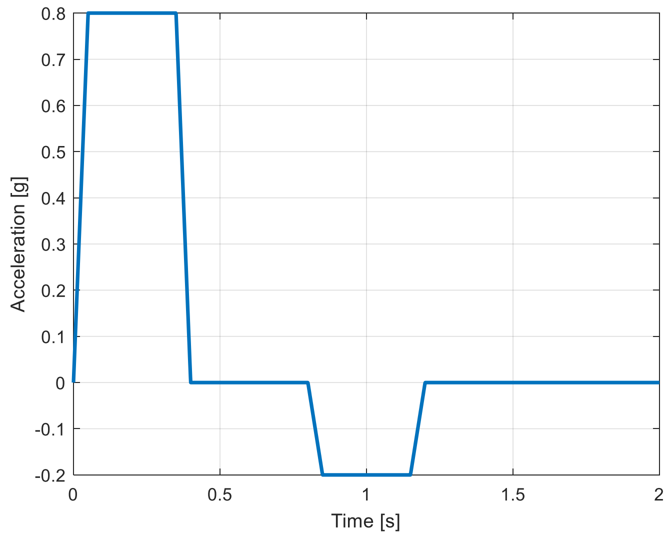

Fig. 3. Graph of the acceleration acting on the load over time

4. ANALYSIS OF THE RESULT DATA SET

As a result of the simulation, a set of data was obtained $\{(N_o, \mu, M_t, H_t, N_l)_i\ ; i = 1, \ldots, 108\}$, where N_0 is the number of wraps ensuring the stability of the load unit in accordance with the standard EUMOS 40509. Analysis of variance was performed on the dataset to establish the relationship between the independent (explanatory) variables μ, M_t, H_t, N_l and the dependent variable (response) N_o.

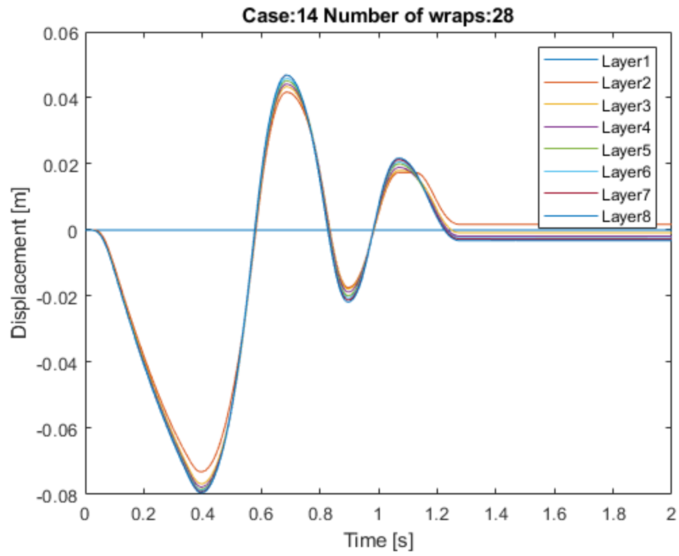

Fig. 4. A typical graph of the cargo layers displacements during the acceleration test

Based on the main effects plot for grouped data (Fig. 5) it can be seen that none of the lines in the chart is horizontal and that all four independent variables have an influence on the average number of wraps. The number of wraps increases with increasing weight and decreases with increasing height and, to a lesser extent, with increasing values of the friction coefficient. The influence of the number of cargo layers on the main effect is the smallest, with a global minimum for 8 layers. It appears that the number of cargo layers can be omitted from the regression analysis. The above observations are also confirmed by the analysis of "multivari chart" for data with four grouping variables (Fig. 6).

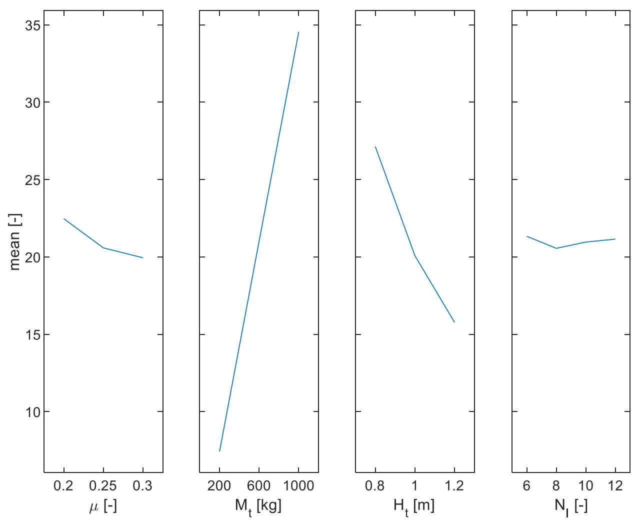

Fig. 5. Main effects plot of grouped data

The study of interactions between the variables (Fig. 7) leads to the conclusion that the most non-parallel lines in the plot occur in the case of combinations of variables M_t and H_t. Since the weight and height of the load have the greatest impact on the number of wraps, an attempt was made to divide the data set into 9 clusters using the k-means method. The overlap of the data presented in the subspace (N_o, M_t, H_t) with the clusters obtained by the k-means method would mean that the number of wraps depends only on the weight and height. However, based on the diagram (Fig. 8), it can be concluded that such a thesis is not true. In particular, this applies to low-height heavy loads, which have been classified into 4 different clusters.

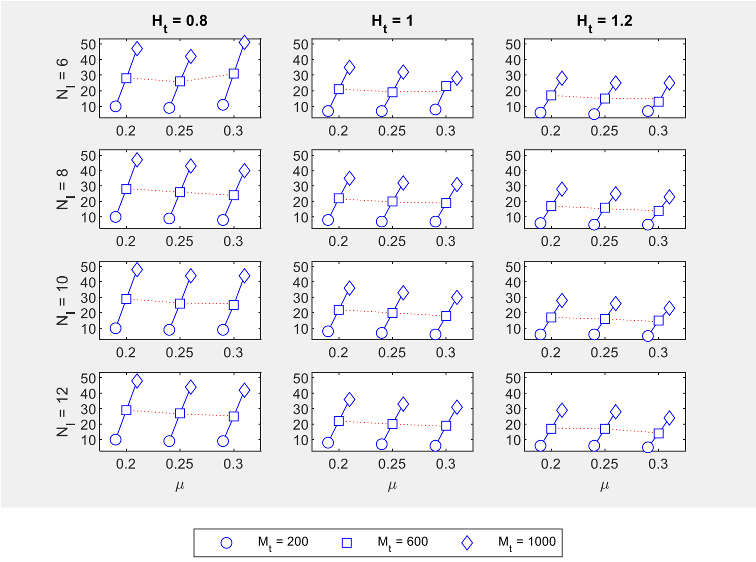

Fig. 6. Multivariant chart for data with four grouping variables

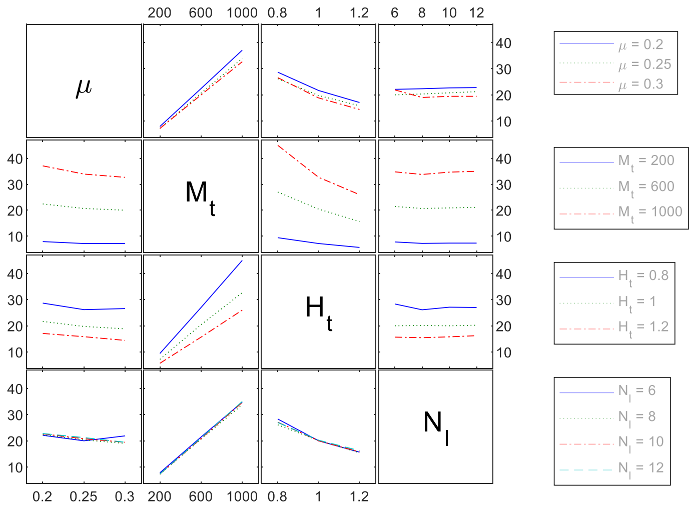

Fig. 7. Interaction plots for the four factors

5. MULTIVARIATE LINEAR REGRESSION MODEL

The first tested multivariate linear regression model included all linear and quadratic factors, as well as products obtained from two-element combinations from a set of four independent variables. A good fit of the model was obtained, as shown in the chart (Fig. 9). Relatively few measuring points go beyond Cook's standard distance (Fig. 10). The error between the number of wraps estimated from the model and the number of wraps determined by the simulation is acceptable (Fig.11 and Fig.12). The mean of the absolute error values is *0.73*, which is less than one foil wrap. However, the analysis of Table 1 shows that in the case of some regression factors, the null hypothesis cannot be rejected, i.e. that some determined regression model coefficients may be equal to zero (p-value greater than *0.05*). In all presented tables, the Wilkinson notation was used.

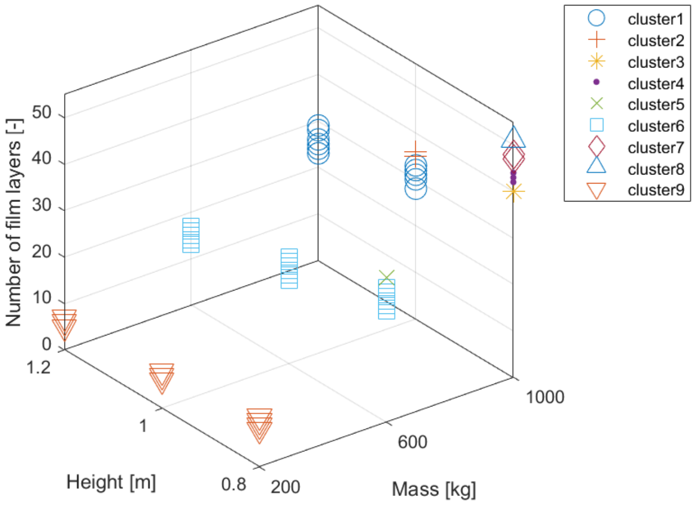

Fig. 8. Cluster data using k-means clustering algorithm

Tab. 1

First regression model

Linear regression model:
y ~ 1 + x1*x2 + x1*x3 + x1*x4 + x2*x3 + x2*x4 + x3*x4 + x1^2 + x2^2 + x3^2 + x4^2
Estimated Coefficients:

	Estimate	SE	tStat	pValue
(Intercept)	45.682	12.212	3.7406	0.000317
x1	-66.694	60.598	-1.1006	0.27391
x2	0.091788	0.00437	21.002	4.54E-37
x3	-70.538	15.15	-4.6561	1.07E-05
x4	-0.66713	0.78578	-0.849	0.39806
x1:x2	-0.04583	0.009805	-4.6744	9.94E-06
x1:x3	-14.583	19.61	-0.74365	0.45896
x1:x4	-4.6111	1.4321	-3.2197	0.001768
x2:x3	-0.04766	0.002451	-19.441	1.60E-34
x2:x4	0.000174	0.000179	0.9698	0.33466
x3:x4	0.625	0.35804	1.7456	0.084178
x1^2	250	110.93	2.2536	0.026571
x2^2	-2.60E-07	1.73E-06	-0.15024	0.8809
x3^2	34.375	6.9333	4.9579	3.19E-06
x4^2	0.060185	0.032684	1.8414	0.068748

Number of observations: 108. Error degrees of freedom: 93
Root Mean Squared Error: 1.36
R-squared: 0.99. Adjusted R-Squared: 0.988
F-statistic vs. constant model: 639. p-value = 7.47e-86

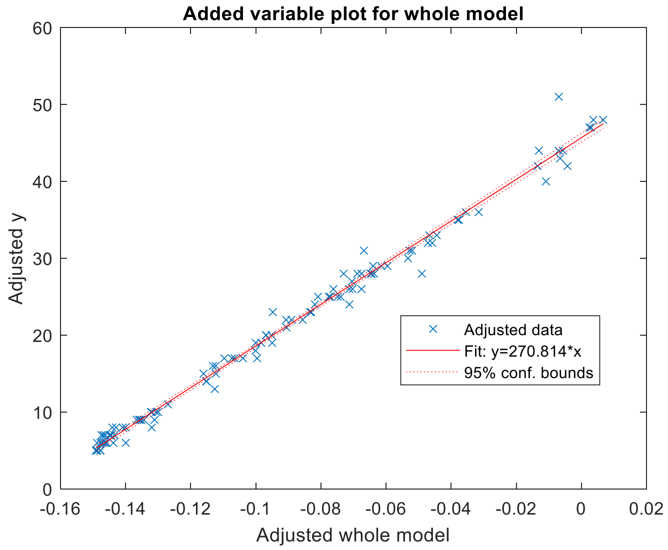

Fig. 9. Whole model fitting

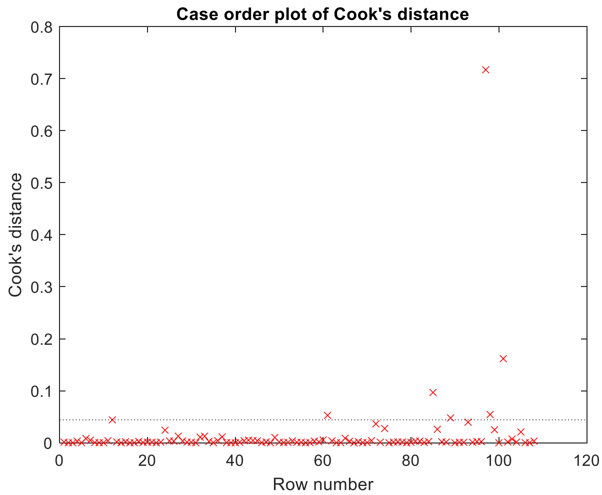

Fig. 10. Cook's distance plot

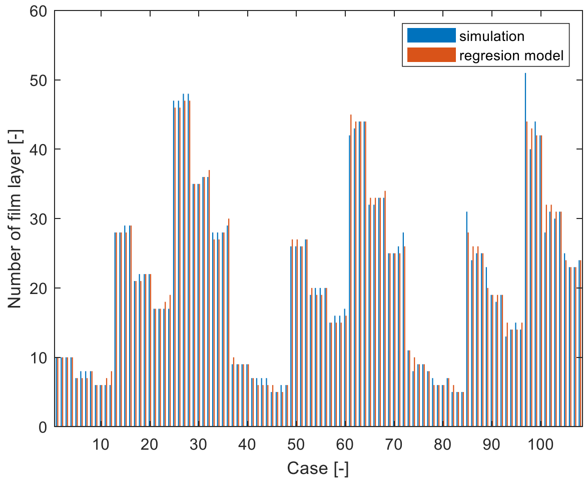

Fig. 11. Comparing the estimate from the first regression model with the simulation results

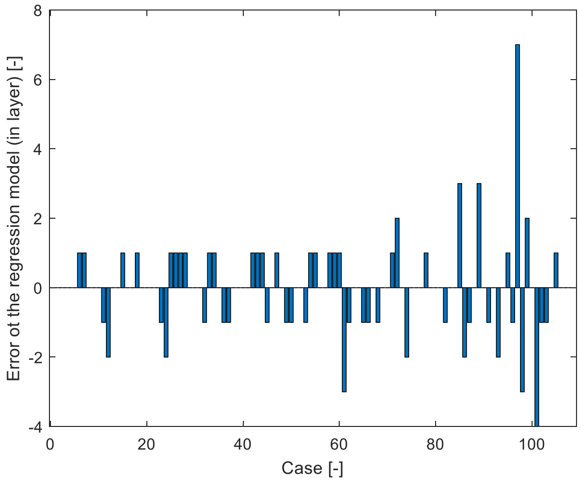

Fig. 12. Errors of the full (first) regression model

In the second linear regression model (Table 2), all polynomial factors that did not meet the null hypothesis criterion were rejected. Model errors are comparable to the full model (Fig. 13). The mean of the absolute error values is *0.87*. In the second model, again, some of the polynomial coefficients do not meet the null hypothesis criterion. After their rejection, the third model was obtained, maximally simplified, in which all p-values are less than *0.05* (Tab. 3). The mean model error *0.85* (Fig. 14). All regression models are compared in Fig. 15.

Tab. 2

Second regression model

Linear regression model: y ~ 1 + x1:x2 + x2*x3 + x1:x4 + x1^2 + x3^2 Estimated Coefficients:				
	Estimate	SE	tStat	pValue
(Intercept)	33.587	7.544	4.4522	2.21E-05
x2	0.093598	0.003742	25.01	7.95E-45
x3	-68.559	15.02	-4.5645	1.43E-05
x1:x2	-0.04808	0.010486	-4.5848	1.32E-05
x2:x3	-0.04766	0.002636	-18.079	2.78E-33
x1:x4	-0.16726	0.24803	-0.67433	0.50166
x1^2	10.941	14.964	0.73119	0.46638
x3^2	34.375	7.4559	4.6105	1.19E-05
Number of observations: 108. Error degrees of freedom: 100 Root Mean Squared Error: 1.46 R-squared: 0.987. Adjusted R-Squared: 0.986 F-statistic vs. constant model: 1.1e+03. p-value = 1.22e-91				

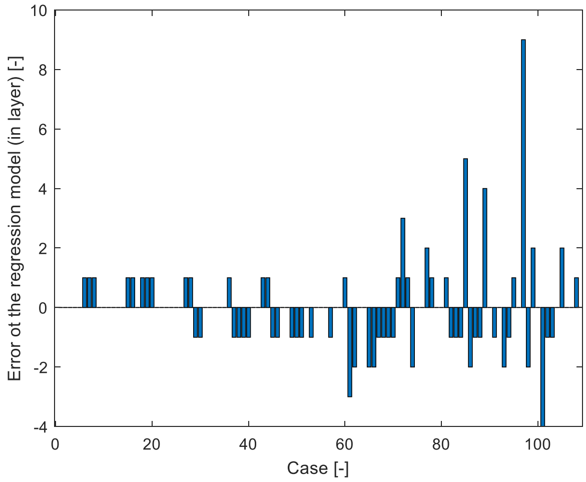

Fig. 13. Errors of the second regression model

Tab. 3

Third regression model

Linear regression model: y ~ 1 + x1:x2 + x2*x3 + x3^2 Estimated Coefficients:				
	Estimate	SE	tStat	pValue
(Intercept)	33.913	7.4375	4.5598	1.43E-05
x2	0.092324	0.002935	31.452	2.65E-54
x3	-68.559	14.929	-4.5924	1.25E-05
x1:x2	-0.04298	0.005011	-8.5773	1.13E-13
x2:x3	-0.04766	0.00262	-18.189	8.70E-34
x3^2	34.375	7.4106	4.6386	1.04E-05
Number of observations: 108, Error degrees of freedom: 102 Root Mean Squared Error: 1.45 R-squared: 0.987, Adjusted R-Squared: 0.986 F-statistic vs. constant model: 1.56e+03, p-value = 1.15e-94				

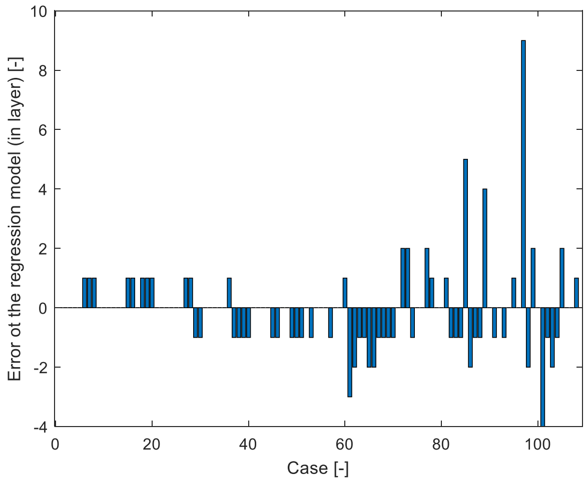

Fig. 14. Errors of the third regression model

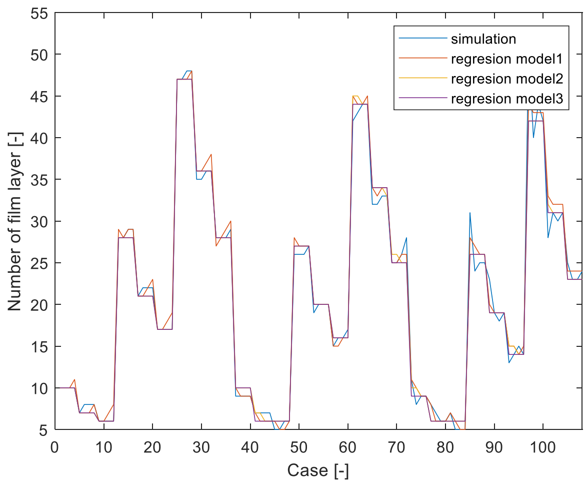

Fig. 15. Comparison of simulation results and three regression mod

6. TESTS OF THE LINEAR REGRESSION MODEL

The resulting linear regression model number 3 was tested on randomly generated data. It was assumed that the coefficient of friction is a random real number from the interval $< 0.2; 0.3 >$, similarly the total weight from $< 200; 1000 > kg$; total height $< 0.8; 1.2 > m$; and the number of cargo layers is a random integer from $< 6; 12 >$.

A hundred cases were analysed. The results were presented in the error plot, which was the difference between the forecast of the necessary number of wraps from the regression model number 3 and the number of wraps obtained by the simulation (Fig. 16). The maximum estimation error is 4 wrappings.

The regression model was developed for the data from simulations carried out with the assumption of certain values of the coefficients defining the strength properties of the stretch film. The model's suitability was checked by performing another 100 tests of loading units with randomly selected parameters. However, it was assumed that the restraining force of one foil layer per unit length (n_0) and stiffnesses (n_H, n_V) constitute 75% of the previously adopted values. The proportionality rule (5) was used to estimate the number of wrappings. As can be seen in Fig. 17, the estimation errors are of a similar range as before. This proves a fairly universal scope of applications of the developed model.

7. CONCLUSIONS

Based on the results of the simulation tests, a multiple regression model was developed, which with a fairly good accuracy allows estimating the number of wraps of a pallet with a load of a certain weight, height, number of layers, and friction coefficient between the layers. It was also confirmed that when changing the strength parameters of the stretch film, the proposed method of calculating the number of wraps also provides a sufficiently good estimate.

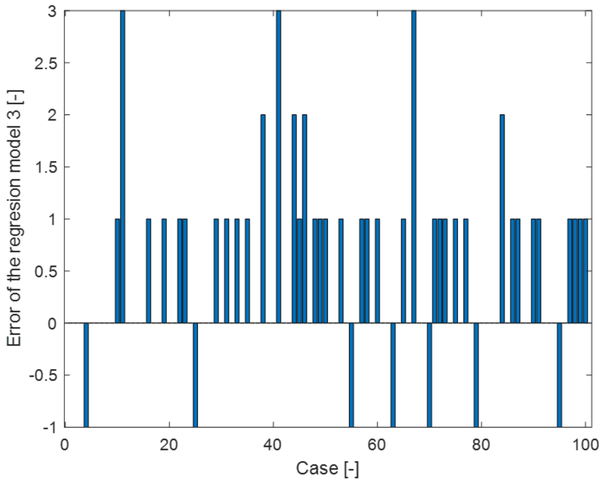

Fig. 16. Error of the regression model 3 for random data

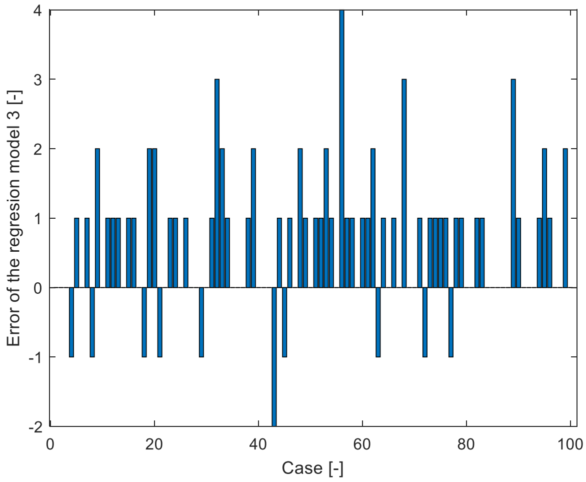

Fig. 17. Error of the regression model 3 for random data after stretch film properties modification

In practice, in accordance with the EUMOS 50409 standard, obtaining a certificate of stability and safety of a load unit requires conducting experimental tests on a real object. The ability to pre-estimate the number of film layers necessary to ensure the stability of the pallet unit will reduce the number of such tests. Additionally, it can contribute to a more rational management of the stretch film consumption and reduce the amount of waste.

It is noted that the biggest influence on the required number of the film wraps has a total weight and the total height of cargo. As expected, the number of necessary film layers increases with increasing weight and decreases with increasing cargo height. In the first case, the inertia force during emergency braking increases. In the second case, the effective force holding back the cargo rises.

The friction coefficient in the accepted range of its variability has a much smaller impact on the number of wraps. Increasing the value of the friction coefficient reduces the number of film layers needed, which was also expected.

The most ambiguous effect is the number of cargo layers, at least within the range of its variability assumed in the study. It is clear that the more layers of cargo, the less layer's mass.

At the same time, the smaller is the inertia force acting on the layer. However, as the number of layers of load increases, the effective containment force per layer also decreases.

The regression model was developed for the most common case when all layers of the load unit are homogeneous. There are no obstacles to use the proposed procedure for other special cases of creating a non-uniform stratified unit load.

On the basis of the third regression model, which omits the number of layers of a load unit, a graph was prepared that allows estimating the number of foil wraps based on the total weight of the load and its height (Fig. 18). When using foil with other parameters, the number of wraps can be easily converted according to the formula (3).

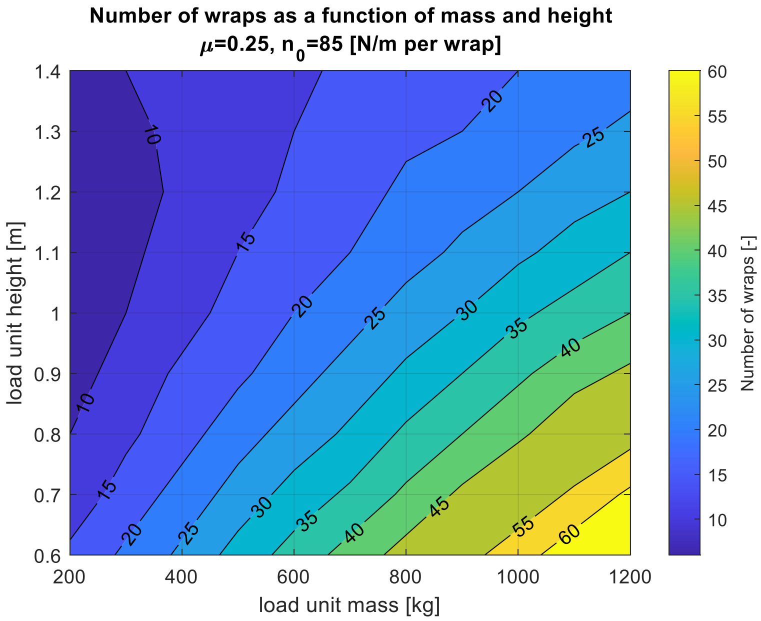

Fig. 18. Dependence of the wraps number on the weight and height of the cargo unit

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