Securing cargo in road transport – Who knows the truth?

Contents

Preface ... 2
Introduction ... 3
1. Investigation of load assumptions ... 4
  1.1 Full braking ... 4
  1.2 Cornering ... 6
  1.3 Lane changing ... 8
  1.4 Obstacle avoidance ... 9
  1.5 Rolling factor ... 10
2. Conventional rules and calculation methods ... 13
  2.1 Direct lashing ... 13
    2.1.1 Securing against sliding ... 13
    2.1.2 Securing against tipping ... 14
  2.2 Tie-down lashing ... 16
    2.2.1 Securing against sliding ... 16
    2.2.2 Securing against tipping ... 17
3. Extended approaches ... 19
  3.1 Cargo movement ... 19
  3.2 Deformation and force development of securing devices ... 21
  3.3 Horizontal components of tie-down lashings ... 22
  3.4 Semi-dynamic approach to calculation ... 24
    3.4.1 Iterative method ... 24
    3.4.2 Selective methods ... 25
  3.5 Fully dynamic approach to calculation ... 25
4. Practical examples ... 26
  4.1 Direct securing in the longitudinal direction with belts and timber blocking ... 26
  4.2 Direct securing with chains at unfavorable angles ... 27
  4.3 Securing against sliding in the longitudinal direction with slack tie-down lashing ... 29
  4.4 Securing against sliding in the transverse direction by slack tie-down lashings ... 30
5. Summary, outlook and objectives ... 32
  5.1 Load assumptions ... 32
  5.2 Rolling factor ... 32
  5.3 Conventional balance calculation methods ... 33
  5.4 Cargo movement and deformation of securing devices ... 33
  5.5 Calculation methods ... 33

Preface

Even casual observers of the specialist press or those who search the Internet for certain terms will soon notice that the hitherto perfect world of "proclamations" with respect to cargo securing in road transport has been becoming rather untidy over the past few years.

So what happened? Europe is coming together. The volume of freight transported by road, rail and water has continued to increase, and the understandable calls for harmonized rules, not only in respect of cargo securing, have been heard.

A standard intended to ensure a uniform level of safety across the whole of Europe was drafted, and EN 12195-1, which has already been revised several times, has met with a varied response from practitioners. Those interests that have influenced the development of the standard are, understandably, many and varied, even going as far as referencing the regulations of the IMO, which, being an organization within the UNO, is truly not responsible for road traffic in Europe.

The most recent version of the draft standard represents the compromise negotiated in September 2008, which in turn corresponds to a great extent to VDI Guideline 2700, Part 2 of November 2002, but which ignores "findings" from the intervening years. From a German perspective, these include the k factor that applies with tie-down lashings tensioned on one side only, the treatment of coefficients of friction and the "rolling" factor; and, from the perspective of some other European representatives, the forward g force to be assumed for calculating adequate cargo securing measures.

This is lamented by critics who are justifiably concerned that a decline in safety may result and correctly insist that the laws of physics have not changed and that the (German) regulations that had applied previously must continue to apply.

It is undeniable that the laws of physics have not changed, but exactly how much physics has been used in the extremely simplified models used for calculation in the field of cargo securing to date? The models should be easy to comprehend and use. What compromises have been made? Could it be that the intuitive objections of practitioners to a nonsensically high number of tie-down lashings proposed under certain circumstances may well sometimes be justified because the high number is the result of shortcomings in the model used for calculation? This would not be the fault of the laws of physics.

In the context of the upcoming revision of their Cargo Securing Manual as published in 1997, the German Insurers' Association (GDV) therefore decided to investigate the underlying physical principles used in the current regulations for calculating adequate cargo securing measures. It is easy to derive these principles from the models used for calculation, but it is not easy to draw such conclusions about the reasoning behind the simplifications and assumptions that have been made. Taking a further step backwards and closely examining what really happens to a cargo assembly when a truck undergoes full braking or changes lane quickly thus seemed unavoidable.

The findings were not surprising, namely that the simplifications applied in the models hitherto used for calculation deviate unacceptably from reality, erring sometimes on the side of caution and sometimes on the side of danger. Irrespective of the need to present simple rules for adequate cargo securing in the upcoming Cargo Securing Manual, it was therefore necessary to examine closely all the factors that have an impact on securing performance.

Introduction

Quite apart from the fundamental questions about the simplified models used for calculation, changing circumstances also need to be taken into account in a revision of this kind.

Modern commercial vehicles are equipped with more powerful brakes and steering assistance systems. This means that higher acceleration forces may be expected. The roads themselves are better and engines are more powerful, and these factors result in higher speeds. Loading technology has been mechanized and thoroughly rationalized, which does not necessarily improve the conditions for securing units of cargo. This is compounded by time pressure and a lack of staff, with the result that both expenditure on and the quality of cargo securing measures could be under threat.

On the other hand, better securing equipment is available, and the availability of calculation software boosts the attractiveness of more complex calculation models for planning and checking securing strategies. Internationalization of traffic flows necessitates uniform regulations to allow effective monitoring. In other words, it is both possible and necessary to develop calculation procedures that both provide legal security and make sense in terms of the underlying physics.

All these aspects need to be taken into account. Ultimately, it is important that any simplified rules and approaches to calculation are only published in conjunction with the underlying philosophy and stating the way in which they were derived, so that nobody runs the risk of taking the simplifications as true reflections of reality and exploiting them in the name of the laws of physics.

1. Investigation of load assumptions

Due to the considerable variation in vehicle characteristics, road conditions and behavior of individual drivers, current calculation practice makes use of all-inclusive, generalized acceleration values for road freight traffic. According to the current consensus in Germany and a number of other European countries, these are as follows:

Forward:	0.8 g
Rearward:	0.5 g
Sideways:	0.5 g

In several other European countries, the forward acceleration is assumed to be 1.0 g.

The force acting perpendicularly to the loading area that is important both for the friction on the loading area and for the stabilizing moment of a cargo unit is taken as 1.0 g, i.e. the full force of acceleration due to gravity.

In order to get a clearer picture of the situation in reality, typical borderline cases for external loads will be investigated. Accident events will be excluded.

1.1 Full braking

Full braking is the greatest load to which a forward securing arrangement is exposed. Recent developments in the field of truck tires, coupled with modern brake systems and asphalt roads, permit braking deceleration values that are perfectly capable of approaching 0.8 g[1]. Other factors, such as the distribution of axle weights, also play a role in this context.

The connection between the loading area of a truck or semitrailer and the tyre footprints is not rigid but resilient, which means that the inertial force of the cargo does not follow directly from the braking deceleration, but instead initially brings about a forward tilting of the loading area. This "pitching angle" is not at a steady state throughout full braking, but has pitching oscillations superimposed on it. The amplitude of the pitching oscillations is very highly dependent on buildup time, i.e. the time taken for the braking force to increase to its full value.

During full braking, the following forces act forwards on the cargo in the coordinate system of the loading area (parallel to the loading area):

- inertial force component from the braking maneuver,
- downhill force (weight component) arising from the geodetic inclination of the loading area (pitching angle and gradient of road),
- inertial force arising from tangential acceleration from superimposed pitching oscillation.

The normal force acting from the cargo on the loading area is generally reduced by two causes, namely, as a result of the inclination of the loading area, by the

- upwardly directed vertical component of the inertial force,
- reduced normal component of the weight-force.

The upwardly directed vertical component of the inertial force, and the reduced normal force arising from the geodetic inclination of the loading area reduce both the friction relative to the loading area and the moment of stableness of a cargo unit.

[1] cf. H. Huinink; "Das 30 m - Auto" ("The 30 m car"), VDA Conference, Bad Homburg, 2001

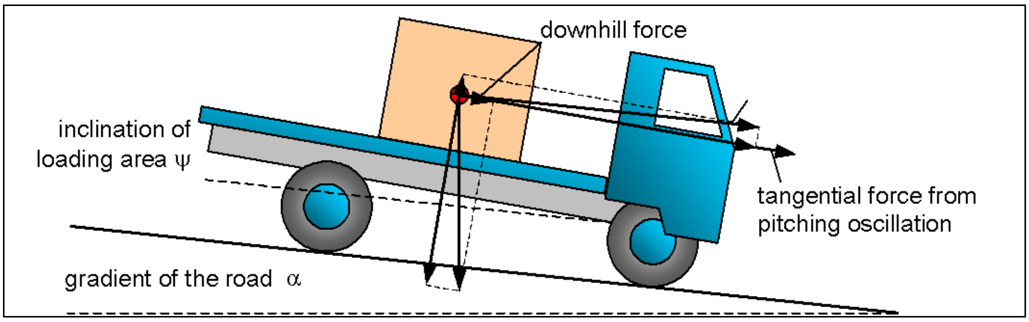

Figure 1: Full braking on downward sloping road

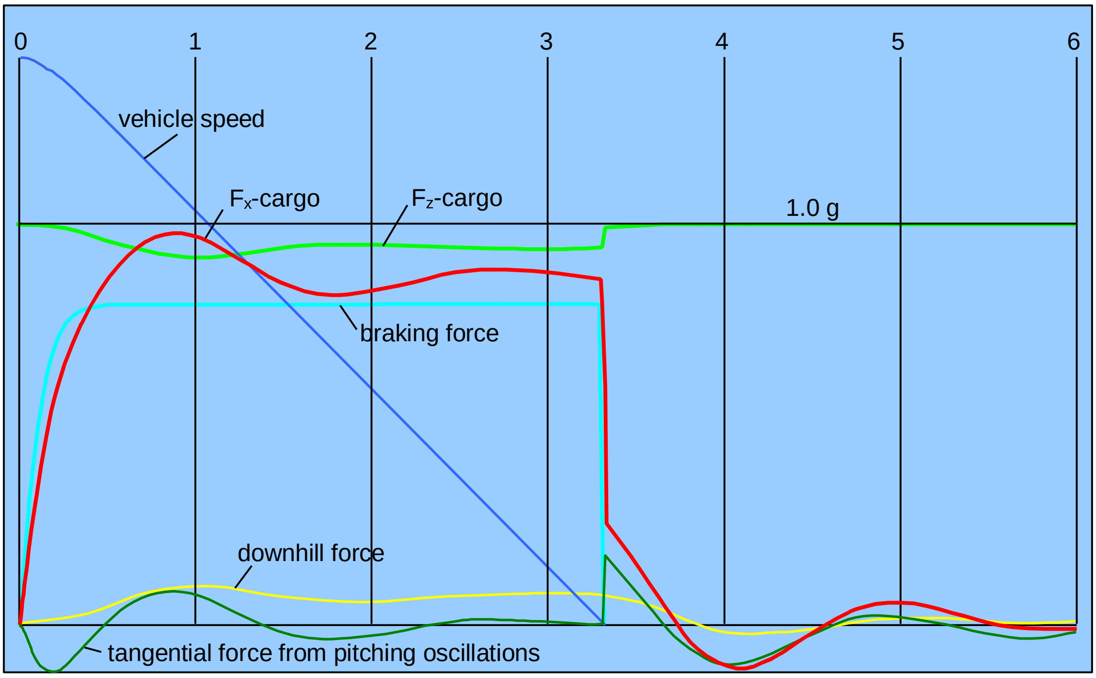

Figure 2: Full braking on a level road from 90 km/h with 0.8 g braking deceleration and 0.3 s buildup time; stopping distance = 42.9 m

Figure 2 shows the numerical solution of the equations of motion over a period of 6 seconds. The forces acting on the Cargo have been converted into units of g. The vehicle is stationary after approx. 3.3 seconds.

The truck is loaded in such a way that, at 0.8 g deceleration, a steady-state pitching angle of 4° is obtained. The maximum pitching angle after 0.9 seconds amounts to 5.5° as a result of the superimposed pitching oscillation. This oscillation is strongly damped and largely subsides by the time the vehicle is at a standstill, but is re-excited by the familiar jerk at the end of the braking maneuver.

The maximum longitudinal load on the cargo at 0.9 seconds amounts to 0.98 g, at which point the normal force has simultaneously declined to 0.92 g.

Numerous further simulated full braking maneuvers at other speeds, uphill and downhill road gradients and other vehicle types (e.g. semi trailer with a smaller pitching angle) reveal similar profiles. The following general conclusions may be drawn:

- Calculating on the basis of braking force transfer corresponding to 0.8 g, cargo securing must be designed for just about 1.0 g, because the downhill force from the pitching angle plus the tangential force from the superimposed pitching oscillation add about 0.2 g.

- Full braking from lower initial speeds results in only insignificantly more favorable results. Only at speeds of below 15 km/h may it happen that the vehicle is already stationary before the maximum longitudinal force has been reached.
- Semi trailers, which are assumed to have half the pitching angle, experience approx. 3% lower longitudinal forces and a 4% lower reduction in normal force. The outcome is no more favorable than this because the pitching oscillation period simultaneously becomes shorter and the amplitudes of the pitching oscillations are only insignificantly smaller than in a vehicle with a 4° steady-state pitching angle.
- The more rigidly is a loading area mounted, i.e. the less it responds to deceleration with a pitching angle and with pitching oscillations, the closer the longitudinal force acting on the cargo approximates to the pure inertial force from the braking deceleration.
- Gentler braking maneuvers with buildup times of longer than 2 seconds result in virtually no superimposed pitching oscillations. Calculating on the basis of 0.8 g maximum braking deceleration, the only further allowance which need be made is for the parallel component of the force of gravity from a steady-state pitching angle. The allowance is obtained from the sine of this angle.
- On full braking uphill from a speed of 50 km/h, the braking force is increased by the backward downhill force and, as a result, the braking distance is distinctly shorter than on a level road. The effective pitching angle is, however, reduced by the rearwardly directed inclination of the road, such that the difference in longitudinal force on the cargo is almost equalized compared to the situation on a level road. Under the selected conditions according to Figure 2, the cargo should be secured against acceleration of 0.99 g.
- On full braking downhill from a speed of 50 km/h, the longitudinal force on the cargo is somewhat smaller than in the event of full braking on a level street. The effective braking force is smaller and the braking distance greater. The downhill force is, however, increased by the inclination of the road. Under the selected conditions, the cargo should be secured against acceleration of 0.96 g.
- Calculation methods for dimensioning longitudinal cargo securing should take suitable account of the decrease in normal force (weight).

1.2 Cornering

Similar phenomena occur on tight cornering as occur on full braking. In the steady-state phase of cornering, the loading area is inclined laterally by a rolling angle. A rapid buildup in centrifugal force up to its maximum value gives rise to a rolling oscillation with amplitudes which are superimposed on the steady-state rolling angle. The transverse force parallel to the loading area acting on the cargo is therefore made up of:

- centrifugal force component from cornering,
- downhill force arising from the geodetic inclination of the loading area,
- inertial force arising from tangential acceleration from a rolling oscillation.

In this case too, the normal force acting from the cargo on the loading area is reduced by two causes, namely, as a result of the inclination of the loading area, by the

- upwardly directed vertical component of the centrifugal force of cornering,
- reduced normal component of the weight-force.

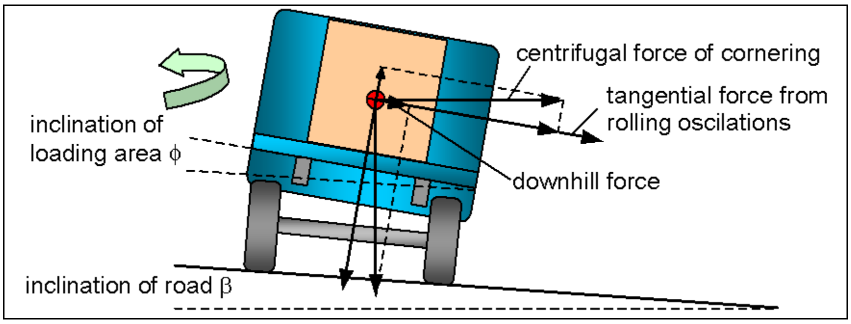

Figure 3: Cornering with unfavorable inclination β of the road

Unlike in the longitudinal direction, the centrifugal force is oriented horizontally in the geodetic reference system, i.e. not parallel to the inclination of the road. Thus the inclination of the road has a direct impact on the centrifugal force components through the downhill force.

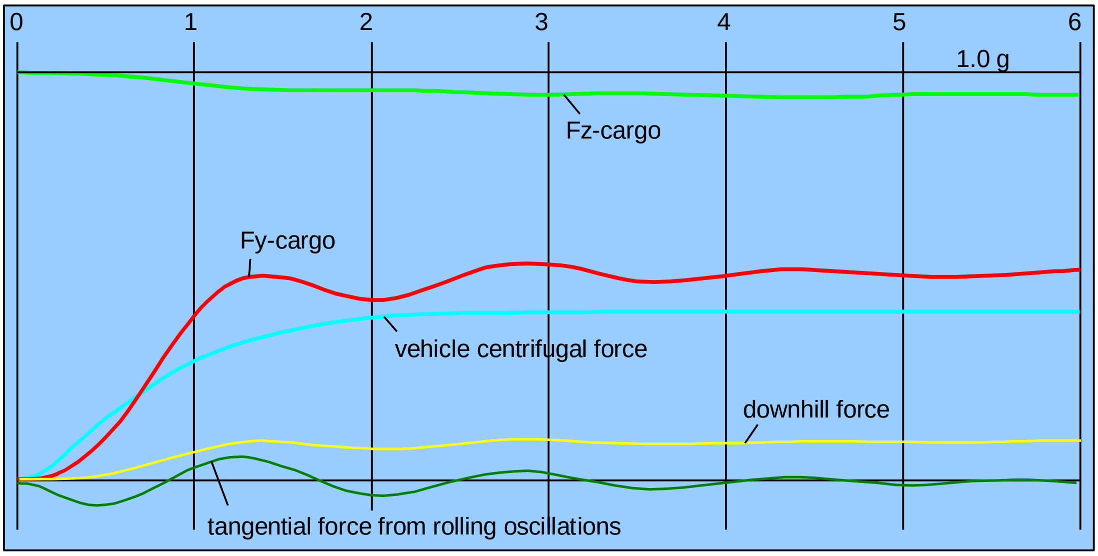

Figure 4: Cornering on a level road with 0.42 g centrifugal acceleration and 0.54 g maximum transverse acceleration, maximum rolling amplitude = 5.8°.

Figure 4 shows the numerical solution of the equations of motion over a period of 6 seconds. The forces acting on the cargo have been converted into units of g.

Maximum centrifugal acceleration was deliberately selected at 0.42 g such that, once the rolling oscillations have subsided, a steady-state transverse acceleration of 0.50 g is established. As a consequence, the first rolling amplitude gives rise to a maximum transverse acceleration of 0.54 g. This value increases if the buildup time is shortened or damping of the rolling oscillations is reduced.

Further simulated cornering maneuvers with other loading area spring constants and with favorable and unfavorable corner inclination of the road reveal comparable profiles. The following general conclusions may be drawn:

- The generally accepted assumption of transverse acceleration of 0.5 g for dimensioning cargo securing against sideways sliding must not be interpreted in such a way that this value could be solely attributable to the centrifugal force. Instead, between 20 and 30% of this value must be reserved for the downhill force from the inclination of the loading area and the tangential forces from superimposed rolling oscillations.
- In steady-state cornering, the inclination of the loading area is still present even after the rolling oscillations have subsided and contributes just about 20% to transverse acceleration.

- The transverse force allowances from the downhill force and tangential forces have nothing to do with the "rolling factor", which is required in VDI Guideline 2700 Sheet 2. The rolling factor takes account of dynamic tipping moments, while the stated allowances are forces acting at the center of gravity.
- In favorably constructed curves (road inclined towards the center point of the curve), the parallel component of the force of gravity is partially offset by the inclination of the road. The opposite applies when the road is inclined unfavorably.
- As previously with full braking, stiffer loading area suspension gives rise to smaller rolling angles and the transverse forces thus approximate to pure centrifugal forces.
- Starting to corner more slowly with buildup times of distinctly more than two seconds allows the superimposed rolling oscillations to become insignificant if damping is adequate, because the initial amplitudes fall within the range of the still increasing centrifugal force.
- The normal force from a given cargo unit is reduced by an order of magnitude of around 5%. This has a negative impact both on friction and on stableness.

1.3 Lane changing

Rapid lane changing is also included among problematic driving situations. It may be concluded from publications[2] that conventional lane changing for a truck involves a lateral offset of 3.75 m and a lane change lasting 4 seconds may be regarded as very rapid.

Analysis of such a lane change is based on the driven geometric contour of the vehicle's center of gravity. This contour is often represented by an "inclined sine curve". There are, however, also other meaningful mapping functions. The second time derivative of the mapping function reveals the profile of the transverse acceleration of the vehicle, which may be equated with a good approximation to the centrifugal force. Representing centrifugal force more accurately with the assistance of the curve radius does not reveal any appreciable difference with the conventionally slender curve profiles.

Inclined sine curve: $$y = \frac{y_{max}}{x_{max}} \cdot x - \frac{y_{max}}{2\pi} \cdot \sin\left(\frac{2\pi}{x_{max}} \cdot x\right) [m]$$

Alternative lane changing profile: $$y = y_{max} \cdot \left(1 - e^{-s \cdot x}\right)^z \ [m]$$

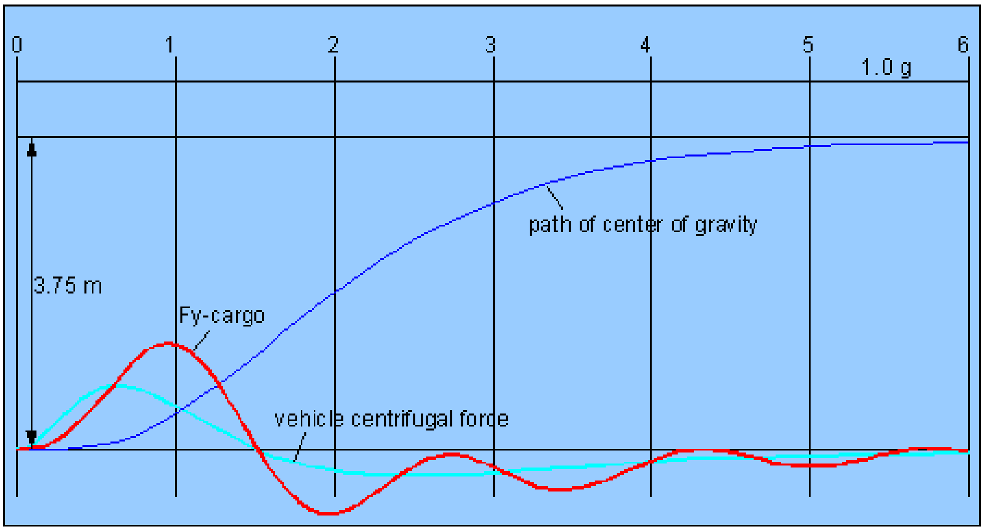

Figure 5: Lane changing according to the alternative calculation profile

[2] Paper by Schulze, Becke in VerkehrsRechtsReport, publ. ZAP-Verlag, Münster, 4/2007

The lane change shown in Figure 5 was calculated using the alternative, asymmetric profile. In order to maintain comparability with the inclined sine curve in the first half, the lane changing time of 4 seconds is determined by doubling the time required for half the transverse distance.

With a half-value period of 2 seconds, this is already a very rapid lane change. The transverse force acting on the cargo reaches just about 0.3 g after around one second and is already appreciably out of phase with the distinctly smaller centrifugal force. The rolling oscillations are pronounced. There is, however, no discernible resonant buildup.

A series of test runs with modified input variables allows the following general conclusions to be drawn:

- Even extremely short lane changing times do not give rise to transverse acceleration values of greater than 0.5 g. A lane changing time of for example 3 seconds (half-value period 1.5 seconds) generates 0.48 g. However, according to available sources, this time cannot be achieved with a truck.
- Reduced damping of rolling oscillations brings about a slight increase in transverse acceleration values, while greater rolling stiffness reduces the values.
- The reduction in normal force is negligibly small because the rolling angles reach only small values.
- The distinct phase shift is indicative of the onset of resonance between the rolling oscillations and steering movements. Resonance ought to become distinctly perceptible once half the rolling period is equal to the half-value period of the lane change. The result would be a larger transverse acceleration value in the second semi-oscillation of the rolling process.

1.4 Obstacle avoidance

The stated observation of the onset of resonance during quick lane changes led to an investigation of an "obstacle avoidance" maneuver similar to lane changing in which the transverse distance is distinctly smaller, meaning that the achievable lane changing time may also be shorter. Since no observations under practical conditions were available, experienced truck drivers were asked whether it would be possible to change lanes in a loaded truck with a sideways offset of one meter within 1.5 seconds. The answers were in the affirmative, but the drivers' "gut feeling" was that this was a borderline maneuver.

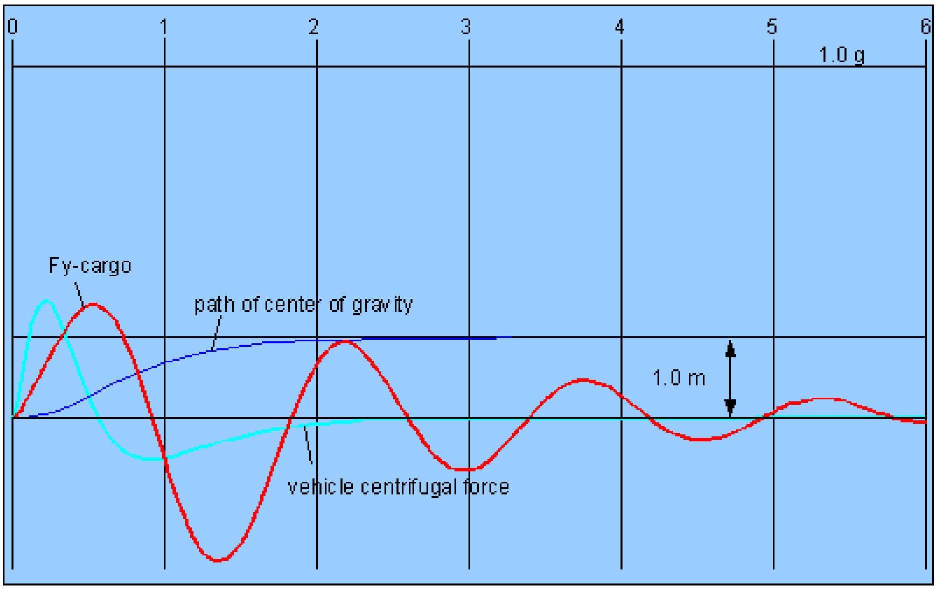

Figure 6: Obstacle avoidance action of 1.0 m with a half-value period of 0.75 s

The results are in line with expectations. Figure 6 shows the evasive maneuver of 1 meter sideways with a half-value period of 0.75 seconds. The forces are shown normalized to acceleration values in the unit g. The transverse force on the cargo is distinctly out of phase with the centrifugal force with an oscillation offset of approx. $\pi/2$. This means that at least the first maximum of the transverse force, corresponding to 0.32 g, is made up solely of the downhill force and tangential forces, because the centrifugal force is equal to zero at that point. The second maximum is greater in absolute terms than the first and reaches 0.41 g. At this maximum too, the tangential acceleration from the rolling oscillation predominates. The rise from 0.32 g to 0.41 g is attributable to resonant excitation.

It may thus be concluded that while extremely short avoidance maneuvers similar to lane changing (objects on the roadway) do not necessarily cause transverse acceleration values of greater than 0.5 g, they may involve significant rolling acceleration components which must be taken into account inter alia for assessing the rolling factor.

1.5 Rolling factor

The rolling factor was introduced by VDI Guideline 2700 and "*takes account of dynamic tipping moments brought about by a non-steady-state lateral inclination or by angular acceleration from rolling oscillations of the vehicle about its longitudinal axis*". This description is unambiguous and complete. It relates to dynamic tipping moments.

The quasistatic tipping moment on a cargo unit is calculated from the force F_x or F_y acting at its center of gravity multiplied by the distance d of this force vector from the effective tipping axis (Figure 7 left). The force F_x or F_y is also the force which must be taken into account when securing the cargo against sliding.

Dynamic tipping moments in the longitudinal or transverse directions arise from the rotational inertia of the cargo mass against the angular acceleration caused by pitching or rolling oscillations. These give rise to a "dynamic" turning moment on the cargo unit in question which is independent of the location of the tipping axis and center of gravity of the unit (Figure 7 right). The following applies to the magnitude of this additional moment:

Transverse direction: $M_{dyn} = -J \cdot \ddot{\phi}$ [N·m]

Longitudinal direction: $M_{dyn} = -J \cdot \ddot{\psi}$ [N·m]

For homogeneous or hollow cubical cargo units, the moment of rotational inertia J about an axis through the center of gravity may be approximately determined by:

$$J_{homogeneous} \approx m \cdot \left(\frac{b^2 + h^2}{12} \right) [\text{kg·m}^2] \qquad J_{hollow} \approx m \cdot \left(\frac{(b+h)^2}{12} \right) [\text{kg·m}^2]$$

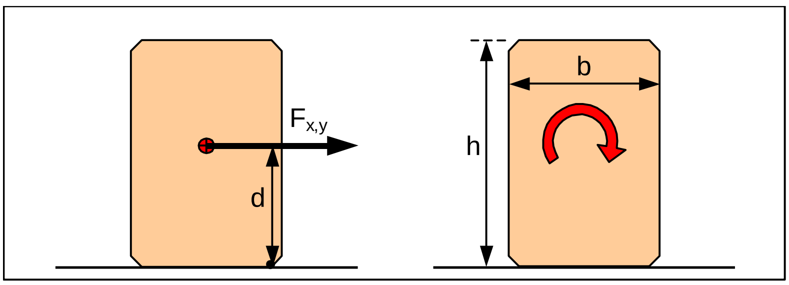

Figure 7: Static and dynamic tipping moment

The applicable VDI Guideline 2700, Sheet 2 requires an allowance of 0.2 g for securing cargo units at risk of tipping on the assumption of sideways acceleration of 0.5 g. The rolling factor is explicitly not used for testing and dimensioning the securing against sliding of these cargo units at risk of tipping.

In order to verify the reasonableness of the order of magnitude of this rolling factor, the rotational inertia of a cargo unit at risk of tipping ($h \geq 2 \cdot b$) of maximum height (road transport: h = 3 m) is converted into an allowance w for transverse acceleration.

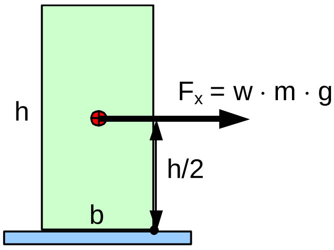

Figure 8: Conversion of a rotational tipping moment into a rolling factor

Tipping moment from rotational inertia:

$$M_{dyn} = m \cdot \ddot{\phi} \cdot \left(\frac{b^2 + h^2}{12}\right) \quad \text{through} \quad m \cdot \ddot{\phi} \cdot \left(\frac{(b+h)^2}{12}\right) \ [\mathrm{N{\cdot}m}]$$

Equivalent tipping moment: $M_{equ} = w \cdot m \cdot g \cdot h / 2 \ [\mathrm{N{\cdot}m}]$ (w = rolling factor)

Acceleration allowance, homogeneous: $$w = \frac{m \cdot \ddot{\phi} \cdot (b^2 + h^2)/12}{m \cdot g \cdot h / 2} = \ddot{\phi} \cdot \frac{h \cdot 1.25}{6 \cdot g} = 0.0637 \cdot \ddot{\phi}$$

Acceleration allowance, hollow: $$w = \frac{m \cdot \ddot{\phi} \cdot (b + h)^2)/12}{m \cdot g \cdot h / 2} = \ddot{\phi} \cdot \frac{h \cdot 2.25}{6 \cdot g} = 0.1147 \cdot \ddot{\phi}$$

The angular acceleration from rolling oscillations or pitching oscillations to be used may be estimated from the described simulation calculations. Since these simulations may all be considered borderline situations, the results are usable for the stated purpose.

Full braking, cornering and lane changing exhibit maximum angular acceleration values of 0.5 s^{-2} or lower[3]. Only the avoidance maneuver exhibits distinctly larger values of up to 1.3 s^{-2}. It must, however, be borne in mind that, due to phase shift, these elevated angular acceleration values without exception occur together with relatively small centrifugal forces, such that the effective transverse acceleration values still remain far below 0.5 g. This offsets the need for a larger rolling factor.

If generous angular accelerations of up to 1 s^{-2} are used for the calculation, this justifies an acceleration allowance for securing against tipping of 0.064 to 0.115 g. In the vast majority of cases of full braking, cornering or lane changing maneuvers, however, half this value would be sufficient. A requirement still remains for real world measurements.

[3] The greater excursion on full braking at time 3.4 s occurs simultaneously with the discontinuation of the braking force, i.e. when the vehicle comes to a standstill.

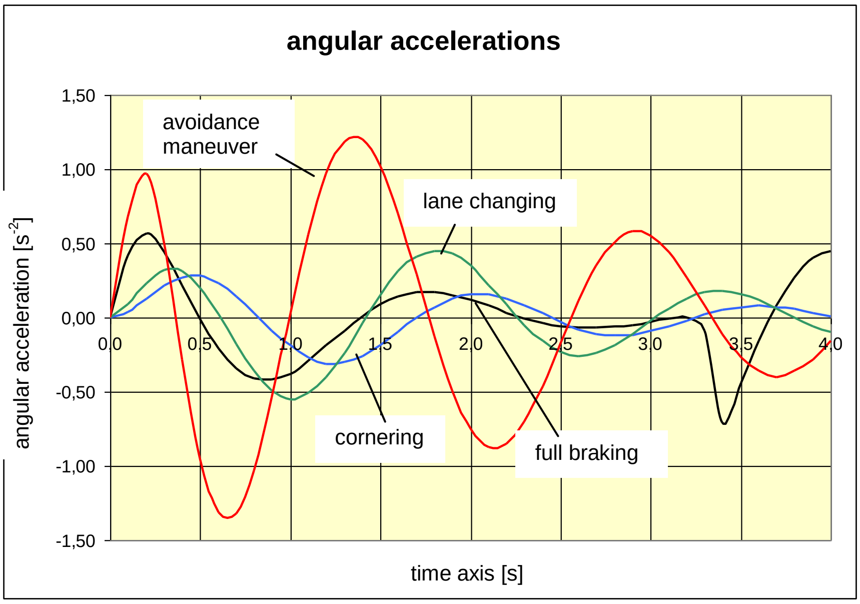

Figure 9: Angular acceleration values for pitching or rolling oscillations

For securing unstable cargo units against tipping, the relatively recent draft of DIN EN 12195-1 (01/2009) only requires 0.6 g to be assumed as transverse acceleration, i.e. an allowance of 0.1 g. An equivalent pitching factor does not apply in the longitudinal direction of the vehicle.

The conclusion which may be drawn from the above considerations is as follows: It is possible to support the assumption of 0.1 g as a reasonable acceleration allowance for securing cargo units at risk of tipping against tipping. The allowance should, however, also be used for securing such cargo units against tipping in the longitudinal direction.

2. Conventional rules and calculation methods

Conventional calculation methods distinguish between direct lashing and tie-down lashing and apply both kinds of securing to the aims of securing items against sliding and tipping. Virtually no account is taken in the calculations of compaction, which is often encountered in road freight transport in the form of strapping or bundling.

Conventional calculation methods are briefly presented below, with emphasis on the general conditions and simplifying assumptions which apply. In order to clarify the most recent trends, the calculation conventions from three regulatory texts will be presented and, if necessary, compared:

Source [1] VDI 2700, Sheet 2, November 2002,
Source [2] DIN EN 12195-1, April 2004,
Source [3] DIN EN 12195-1, January 2009.

The systems of notation for the operands in the formulae vary between the stated regulatory texts. In order to facilitate comparability, the following standard system is used for the purposes of this presentation:

F = force in the securing device assumed in the calculation [kN]
Fx, Fy, Fz = force components in the system of coordinates of the loading area [kN]
L = length of the securing device [m]
X, Y, Z = geometric components of length L [m]
m = cargo mass [t]
f_x, f_y = coefficients of acceleration in the longitudinal and transverse directions
μ = coefficient of friction
n = number of parallel securing devices

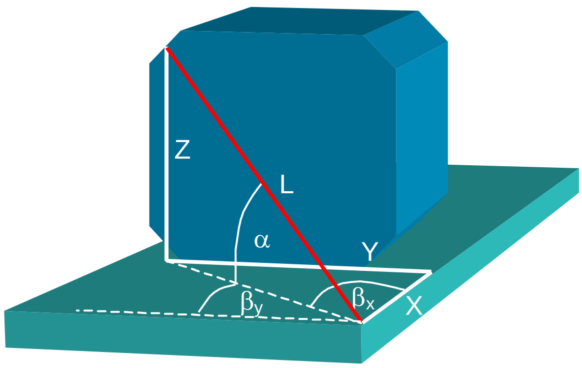

Figure 10: Spatial coordinates of a securing device

2.1 Direct lashing

Direct securing connects the cargo and the vehicle with securing devices which are capable of transferring forces directly by tensile, compressive or shear stress. According to conventional assessment, this type of securing is limited solely by the strength capacity of these securing devices and the participating fastening points on cargo unit and vehicle.

2.1.1 Securing against sliding

The balances compare the load assumption related to the cargo mass with the friction plus the action of the securing devices. Friction is generally calculated using the coefficient of dynamic friction and the normal force = cargo weight. The action of the securing devices is made up of the horizontal force component plus the vertical force component multiplied by the coefficient of dynamic friction.

In source [1], the balance for the transverse direction reads:

$$m \cdot g \cdot f_y \leq m \cdot g \cdot \mu + n \cdot F \cdot \frac{Y + \mu \cdot Z}{L}$$

The balances in the longitudinal direction look similar. The balances are solved to find n or F in order to determine the necessary amount of securing.

The stated approach is basically also used in the other sources. Sources [2] and [3] do not, however, specify force components with the assistance of the length components, but instead with corresponding angular functions of the lashing angles α and β_x or β_y. The relations are:

$$X/L = \cos\alpha \cdot \cos\beta_x,\ \ Y/L = \cos\alpha \cdot \cos\beta_y,\ \ Z/L = \sin\alpha$$

Sources [2] and [3] additionally indicate a variant of the balance for securing against sliding with direct lashing and blocking, in which the blocking force BC is added to the securing forces without taking account of the stiffness of the blocking.

$$m \cdot g \cdot f_y \leq m \cdot g \cdot \mu + n \cdot F \cdot \frac{Y + \mu \cdot Z}{L} + BC$$

As to coefficients of friction, source [3] makes use of "standard values" which are reduced by a factor of 0.85 in the sliding balance. These standard values are means from series of measurements of coefficients of static friction, which were multiplied by 0.925, and coefficients of dynamic friction, which were divided by 0.925, in each case for the same material pair. The balance in the transverse direction then reads:

$$m \cdot g \cdot f_y \leq m \cdot g \cdot 0.85 \cdot \mu + n \cdot F \cdot \frac{Y + \mu \cdot 0.85 \cdot Z}{L}$$

2.1.2 Securing against tipping

Securing against tipping is only tested if the inherent stableness of a cargo unit is insufficient. The test criteria for inherent stableness are thus an integral part of the calculation model.

According to source [1], the test criteria for sufficient inherent stableness, where L, B, H = length, breadth, height of a (cubical) cargo unit with a center of gravity in the geometric center and $f_w = 0.2$ (rolling factor) are:

Testing of tipping stableness in transverse direction B: $H > (f_y + f_w)$,

Testing of tipping stableness in longitudinal direction L: $H > f_x$

The balance in the transverse direction reads:

$$m \cdot g \cdot (f_y + f_w) \cdot H/2 \leq m \cdot g \cdot B/2 + n \cdot F \cdot \frac{H \cdot Y + B \cdot Z}{L}$$

The balances in the longitudinal direction look similar, but without the rolling factor. The balances are solved to obtain n or F in order to determine the necessary amount of securing. The possibility of an asymmetric center of gravity is not addressed separately.

Source [2] does not provide an adequate treatment of securing against tipping with the assistance of direct lashing. The test criteria for tipping stableness are as in [1], but with lack of clarity with regard to the coefficient of transverse acceleration to be used in the test. No separate tipping balance is stated, however, but instead a system of inequalities, which are intended to demonstrate both sliding and tipping resistance in the event of securing with diagonal lashing combined with blocking.

The system of inequalities is, however, only appropriate for demonstrating securing against sliding, albeit while disregarding the different load generation of lashing and blocking (see 2.1.1). It is unusable for demonstrating securing against tipping and readily leads to erroneous results. In the original text, the formulae for the transverse direction with n = 2 lashings per side are:

Formula 17: $BC + 2 \cdot (\cos\alpha \cdot \cos\beta_y + \mu_D \cdot \sin\alpha) \cdot LC > (c_y - \mu_D \cdot c_z) \cdot m \cdot g$

Formula 18: $2 \cdot (\cos\alpha \cdot \cos\beta_y + \mu_D \cdot \sin\alpha) \cdot LC > \frac{d-b}{h} \cdot (c_y - \mu_D \cdot c_z) \cdot m \cdot g$

Formula 19: $BC > \frac{h-d-b}{h} \cdot (c_y - \mu_D \cdot c_z) \cdot m \cdot g$

BC = blocking force [kN]
α = vertical lashing angle
β = horizontal lashing angle
μ_D = coefficient of dynamic friction
LC = lashing capacity (admissible lashing force) [kN]
c_y = coefficient of transverse acceleration
c_z = coefficient of vertical acceleration
m = cargo mass [t]
g = acceleration due to gravity = [m/s^2]

The variables d, b, w and h are illustrated in Figure 11. Figure 11 shows a securing situation as presented in VDI Guideline 2700, Sheet 2, Figure 14.

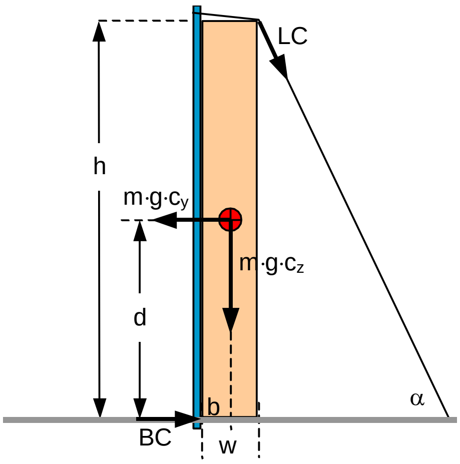

Figure 11: Application of testing of securing against tipping to DIN EN 12195-1

Formula 17 corresponds to the conventional approach to demonstrating sliding resistance. Formula 18 is intended to demonstrate securing against tipping by lashing. Blocking makes no contribution to tipping resistance. Formula 19 is superfluous in this respect.

An example calculation shows the unsuitability of formula 18 with the values m = 10 t, c_y = 0.7, c_z = 1, h = 3.0 m, d = 1.5 m, b = 0.25 m, w = 0.5 m, α = 64°, β_y = 0°, μ_D = 0.4, n= 2

$$LC_{min} = \frac{(d-b) \cdot (c_y - \mu_D \cdot c_z) \cdot m \cdot g}{2 \cdot h \cdot (\cos\alpha \cdot \cos\beta_y + \mu_D \cdot \sin\alpha)} = \frac{1.25 \cdot 0.3 \cdot 10 \cdot 9.81}{6 \cdot (0.44 + 0.36)} = 7.66 kN$$

According to source [1], the tipping balance reads:

$$m \cdot g \cdot (f_y + f_w) \cdot H/2 \le m \cdot g \cdot B/2 + n \cdot F \cdot \frac{H \cdot Y + B \cdot Z}{L}$$

The following replacements are made for comparability: H/2 = d, B/2 = b, H = h, B = w. The angle α provides the variables Y, Z and L. Z = h = 3.0 m, L = h/sinα = 3.34 m and Y = L · cosα = 1.46 m.

$$LC_{min} = \frac{m \cdot g \cdot \left((f_y + f_w) \cdot d - b\right) \cdot L}{n \cdot (h \cdot Y + w \cdot Z)} = \frac{10 \cdot 9.81 \cdot (0.7 \cdot 1.5 - 0.25) \cdot 3.34}{2 \cdot (3 \cdot 1.46 + 0.5 \cdot 3)} = 22.29 \text{ kN}$$

The formula according to source [2] provides a result in this example which is substantially too small. The difference becomes all the more serious, the greater is the coefficient of friction μ_D, which fundamentally has no place in a tipping balance.

Source [3] contains a reduced rolling factor, the calculation being intended to be carried out with a coefficient of acceleration c_y = 0.6 for cargo units at risk of tipping and direct lashing. Testing of tipping stableness is, however, calculated with c_y = 0.5 and c_z = 1:

Testing of tipping stableness in transverse direction $b : d > c_y : c_z$,

The recently included tipping balance is equivalent to the one stated in source [1]. The partially unsuitable system of inequalities, which is already to be found in source [2], is however additionally still present.

2.2 Tie-down lashing

Tie-down lashing is conventionally treated for the most part such that only the vertical component of the pre-tensioning force is regarded either as enhancing friction or as increasing tipping stableness. Tie-down lashings generally do not have a horizontal lashing angle and are moreover virtually always applied in the transverse direction of the vehicle.

2.2.1 Securing against sliding

Source [1] provides the sliding balance in the notation agreed above:

$$m \cdot g \cdot f_y \le m \cdot g \cdot \mu + 2 \cdot n \cdot F \cdot \mu \cdot \frac{Z}{L}$$

The balance may be solved to find n or F. A minimum pre-tensioning force is recommended for F, but it should not exceed 50% of LC. In the case of one-sided pre-tensioning, it is recommended initially to apply a higher force on the tensioning side so that, on equalization during the journey, the overall loss of pretension is not so high. No k-factor for friction losses during pre-tensioning is provided. The coefficient of dynamic friction is used for μ.

Source [2] adopts this approach, but in the case of one-sided pretension uses the k-factor which replaces the factor 2 (two legs to be tied down per string of lashing).

$$m \cdot g \cdot f_y \le m \cdot g \cdot \mu + k \cdot n \cdot F \cdot \mu \cdot \frac{Z}{L}$$

In the case of one-sided pre-tensioning, k = 1.5, in the case of two-sided pre-tensioning k = 2. The coefficient of dynamic friction is likewise used. In this approach, the two different horizontal components of the lashing-loops are disregarded. The difference between these forces could be introduced into the balance. The two forces amount to:

Pre-tensioning side: $n \cdot F \cdot \frac{Y}{L}$ Opposite side: $n \cdot (k-1) \cdot F \cdot \frac{Y}{L}$

Source [3] again turns away from the k-factor, but does introduce a safety factor $f_s = 1.1$, which increases the necessary pre-tensioning force by 10%. The balance reads:

$$m \cdot g \cdot f_y \leq m \cdot g \cdot \mu + \frac{2}{f_s} \cdot n \cdot F \cdot \mu \cdot \frac{Z}{L}$$

This agreement corresponds to a k-factor of 1.82. The reason stated for the safety factor in [3] is, however, not pre-tension loss by friction but instead calculation uncertainty.

Source [3] moreover contains a sliding balance for the combination of tie-down lashing and blocking, again disregarding the load-bearing behavior of the two different securing means.

2.2.2 Securing against tipping

Source [1] interprets the effect of the tie-down lashing as increasing the normal force onto the loading area, which increases the stabilizing moment with the half breadth as lever. Horizontal force components of the tie-down lashings here cancel each other out.

$$m \cdot g \cdot (f_y + f_w) \cdot H/2 \leq m \cdot g \cdot B/2 + 2 \cdot n \cdot F \cdot \frac{Z}{L} \cdot B/2$$

A similar formula is stated for the longitudinal direction, which however assumes longitudinally oriented lashing loops. Securing effects against tipping in the longitudinal direction by transverse tie-down lashings are not addressed.

Source [2] treats the forces on the two sides of the cargo unit separately in the tipping balance and assumes the less favorable case in which the external force acts towards the pre-tensioned side. The expanded balance in the agreed notation reads:

$$m \cdot g \cdot (f_y + f_w) \cdot H/2 \leq m \cdot g \cdot B/2 + n \cdot (k-1) \cdot B \cdot F \cdot \frac{Z}{L} + n \cdot (k-1) \cdot H \cdot F \cdot \frac{Y}{L} - n \cdot H \cdot F \cdot \frac{Y}{L}$$

If this balance is solved to get $n \cdot F$, the following is obtained:

$$n \cdot F = \frac{m \cdot g \cdot \left((f_y + f_w) \cdot H/2 - B/2\right)}{(k-1) \cdot B \cdot \frac{Z}{L} - (2-k) \cdot H \cdot \frac{Y}{L}}$$

This formula for determining the necessary amount of securing has the unfortunate characteristic that, on the right-hand side, the denominator of the fraction may readily assume a value of zero. This gives rise to a result tending towards infinity on the left-hand side. If the denominator is equal to zero, then a combination of the variables B, Z, H and Y is present in which each further added tie-down lashing cancels out the vertical component, which increases tipping stability, due to the difference between its horizontal components, i.e. it has no effect.

Anticipating section 3, it should be noted at this point that "permitting" a small offset, shift or tipping of the cargo unit under the external load reverses the forces. The balance then reads:

$$m \cdot g \cdot (f_y + f_w) \cdot H/2 \leq m \cdot g \cdot B/2 + n \cdot B \cdot F \cdot \frac{Z}{L} - n \cdot (k-1) \cdot H \cdot F \cdot \frac{Y}{L} + n \cdot H \cdot F \cdot \frac{Y}{L}$$

Once solved for n · F, the following is obtained:

$$n \cdot F = \frac{m \cdot g \cdot \left((f_y + f_w) \cdot H/2 - B/2\right)}{B \cdot \frac{Z}{L} + (2-k) \cdot H \cdot \frac{Y}{L}}$$

The difference in the results is demonstrated with an example. The values are: H = Z = 2.75 m, B = 1.5 m, Y = 0.5 m, L = 2.8 m, F = 2.5 kN, m = 6 t

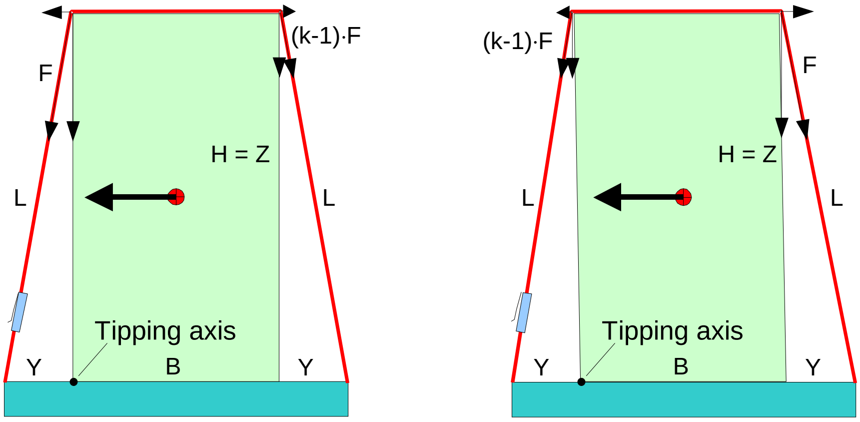

Figure 12: Tipping balance according to source [2] on the left; alternative on the right

According to source [2] on the left in Figure 12, 10 tie-down lashings are required for securing against tipping. If the calculation is performed with changed belt tensions as on the right in Figure 12, 3 tie-down lashings are enough. In this case too, the distribution of belt tensions corresponds to the decline in force due to friction at the top edges of the cargo unit. Elongation of the belts as a result of the slight shift of the cargo unit and the favorable increase in force has again not been taken into account in this comparison.

$$n = \frac{m \cdot g \cdot \left((f_y + f_w) \cdot H/2 - B/2\right)}{F \cdot \left((k-1) \cdot B \cdot \frac{Z}{L} - (2-k) \cdot H \cdot \frac{Y}{L}\right)} = \frac{6 \cdot 9.81 \cdot (0.7 \cdot 1.375 - 0.75)}{2.5 \cdot (0.5 \cdot 1.5 \cdot 2.75/2.8 - 0.5 \cdot 2.75 \cdot 0.5/2.8)} = \frac{12.508}{1.228} = 10$$

$$n = \frac{m \cdot g \cdot \left((f_y + f_w) \cdot H/2 - B/2\right)}{F \cdot \left(B \cdot \frac{Z}{L} + (2-k) \cdot H \cdot \frac{Y}{L}\right)} = \frac{6 \cdot 9.81 \cdot (0.7 \cdot 1.375 - 0.75)}{2.5 \cdot (1.5 \cdot 2.75/2.8 + 0.5 \cdot 2.75 \cdot 0.5/2.8)} = \frac{12.508}{4.297} = 3$$

If the breadth B is reduced to 0.5 m, the number of tie-down lashings required according to the calculation in source [2] tends towards infinity, while taking a small movement of the cargo into account results in 7 tie-down lashings.

Source [3] no longer uses the k-factor and so avoids the unfortunate calculation for securing against tipping. The approach from source [1] is adopted with the following modifications:

- coefficient of transverse acceleration $f_y = 0.5$, if pretension $F_T = S_{TF}$.
- coefficient of transverse acceleration $f_y = 0.6$, if pretension $F_T = 0.5 \cdot LC$.
- a safety factor $f_s = 1.1$ leads to a required increase in pretension or the number n.

$$m \cdot g \cdot f_y \cdot H/2 \leq m \cdot g \cdot B/2 + \frac{2}{f_s} \cdot n \cdot F \cdot \frac{Z}{L} \cdot B/2$$

Source [3] additionally contains a calculation approach which tests the compacting action of tie-down lashings on a group of tall, narrow unit loads standing adjacent one another with regard to securing against tipping. This approach may be regarded as pointing the way towards the computational evaluation of compaction measures.

3. Extended approaches

An extended approach should certainly take account of the movement of cargo units associated with direct securing, without which a deformation of the securing devices and thus the necessary generation of force is not possible. If it is possible in this way to define "acceptable" cargo movements, identical movements could also be permitted for arrangements with frictional securing (tie-down lashings). This could in turn lead to a re-assessment of this securing method, possibly with more favorable results.

3.1 Cargo movement

Cargo movements which result in necessary deformation (usually changes in length) of securing devices, primarily involve sliding or slight tilting and many and varied changes in the shape of the unit itself which may be superimposed on the first two types of movement mentioned. Sliding is generally irreversible, while slight tilting is reversed once the external tipping moment has disappeared.

Changes in the shape of the cargo unit may be elastic, but there is usually a considerable plastic component to the change. Since extreme loads occur as individual events in road transport, permanent deformation of the loading arrangement is more readily acceptable because checking and remedying the securing arrangement is immediately and straightforwardly possible.

This assessment may be explained by making reference to maritime transport, where extreme loads are associated with storms and rough seas. These conditions may last for an extended period, as a result of which an unforeseeable succession of extreme loads may occur and checking and remedying cargo securing arrangements during this period can often only be carried out at risk to life.

Figures 13 and 14 show the basic cargo movements, while some further cases could certainly be added to the deformations shown in Figure 14.

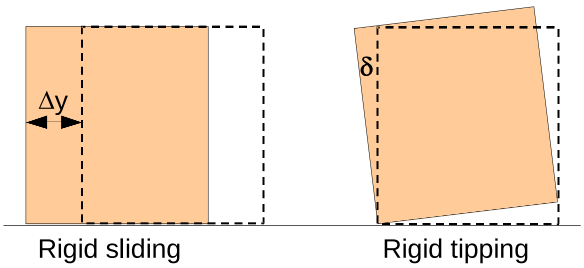

Figure 13: Types of movement of rigid cargo units

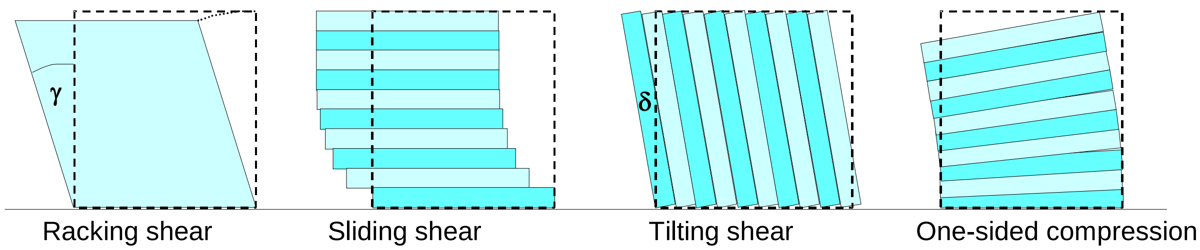

Figure 14: Types of movement of flexible loading arrangements

Which kinds and amounts of movement of secured cargo can be tolerated in road transport has not previously been specified or recommended in any regulatory texts, guidelines or similar documents. Some influencing variables which can play a part in such considerations will thus firstly be mentioned.

The **frequency** of a load causing cargo movement could influence the tolerable extent such, that rare events, such as full braking or extreme centrifugal forces, are allowed larger movements than would be accepted in normal travel, since it is reasonable after an extreme event to drive into a parking place and check the securing arrangements.

The **nature of the movement** likewise has an influence on its tolerable extent. A sliding offset movement shifts the center of gravity of the cargo and may moreover exceed the loading area limit. Racking (shear deformation) of compact cargo units, on the other hand, may remain within the elastic deformation range and is therefore less critical. Racking of bundled units, however, is quasi-plastic and ought therefore to be limited in a similar way to sliding offset. Tilting of a cargo unit should be limited to very small angles due to the low damping of the tilting process.

The **direction of movement** is influential. Movements in the longitudinal direction are less critical than movements in the transverse direction, because the latter may exceed the admissible breadth of the vehicle and may also have a major effect on the transverse center of gravity.

In order to gain an impression of the magnitude of cargo movements which have not previously been scientifically accepted, it is worthwhile analyzing direct securing methods which have conventionally been regarded as "good". This does not, however, mean that the identified movements may thus generally be recommended as being tolerable.

The proper and rational way of defining and recommending tolerable cargo movements should ultimately proceed by applying numerical criteria:

- admissible sliding/racking in the longitudinal direction and transverse direction with regard to cargo geometry and center of gravity,
- admissible tilting angle with regard to dynamic loading of the securing devices,
- general dynamic overstressing the capacity of securing devices.

If this is to be achieved, typical loading situations must be fully calculated. In order at this point to provide an initial impression of the order of magnitude of previously accepted cargo movement, one example of conventional direct lashing will be presented, using some formulae taken from section 3.2 below.

A cargo unit with the dimensions breadth = 2.1 m, height = 2.5 m is secured in the transverse direction onto the vehicle with diagonal synthetic fiber belts which are attached to the upper corners of the unit. The geometric components of the belts are X = 1.0 m, Y = 2.3 m, Z = 2.5 m, while the loaded length L = 3.54 m. The belts have an LC = 25 kN and an elongation of 3.75% once the LC is reached. The spring constant of the belt is thus:

$$D = \frac{100 \cdot 25}{3.75 \cdot 3.54} = 188 \text{ kN/m}$$

The belts are pre-tensioned to 2.5 kN. The sliding balance (not shown here) shows that LC of the belts is just reached. The change in length of the belts must then be:

$$\Delta L = \frac{\Delta F}{D} = \frac{22.5}{188} = 0.12\text{m}$$

In order to achieve this elongation, the upper corner of the cargo unit must be deflected to the side by the amount ΔY by undergoing a sliding or racking movement or by a combination of both movements:

$$\Delta Y = \Delta L \cdot \frac{L}{Y} = 0.12 \cdot \frac{3.54}{2.3} = 0.18 \text{ m}$$

The lateral movement of 0.18 m transverse relative to the vehicle under extreme loading would appear to be acceptable and, under certain circumstances, for example with elastic deformation, an even larger deformation could be accepted.

3.2 Deformation and force development of securing devices

Breaking the direction of action of securing devices down into Cartesian components has already been presented in section 2. In geometric terms, each securing device has the components X, Y and Z assigned to it, with the Pythagorean relation to its length L:

$$L = \sqrt{X^2 + Y^2 + Z^2} \text{ [m]}$$

Cargo movement or deformation is expressed by specific, small changes ΔX, ΔY and ΔZ in these components. Change in length ΔL is then precisely calculated by:

$$\Delta L = \sqrt{(X + \Delta X)^2 + (Y + \Delta Y)^2 + (Z + \Delta Z)^2} - L \text{ [m]}$$

If the individual changes are small relative to the total length L, the change in length ΔL may in most cases sufficiently accurately also be determined by an approximation equation as follows:

$$\Delta L = \frac{X \cdot \Delta X + Y \cdot \Delta Y + Z \cdot \Delta Z}{L} \text{ [m]}$$

This approximation equation should, however, not be used if for example component Y is close to zero and a cargo shift involving a ΔY is to be investigated. This case in particular applies to steep tie-down lashings.

If force development by securing devices as a result of cargo movement or deformation is to be determined, it is advisable to assign a "personal" factor to each securing device which makes it possible to calculate the force change ΔF directly from the change in length ΔL. This factor is the spring constant D conventionally used in industrial mechanics. The relation

$$D = \frac{\Delta F}{\Delta L} \text{ [daN/m] or [kN/m] applies.}$$

The spring constant includes the cross-section, modulus of elasticity and length of the securing device as influencing variables in accordance with Hooke's law:

$$\Delta F = \frac{A \cdot E}{L} \cdot \Delta L \text{ [daN] or [kN]} \qquad \text{with} \quad D = \frac{A \cdot E}{L} \text{ [daN/m] or [kN/m].}$$

ΔF = force change in the securing device [daN] or [kN]
A = cross-section of securing device [cm^2]
E = modulus of elasticity [daN/cm^2] or [kN/cm^2]
L = loaded length of securing device [m]
ΔL = change in length of securing device [m]

The spring constant is not generally stated in data provided by manufacturers of securing equipment. There are several ways of determining the spring constant depending on the information which is available about the securing material.

Manufacturers of ropes, chains and belts often state that the elongation of the material is P % when the material is loaded with a specific force F (LC is usually stated here). The force F stated corresponds to the force change ΔF starting from zero load and assuming approximately linear load/elongation behavior, which is generally the case in the limited load range between pretension F_0 and admissible load LC. The spring constant is thus:

$$D = \frac{100 \cdot \Delta F}{P \cdot L} \text{ [daN/m] or [kN/m]}$$

If the length of the lashings is initially unknown, a normalized spring constant D_N for the unit length of 1 m may be used for the lashing material, the following applying:

$$D_N = \frac{100 \cdot \Delta F}{P} \text{ [daN] or [kN] with } D = \frac{D_N}{L} \text{ [daN/m] or [kN/m].}$$

The spring constants of pressure transferring element, e.g. squared lumber, may be estimated from the three variables cross-section A, modulus of elasticity E and length L:

$$D = \frac{A \cdot E}{L} \text{ [daN/m] or [kN/m].}$$

The spring constant of end walls and stanchions on a truck loading area may be estimated by regarding them as beams clamped on one end. The spring constant is then calculated on the basis of the bending equation for cantilevers:

$$D = \frac{3 \cdot E \cdot I}{10^4 \cdot d^3} \text{ [daN/m] or [kN/m]}$$

E = modulus of elasticity [daN/cm^2] or [kN/cm^2]
I = geometrical moment of inertia in clamping point [cm^4]
d = lever length of clamped beam [m]

In practice, however, this solution will provide excessively large values for D, since the wall or stanchion is not clamped absolutely rigidly, the load-bearing substructure instead likewise deforming. It is therefore advisable to establish a correction factor by making representative measurements or to determine the entire spring constant experimentally. The same also applies to sidewalls of truck loading areas which are differently designed and often receive some support over their length from the roof structure. A simple formula can no longer be stated in this case.

The following formula applies to devices arranged in parallel: $D = D_1 + D_2 + ... + D_n$

The following formula applies to devices arranged in series: $1/D = 1/D_1 + 1/D_2 + ... + 1/D_n$

3.3 Horizontal components of tie-down lashings

Almost all conventional approaches to calculation disregard the horizontal components of an inclined tie-down lashing. If identical pre-tensioning on both sides is assumed, these components cancel each other out. A one-sided tensioning device provides a resultant which, while acting favorably on one side, acts unfavorably on the other. If, for safety's sake, the calculation is carried out with the unfavorable side, the peculiarity occurs which does not correspond to reality, as was described in section 2.2.2.

Tied-down cargo units do in fact move under the influence of external forces, so changing the geometry of the tie-down lashing with various consequences:

- The tie-down lashing is (slightly) lengthened with a (small) increase in overall forces.
- In the event of transverse movement of the cargo unit, distribution of forces on both sides of the tie-down lashing adapts to the ratio of forces determined by friction at the deflection points. A "favorable" resultant of the transverse components is inevitably obtained.
- In the event of longitudinal movement of the cargo unit (assuming a transverse tie-down lashing), a "favorable" horizontal component of the lashing force likewise arises on both

sides, which increases continuously with the movement and only remains constant when the belt slips on top of the cargo unit.

The smallest possible ratio of forces between the two sides of a transverse tie-down lashing and thus the transverse component with the greatest possible securing effect may be sufficiently reliably calculated using the known Euler's relation.

$$\frac{F}{F_0} = e^{-\mu \cdot \gamma}$$

F and F_0 = forces on both sides of the tie-down lashing [daN] or [kN]
e = Euler's constant (2.718281828)
μ = coefficient of friction at the deflection point
γ = angle of deflection (change of direction) of the tie-down lashing [rad]

The magnitude of the transverse component, which has a securing effect, of a tie-down lashing is, however, crucially determined by the vertical lashing angle α. At $\mu = 0.25$, the transverse component is at its greatest with $\alpha = 45°$ on both sides. The overall ideal vertical lashing angle α is, however, always at distinctly higher values, since the main action of a tie-down lashing depends on the friction-enhancing vertical component which, as is known, increases with the sine of the lashing angle α.

There is no transverse component with a purely vertical tie-down lashing. In such a case, only once an appreciable displacement is reached, are favorable transverse components obtained on both sides, the magnitude of which is, however, not limited by the friction between lashing device and the cargo. This is a borderline case of direct securing, i.e. it is based on a different effect compared to the transverse component from Euler's friction.

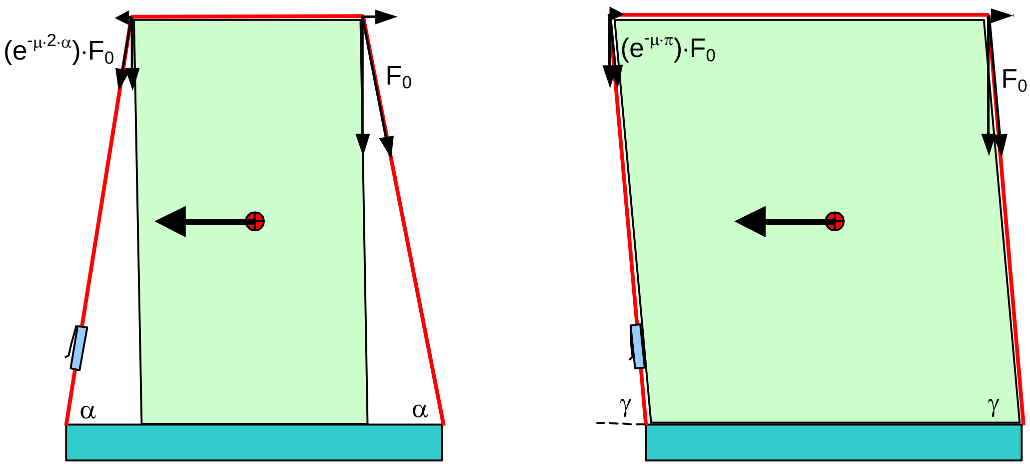

Figure 15: Transverse components of transverse tie-down lashings

The transverse component of the tie-down lashing on the left in Figure 15 amounts to $F_0 \cdot (1 - e^{-\mu \cdot 2 \cdot \alpha}) \cdot \cos\alpha$. The transverse component of the tie-down lashing on the right in Figure 15 amounts to $F_0 \cdot (1 + e^{-\mu \cdot \pi}) \cdot \cos\gamma$. In order to clarify the orders of magnitude, an example with plausible values is obtained with: $F_0 = 2$ kN, $\mu = 0.25$, $\alpha = 75°$, $\gamma = 85°$.

Transverse component on left in Figure 15 = 0.25 kN; transverse component on right in Figure 15 = 0.13 kN.

Neither value takes account of the possible elongation of the lashing belt by the change in geometric conditions. This entails more complex calculation, which is not shown here.

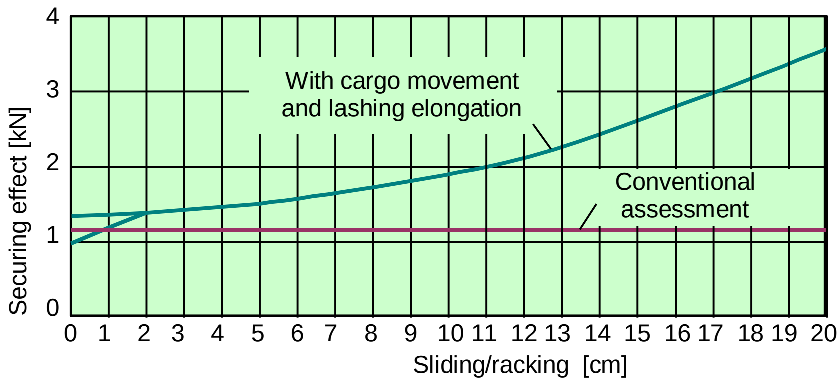

Figure 16: Securing effect in the transverse direction of a tie-down lashing with α = 80°

Using a tie-down lashing with α = 80° by way of example, Figure 16 compares the securing effect according to a conventional assessment and the enhanced securing effect taking account of the transverse component and the increase in force due to a change in the geometry as a result of a sliding or racking movement.

Up to a transverse movement of approx 1.9 cm, the effects differ depending on the direction of loading. In the event of loading towards the pre-tensioned side, smaller values are initially obtained. From 1.9 cm, the belt slips and the greatest possible transverse component, arising from Euler's friction between belt and cargo, takes effect. In the event of loading on the opposite side, the belt slips from the start, so providing the greatest possible transverse component. It is thus clear that while the usual one-sided tensioning device does overall impair securing, so entirely justifying the k-factor, it does not bring about any detrimental asymmetry in the securing effect.

The further increase is attributable to increasing elongation of the belt. Already with a transverse movement of 15 cm, the securing effect achieved in this example is a good twice that obtained in the conventional assessment.

3.4 Semi-dynamic approach to calculation

Taking account of cargo movement and elastic deformation of the securing devices makes approaches to calculation other than those conventionally used necessary, since the input variables for simple equilibrium methods are initially unknown. They are only obtained in the course of a relatively long calculation process. A distinction may be drawn between a semi-dynamic and a fully dynamic approach.

The term "semi-dynamic" is here intended to indicate that while cargo movements are indeed taken into consideration, they are only used to determine the different loads assumed by the securing devices up until equilibrium with the external force. Further dynamic effects arising from the cargo having started to move are ignored and are still to be covered by the safety margin between LC and breaking load.

3.4.1 Iterative method

In an iterative calculation method, the cargo is moved stepwise under the action of an external force in a predetermined manner (sliding, tipping, racking). For each step, on the basis of this movement, the deformation of the securing devices involved and the force it has developed is determined. The developed force is added to the initial pretension and is broken down as a securing force into Cartesian components.

These components are included in the securing balances against horizontal sliding/racking and against tipping. Horizontal components act directly against sliding/racking and vertical components act via the coefficient of friction, while against tipping the horizontal and the vertical components are introduced into the calculation with the associated levers to the applicable tipping axis. If the securing arrangement consists of tie-down lashings, a similar procedure must be applied which also takes account of Euler's friction at the edges of the cargo unit.

The calculation is terminated once equilibrium with the external force or with the external moment is reached. It may then be established which loads have been assumed by the individual securing devices and how large the cargo movement or deformation has become. The suitability or admissibility of the securing arrangement in question may be assessed on the basis of these two items of information. In addition, the results may point to possible improvements and increases in efficiency for a securing arrangement.

If reliable experience relating to additional dynamic loads is available, the iterative calculation procedure may also be terminated a little later than when static equilibrium is reached. The amount of this allowance could be selected to be approximately proportional to the cargo movement which has occurred up to equilibrium. This would enable a pragmatic step to be taken towards a dynamic approach to calculation.

Obviously, this calculation process can only be carried out with a programmed computer and thus cannot be considered for on the spot dimensioning or verification of a securing arrangement, but it may be considered for individual planning of critical transport operations or for designing standard securing arrangements for long-term use.

3.4.2 Selective methods

A selective approach to direct securing starts from the securing device in the arrangement in question which is definitely the first to reach its admissible load (LC). On the basis of the deformation of the selected securing device, this loading is converted into a cargo movement/deformation. The latter is used to determine the deformations and loads developed by all further securing devices and these values are input into a balance.

The balance indicates whether the securing arrangement is adequate or requires further improvement. It also makes it possible to identify which securing means may possibly be only inadequately contributing to securing.

For frictional securing, i.e. tie-down lashing, the selective approach should be modified such that the calculation starts from the maximum tolerable cargo movement and uses this as a basis for determining the changes in length, forces and geometric components of the lashings and inputs these values into the sliding and tipping balances.

These selective methods involve less complex calculation and may in most cases also be calculated manually. They are thus also suitable for staff training. A result, one has oneself calculated, carries more weight than a result passively accepted from a computer.

3.5 Fully dynamic approach to calculation

A fully dynamic approach to calculation should not only determine the different loads assumed by the securing devices until equilibrium with the external force, but should also identify the additional forces which are required to bring a cargo unit which has started to move/deform back to a standstill. Such an approach can virtually only be implemented with the assistance of a simulation which models the limited time period of the critical driving situation. The effects of buildup phases and of pitching and rolling oscillations outlined in section 1 can be taken into account in this way.

One essential item of information from typical, calculated cases is the magnitude of the stated additional forces and their dependency on the parameters involved, such as friction coefficients and the elasticity of cargo securing devices. Evaluating such items of information should allow for all-inclusive allowances to be defined and recommendations for laying out securing arrangements to be drafted.

4. Practical examples

4.1 Direct securing in the longitudinal direction with belts and timber blocking

This example is intended to demonstrate the incorrect assessment which may be made of a cargo securing arrangement when using the conventional calculation method where securing devices with different spring constants are loaded in parallel. Considering the cargo movement may reveal the error.

A heavy cargo unit is secured against sliding in the transverse direction with transverse, criss-crossed chains and against sliding in the longitudinal direction with longitudinal criss-crossed belts. The securing arrangement is largely symmetrical. Due to the greater requirement for securing against forward sliding, blocking against the end wall of the loading area with two pieces of squared timber is additionally provided. The two lengthwise wooden shores press against transverse pieces of squared timber of identical cross section. The cargo unit itself stands on flat wooden boards.

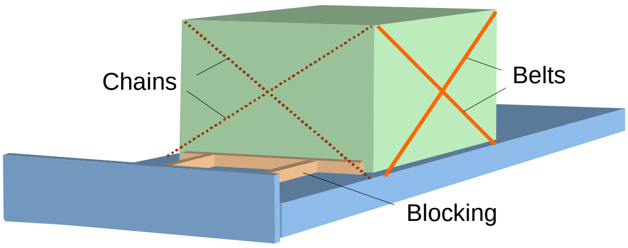

Figure 17: Securing a heavy item against forward sliding

This example solely investigates securing against forward sliding. At best, the chains contribute to securing in the longitudinal direction by their pretension which increases friction. However, since they are only pulled "hand tight", this is not taken into account.

Cargo mass m = 18 t, dimensions l x b x h = 5.0 x 2.4 x 1.9 m, $\mu = 0.3$

4 belts lengthwise: X = 4.9 m, Y = 0.0 m, Z = 1.8 m; L = 5.22 m

LC = 25 kN, elongation at LC = 4.5%, pretension F_0 = 2.5 kN

2 lengthwise wooden shores: Cross-section 9.6 x 9.6 cm, LC = 2 · 92 kN, L = 2.2 m

2 wooden crosspieces: Cross-section 9.6 x 9.6 cm, LC = 2 · 27.65 kN

The external force is determined as conventionally agreed.

$$F_X = c_x \cdot m \cdot g = 0.8 \cdot 18 \cdot 9.81 = 141.3 \text{ kN}$$

Conventional assessment of the securing against forward sliding:

$$F_X \leq \mu \cdot m \cdot g + 2 \cdot LC_{blocking} + 2 \cdot LC_{belt} \cdot \frac{X + \mu \cdot Z}{L} \text{ [kN]}$$

$$141.3 < 0.3 \cdot 18 \cdot 9.81 + 2 \cdot 27.65 + 2 \cdot 25 \cdot \frac{4.9 + 0.3 \cdot 1.8}{5.22} = 53.0 + 55.3 + 52.1 = 160.4 \text{ kN}$$

According to the conventional assessment, this securing exceeds requirements by a good 13%, if, as conventional, the load LC is used for each securing device.

Taking account of cargo shifting:

In the present case, the blocking is clearly the more rigid securing device. Using the previously described selective method, the distance by which the cargo has shifted forward when the blocking has reached the LC of 55.3 kN is first calculated. The spring constant of the blocking is required for this purpose.

The blocking consists of two parallel lengthwise wooden members, each 2.2 m in length, with two serial wooden crosspieces, each 9.6 cm in thickness. The modulus of elasticity is 1100 kN/cm^2 when loaded lengthwise and 100 kN/cm^2 when loaded perpendicular to the grain. The following spring constants are thus obtained:

Lengthwise wooden member: $D_L = A \cdot E / L = 9.6^2 \cdot 1100 / 2.2 = 46080$ kN/m

2 wooden crosspieces: $D_Q = A \cdot E / L = 9.6^2 \cdot 100 / 0.192 = 48000$ kN/m

Arranged in series, the following value is obtained for one wooden member, $D = D_1 \cdot D_2 /(D_1 + D_2) = 23510$ kN/m, the value for both of the wooden members being twice that, or 47020 kN/m. This results in the cargo shifting by $\Delta L = \Delta F / D = 55.3 / 47020 = 0.0012$ m = 1.2 mm. Since the wooden members are placed horizontally, this is also the offset ΔX of the cargo unit.

As a result of the offset ΔX, the rearward pointing belts are extended by the amount

$$\Delta L = \Delta X \cdot \frac{X}{L} = 0.0012 \cdot \frac{4.9}{5.22} = 0.0011\,\mathrm{m}$$

The spring constant of the belts amounts to $D_G = \Delta F / \Delta L = 25 / (5.22 \cdot 0.045) = 106$ kN/m. As a result of the elongation by 0.0011 m, the rearward pointing belts increase their tensile force by $\Delta F = D_G \cdot \Delta L = 106 \cdot 0.0011 = 0.117$ kN from 2.5 to 2.617 kN. The forward pointing belts reduce their tensile force by the same amount from 2.5 to 2.383 kN. They thus still pull forward and assist the longitudinal force F_X. Both values are inserted into a balance:

$$F_X \le \mu \cdot m \cdot g + 2 \cdot LC_{blocking} + 2 \cdot F_{belt\,h} \cdot \frac{X + \mu \cdot Z}{L} + 2 \cdot F_{belt\,v} \cdot \frac{-X + \mu \cdot Z}{L}$$

$$141.3 > 0.3 \cdot 18 \cdot 9.81 + 2 \cdot 27.65 + 2 \cdot 2.617 \cdot \frac{4.9 + 0.3 \cdot 1.8}{5.22} + 2 \cdot 2.383 \cdot \frac{-4.9 + 0.3 \cdot 1.8}{5.22} = 109.8\ \mathrm{kN}$$

The balance is not at equilibrium. The shortfall is a good 22%. In the stated load case, the blocking would be overloaded and could even reach the critical buckling load. By way of remedy, it is proposed to construct the blocking with four instead of two lengthwise wooden members, so that they can alone provide forward securing together with the friction.

4.2 Direct securing with chains at unfavorable angles

This example is intended to demonstrate that a tolerable cargo movement may improve an unfavorable geometry of the securing arrangement in such manner that securing becomes possible without exceeding admissible forces, while the conventional calculation yielded a negative result.

A heavy cargo unit is secured at the front and back with diagonal chains against sliding in the longitudinal and transverse directions. Unfavorably, the chains have very small longitudinal components. The cargo unit itself stands on flat wooden boards. This example solely investigates securing against rearward sliding.

Cargo mass m = 12 t, dimensions l x b x h = 4.0 x 2.3 x 2.2 m, $\mu = 0.3$

2 chains at the front: X = 0.5 m, Y = 2.4 m, Z = 2.2 m; L = 3.294 m

LC = 30 kN, elongation at LC = 1.5%, pretension F_0 = 1.0 kN

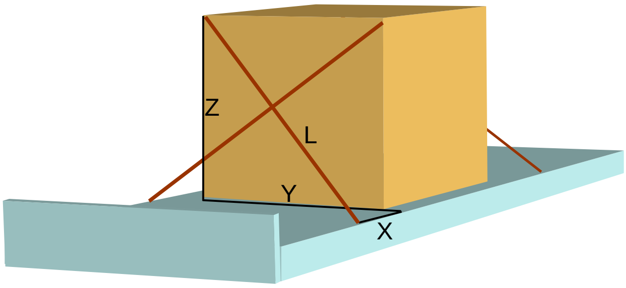

Figure 18: Securing a heavy item against rearward sliding

The external force is determined as conventionally agreed.

$$F_X = c_x \cdot m \cdot g = 0.5 \cdot 12 \cdot 9.81 = 58.9 \text{ kN}$$

Conventional assessment of the securing against rearward sliding:

$$F_X \leq \mu \cdot m \cdot g + 2 \cdot LC_{chain} \cdot \frac{X + \mu \cdot Z}{L} \text{ [kN]}$$

$$58.9 > 0.3 \cdot 12 \cdot 9.81 + 2 \cdot 30 \cdot \frac{0.5 + 0.3 \cdot 2.2}{3.294} = 35.3 + 21.1 = 56.4 \text{ kN}$$

According to the conventional assessment, securing is not adequate, with a shortfall of a good 4%.

Taking account of cargo sliding:

If the cargo is permitted to slide longitudinally, the X component of the two chains grows and thus so too does their securing effect. The exact sliding distance to reach static equilibrium may only be calculated by elaborate adaptation of the balance formula to include the spring constant of the chains. The relationship becomes clearer if the sliding distance until the LC of the chains is reached is calculated and it is then checked whether the balance is fulfilled.

The spring constant of the chains amounts to $D_{Ch} = \Delta F / \Delta L = 30 / (3.294 \cdot 0.015) = 607$ kN/m. On increasing the force from a pretension of 1.0 kN to LC = 30 kN, the chains lengthen by 29 / 607 = 0.04778 m to 3.342 m. As a result, the X component of the chains increases to

$$X = \sqrt{3.342^2 - 2.4^2 - 2.2^2} = 0.754 \text{ m}$$

The cargo unit has shifted rearward by approx. 25 cm. The adapted balance now reads:

$$58.9 < 0.3 \cdot 12 \cdot 9.81 + 2 \cdot 30 \cdot \frac{0.754 + 0.3 \cdot 2.2}{3.342} = 35.3 + 25.4 = 60.7 \text{ kN}$$

The balance is achieved with a surplus of a good 3%. While the improvement is indeed not enormous, the positive trend is indicative for such securing situations. Static equilibrium is reached with a smaller shift of the cargo unit. However, when force equilibrium is reached, the unit has reached a distinguished speed relative to the loading area which must be absorbed by an excess of securing force. This observation leads to a dynamic analysis which is not to be carried out here.

4.3 Securing against sliding in the longitudinal direction with slack tie-down lashing

This example is intended to demonstrate that a tolerable cargo movement may re-establish the securing effect in the longitudinal direction of a transverse tie-down lashing, even if the pretension has first completely disappeared due to settling of the cargo.

Three loaded pallets each of a mass of 1.0 t are placed side by side on the loading area and are tied down with two belts. The dimensions of the units are 1200 x 800 x 1200 mm. The complete package has a height h of 1.2 m and a breadth b of 2.4 m.

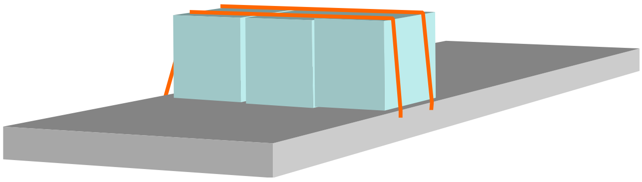

Figure 19: Tie-down lashing of box pallets

The belts run virtually vertically on the external sides. At the beginning of the journey, the belt pretension amounts on average to around F_0 = 2 kN. The coefficient of friction relative to the loading area is assumed to be μ = 0.38 and that between the belts and cargo to be μ_L = 0.25. This example solely investigates securing against forward sliding.

The external force is determined as conventionally agreed.

$$F_X = c_x \cdot m \cdot g = 0.8 \cdot 3.0 \cdot 9.81 = 23.5 \text{ kN}$$

Conventional assessment of the securing against forward sliding:

$$F_X \leq \mu \cdot m \cdot g + 4 \cdot F_0 \cdot \mu \text{ [kN]}$$

$$23.5 > 0.38 \cdot 3.0 \cdot 9.81 + 4 \cdot 2 \cdot 0.38 = 11.2 + 3.0 = 14.2 \text{ kN}$$

According to the conventional assessment, securing is not adequate, with a shortfall of just about 40%.

Taking account of cargo movement:

In order to simplify the following presentation, it is assumed that the pretension has declined to zero by the three pallets having moved closer to one another. If the cargo is permitted to shift forward in the event of an extreme load, belts on the top of the cargo are dragged along without slipping until an equilibrium is reached between the longitudinal component of the belt force F_X and friction on the top of the cargo $F_Z \cdot \mu_L$. The resultant maximum movement distance is calculated:

$$\Delta X = h \cdot \frac{F_X}{F_Z} = h \cdot \mu_L = 1.2 \cdot 0.25 = 0.30 \text{ m}$$

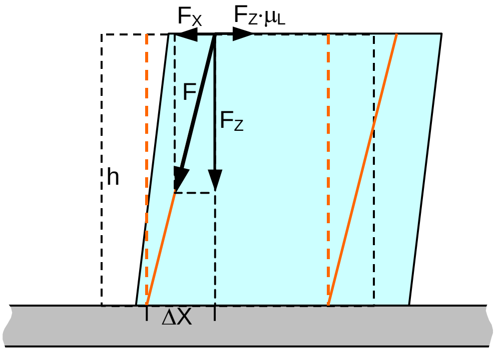

Figure 20: Cargo sliding and racking by ΔX in the longitudinal direction

This distance may be made up of the sliding of the pallets and shear deformation. The belts have lengthened in this state by the amount ΔL.

$$\Delta L = 2 \cdot \left(\sqrt{h^2 + \Delta X^2} - h \right) = 2 \cdot \left(\sqrt{1.2^2 + 0.3^2} - 1.2 \right) = 0.074\,m$$

Lengthening results in force being developed, but this is not uniformly distributed over the length of the belt. The horizontal central part maintains a force which is reduced pro rata with Euler's friction losses at the edges relative to the force in the external parts of the belt.

Each belt has an LC = 25 kN and an elongation of 3.5% when LC is reached. The spring constant of the vertical parts of the belt amounts to $D_v = \Delta F / \Delta L = 25 / (0.035 \cdot 1.2) = 595$ kN/m, that of the horizontal parts of the belt only $D_h = \Delta F / \Delta L = 25 / (0.035 \cdot 2.4) = 298$ kN/m. On this basis, the individual changes in length, which must add up to the total change in length ΔL, may be determined with the initially unknown force F in the external parts of the belt.

$$\Delta L = 2 \cdot \frac{F}{D_v} + e^{-\mu_L \cdot \pi/2} \cdot \frac{F}{D_h} = F \cdot \left(\frac{2}{D_v} + \frac{0.675}{D_h} \right)$$

$$F = \Delta L \cdot \left(\frac{D_v \cdot D_h}{2 \cdot D_h + 0.675 \cdot D_v} \right) = 0.074 \cdot \frac{177310}{998} = 13.15\,kN$$

The belts thus reach a force in the external parts of a good 13 kN on both sides. The horizontal central parts just about reach 9 kN. The longitudinal and vertical components of the external forces are calculated for the sliding balance.

$$F_Z = F \cdot \frac{h}{\sqrt{h^2 + \Delta X^2}} = 13.15 \cdot \frac{1.2}{1.237} = 12.76\,kN$$

$$F_X = F_Z \cdot \mu_L = 12.76 \cdot 0.25 = 3.19\,kN$$

These values are used to make up a sliding balance.

$$F_X \le \mu \cdot m \cdot g + 4 \cdot F_X + 4 \cdot F_Z \cdot \mu \ \text{[kN]}$$

$$23.5 < 0.38 \cdot 3.0 \cdot 9.81 + 4 \cdot 3.19 + 4 \cdot 12.76 \cdot 0.38 = 11.2 + 12.8 + 19.4 = 43.4\ \text{kN}$$

The balance is amply met with a surplus of just about 85%. The cargo will in fact thus not have to slide or distort over the entire 30 cm in order to reach an equilibrium of forces. This example is an impressive demonstration of the securing potential which can be obtained from limited cargo movement. The question as to whether the middle unit remains secured by friction relative to the other two external units and to the loading area is left unanswered here.

4.4 Securing against sliding in the transverse direction by slack tie-down lashings

This example is intended to demonstrate that a tolerable cargo movement may also reestablish the securing effect of slackened tie-down lashings in the transverse direction. The same circumstances as in the preceding example are used for this purpose.

The external force is determined as conventionally agreed.

$$F_Y = c_y \cdot m \cdot g = 0.5 \cdot 3.0 \cdot 9.81 = 14.7\ \text{kN}$$

Conventional assessment of the securing against sideways sliding:

$$F_Y \le \mu \cdot m \cdot g + 4 \cdot F_0 \cdot \mu \ \text{[kN]}$$

$$14.7 > 0.38 \cdot 3.0 \cdot 9.81 + 4 \cdot 2 \cdot 0.38 = 11.2 + 3.0 = 14.2 \text{ kN}$$

According to the conventional assessment, securing is not adequate, with a shortfall of a good 3%. Here too it is subsequently assumed that the pretension F_0 in the tie-down lashing has been lost due to the cargo units moving closer together.

Unlike in the preceding example, where the movement distance selected was the ΔX value at which the belts still just grip the surface of the cargo by friction, in this example the movement distance ΔY to be assumed was to be determined on the basis of the geometric conditions of the loading area.

The cargo package has a breadth of 2.4 m. At an assumed net breadth of the loading area of 2.5 m and with initially central loading, the pallets may slip by 5 cm to the side before coming into contact with the sidewalls. Racking (shear deformation) is additionally assumed, in which the upper edges of the units are pulled a further 10 cm to the side.

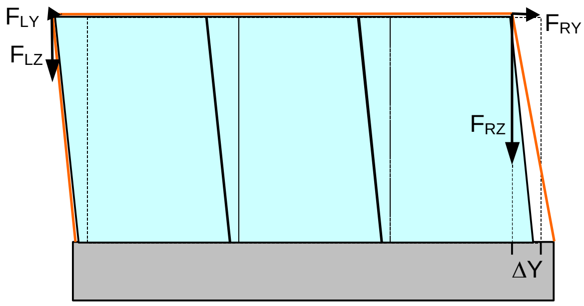

Figure 21: Cargo sliding and racking ΔY in the transverse direction

The lengthening of the belts arising from these movements is calculated:

Initial length of the external parts of the belt: $L_0 = \sqrt{1.2^2 + 0.05^2} = 1.20104\,\text{m}$

New length on the right: $L_R = \sqrt{1.2^2 + 0.20^2} = 1.21655\,\text{m}$

New length on the left: $L_L = \sqrt{1.2^2 + 0.10^2} = 1.20416\,\text{m}$

Change in length: $\Delta L = L_R + L_L - 2 \cdot L_0 = 0.0186\,\text{m}$

This change in length results in force being created in the belt, which is distributed such that the force F_R acts in the right-hand vertical part of the belt, while forces reduced by Euler's friction losses act in the horizontal central part and the left-hand vertical part. The individual changes in length must again correspond to the total change in length. Change of direction on the right amounts to α = 81° = 1.40 rad, while change of direction on the left amounts to β = 95° = 1.66 rad. The coefficient of friction μ_L = 0.25 applies as in the preceding example.

$$\Delta L = \frac{F}{D_v} + e^{-\mu_L \cdot \alpha} \cdot \frac{F}{D_h} + e^{-\mu_L \cdot (\alpha+\beta)} \cdot \frac{F}{D_v} = F \cdot \left(\frac{1.465}{595} + \frac{0.705}{298} \right) = 0.00483 \cdot F$$

$F = \Delta L / 0.00483 = 0.0186 / 0.00483 = 3.851$ kN

F_R = 3.851 kN with F_{RY} = 0.60 kN and F_{RZ} = 3.80 kN accordingly acts in the right-hand part of the belt
$F_L = 0.465 \cdot F_R$ =1.791 kN with F_{LY} = 0.16 kN and F_{LZ} = 1.78 kN acts in the left-hand part of the belt

The balance is completed with these values:

$$F_Y \leq \mu \cdot m \cdot g + 2 \cdot (F_{RZ} + F_{LZ}) \cdot \mu + 2 \cdot (F_{RY} + F_{LY}) \text{ [kN]}$$

$$14.7 < 0.38 \cdot 3.0 \cdot 9.81 + 2 \cdot 5.58 \cdot 0.38 + 2 \cdot 0.76 = 11.2 + 4.2 + 1.5 = 16.9 \text{ kN}$$

The balance is achieved with a surplus of 15%, any possible retention forces arising from the edge of the loading area having been disregarded. This example confirms that a slight cargo movement can compensate the complete loss of pretension. However, it must not be concluded on this basis that pre-tensioning is unimportant. Instead, the actual, more probable mode of action of a tie-down lashing should be pointed out, which does not correspond to that represented in the conventional approach to calculation. The conventional approach to calculation clearly does not adequately model the physics to be applied in this case.

It is not yet possible to state the extent to which the conventional approach to calculation may need to be modified on this basis.

5. Summary, outlook and objectives

5.1 Load assumptions

The considerations and investigations into load assumptions have shown that it is inadmissible to interpret the previously conventional values of 0.8 g forward and in each case 0.5 g rearward and to the sides directly as vehicle accelerations in the form of braking deceleration, starting up acceleration or centrifugal force of cornering. In particular, direct reference to maximum forces which can be transferred by the vehicle tires is inadequate. The forces acting on the cargo are significantly boosted by inclination of the loading area (pitching and rolling angles) and by tangential inertial forces from superimposed pitching and rolling oscillations. At the same time, the normal force which is of importance to friction and inherent stableness of cargo units is reduced, despite always being inserted in conventional securing balances with the full weight of the units.

These findings may mean, for forward load assumptions, that for a vehicle equipped with tires and a braking system capable of delivering braking deceleration of 0.8 g, the acceleration assumed for cargo securing must be 1.0 g.

5.2 Rolling factor

In this context, the rolling factor of 0.2 g set out in VDI Guidelines 2700, Sheet 2 was also investigated, which has previously been intended for use as an allowance for addition to the assumed transverse acceleration of 0.5 g for securing cargo units which are not inherently stable against tipping. It is correct that such an allowance is necessary due to the rotational inertia of units, since the turning moment to be derived there from is not covered by the conventional tipping moment composed of transverse force and lever relative to tipping axis. However, at 0.2 g, the allowance is set too high. An allowance of 0.1 g, as stated in the 2009 draft standard DIN EN 12195-1, would seem entirely adequate. Moreover, a corresponding allowance should also be used for cargo units which are at risk of tipping in the longitudinal direction of the vehicle.

If, including the allowance of 0.1 g, the stableness of a cargo unit is ensured by the inherent stableness, a tipping balance need not be calculated. Further investigations should, however, be carried out to clarify the extent to which this test for inherent stableness should take the actual moment of rotational inertia of the cargo unit and the decrease in normal force into account.

5.3 Conventional balance calculation methods

The analysis of conventional calculation methods compares and comments upon the following sources: VDI 2700, Sheet 2, November 2002, draft DIN EN 12195-1, April 2004, and draft DIN EN 12195-1, January 2009.

Some shortcomings and also errors were identified. The investigated methods are substantially limited, in the case of direct securing, to introducing the maximum loading capacity of the securing devices into the balance, while in the case of frictional securing (tie-down lashing) the vertical components of the nominal pretension of the lashings are used. Shortcomings in direct securing are that the cargo movements necessary for developing the force in the securing devices do not appear in any form, not even as a warning, in the regulatory texts and the shortfalls in securing arising from the different load-deformation behavior of securing devices arranged in parallel are also not mentioned.

With few exceptions, the horizontal components of tie-down lashings arising from frictional engagement are ignored. They are introduced statically into the test of securing against tipping in draft DIN EN 12195-1 of April 2004, in order to take account of the k-factor which had in the meantime been recognized as important. This k-factor takes account of the known circumstance of friction of a lashing at the cargo edges and thus of impaired pre-tensioning if, as is customary, only one side is pre-tensioned. However, for reasons which are not publicly known, the k-factor was dropped again from the later draft of DIN EN 12195-1 of January 2009 and would seem to have been replaced by a half-hearted safety factor.

The k-factor is certainly justified and important as an expression of general weakening of the tie-down lashing principle in the case of a one-sided tensioning device. The stated sources make no meaningful interpretation and use of the underlying causes because there was a desire for simple formulae and there was therefore no willingness to take account of the laws of force and deformation.

5.4 Cargo movement and deformation of securing devices

Direct securing, which is justifiably regarded as highly effective, inevitably involves movement and/or deformation of the cargo. However, tolerable limits for such movement or deformation are not specified anywhere. They nevertheless exist and agreement should be reached. It would then, however, be consistent to allow the same movement latitude to tied down cargo units. The potential of frictional securing, which is itself associated with drawbacks, could be further exploited as a consequence.

The deformation brought about by development of force in portable securing devices may straightforwardly be calculated with sufficient reliability. Obtaining comparable data for fixed fittings and attachments on loading areas, such as sidewalls, end walls and stanchions is problematic. Enquires may be made of the vehicle manufacturers.

Taking account of cargo movement and deformation of securing means, the calculation of which has been demonstrated in a number of examples, demonstrates the worrying order of magnitude of the above-stated shortcomings in conventional calculation methods in both the positive and the negative direction.

5.5 Calculation methods

The objective cannot be to replace the conventional, relatively simple formulae which can be presented in tabular form for dimensioning sufficient securing effort with more complicated calculations, at least not for day to day use. The obvious conclusions must, however, be drawn. In so doing, all the advantages of the extended approach should be used. It must thus already be acknowledged that the tie-down lashing principle will benefit. Its reputation is enhanced and lashing requirements may be reduced to what is physically justifiable. It is as yet unclear which new formulae and associated constraints may be used to achieve this objective.

A similar situation may apply to direct securing, if certain physical laws are more effectively applied than in the past. However, the homogeneity of securing arrangements, i.e. uniform load-deformation behavior and limitation of cargo movement may also give rise to restrictions.

Similar approaches to calculation which are yet to be developed may also be applied to compaction, i.e. bundling and strapping, and enable economically attractive securing systems.

Ultimately, there must be simple, practical and legally reliable rules and guidelines, which may be applied while taking the fullest possible account of the underlying physical phenomena.