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**Tomasz MATYJA**[1]

# SAFETY OF TRANSPORT OPERATIONS PERFORMED USING PALLET LOAD UNITS

**Summary.** During transport operations, even under normal operating conditions, the loading unit is subject to inertial forces, which may cause deformation of the unit, and in extreme cases, its disintegration. Stretch film wrapping is the most commonly used method of securing a load unit. This paper presents a new simplified simulation model of a class A load unit, with a layered structure, secured with stretch film. Between the layers of packaging, stick-slip friction was applied. A method of estimating the containment force was also proposed. This model can be used to pre-determine the number of film layers necessary to ensure load stability. Simulations can reduce the amount of film used and the number of stability tests performed experimentally.

**Keywords:** transport operations, load unit stability, stretch film

## 1. INTRODUCTION

Transport and storage of widely understood goods are commonly carried out using pallet load units. The pallet is the usually used platform for forming a load unit as a collection of smaller packages, while wrapping with stretch film is the most frequently used method of securing the load unit against disintegration [7].

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During transport operations, the loading unit is subject to inertial forces, which may cause displacement of individual packages, deformation of the unit treated as a solid and in extreme cases its disintegration. Even under normal operating conditions, on the load unit may act acceleration with values often close to 1 g. This problem occurs in all modes of transport: road, rail, sea, air and internal transport in warehouses [3, 8, 9, 14-16].

Stability of the load unit (also called rigidity) is understood in literature as maintaining the integrity of packaging included in the unit and maintaining an unchanged shape [12]. A stable load unit, properly secured against shifting in the vehicle's cargo space, guarantees the safety of transport operations. This problem has been noticed in the EU [10]. Load unit stability is checked by experimental methods. Simple static tests on an inclined plane (tilt tests) or dynamic tests (impact tests) on specially adapted mobile platforms were carried out. Suitable pre-stretching of the stretch film causes the appearance of force bonding the whole load; this is called the containment force in the literature [6]. Of course, the more layers the greater the force will be. However, the use of excessive numbers of layers unnecessarily increases costs and negatively affects the environment. In the literature, there are attempts to model the dynamics of load unit containing a smaller packaging, onto the containment force acts.

This paper presents the author's simulation model of a loading unit secured with stretch film. This model can be used to estimate the number of film layers necessary to ensure load stability. Simulations can reduce the amount of film used and the number of experimental stability tests. Such activities contribute to increased transport safety and environmental protection. The model described below was developed in a Matlab environment.

## 2. DYNAMIC MODEL OF A PALLET LOADING UNIT WITH A LAYERED STRUCTURE

The problem of investigating the dynamics of packages that are parts of a pallet loading unit is the complex issue of multi-body contact (MBS) with friction. In addition, the solution of this problem is complicated by the interaction forces between practically mass less stretch film and packages. One way to consider the stretch film in the load unit model is to replace it with a cloud of equidistant points connected by springs of known stiffness [4]. At each step of the simulation, both the positions of the packages relative to each other and the packages relative to the point cloud should be controlled. This type of simulation requires considerable computing power and is time-consuming.

This paper proposes a simplified version of the class A pallet load unit model discussed in the work [11]. It is assumed that the pallet load unit has a clearly layered structure. The class A loading unit consists of identical rectangular packages, whose dimensions and arrangement guarantee perfect filling of the pallet surface.

In the presented model, the method of determining the restoring force caused by the stretch film was simplified. Part of the force resulting from the additional stretching of the film due to the relative displacement of the layers is ignored. Only the pre-stretching of the film in the wrapping process is considered. Due to this, there is no need to determining the position of the stretch film on the moved layers of the load. This shortened the simulation time.

The assumption of a layered structure simplifies the model and means that the layers can only move horizontally relative to each other. Figure 1 shows two successive layers and indicates the forces that affect them. On this basis, the equations of motion of the individual layers can be written:

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

where: $m_i$ – mass of the layer,

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

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

$R_i$ – the resultant reaction force of the stretch film acting on the layer (appears from the containment force),

$x_i$ – displacement of the layer $i$ relative to the global system.

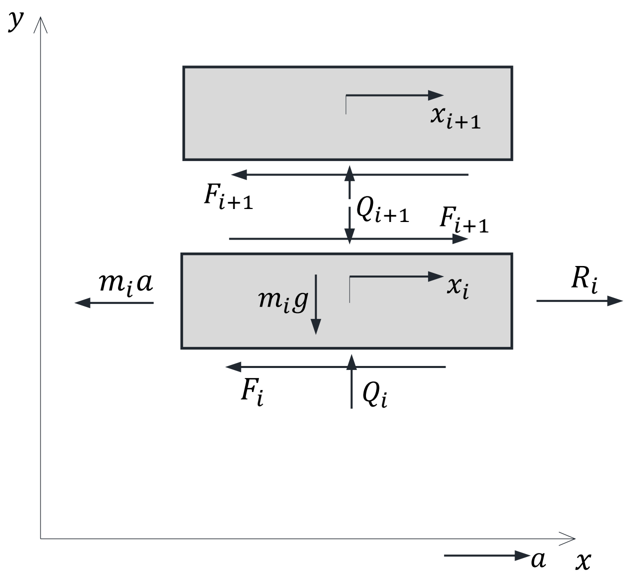


Fig. 1. Free body diagram of the moving layers

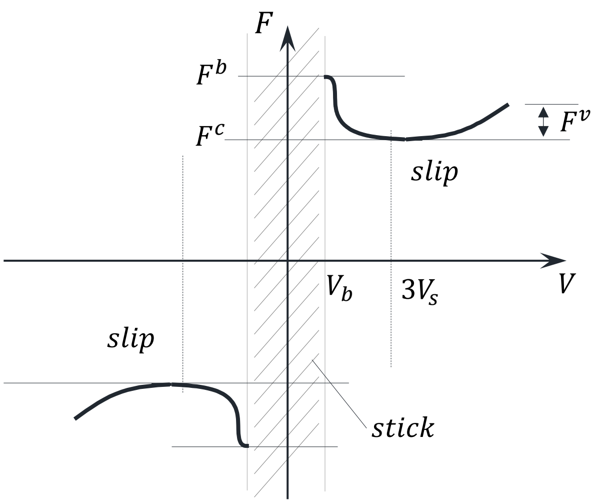


Fig. 2. The illustrative graph of the sliding friction force in the slip-stick model ($V_b$ – speed threshold of the transition from stick to slip, $V_s$ Stribeck speed, $F^c$ – kinematic friction, $F^b$ – maximum static friction, $F^v$ – viscous friction)

Slip-stick friction was considered in the model. When the relative velocity of the layers is lower than the assumed very low speed of the contact break ($|V| < V_b$), then stick occurs and the force of static friction should be determined from the condition of balance of the upper layer relative to the lower one. However, in the case of a slip, the friction force was determined from the formula:

$$F(\mathrm{V}) = \sqrt{2e}(F^b - F^c)\exp\left[-\left(\frac{\mathrm{V}}{V_s}\right)^2\right]\frac{\mathrm{V}}{V_s} + F^c\tanh\left(\frac{\mathrm{V}}{V_c}\right) + b\mathrm{V} \tag{2}$$

where: $F^c$ – kinetic friction force,
$F^b$ – static friction force,
$V_s$ – speed threshold of the Stribeck phenomenon,
$V_c$ – Coulomb speed threshold,
$V_b$ – break speed,
$b$ – viscous friction coefficient,
$V$ – relative speed between two selected layers.

The general ideas of the adopted friction model are illustrated in Figure 2. The hyperbolic tangent in formula (2) guarantees the continuity of the friction force when the relative velocity V passes through zero and replaces the discontinuous sign function. In the discussed model, it was assumed that [10]:

$$V_s = \sqrt{2}V_b \qquad V_c = 0.1 \cdot V_b \tag{3}$$

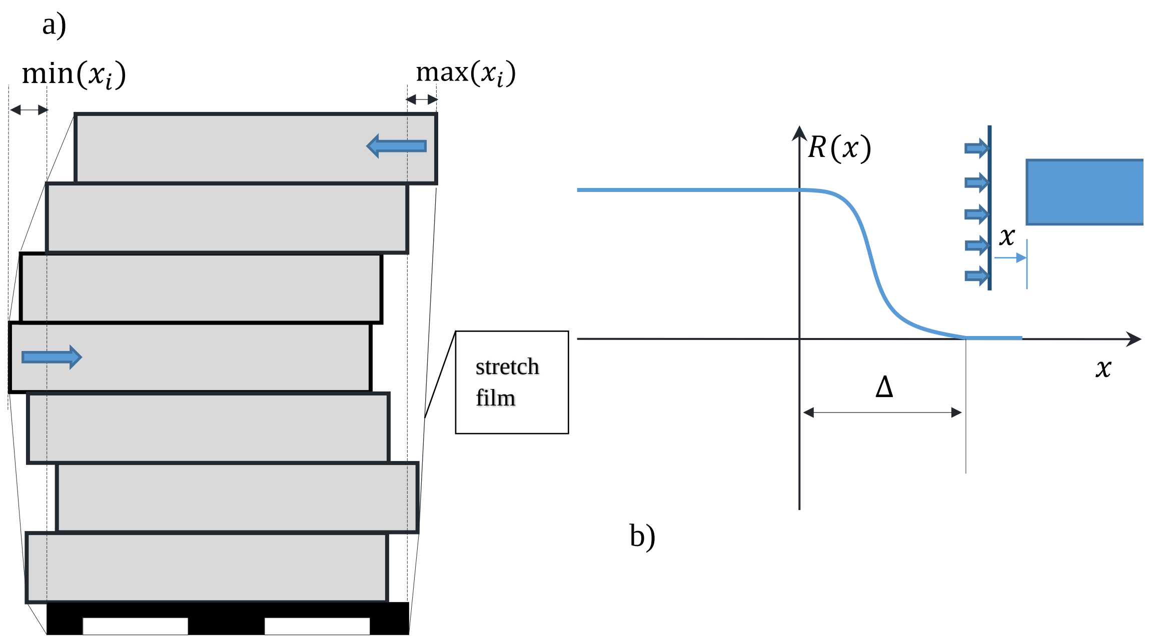


Fig. 3. Modelling of the containment force
(a - the action of the containment force on the most moved out layers of the load,
b - dependence of the containment force on the distance)

In the undeformed state of the loading unit, the containment force acts on the load uniformly from all sides. Containment force results from properly selected pre-stretching of the film. The model of the stretch film interaction on the load layer is illustrated in Figure 3. When the layers of the load press on the surface of the film, the containment force may increase. It has been assumed, however, that changes in the stretching of the film, which will be due to the displacement of the load layer to the left relative to the film surface, do not significantly affect the value of the containment force. However, moving the layer away from the film surface causes a rapid decrease of this force (Figure 3b):

$$R(x) = \begin{cases} R_0 \exp\left[\alpha\left(\frac{x}{\Delta}\right)^2\right] & x \geq 0 \\ R_0 & x < 0 \end{cases} \tag{4}$$

where: $R_0$ – nominal value of the containment force calculated in proportion to the height of the load layer,
$\Delta$ – assumed distance of containment force disappearance,
$\alpha$ – dimensionless force vanishing factor (for example, $\alpha = \ln 0.01$),
$x$ – distance of the load layer from the stretch film surface.

The containment force can be estimated from the stretch film tensile test data or directly measured. Force measurement according to ASTM D4649 using a six-inch disc seems to be of little use in this case [6]. Measurement of the corner force using specialised measuring equipment - for example, a transportable test load unit [13] – will be the most advantageous. Based on the value of the edge force, the containment force per unit of length can be determined in an elementary way. Due to the strong adhesive properties of the stretch film and the good adhesion of subsequent layers, it is possible to assume a proportionality of the containment force to the number of film layers wrapping the load unit. Because the stresses in the stretch film are very quickly relax and reduce by up to 40-50%, the measurement of force should be made after at least an hour after wrapping the test unit with film [2].

## 3. NUMERICAL EXPERIMENT

The developed simulation model was used to estimate the number of layers of stretch film, ensuring the stability of the loading unit formed of eight layers of packages. The basic data adopted for the simulation are summarised in Table 1.

Tab.1.

Basic data adopted for the simulation

| Group | Parameter description | Value | Units |
|---|---|---|---|
| Loading unit | Number of layers | 8 | [-] |
| | Layer length | 1.2 | [m] |
| | Layer height | 0.2 | [m] |
| | Layer weight | 30 | [kg] |
| Friction | Coefficient of kinetic friction between layers (between layer and pallet) | 0.2 (0.3) | [-] |

| | | | |
|---|---|---|---|
| | Coefficient of increase in friction force (Stribeck effect) | 120 | [%] |
| | Breakaway speed | $10^{-5}$ | [m/s] |
| | Coefficient of viscous friction | 20 | [Ns/m] |
| Containment force | Number of wraps | {0,2,4,8,10} | [-] |
| | Force per wrap and per unit length | 85 | [N/m] |
| | Distance of containment force disappearance | 0.02 | [m] |

Emergency braking of a vehicle transporting a load unit with a retardation of $0.8\ g$ during the first $400\ ms$ was simulated (Figure 4). The test was carried out following EUMOS guidelines. These types of tests are usually carried out in real conditions using special mobile platforms [13].

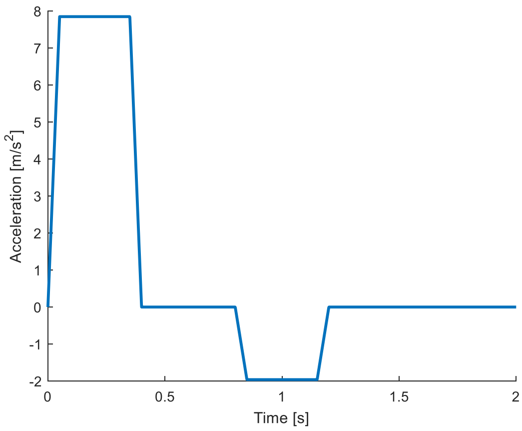


Fig. 4. Acceleration graph during emergency braking test

## 4. RESULTS OF SIMULATION TESTS

Five cases were examined by simulation methods. First, the stability of the load unit in absence of stretch film wraps was assessed. Thereafter, stability was tested when two, four, eight and ten layers of stretch film were used.

### 4.1. The case when stretch film was not used

Figure 5 shows the displacements and velocities of layers of the cargo unsecured with stretch film. Due to the increased friction between the first (bottom) load layer and the pallet, this layer remains at rest. The model does not provide for the possibility of layers rotation. Therefore, the simulation stops automatically when it detects a loss of stack stability when the centre of gravity the top or several subsequent top layers extend beyond their base (Figure 6).

### 4.2. Wrapping with two layers of stretch film

Wrapping the tested loading unit with two layers of film is insufficient, as shown in Figures 7 and 8. Although the stack of layers maintains stability, the loading unit deforms significantly.

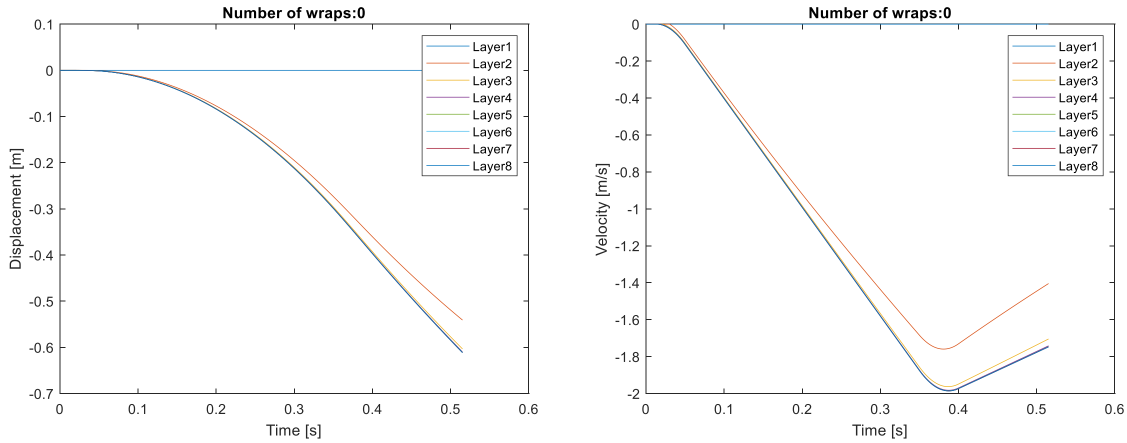


Fig. 5. Displacements (left) and speeds (right) of individual layers of load

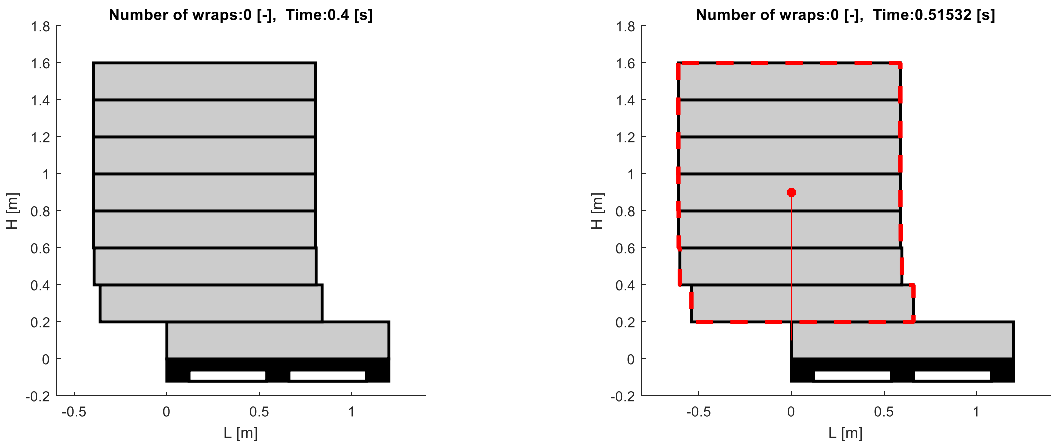


Fig. 6. Visualisation of displacement of layers in two moments of simulation

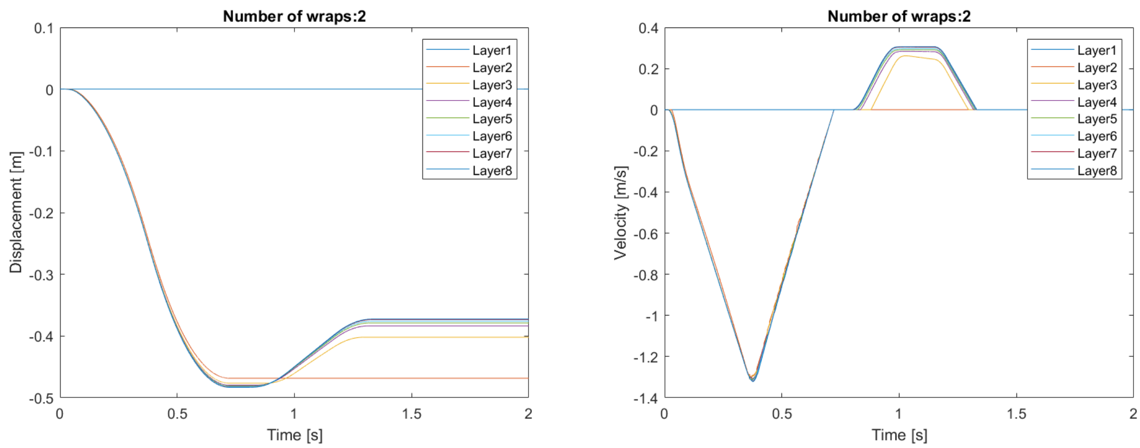


Fig. 7. Displacements and velocities of load layers wrapped in two layers of film

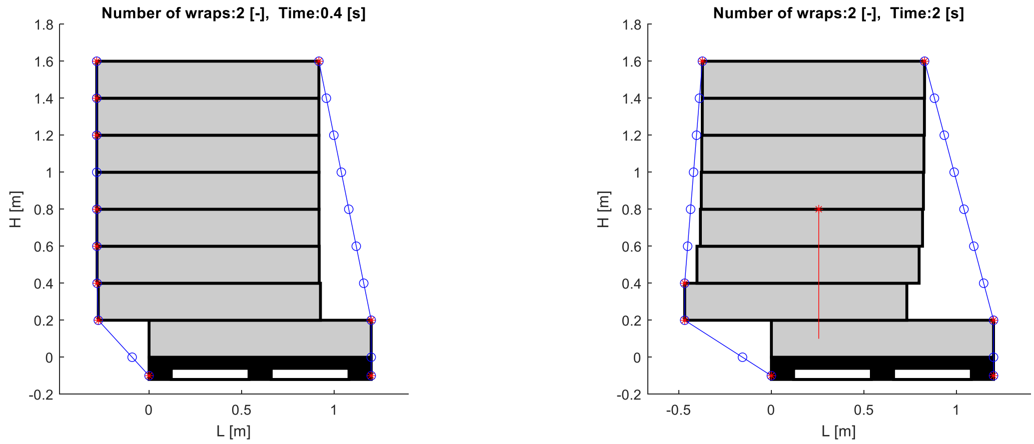


Fig. 8. Visualisation of displacement of the load wrapped twice with film

## 4.3.Wrapping with four layers of stretch film

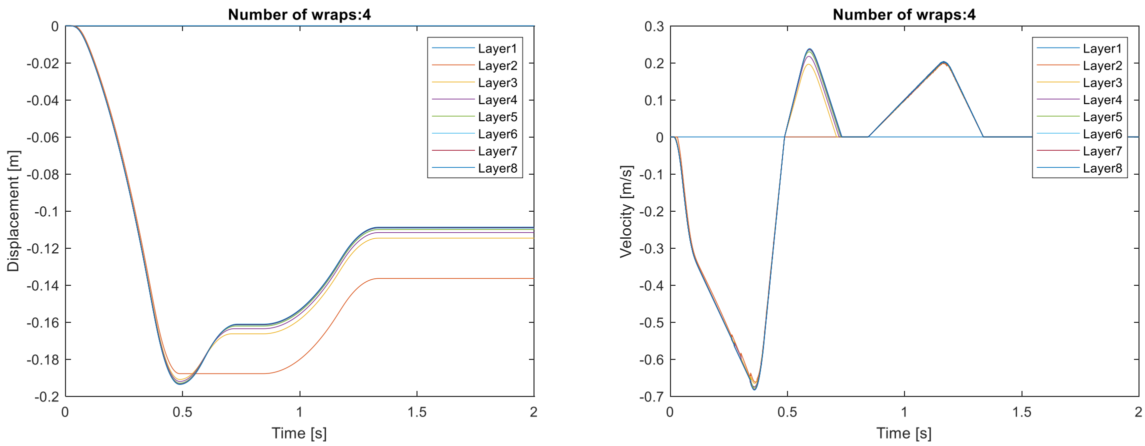


Fig. 9. Displacements and velocities of load layers wrapped in four layers of film

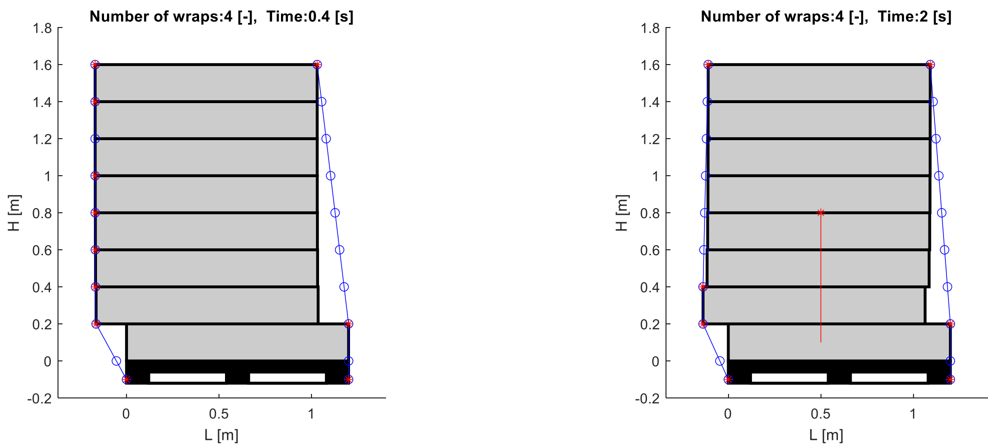


Fig. 10. Visualisation of displacement of the load wrapped four times with film

Wrapping the load four times with foil reduces layer displacement. However, displacement of the second layer by more than 10 cm is still not acceptable.

### 4.4. Eight and ten layers

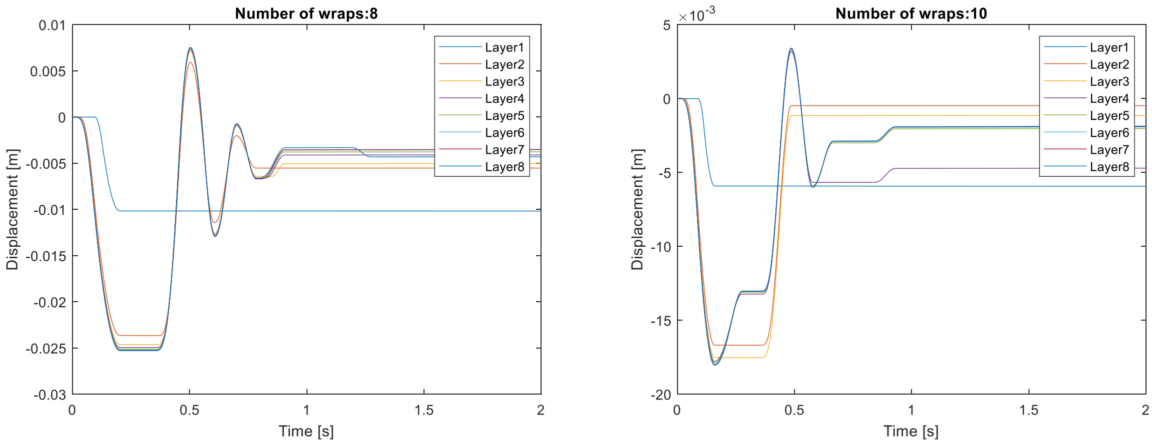


Fig. 11. Comparison of displacement of load layers for 8 and 10 wraps of film

As it results from Figure 11, the application of 8 or 10 wraps of stretch film satisfactorily limits both the maximum momentary displacement of the load and the final displacements. In this case, wrapping the load eight times will be sufficient.

### 4.5. Kinetic energy as a measure of load unit stability

When assessing the stability of a loading unit, the basic and obvious criterion is the amount of displacement. In the case of simulation tests, it is easy to calculate another indicator in the form of the kinetic energy of the whole unit. Comparing the results (Figure 12), one can notice a rapid decrease in the maximum values of kinetic energy along with the increase in the number of wraps. An analysis of the kinetic energy value shows that this decrease is of exponential nature.

However, to use the criterion of kinetic energy in practice, it should be related to the energy of elastic and permanent deformation of the stretch film, which requires further research.

### 4.6.Results compared with the full model

If the results of the full model [11] are taken as the reference point, then the error of the presented simplified model can be expressed as a function:

$$E_r(t) = \sum_{i=1}^{N_l} \left| x_{fi}(t) - x_{si}(t) \right| \tag{5}$$

where: $x_{fi}(t), x_{si}(t)$ – displacement of cargo layers from the full and simplified model, respectively; $N_l$ – number of layers.

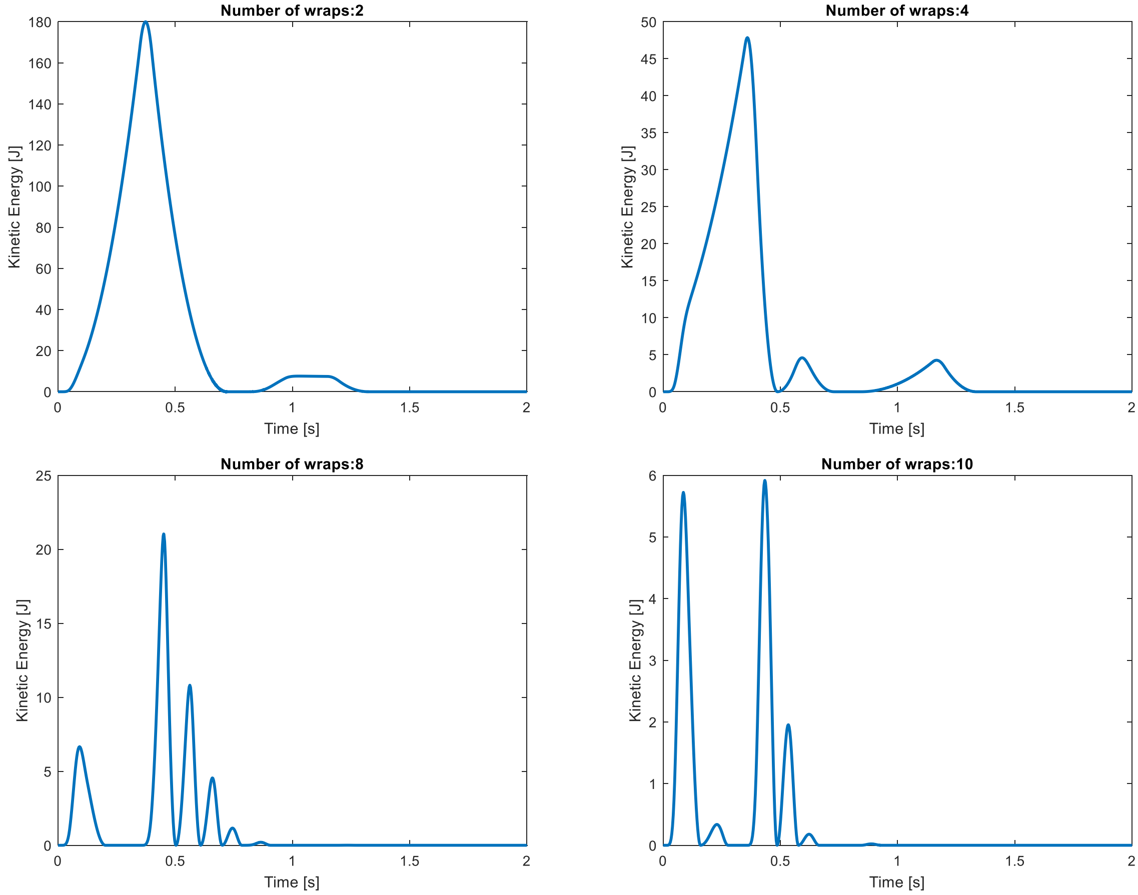


Fig. 12. Comparison of the kinetic energy of the load depending on the number of wraps

To determine the error value, all simulation results from both models should be adjusted to a constant time step, in this case *0.01 s*, using linear interpolation. When there are not enough wraps with stretch film and the layer displacements are significant ($N_o = 4$), the error calculated in this way also reaches considerable values (Figure 13a). Along with the stabilisation of the cargo, the error significantly decreases (Figure 13b), although it is not a monotonic relationship. The change of foil stiffness with an increase in the number of wraps changes the nature of vibrations of the load layers.

## 5. CONCLUSIONS

Assuming a layered structure of the loading unit means that the results obtained based on the model presented in this work will be coarse when the layer contains several packages that can move relative to each other. In this case, the method of stacking packaging, column or bricks will be important. The model, however, guarantees results that are more accurate when the layer is one package and is ideal for packet units (for example, a special pallet with drywall or wood-based panels). In general, it can be argued that the better the load on the pallet is secured by the containment force, the smaller the displacement of the layers and the results obtained from the model are closer to the real one. This remark similarly applies to the method chosen in the model for describing the interaction of the stretched film with the load layers.

The main purpose of the simulation is to estimate the value of the containment force (indirectly the number of film layers and its initial stretching) guaranteeing the stability of the loading unit. However, the goal is not to accurately determine the displacement of individual layers. Therefore, the proposed model seems to be sufficiently effective.

The simulation tests carried out suggest that a good measure of load unit stability assessment can be the maximum kinetic energy generated as a result of the movement of individual layers during a standard emergency braking test. The lower the kinetic energy, the better the load protection and stability.

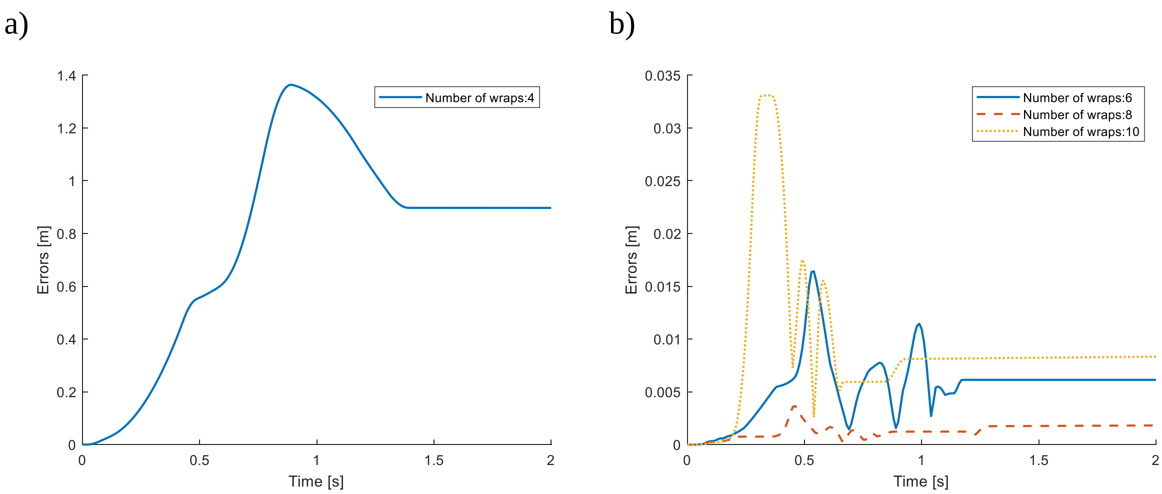


Fig. 13. Sum of absolute displacement errors depending on the number of wraps

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