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TILT TEST OF A PALLET LOAD UNIT – SIMULATION STUDIES

Summary. This paper presents a dynamic model of a palletised load unit during a static tilt test. The stability (also called rigidity) of a load unit was evaluated. The palletised load unit was built of packages forming layers and protected against disintegration by stretch film. The aim of this study was to compare the results of a static tilt test with a commonly used and recommended dynamic acceleration test.
Keywords: tilt test, load unit, stability, simulation model

1. INTRODUCTION

In road transport, loads that are carried will be affected by inertia forces of considerable value. It is assumed that during sudden braking, usually resulting from a dangerous road situation, the vehicle and the load may be subject to retardation of the range 1*g* [3, 6-9]. Inertial forces may cause the load to shift in the cargo space, resulting in permanent deformation and even damage [13]. For loading units made of many smaller packages, the unit may disintegrate. A sharp change in the centre of gravity position of the load poses a great threat to the vehicle and driver. A significant part of road accidents is caused directly or indirectly by improper load fastening or inadequate securing. To protect against the disintegration of a load unit formed on a pallet from smaller packages, the stretch film is commonly used. It is the cheapest and easiest method to use to ensure unit stability (rigidity) [1, 2, 11].

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Directive 2014/47/EU [8] and EUMOS 40509 [9] recommend checking the stability of a load unit by means of dynamic tests, which may consist of appropriate rapid acceleration of the load (acceleration tests) or its stopping (crash tests). In both cases, access to specialised devices in the form of mobile platforms is required. Therefore, dynamic testing is expensive.

When there is no access to such devices, the stability of the load unit can also be assessed by performing a static test on an inclined plane [10]. It is for this purpose that a rigid plate with dimensions enabling the pallet to be placed on it and a forklift to raise the end of the plate (Fig. 1). Tilt tests have another application; testing the stress relaxation and creep of the film stretch in time (endurance tests). This type of testing is not a subject of interest in this work.

This paper presents a simplified model of a pallet load unit with a layered structure during a quasi-static tilt test. Cargo layers shifts were limited by pre-stretched stretch film. The tilt test simulation results were compared with the simulation results of a typical dynamic test performed in accordance with standards [5, 12]. The developed mathematical model of the tilt test was implemented in the Matlab environment.

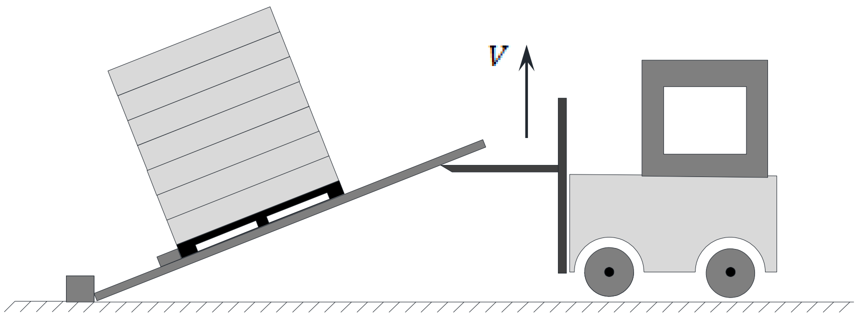

Fig. 1. Performing a static test using a forklift

2. TILT TEST SIMULATION MODEL

During dynamic tests, the acceleration acting on the load unit should reach the value of 0.8*g* [5, 12]. This value of acceleration acting down the ramp can be obtained with a slope 53.13°. Of course, this is accompanied by a decrease in the force pressing the load unit perpendicular to the inclined plane. Therefore, it is difficult to directly compare the effectiveness of both dynamic and static tests. It seems expedient to consider the acceleration ratio Λ, which is the quotient of the acceleration components parallel and perpendicular to the pallet plane. For the maximum acceleration value will be:

$$\Lambda = \frac{a_{\parallel}}{a_{\perp}} \ , \quad \Lambda_{max} = \frac{a_{max}}{g} = \left(\frac{g \sin\alpha}{g \cos\alpha}\right)_{max} = \tan\alpha_{max} = 0.8 \tag{1}$$

Equation 1 shows that to achieve comparable conditions to the dynamic test, a tilt of the ramp at an angle 38.66° is necessary. When the lifting speed of the forklift is constant *V=const*, the height of the lift *H(t)=Vt* and based on the drawing (Fig.3), the angle of inclination of the ramp changes according to the relationship:

$$\alpha(t) = \text{atan}\frac{Vt}{\sqrt{D^2 - V^2t^2}} \tag{2}$$

At a typical value of forklift speed *V*=0.2*m/s* and plate length *D=2m*, the time needed to achieve the suitable angle of inclination is equal *t*=6.25*s*. Differences in acceleration ratio during dynamic and static tests are explained in Fig. 2.

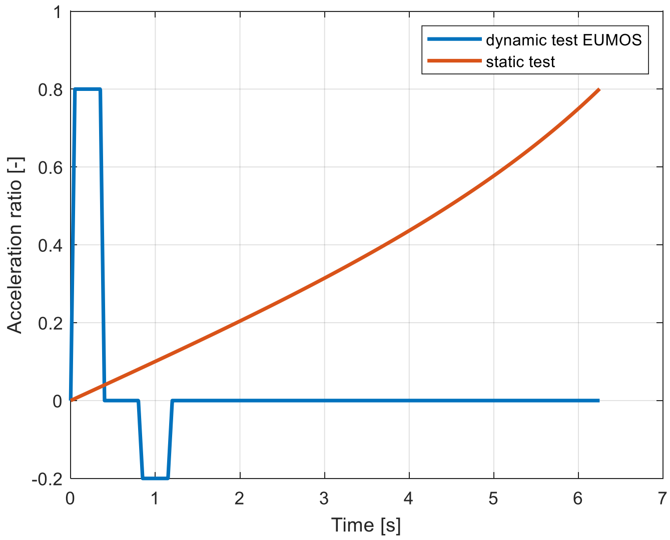

Fig. 2. The time course of the acceleration ratio in dynamic and static tests

It can be assumed that the lifting process is slow enough to neglect the inertia forces associated with rotation in the cargo movement equations. This is confirmed by the considerations presented below. By differentiating twice formula for the sine of the angle α, we get:

$$\sin\alpha = \frac{Ht}{D} \quad \rightarrow \quad \dot{\alpha}\cos\alpha = \frac{V}{D} \quad , \quad \ddot{\alpha}\cos\alpha - \dot{\alpha}^2\sin\alpha = 0 \tag{3}$$

And after transformations finally:

$$\dot{\alpha} = \frac{V}{D\cos\alpha} \quad , \quad \ddot{\alpha} = \frac{\dot{\alpha}^2\sin\alpha}{\cos\alpha} = \frac{V^2}{D^2}\frac{\sin\alpha}{\cos^3\alpha} \tag{4}$$

When α changes from 0^o to 60^o then the angular velocity changes from *V/D* to *2V/D*. At the same time, the angular acceleration varies from 0 to $4\sqrt{3}\,V^2/D^2$. In addition to gravitational acceleration, the cargo will also be affected by inertial accelerations: centrifugal, tangential and Corilois acceleration. The maximum acceleration values in the anticipated platform rotation range will be, respectively:

$$a_\omega = \dot{\alpha}^2 r = \frac{4V^2}{D^2} r \quad , \quad a_\varepsilon = \ddot{\alpha} r = 4\sqrt{3}\frac{V^2}{D^2} r \quad , \quad a_C = 2\dot{\alpha}\dot{x} = \frac{4V}{D}\dot{x} \tag{5}$$

At a low lifting speed $V = 0.2m/s$, relative speed $\dot{x} = 1m/s$ and dimensions $D = r = 2m$, these accelerations will be respectively: $a_\omega = 0.08m/s^2$, $a_\varepsilon = 0.14m/s^2$, $a_C = 0.04m/s^2$ and are much smaller than the parallel component to the platform $g \sin \alpha$, which at the maximum tilt of the platform is equal $8.5m/s^2$.

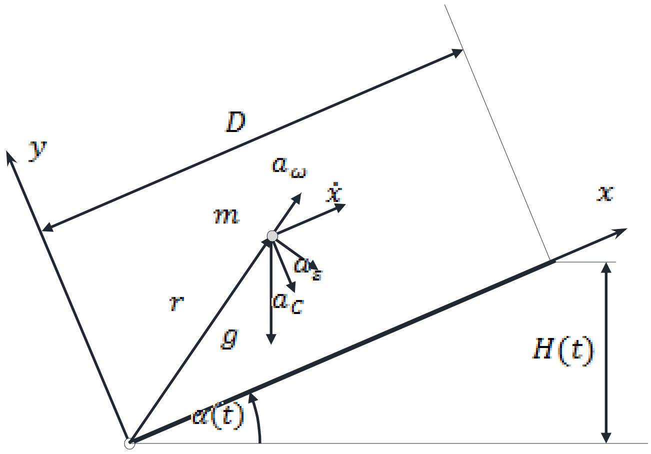

Fig. 3. Acceleration acting on the load when the platform is lifting

The equation of motion of a selected layer of cargo, in a direction parallel to the ramp, in a non-inertial coordinate system, after neglecting the accelerations caused by rotation, has the form (Fig. 4):

$$m_i \ddot{x}_i = -m_i g \sin\alpha - F_i + F_{i+1} + R_i \quad , \quad i = 1, \dots, N \tag{6}$$

where: F_i, F_{i+1} – friction forces on the upper and lower surface of the layer,
R_i – resultant force of the stretch film reaction.

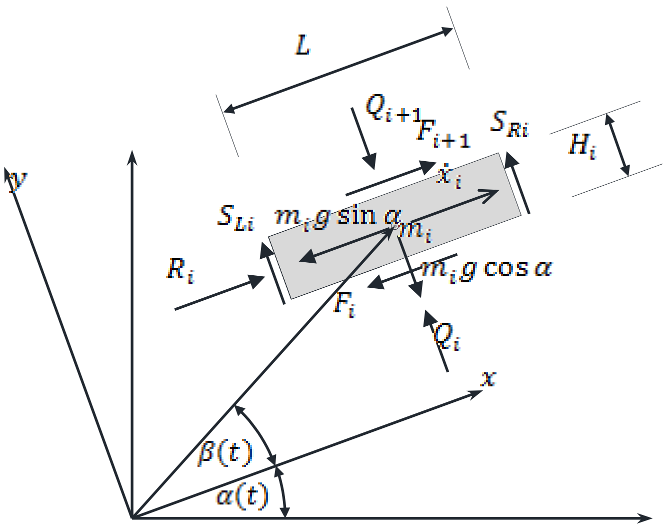

Fig. 4. Forces acting on the selected layer of load

The friction model adopted in the task includes the stick-slip phenomenon, Coulomb friction, the Stribeck effect and viscous friction. Friction force is a function of:

$$F_i = F_i(\Delta\dot{x}_i, V_b, V_S, V_C, \mu_s, \mu_k, b) \quad (7)$$

where: $\Delta\dot{x}_i = \dot{x}_i - \dot{x}_{i-1}$ speed of layer i relative to the layer below,
V_b – is the velocity of the load layers breaking,
$V_S = \sqrt{2}V_b$ – speed threshold of the Stribeck phenomenon,
V_C – Coulomb speed threshold,
μ_s, μ_k – static and kinetic friction coefficients,
b – viscous friction coefficient.

Friction forces depend on the value of pressure forces between the layers, which can be determined from the formula:

$$Q_i = m_i g \cos\alpha + Q_{i+1} - S_{Li} - S_{Ri} \quad , \quad i = N, \dots, 1, \quad Q_{N+1} = 0 \quad (8)$$

where: S_{Li}, S_{Ri} – action forces of the packaging with stretch film.

Restoring force $R_i = R_i(x_1, \dots, x_N)$ works on the most shifted layers of cargo and is results of the containment force (tension force obtained initially it the wrapping process) and increase of this force due to additional stretching of the film in a direction parallel to the pallet (Fig. 5). A simplified linear model of stretch film deformation was assumed, which is spanned on the most put forward vertices of the load layers. An additional effect of stretching the film in a direction perpendicular to the surface of the pallet are tensions whose resultants are the forces $S_{Li} = S_{Li}(x_1, \dots, x_N)$ and $S_{Ri} = S_{Ri}(x_1, \dots, x_N)$ operated on the side edges of the layer.

The model assumes that the layers of cargo can only slide on each other and will not rotate. Therefore, the simulation should be stopped when the stability of the stack of cargo layers cannot be maintained. This occurs when the resultant of forces acting on the layer in direction perpendicular to the pallet goes beyond the zone of contact with the layer below. The developed software automatically detects this case. Stability of the stack must be checked starting from the top layer down.

3. RESULTS OF SIMULATION TESTS

Stability test of a load unit made of 9 identical layers of packages was simulated, each with a mass 50*kg* and height 0.15*m*. The coefficient of kinetic friction between the layers was 0.3 and between the bottom layer and the palette 0.8. The static friction coefficient was 20% higher than the kinetic.

In the beginning, simulations of the load unit tilt test without stretch film were carried out. With a relatively small angle of inclination, the layers of the load shifted so much that the stack lost its stability (Fig. 6). The first layer remained stationary due to the much higher coefficient of friction between it and the pallet.

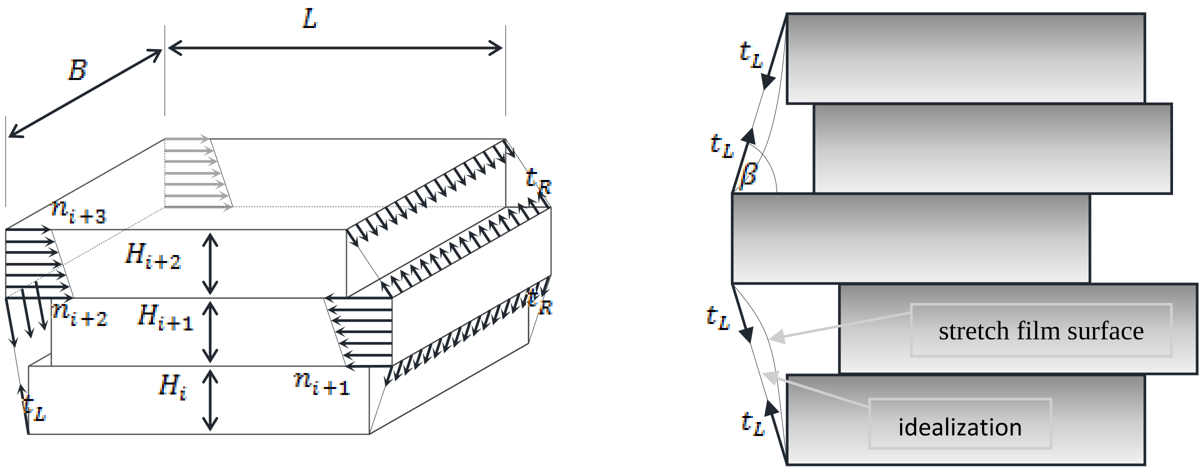

Fig. 5. Assumed tension distribution in the stretch film and stretch film surface idealisation

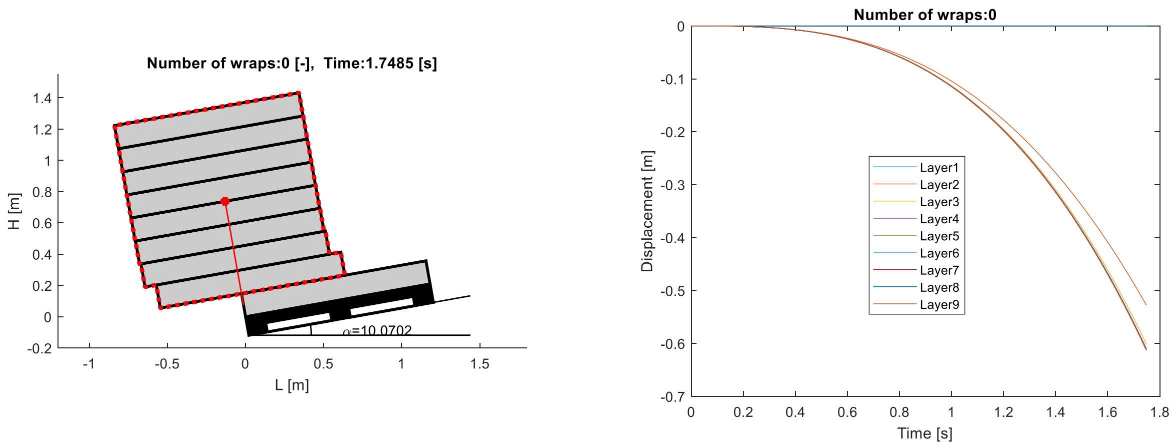

Fig. 6. Stack of packaging without stretch film wrapping

Then, the load was wrapped with four layers of stretch film, which corresponded to a containment force of *51N*. The results of the tilt test simulation are shown in Fig. 6. The four layers of film do not protect the packaging against sliding relative to each other and relative to the pallet, but to some extent keep them in a group. For this reason also, the first layer begins to slide off the palette. The simulation was interrupted when the packaging stack lost stability.

Next, the cargo wrapped with ten layers of film was simulated (containment force equal 127.5 N). This amount of wrapping seems sufficient to maintain the stability of the loading unit. This was based on a dynamic test. Figs. 8 to 12 enable comparison of the results of simulations of both static and dynamic tests. In the case of dynamic test simulation, the factor $m_i g \sin\alpha$ in the equations of motion (6) must be replaced by $m_i a(t)$, where $a(t)$ acceleration changes over time according to [8]. The formula (8) for determining pressure forces should also be modified.

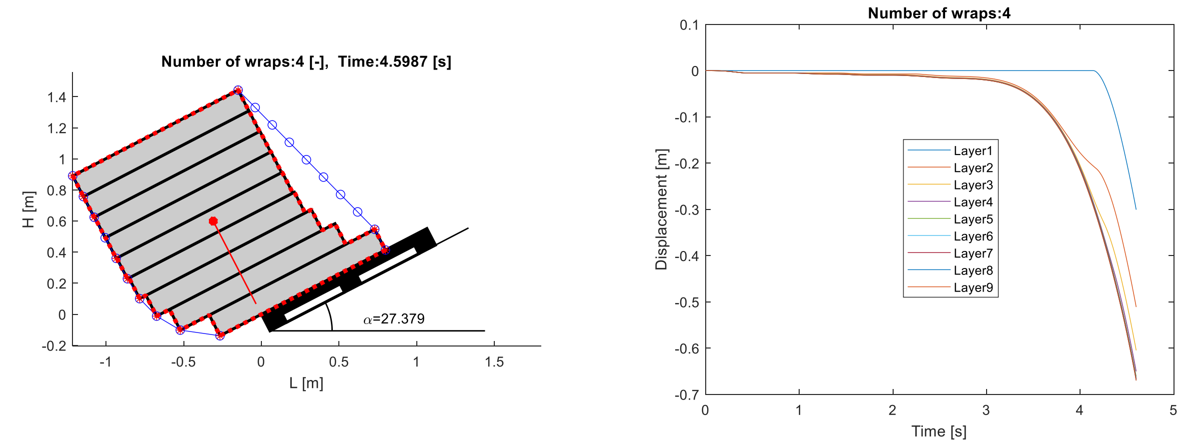

Fig. 7. Displacement of the layers (cargo wrapped four times with stretch film)

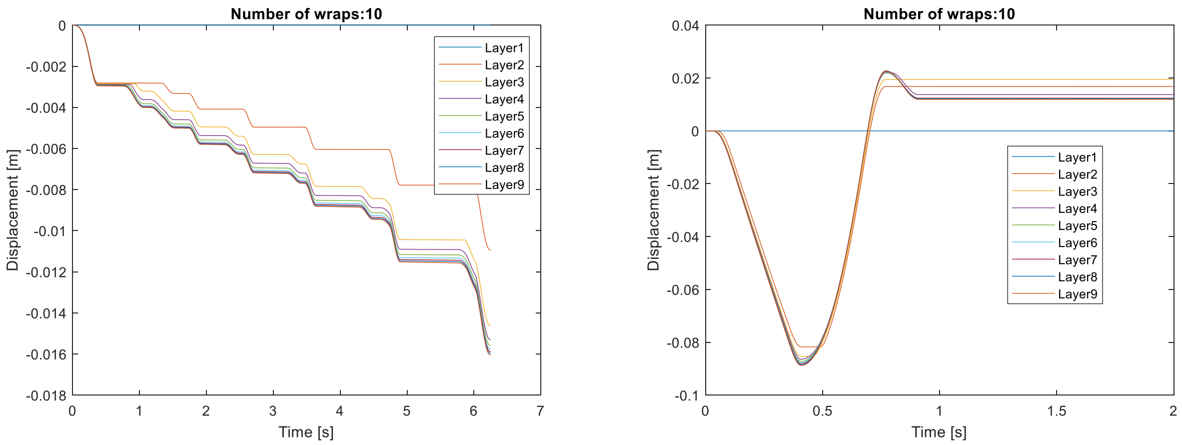

Fig. 8. Cargo layers displacement (left: tilt test; right: acceleration test)

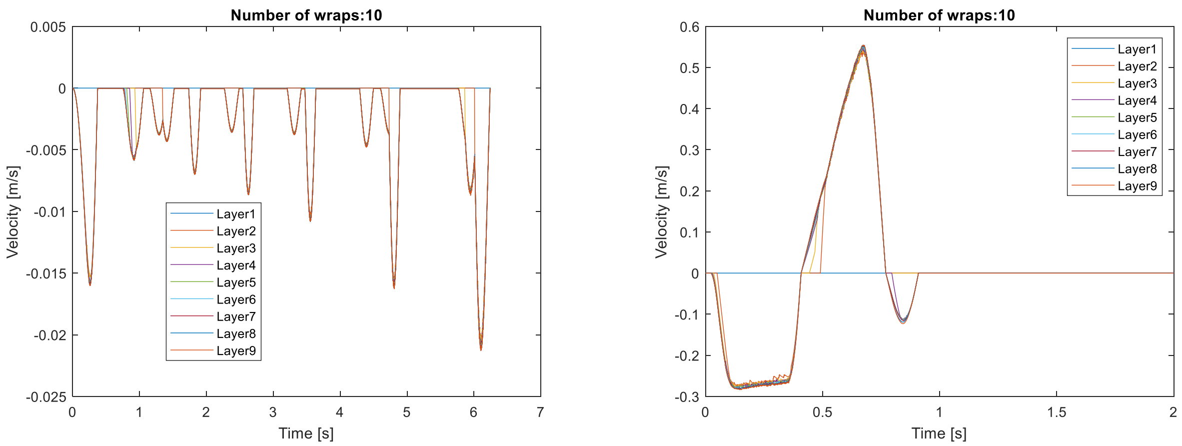

Fig. 9. Cargo layers displacement velocities

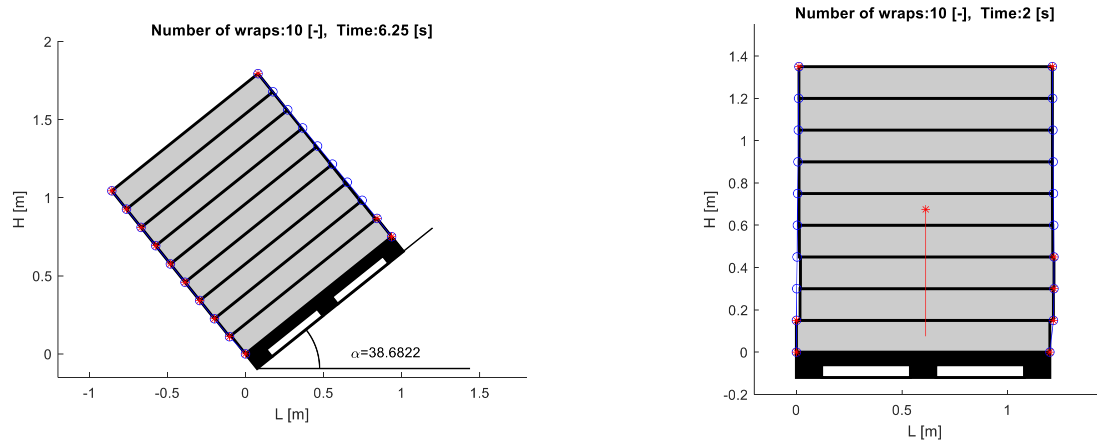

Fig. 10. Visualisation of the cargo layers displacement (at the end of the simulation)

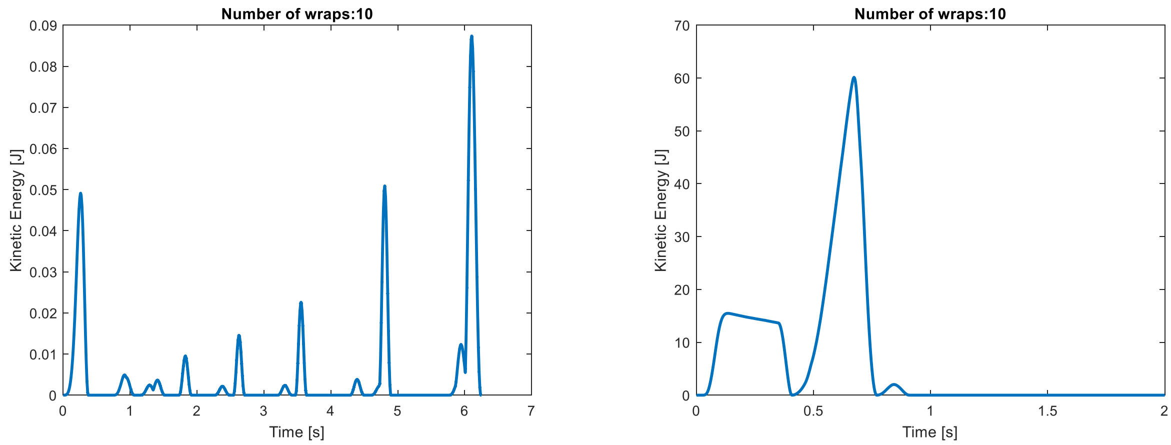

Fig. 11. Graph of the total kinetic energy of cargo

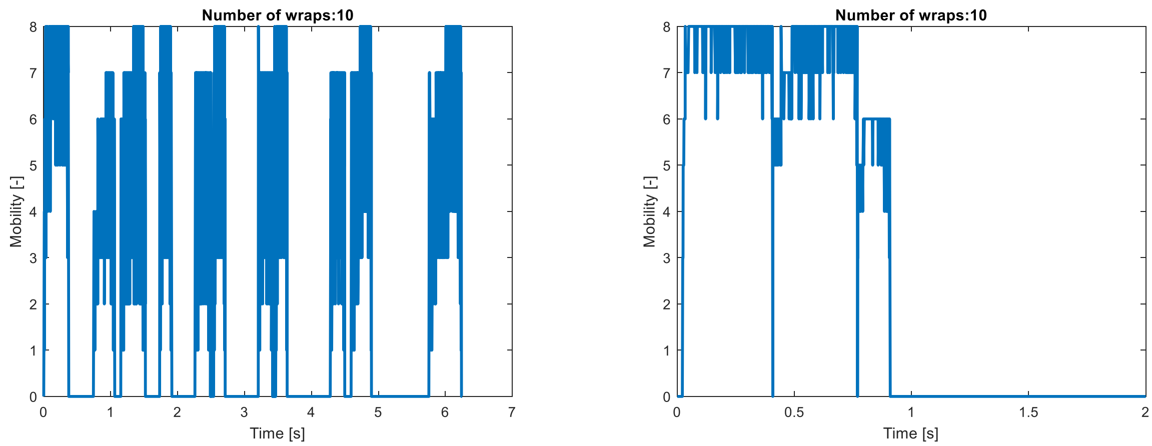

Fig. 12. Total mobility of cargo layers

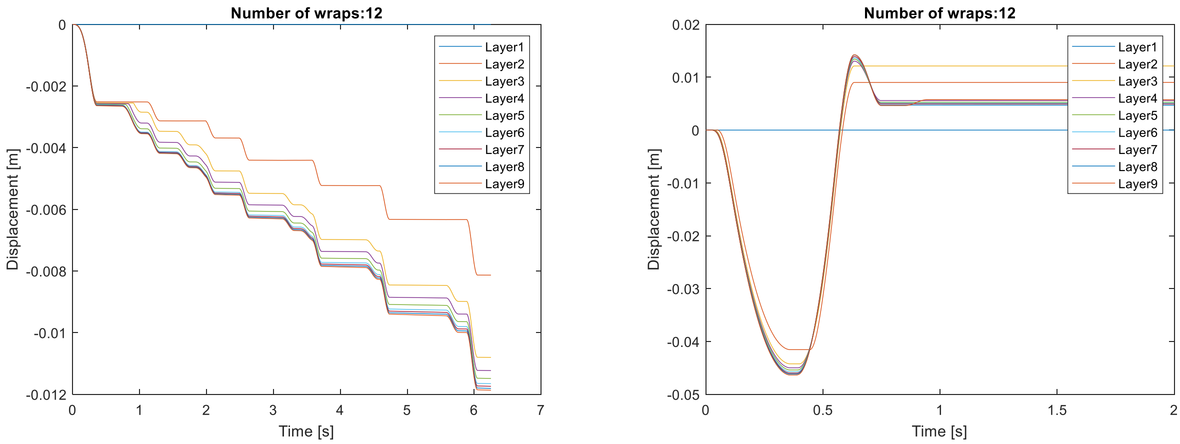

Fig. 13. Cargo layers displacement (twelve layers of stretch film)

During the dynamic test, the layers of cargo moved first to the left by about 8 cm and then under the influence of the restoring force to the right, remaining shifted by about 20 mm. However, during the tilt test, the load systematically moved to the left, sliding down the pallet in stages. Finally, the displacement was about 16 mm (Fig. 8 and 10). From the analysis of the speed diagram (Fig. 9), it can be seen that slips and sticks occurred at that time. In both cases, the first layer remained stationary. The graphs of total kinetic energy (Fig. 11) and layer mobility differ significantly as well (Fig. 12).

Simulations, when the cargo is secured with twelve layers of stretch film, were also carried out. The results in the form of displacements and kinetic energy are shown in the charts (Figs. 13 and 14). It can be observed that increasing the number of wraps by two increases the stability of the cargo more than 20%. Other simulation studies have shown that the relationship between load stability and the number of stretch film layers is not linear. Initially, a rapid improvement in stability with each successive layer of film is observed. Then this increase is getting smaller. There is a certain limit value of the number of stretch film layers, which its further increase no longer adds improvement. Optimal use of film has an impact on costs and the environment.

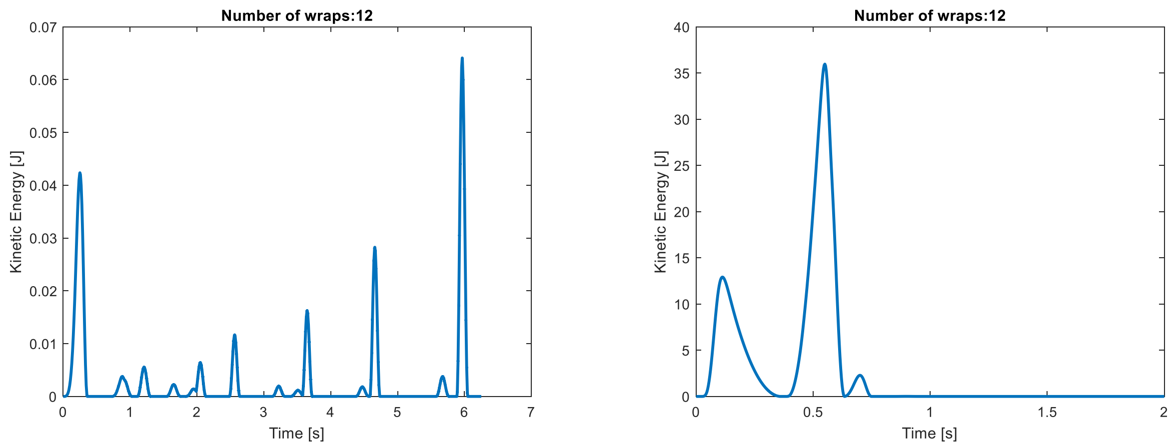

Fig. 14. Total kinetic energy of cargo (twelve layers of stretch film)

As the simulation shows, static and dynamic tests are completely different. However, practical conclusions from both tests are comparable. In the analysed case, ten layers of stretch film are able to sufficiently secure the load on the pallet against disintegration.

4. CONCLUSIONS

Based on the simulation tests carried out, it can be stated that the dynamic test cannot be replaced by a static test. The detailed results obtained, in the form of displacement values, packaging speed and other tested parameters are radically different in both tests. On the other hand, the effect of tests in the form of determining the minimum number of stretch film wraps is comparable. The static test is also cheap and very easy to perform. Therefore, it can be used when there are no other options, and as a pre-test before performing a dynamic test to reduce its costs.

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