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INFLUENCE OF FASTENING METHOD OF WHEELED ARMORED VEHICLE ON FLAT WAGON FOR FORCES TRANSMITTED BY LASHING ELEMENTS

Summary. During the transportation of cargo on the type Slmmps wagon platform, significant attention is paid to securing the transported load on a given wagon platform, primarily based on the imposed loading instructions. In the subject literature, there are no direct computational analyses on the forces acting on a specific type of cargo with a given mass, particularly under critical conditions. This article presents an analysis of the security of an armored vehicle in a platform wagon under critical conditions. Securing analysis was conducted for two fastening methods: the cross method (with a large strap angle relative to the direction of travel) and the straight method (with a small strap angle relative to the direction of travel). On the basis of these fastening methods, an assessment was made of the security of the transported cargo in the form of an armored vehicle. Armored vehicles are most commonly secured using the cross-fastening method with four securing straps. This study compares the force magnitudes concentrated on the securing straps in the cross-fastening and straight-fastening methods.
Keywords: fastening, lashing capacity, armored transporter

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1. INTRODUCTION

The correct securement of the transported load influences the safety of the transported cargo. It is a significant logistic element in a transport chain. Properly secured loads do not cause interruptions in the logistics chain caused by faulty cargo securing and do not threaten the transport infrastructure. The nature of the threat depends on the type and form of cargo transported, the means of transport, and the methods of securing the cargo for the duration of the transport [2, 3, 10, 15, 16, 19, 22].

Military operations units conduct various types of operational or training activities, most often outside of their permanent accommodation. In such cases, it becomes necessary to relocate units along with their combat equipment to the site of military operations, either at a firing range or to an area designated for operational use. Given the dimensions and quantity of military equipment, the most advantageous and cost-effective method of such transport is by rail. In railway transport, specific transportation procedures are applied, as regulated by the appropriate normative documents [14, 27, 29].

A significant advantage of using rail transport for military logistics is the availability of the necessary rail platforms designed for the transport of armored vehicles. One such platform is the Slmmps series platform, which is capable of operating throughout Europe. The general parameters of the Slmmps series rail platform allow for the loading and transportation of, among other things, armored vehicles equipped with tracks and those fitted with rubber wheels. Each wagon of this type of platform has 6 axles, a maximum load capacity of 60 tons, a loading length of 10.94 meters, a width of 3.09 meters, and a tare mass of 20 tons [29, 38].

Various means of transport are used to transfer military personnel and military equipment. For strategic transfer of armed forces, sea and air transport are used, and for operational and tactical transport, primarily land transport. Strategic transport occurs between seaports and airports. The delivery of military forces and resources to the ports of embarkation and from the ports of disembarkation to the areas of operational destination occurs primarily by land transport, such as road or rail. The choice of means of transport depends on the operational and economic criteria adopted. The most important include the time of movement forces and the cost of the transport operation. High-mass cargo transport irregularities and operational needs characterize military loads. In particular, there is a need to maintain appropriate precautions in preparation for transporting heavy loads of military technology. Depending on the nature and purpose, military loads are divided into [23, 29]:

– operational load – includes the transport of soldiers with their equipment;
– supply load – includes the transport of weapons, military equipment, and combat means;
– evacuation loads – related to the evacuation of unnecessary equipment, damaged or inoperable equipment, and packaging.

The choice of means of transport for military transport is one of the most important strategic decisions. When planned, military transport should primarily strive to achieve two goal functions: ensuring timely completion of the task and an acceptable level of incurred costs. Rail transport can transport large loads at speeds higher than the speed of trucks in road transport, which means that rail transport has greater inertia forces [1, 5, 8, 9, 17, 18, 24, 26, 30]. Failure to adequately secure the transported load can cause the destruction of the load itself, the rail infrastructure, and the death of people in the immediate vicinity and other technical means. Due to the specific nature of its construction, the transport of armored vehicle carriers causes numerous difficulties. Starting from the plan of the transportation organization, through the selection of the appropriate transport set, and focusing on its proper securing through its proper lashing on the flat wagon. Wheeled armored vehicles as a means of combat transport are characterized by high combat mobility, which is why they are very often used in military operations. On the other hand, on long railway routes, wagon platforms are used for them. Due to the specificity of this type of freestanding load on the wagon platform, they should be properly secured by general standards [4, 5]. An appropriate securing method should be provided for this type of load to ensure maximum safety during its movement. Therefore, in the present work, recommendations and guidelines have been taken into account with respect to the requirements imposed on railway transport contained in TSI-related regulations, the EN 12663-2:2010 railway standards [5], and national instructions Ch-6 [25]. Military combat vehicles are delivered to combat areas by rail or road transport, which is used in civilian transport. Armored vehicles are moved using wagon platforms or semitrailers [15, 20, 26, 30]. The general legal regulations in Poland regarding cargo securing are specified in the PN-EN 12195 standard, which is detailed with the principles defining cargo securing [4]. However, the requirements for securing military vehicles by rail transport are included in the "Instruction on the carriage of soldiers by rail", which provides examples of securing wheeled and tracked vehicles on rail wagons [20, 29]. When conducting military transports using rail transport, a variety of requirements must be met, stipulated by railway regulations and those that take into account the specific nature of military needs [4, 5, 8, 14, 20, 29]. When securing the cargo on a flat wagon, the main forces acting on the armored vehicle "Rosomak" are at work [14]. This is the main guideline taken into account in the calculations according to the PN-EN 12195 standard, which also describes the forces coming from the anchoring elements used in various methods of securing cargo (including strapping, anchoring, and blocking) [4, 5, 8]. During movement, the armored transporter is mainly exposed to mechanical impact in the form of inertia forces, which are the main forces that cause the transported load to slide off the flat wagon. Due to the nature of the impact, these loads are the impact of dynamic forces, mainly related to the change in the speed of the wagon itself and the change in the direction of movement on the track arcs. Dynamic forces acting on the armored transporter can be short-term in the form of an impact or quickly changing in the form of vibrations. This sensitivity of the load to mechanical impact can be minimized by appropriate immobilization using appropriate fastening elements. For practical fastening, there are fastening elements in the form of belt lashings, chain lashings, and various types of blocking elements with nonslip mats [4, 5, 9, 14, 17, 18, 21, 29, 30].

2. LOAD SECURITY RESEARCH

The protection of cargo has a significant impact on the handling and stability of wheeled transport. The center of gravity influences the stability of the means of transport. The study of the influence of the center of gravity on the level of active vehicle safety was carried out by Skrucany [31] and Azadi [2]. Depending on the method of securing the load, ready-made formulas are used to calculate the tension force, which was proposed by Vlkovsky [36].

Turanov presented research on the behavior of cargo on railway platforms in his work. He mainly focused on the longitudinal forces experienced by the cargo securing elements. This approach allowed for the determination of the displacement of cargo along the wagon, elongation, and the forces in flexible securing elements. To prevent displacement, the author proposed additional secure components, such as connectors with nails, to further secure the transported cargo on rolling stock against shifting [32, 33, 34, 35].

The most popular method of securing loads is using lashing belts or lashing chains. Additionally, to reduce the risk of shifting the transported load, carriers also use special slip mats and floor coverings under loads; the basic task is to increase the coefficient of friction. The EN 12195-2 standard specifies the safety requirements declared by the plastic lashing belts [4]. The lashing belt may be used only if it is undamaged and must have a visible, undamaged label. The inscriptions on the label must be clear so that the following markings can be read, in particular [7]:

– lashing capacity (LC [daN]) - this is the highest tensile force when lashing from point to point;
– nominal pretension force (STF [daN]) – this is the normal tension force that acts on the tensioning mechanism.

Information on issues related to loading work and securing cargo during transport is contained in various regulations, instructions, and legal documents, for example:

– instructions: loading service, handling of loading machines (technical and operational documentation, DTR);
– regulations: station, work stations, loading stations;
– railway loading regulations: PKP, RIV, SMGS;
– regulations on dangerous goods: RID (in rail transport), ADR (in road transport), IMO (in sea transport), IATA (in air transport);
– railway requirements with respect to the transportation of extraordinary shipments [17];
– PKP CARGO S.A. instruction on loading and securing freight shipments, Ch-6 [25];
– regulations for the transportation of military shipments by PKP Cargo S.A. (RPW);
– national and international standards: PN, ISO, EN, IMO, PRS, other countries;
– legal documents: Railway Acts (GCU/AVV), Road Traffic Act, International Agreements (AGC, AGTC), customs regulations, etc.

In rail transport, the primary instructions are the UIC guidelines:

– Loading guidelines, Section 1: Principles of UIC International Unions for Railway [18];
– Loading guidelines, Section 2: Goods, UIC International Unions for Railway [17].

In addition to the above standards, cargo securing is presented by several authors in monographic publications. One of them is T. Lerher [16], who discusses cargo securing and methods of securing from above using the strapping method; other authors include G. Grossmann and Kassmann [6], who discuss the methods of safe packaging and proper securing of transported cargo. The authors present mathematical models concerning the method of cargo securing. Other authors who write about the subject of cargo securing include the articles by J. Jagelcak and J. Gnap [11], J. Jagelcak and J. Sanigi [12], who, in addition to the securing technique, also discuss cargo areas.

In transport practice, those responsible for securing loads ofted do so based on available simplified securing tables [4, 5, 17, 18, 25, 29, 39]. The use of calculation formulas given in standards is very often not used due to the limited loading time. On the other hand, the EN 12195-2 standard uses a short calculation analysis using the shortened formulas included there. In the EN 12195-1 standard, the legislator specified mathematical formulas to select the number and capacity of the securing elements used to secure the load on the vehicle based on the maximum accelerations acting on the load during travel. It should be noted that the values provided in EN 12195 [4, 39] are mainly related to road transport. As mentioned above, they are universal to be applied in rail cargo transport. However, due to the specific nature of rail transport, the maximum accelerations that act on the load during transport on rail and road are different [1, 13].

This is due to the fact that for the transport of cargo by rail wagons, in addition to operating conditions such as braking, negotiating curves, etc., there occur cases that are unique to rail transport. One such case is the shunting of loaded wagons, during which significantly greater forces and overloads can occur than in other situations. According to the TSI regulations [25] and EN 12663-2:2010 [5], during the initial braking tests of wagons, forces of up to 3000 kN can occur. Therefore, in addition to the strength requirements imposed on the wagons, it is important to secure the cargo, especially the heavy cargo, properly. The document that comprehensively presents and describes issues related to cargo in rail transport, including shunting tests, calculations, protocols, etc., is the PKP CARGO S.A. instruction on loading and securing freight shipments [25].

The securing of military tracked and wheeled vehicles during transport within Poland and in countries that have ratified the NATO Standardization Agreement STANAG 2468 is regulated by the document "Technical Aspects of the Transport of Military Materials by Railroad" (AMovP-4). Additionally, during loading, the "UIC Loading Guidelines" provisions apply. The binding means for longitudinal and lateral securing include (as reusable binding means): a) steel chains, b) Steel cables, c) polyester fabric straps with an elongation of up to 7% under the allowed lashing capacity [29]. Instruction Ch-6 specifies that lashings made of natural or synthetic fibers, as well as steel ropes and chains, must have a breaking strength of at least 32000 daN, calculated for every 1000 kg of secured load transported on the wagon platform [25]. The binding means must have tensioning elements secured against accidental undoing. The binding means, tags, or labels must be marked with: LC = 1/2 break strength and the maximum allowed weight of wheeled and tracked vehicles. Belts and tapes must be protected against abrasion if necessary (Tab. 1) [29].

Tab. 1

Allowable fixing capacity of reusable bonding agents

Permissible attachment capacity of the attachment means	Permitted for	
	A wheeled vehicle with a mass of up to:	Tracked vehicle weighing up to:
25 [t]	8,5 [t]	11,0 [t]
40 [t]	15,0 [t]	25,0 [t]
80 [t]	28,0 [t]	52,0 [t]
100 [t]	38,0 [t]	60,0 [t]
Note: Permissible fastening capacity LC=1/2 of the breaking load		

3. CHARACTERISTICS AND FORCES AFFECTING THE TRANSPORTED LOAD

The load is worked with not only the force of its gravity but also inertia forces. These forces are particularly evident during braking, acceleration, and driving in track arcs. Additionally, the friction forces between the surface of the flat wagon and the load are not sufficient to protect the load from shifting. Elements such as tension belts or chains equipped with tensioning devices for fixed loads are used to secure loads on the flat wagon.

The legislators specified the inertia force based on the acceleration coefficient "c" in relation to the acceleration "g" [21]. In the standard [8] (Tab. 2) the acceleration "g" is assumed to be the product of the acceleration coefficient "c".

Inertia forces mainly perform the transported load. This is the force acting on the load with the mass of the load m_L [kg] or [t], multiplied by the acceleration "a" measured in [m/s²] (1):

$$Q_L = m_L \cdot g\ [N] \tag{1}$$

where: m_L – mass of the transported load, g – the acceleration of gravity

The acceleration value a is related to the acceleration of gravity a=g=9.81[m/s^2], multiplied by the coefficient "c" depending on the transport conditions according to Tab. 2, such as braking, driving in an arc, etc. [8]. These accelerations are expressed as the product of the acceleration of gravity "g" and the acceleration coefficient "c", (a = c·g) according to Tab. 2 [8].

Tab. 2

The CTU of force gravity guidelines

Mode of transport: Railway	Forward acting forces	Backward acting forces	Sideways acting forces
Rail cars subject to shunting [switching]*	a=4,0 g	a=4,0 g	a=0,5 (± 0.3)g
Combined transport**	a=1,0 g	a=1,0 g	a=0,5 (± 0.3)g
The above values should be combined with a static gravity force of 1.0 g acting downwards and a dynamic variation of (a) = ± 0.3 g.			
* Use of specifically equipped rolling stock is advisable (e.g., high-performance shock absorbers, instructions for shunting [switching] restrictions).			
**"Combined transport" means "wagons [cars] with containers, swap-bodies, semi-trailers, and trucks, as well as block trains (UIC and RIV)".			

To prevent the load from moving, it must be secured in the longitudinal and transverse directions according to the worst-case combination of acceleration (Tab. 2). The securing system must be designed to keep the inertia forces generated at the time of acceleration in each horizontal direction (longitudinal and transverse). In addition to these acceleration coefficients, the European standard also specifies the values of the friction coefficient "μ" for different materials in contact. The use of lashing straps is presented in the EN 12663-2 standard [5].

For long-distance transport of the armored vehicle type, flat wagons (Slmmps) are used (Fig. 1). Flat wagons are designed to transport concentrated loads weighing up to 60 tons for heavy vehicles on rubber wheels and for heavy-track vehicles on a wheelbase of 3,550 mm. Heavy vehicles on rubber wheels or tracked vehicles are loaded using side or front-loading ramps. The flat wagons can run at a speed of v_{max}=120 km/h. The data characterizing the flat wagon S (Slmmps) are given in Tab. 3 [38].

The flat wagon is generally used to transport the wheeled armored vehicle like the KTO 8x8 "Rosomak". It is a flat six-axle wagon with a loading length of L = 10.94 m, a construction weight of m_L = 20 tons, and a minimum track arc R = 75 m. The load limit for the A-class railway line is 41.5 tons. The flat wagon of the loading platform is covered with wooden beams.

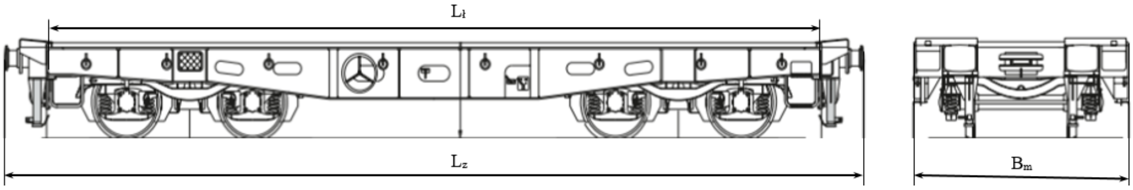


Fig. 1. Wagon platform type S (Slmmps) [38]

Tab. 3

Technical parameters of the flat wagon Slmmps [38]

The Flat Wagon Series	Designation	Type S (Slmmps)
Track width (wheel spacing)	B_t	1.44[m]
Length of wagon with bumpers	L_z	12.34[m]
Width of the flat wagon	B_w	3.13[m]
Cargo length	L_l	10.94[m]
Maximum speed	V	120[km/h]
Minimum trackarc	R	75.0[m]

The weight of the armored vehicle "Rosomak" is less than the maximum load capacity of the flat wagon, and the dimensions of the wagon's loading flat are sufficient to place the armored vehicle "Rosomak" on it. The loading length of the flat wagon is L_l = 10.9 m, with a loading width of H=3.0m. When the length of the armored vehicle "Rosomak" is L_R = 7.88 m and the width B_R = 2.83 m. The armored vehicle "Rosomak" is produced in several versions, differing in equipment. For the analysis, used the basic vehicle version without a turret (Fig. 3). Each version has the same chassis layout and towing eyelets as the basic version (Fig. 2) [37]. The weight of the transporter changes, and the weight of the base vehicle is m_L=22,500 kg and the combat weight of the turret is 2,900 kg (Tab. 4) [14].

a) Front view b) Cross type mount

Fig. 2. Towing eyelets in the armored vehicle at the front [37]

The wheeled armored vehicle "Rosomak" does not have special eyelets designed to secure the armored vehicle on the flat wagon. Only the towing eyelets are used to analyze attachment to the flat wagon (Fig. 2). The wheeled armored vehicle has two towing eyelets in the front (Fig. 3) and two towing eyelets in the back. In the front part, the towing eyelets are located at a height of h_1=1.24 [m], while the back towing eyelets are located at a height of h_2=0.9 [m] [14].

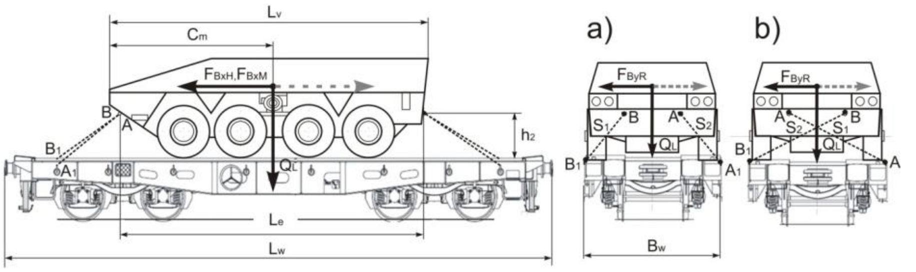


Fig. 3. The Armored vehicle on a flat wagon; a) straight fixing S_1, S_2; cross fixing S_1, S_2

Tab. 4

Details parameters dimension of the wheeled armored vehicle „Rosomak” [14]

Parameters name	Designation	Value
Mass of the wheeled armored vehicle	m_L	22 500[kg]
Length of the wheeled armored vehicle	L_V	7.88[m]
Width of the wheeled armored vehicle	B_w	2.83[m]
Min. height of the wheeled armored Vehicle	$H_ł$	2.14[m]
Vehicle height	H_p	3.30[m]
Height of the front towing eyelets	h_1	1.24[m]
Height of the back towing eyelets	h_2	0.90[m]
Spacing of the front towing eyelets	R_p	1.69[m]
Spacing of the back towing eyelets	R_t	1.69[m]
Distance between the towing eyelets	L_u	7.06[m]
Distance to the center of mass vehicle	C_m	3.76[m]

3.1. Analysis and selection of lashings for the armored transporter on the flat wagon

The analysis related to the selection of lashings for straight anchoring (Fig. 4a) and cross anchoring (Fig. 4b) consists of determining the value of the lashing capacity for each of the lashings placed at the front and the back of the armored vehicle on the flat wagon.

The input parameters needed to read the belt load are the mass of the loaded m_L, the angle α of the inclination of the lashing belt to the surface of the flat wagon, the coefficient of friction μ between the load and the surface of the flat wagon. The requirements related to securing loads are mainly based on the EN 12663-1:2010 standard [5]. The European standard is based on a coefficient based on empirical studies and presents a statistically estimated value of the acceleration coefficient for means of transport (Tab. 2) [8]: c_x - acceleration coefficient in the direction of the x-axis for forward braking and backward acceleration, respectively, maximum is c_x=0.8 and a railway maneuvering impact is maximum c_x=4.0; c_y – acceleration coefficient in the centrifugal direction relative to the y-axis and maximum is c_y=0.8.

During transport on a flat wagon, the load is subject to inertia forces in the longitudinal direction (x direction) and transverse direction (y direction). In the longitudinal direction, the load is subject to the force F_{bx} (Tab. 2), which occurs during braking or when the wagon is maneuvered. When driving on a track arc, a transverse inertia force is generated, which is the centrifugal force F_{by} (Tab. 2). On the other hand, the uneven track is the source of the inertia force F_{bz}, which acts vertically in the form of vibrations. We will not analyze this force because of its low value. According to the standard [4], the value of the inertia force is calculated as the product of the acceleration coefficient $c_{x,y}$ and the gravity force of the transported load Q_L[N] according to the relationship (2):

$$F_{byR} = c_{xR} \cdot Q_L, \qquad F_{bxH} = c_{xH} \cdot Q_L, \qquad F_{bxM} = c_{xM} \cdot Q_L, \tag{2}$$

where: c_{xR} – acceleration coefficient to the x-axis on railway arch, c_{xH} – acceleration coefficient to the x-axis on emergency braking, c_{xM} – acceleration coefficient to the x-axis on railway maneuvering, Q_L– mass of the transported load.

The values of the acceleration coefficient are normalized for the individual directions of the inertia force, and for a railway wagon, they are (Tab. 1) [38].

Further analysis took the coefficients c_{xH}, c_{xM}, and c_{yR} with the highest values, the most unfavorable moments that can occur in rail transport.

In railway transport, like road transport, various methods of securing loads on the flat wagon can be used. The basic ones include [8]:

– blocking;
– anchoring using lashings (Fig. 4);
– increasing the value of the friction force on the flat floor of the wagon.

To secure the wheeled armored vehicle "Rosomak", the method of straight anchoring at the front and back (Fig. 4a) was compared with the second method of cross-linking at the front and back (Fig. 4b). These methods were chosen because of the location of the towing eyelets made by the manufacturer. The straight method of fasting and the cross method of fasting allow the armored vehicle carrier to be secured using four belt lashings. The belt lashings secure the transported load against movement between the towing eyelets and the handles on the flat wagon.

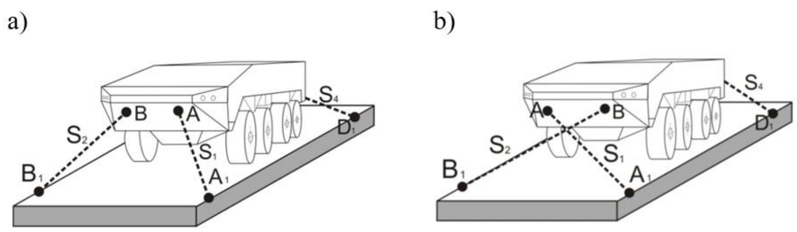


Fig. 4. Fastening methods using straight anchoring (a) and cross anchoring (b)

After analyzing these two methods, we will be able to answer the following question: What forces act on the securing lashings in these two securing methods? That is, what strength of the belt lashings will be used in the straight anchoring method, and what strength in the cross-anchoring method? The wheeled armored vehicle rests on the flat wagon on eight rubber-tired wheels. The friction coefficient "μ" at the contact of two specific materials should be determined according to the description given in the EN12663-1 standard [5]. In our case, we do not need to use anti-slip mats, which are used to increase the friction coefficient "μ". Cooperating materials are the rubber of the transporter tires and the flat platform made of wood. The friction coefficient of the materials is μ=0.6 for clean contact surfaces. In the case of a contact surface covered with snow, ice, grease, or oil, the friction coefficient is much lower according to the EN12663-1 standard [5].

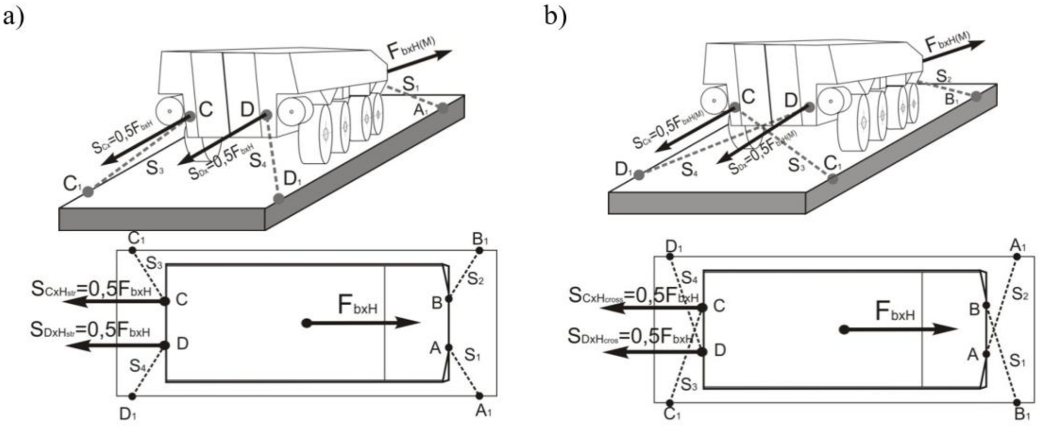


Fig. 5. Forces acting in the direction of travel during braking and impact force during maneuvering; a) straight anchoring method; b) cross anchoring method

The load analyzed is secured using 4 lashing belts S_1, S_2, S_3, S_4 connecting the flat wagon handles A_1, B_2, C_3, D_4 with the towing eyelets of the armored vehicle A, B, C, and D. Two belts at the front S_1, S_2 and two at the back S_3, S_4 according to the diagram in the Tab. 4.

In the longitudinal direction, the load is affected by the inertia force F_{bxH}, which occurs during braking. When driving in a track arc, the centrifugal force F_{byR} is generated.

The cross-anchored method (Fig. 6b) and the straight anchoring method (Fig. 6a) were used to secure the armored vehicle. The calculations are made for the straight and cross-anchored methods separately to determine which of these methods causes smaller forces concentrated on the belts fastening elements S_1, S_2, S_3 and S_4. Both methods use four lashings S_1, S_2, S_3, and S_4 which secure the armored vehicle against movement in the longitudinal direction (direction x) and transversely (direction y). In the longitudinal direction, the load is affected by the inertia force F_{bxH}, which occurs during braking. When driving in a track arc, the centrifugal force F_{byR} is generated (Fig. 6).

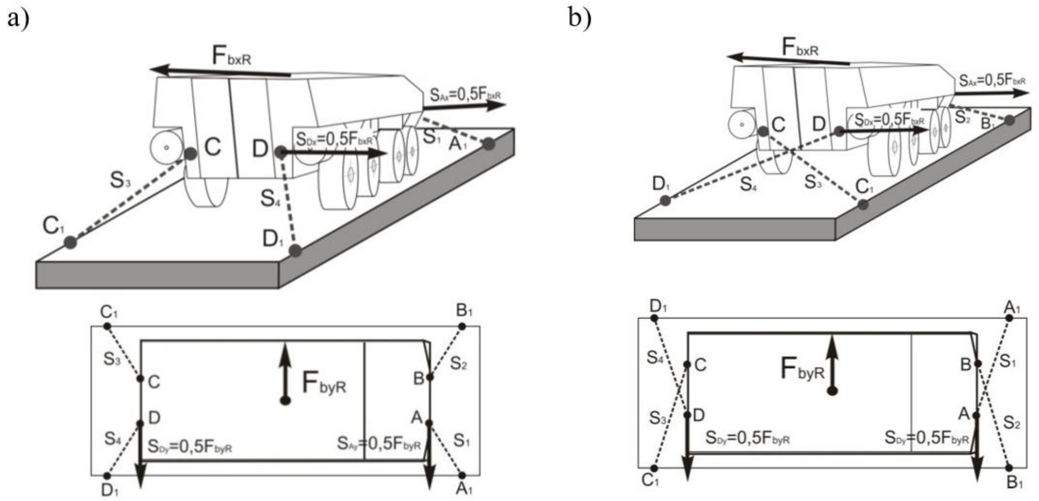


Fig. 6. Forces acting in the transverse direction when driving on track arcs; a) straight anchoring method; b) cross anchoring method

The cross-anchored method (Fig. 6b) and the straight anchoring method (Fig. 6a) were used to secure the armored vehicle. The calculations are made for the straight and cross-anchored methods separately to determine which of these methods causes smaller forces concentrated on the belts fastening elements S_1, S_2, S_3, and S_4. Both methods use four lashings S_1, S_2, S_3, and S_4, which secure the armored vehicle against movement in the longitudinal direction (direction x) and transversely (direction y). The selection of cross and straight anchoring consists of determining the minimum value of the securing lashing capacity (LC) for each of the lashings S_1, S_2 placed in front and the back S_3, S_4 of the armored wheeled transporter to the flat wagon. To determine the lashing capacity (LC) of the lashings, an inertial analysis of the transported load is necessary under the most unfavorable railway conditions.

The calculations and analysis show that during braking and driving on a tracking arc, the armored vehicle is subjected to the inertial forces F_{bxH}, F_{bxM}, F_{byR} which, according to the relationships (1), (2) are, respectively (Tab. 5).

Based on the calculation (Tab. 5), the result is that in the most unfavorable braking conditions, the load is subjected to the inertia force of the maximum value F_{bxh}=220,725[N], while in railway maneuvering work (where an impact occurs), the maximum inertia force is F_{bxM}=882,900[N]. On the track arc, under the most unfavorable conditions, the inertia force is F_{byR}=176,580[N].

Tab. 5

Maximum inertial forces exerted on the wheeled armored vehicle "Rosomak"

Driving conditions (C-factor value)	The value of inertial forces
Braking for C_h=1,0	$F_{bxH} = 220\ 725[N]$
Maneuvering for C_M=4,0	$F_{bxM} = 882\ 900[N]$
Track arc for C_R=0.8(centrifugal force)	$F_{byR} = 176\ 580[N]$

where: F_{bxH} – maximum acceleration (deceleration) value resulting from the movement of the flat wagon, F_{bxM} – maximum acceleration value at the moment of impact of the shunting of the flat wagon.

The transported load is additionally counteracted by the friction force F_T between the wooden surface of the flat wagon and the tires. The friction force F_T is directed opposite to the direction of the inertia forces, so the maximum inertia forces were additionally reduced by the friction force. The friction coefficient μ between the wood and rubber material of the tires was assumed for the most unfavorable conditions when the surface is wet, and for these conditions, the friction coefficient μ=0.3 was used for the calculations. In addition to these forces, in our case, the load was also pressed by the tension of the belts S_1, S_2, S_3, S_4. Then an additional pressure force P_n acts on the load; that is, in addition to the gravity force G of the load, an additional pressing force acts on the load. Belt tensions increase the pressing force by the value P_n=5000N (in the STF standard [lit] the tension force of the security belt is specified). After taking into account this value of P_n in the analysis, the friction force is F_T (3):

$$F_T = \mu \cdot (Q_L + P_n) = \mu \cdot [(m_L \cdot g) + P_n] \cong 67\ 718[N] \tag{3}$$

where: m_L - the mass of the armored vehicle load, μ – coefficient of friction between the tires and the platform of the flat wagon, P_n- the additional pressing force resulting from the tension of the securing belts.

The friction force after taking into account the load forces of the mass m_L [kg] and the pressing force P_n [N], the determined friction force is F_T=67,718[N] (3).

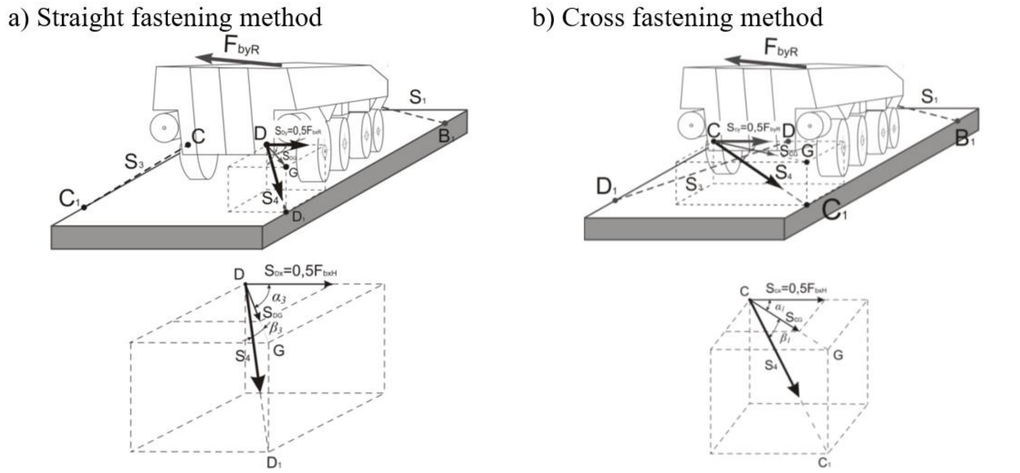
During braking, the transported load of the armored vehicle is secured by two lashings belts, S_3 and S_4 in the cross method and the straight method also by two lashings belts S_3, and S_4. On the arc to the right, they are secured by two lashings belts, S_1, S_4 in the cross method and the straight method also by two lashing belts, S_1, S_4. On the left side, the inertia forces are concentrated on the lashing belts for the straight method S_2, S_3, and in the cross method S_2, S_3. For the strength analysis of the lashing belts, only one attachment point was taken, where half of the force, acts on the inertia force, and the determined values are given in Tab. 6.

Tab. 6

The magnitude of forces acting on a single belt tension in railway conditions

Transport conditions	The magnitude of the inertia force in one lashing belt
Braking	$S_{DxH} = S_{CxH} = 0{,}5 \cdot F_{bxH} = 76\ 504[N]$
Maneuvering	$S_{DxM} = S_{CxM} = 0{,}5 \cdot F_{bxM} = 407\ 591[N]$
Driving on a track arc	$S_{DxR} = S_{CxR} = 0{,}5 \cdot F_{byR} = 54\ 431[N]$

Distribution of forces for a single belt S_4 (Fig. 7) of travel during driving on a way arc in the most unfavorable railway conditions. Further analysis of the strength capacity of the lashing belt was carried out for the lashing belt S_4 attached between points D in the straight method (Fig. 7a) and C in the cross method (Fig. 7b). In the cross analysis, the point of interest is the attachment point C, and in the analysis of the partial attachment, we are interested in point D (Fig. 7a) shows the distribution of force and concentrating angles at point D of the lashing belt S_4 (Fig. 7b) (according to the formula (5)) in the cross method and shows the distribution of forces and concentrating angles at point D on the lashing strap S_4 (Fig. 7a) in the straight method (according to the formula (4)).

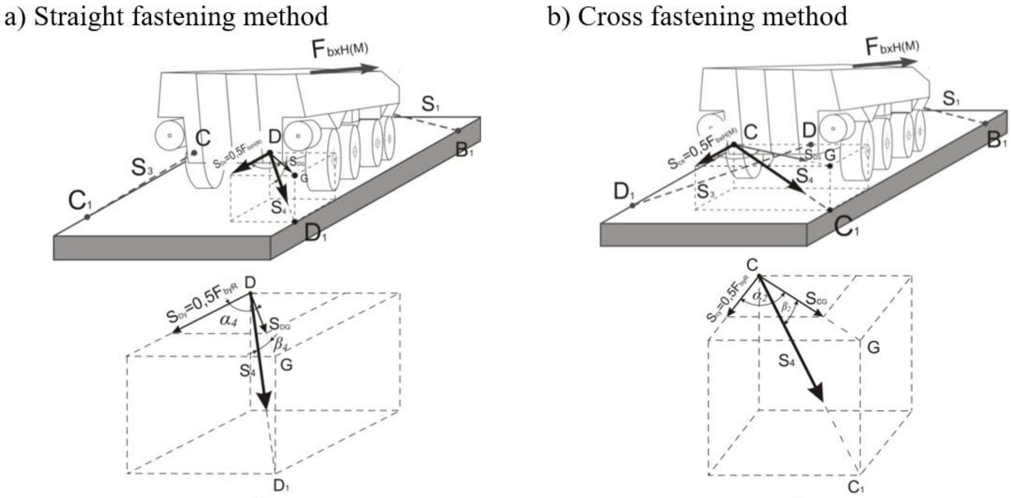


$$S_{4D} = \frac{S_{Dx}}{\cos\alpha_3 \cdot \cos\beta_3} \qquad (4)$$

$$S_{4C} = \frac{S_{Cx}}{\cos\alpha_1 \cdot \cos\beta_1} \qquad (5)$$

Fig. 7. Travel during driving on way arc, force components of a single belt S_4 at the point of attachment D in the straight fastening method (a) and of the tension S_4 at the attachment point C in the cross-fastening method (b)

Distribution of forces for a single S_4 belt in the direction of travel during braking and impact forces during maneuvering (Fig. 8).



$$S_{4D} = \frac{S_{Dy}}{\cos\alpha_4 \cdot \cos\beta_4} \quad (6)$$

$$S_{4C} = \frac{S_{Cy}}{\cos\alpha_2 \cdot \cos\beta_2} \quad (7)$$

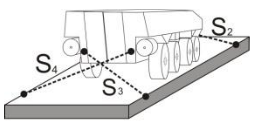
Fig. 8. Travel during braking and impact forces during maneuvering, the force components of a single belt S_4 at the point of attachment C in the straight fastening method (a) and of the tension S_4 at the attachment point D in the cross-fastening method (b)

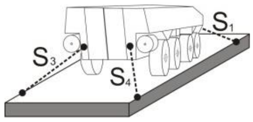
In the further part of the analysis, dependencies were determined that describe the force acting on the S_4 belt depending on the forces directed along the braking direction S_{Cx} the forces acting along the y direction for the S_{Cy} force for the straight fastening method (Fig. 8a) and the corresponding S_{Dy} forces in the case of the cross-fastening method (Fig. 8b).

The values obtained for S_1, S_2, S_3, and S_4 are the forces concentrated in one lashing during maximum braking, maneuvering (impact force), and forces during driving on the way arc in the most unfavorable railway conditions. The force with the highest value has a decisive influence on the strength value of the lashing belt used in the straight method and the cross method (Tab. 7).

Tab. 7

The values of inertia forces acting on the securing belts

Fixing method	Number of the belt	The direction of driving a flat wagon	The value of maximum force in the single fixing belt
	S_4 or S_3	The direction of longitudinal movement at the moment of maximum braking.	$S_3 = S_4 = 176\ 677\ N$
		The direction of longitudinal movement during maneuvering works.	$S_3 = S_4 = 941\ 292\ N$
	S_1	Driving on a way arc to the right	$S_1 = S_4 = 72\ 575\ N$
	S_4		

	S_2	Driving on a way arc to the left	$S_2 = S_3 = 72\,575\ N$
	S_3		
	S_4 or S_3	The direction of longitudinal movement at the moment of maximum braking.	$S_3 = S_4 = 94\,008\ N$
		The direction of longitudinal movement during maneuvering works	$S_3 = S_4 = 500\,850\ N$
	S_1	Driving on a way arc to the right	$S_1 = S_4 = 183\,766 N$
	S_4		
	S_2	Driving on a way arc to the left	$S_2 = S_3 = 183\,766\ N$
	S_3		

The calculation analysis presented in Tab. 7 shows that in the straight method of lashing of the S_3 and S_4 fastening belts, under the most unfavorable railway conditions, the tensile force is at the level of S_3=S_4=94,008N during extreme braking. The impact force during the impact of maneuvering is at the level of S_3=S_4=500,850N. On railway arcs, the tensile forces are transferred by the S_1 and S_3 or S_2 and S_4 belts at the level of 183,766N.

In the cross-fastening method in the direction of extreme braking, the tensile forces are transferred by the S_4 and S_3 belts at the level of S_3=S_4=176,677N. During the impact of maneuvering, the force level in the S_3 and S_4 fastening belts is S_3=S_4=941,292N. In extreme conditions of railway arcs, the force concentrated on the S_1 and S_3 or S_2 and S_4 belts is 72,575N (Tab. 7).

3.2. Selection of lashings securing belts for transported vehicle

For the analysis performed with lashing, it is necessary to select the appropriate lashing belts for the transmitted tensile forces under the most unfavorable transport conditions. It is necessary to select the right lashing belt with an appropriate lashing capacity LC [7]. To secure the armored vehicle, the generally available lashing belts offered by manufacturers that produce according to the EN 12663-2 standard were selected [5]. Each belt is marked with the appropriate information, which includes the following data: lashing capacity (LC) and standard tension force (STF), which is obtained when a manual force (SHF) is applied to the tensioner.
According to the manufacturers of chain lashings with a turnbuckle, we can choose chains of lashings with chain class G8. In class G8, the lashing strength capacity of the chains (LC) is from 40 kN to 106 kN (Tab. 8) [7].

Tab. 8

Fastening strap used for lashings S_1, S_2 and S_3, S_4 [7]

	Type	Fixing capacity LC [kN]	Nominal tension force STF [daN]
	ZRS G8 8	40	1 000
	ZRS G8 8	63	1 575
	ZRS G8 8	106	1 500

Based on these values, it can be seen that it is not possible to select a chain lashing that secures the tensile force values in extreme transport situations of the armored vehicle load; this applies only to emergency braking and driving on a railway curve (Tab. 8). In the cross-securing method, there is no possibility of securing the chain lashing due to exceeding the permitted chain strength for emergency braking and shunting maneuvers. For these force values, only chain lashings with a strength of LC=106kN can be used, which is carried out by a chain lashing type ZRS G8 8 (Tab. 8). In the cross-lashing method, it can be seen that the situation is very similar, with the difference that the force for extreme braking will increase for a single lashing S3 and S4 to a value of 176 kN. During the shunt, the force will increase for S_3 and S_4 to a level of 941 kN. This value indicates that there is no single security for this load during shunting operations for the cross-lashing method. These forces can occur during the formation of railway wagons on railway sidings. Only the forces on the railway curves, in the cross-lashing method, decreased to a value of 72 kN (Tab. 7).

Figs. 9, 10, and 11 present the force values for individual single forces that prevail in the lashing straps for extreme conditions that can occur during extreme braking, driving on a curve, and shunting that can occur in railway conditions for the simple and cross-lashing methods.

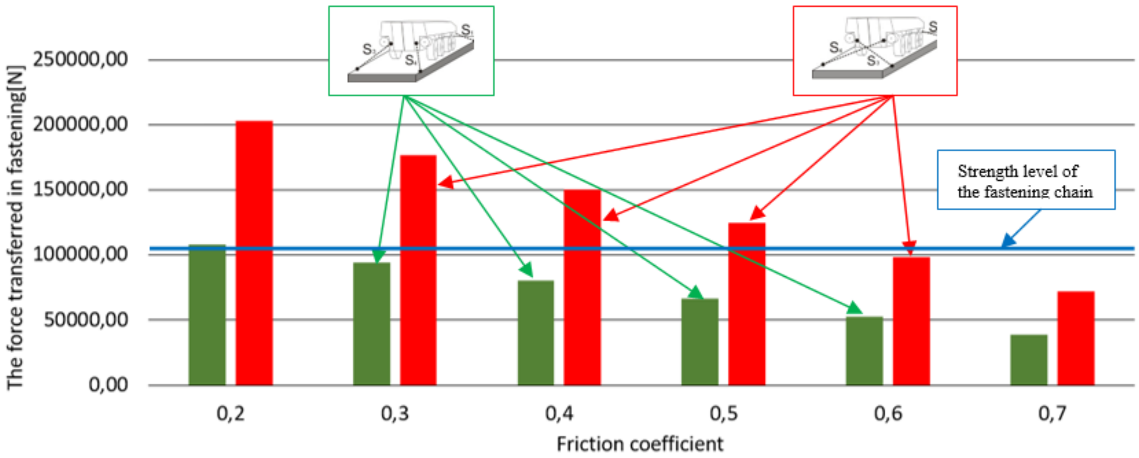


Fig. 9. Diagram of forces during emergency braking

Based on the analysis conducted on the transport of an armored personnel carrier weighing approximately 22.5 tons, and after comparing the results presented in Figs. 9, 10, and 11, the following conclusions can be drawn. Assuming that the securing chain strap has a lashing capacity of LC = 106 kN (Tab. 7), only the straight securing method ensures that the load-bearing capacity remains within limits, not exceeding the forces acting on the securing straps during emergency braking. Even when the friction coefficient between the wheels and the wagon surface is reduced to an extremely low value of $\mu = 0.2$, the inertial force remains equal to the load capacity of the securing chain strap. However, in the cross method (commonly used to secure armored personnel carriers), a significant overload is observed for friction coefficients between $\mu = 0.2 \div 0.7$. Only when $\mu = 0.6$ is reached do the inertial forces equal the load capacity of the chains that secure the armored vehicle. This indicates that when the cross-securing method is used, particular care must be taken to ensure a sufficiently high friction coefficient between the tires and the wagon surface.

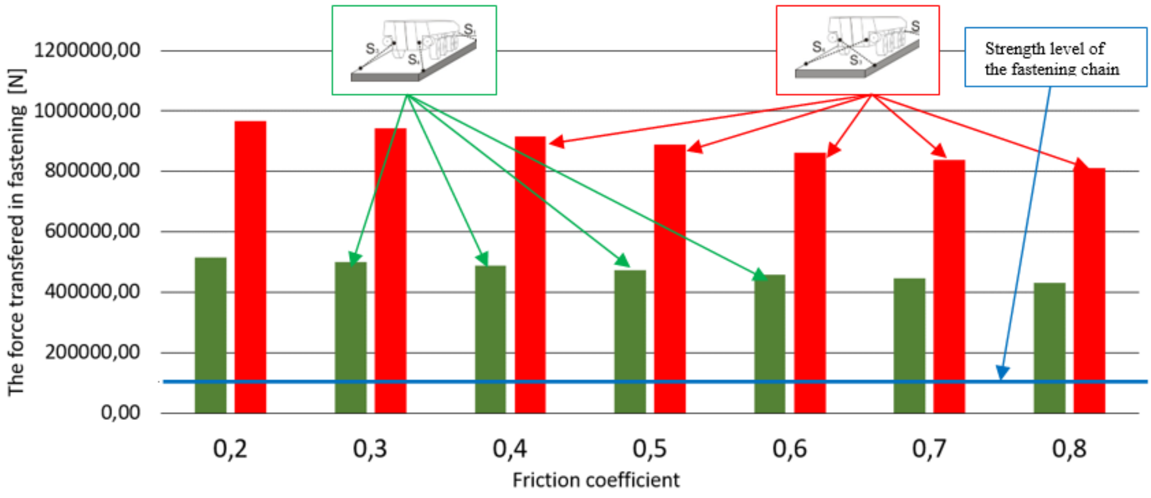


Fig. 10. Diagram of forces during maneuvering work

However, the situation differs significantly when conducting shunting operations with armored personnel carriers. As shown in the analysis in Fig. 10, it is evident that such operations are unacceptable for armored personnel carriers. Both the straight and cross securing methods cause a significant exceedance of the load-bearing capacity of the securing chains. Based on the force distribution graph in relation to the friction coefficient μ, it follows that such shunting operations are impermissible if the train consists of cars carrying armored personnel carriers.

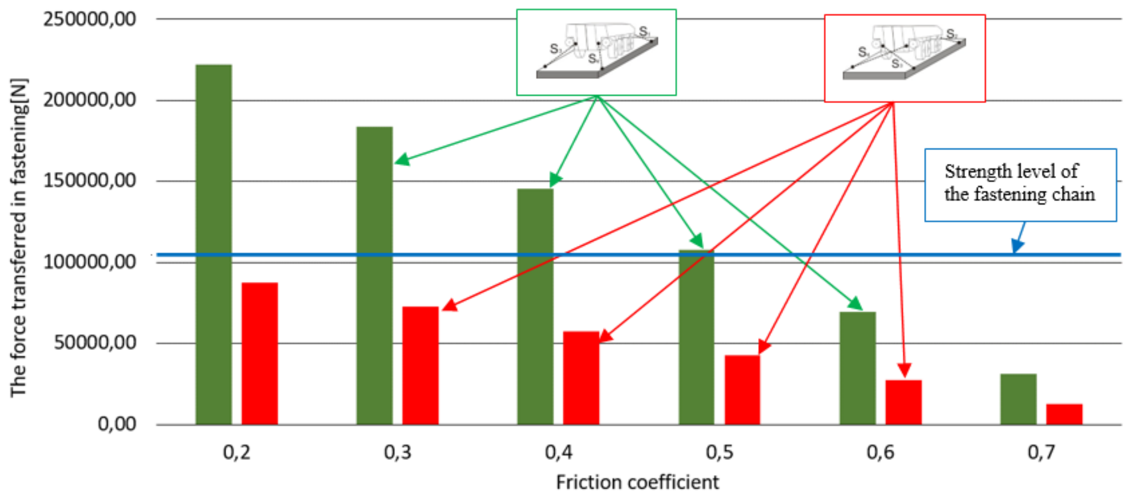


Fig. 11. Diagram of forces during driving on a truck curve

Only the cross-securing method ensures the load-bearing capacity of the securing chains when traveling on railway curves in the worst-case scenario (Fig. 11). This suggests that the designers of the armored personnel carrier securing system considered only protection on railway curves. Within the entire range of μ=0.2÷0.7, the cross-securing method prevents exceeding the load-bearing capacity of the securing chains. The straight securing method guarantees adequate securing only when the friction coefficient exceeds μ = 0.5 (Fig. 11).

4. CONCLUSIONS

The wheeled armored vehicle "Rosomak" is standardly secured using the cross-securing method with four chain tie-downs or flexible straps. This article analyzes the forces acting on the tie-downs, which are concentrated in both the cross-securing and straight-securing methods. The analysis compares the forces that occur in these two methods, the straight securing method and the cross-securing method, which is the standard approach to secure armored personnel carriers. In these securing methods, only four chains or flexible straps are used, with one tie-down at each corner (S_1, S_2, S_3, and S_4). Taking into account the frictional forces of the load and the load-bearing capacity of the tie-downs in relation to the main inertial forces during the maximum generation of impact force in shunting operations, the study shows that these securing methods are insufficient, as they significantly exceed the load capacity of the securing chains. During sudden brakes of railway wagons, only the straight securing method is capable of effectively securing armored vehicles, provided that an adequate friction coefficient is maintained. The choice of securing method should primarily depend on the inertial forces acting on the transported armored vehicle and should be preceded by a detailed computational analysis.

The analysis of securing the wheeled armored vehicle "Rosomak" on a railway platform, presented in Fig. 3, shows that when using single securing straps, different tensile force values occur depending on the securing method, straight securing (Fig. 3a) and cross securing (Fig. 3b). Analysis reveals that in the straight securing method, the highest tensile forces in the straps prevail during shunting operations (impact conditions), reaching 500 kN. On the contrary, in the straight securing method, during shunting operations (impact conditions), the straps experience tensile forces of 941 kN.

In conclusion, based on the conducted analysis of the wheeled armored vehicle, it appears reasonable to combine both straight and cross-securing methods. This hybrid approach should be incorporated into the standard securing procedure for armored personnel carriers. Future research by the authors will focus on further analysis of the security of heavier armored vehicles.

References

1. Anderson N., P. Anderson, R. Bylander, S. Sokjer, Petersen and Bob Zether. 2004. „Equipment for Rational Securing of Cargo on Railway Wagons”. *VINNOVA*. Report/Rapport VR 2004:05.
2. Azadi S., A. Jafari, M. Samadian. 2014. „Effect of tank shape on roll dynamic response of an articulated vehicle carrying liquids”. *International. Journal of Heavy Vehicle Systems* 21(3): 221-240.
3. Cieśla M., G. Hat-Garncarz. 2013. „The problem of proper cargo securing in road transport – case study”. *Transport Problems* 8(4): 27-33.
4. EN 12195-1:2011. „Load Restraining on Road Vehicles – Safety – Part 1. Calculation of Securing Forces”. *Brusel: European Committee for Standardization*: 48.
5. EN 12663-2:2010 Railway applications – Structural requirements of railway vehicle bodies – Part 2: Freight wagons.
6. Grossmann G., M. Kassman. 2018. *Transport safe packaging and cargo securing*. 3ed. Renningen: Expert Verlag. ISBN: 978-3-8169-3334-2.
7. Pewag. Available at: https://security-chains.pewag.pl.

8. IMO/ILO/UNECE. 2024. Code of practice for packing of cargo transport units (CTU Code). United Nations Economic Commission for Europe. Available at: https://www.unece.org/fileadmin/DAM/trans/doc/2014/wp24/CTU.
9. Jagelcak J. 2007. „Equation of the standard EN 12195-1 stipulates unreasonable demands for cargo securing”. *Komunikacie* 9(4): 30-33. ISSN: 1335-4205.
10. Jagelcak J., J. Saniga. 2013. „Analysis of Elongation of Lashing Straps on Movements of Cargo Secured by a Top-over Lashing at Sliding in Longitudinal Direction”. *Perner's Contacts* 8(2): 53-62. ISSN: 1801-674X.
11. Jagelcak J., J. Gnap. 2011. „Different Measures for Load Securing Create Barriers in International Road Freight Transport”. *Archives of Transport Systems Telematics* 4(2): 10-17.
12. Jagelcak J., J. Saniga. 2013. „Analysis of elongation of lashing straps on movements of cargo secured by a top-over lashing at sliding in longitudinal direction”. *Perner's Contacts* 8(2): 53-62. ISSN: 1801-674X.
13. Jagelcak J. 2015. *Loading and fastening of freight in road transport*. 2nd edition. ISBN: 978-80-554-1083-8.
14. Kołowy Transporter Opancerzony 8×8 „Rosomak”. 2004. *Instrukcja eksploatacji. Opis i użytkowanie.* Wojskowe Zakłady Mechaniczne S.A. Siemianowice Śląskie. [|In Polish: 8×8 Wheeled Armored Personnel Carrier ”Rosomak”. 2004. *Operation Manual. Description and Usage.* Military Mechanical Works S.A. Siemianowice Śląskie].
15. Kwac L.K., J.Y. Kim, H.W. Kim, J.H. Han, Y.S. Lee. 2006. „Stability analysis of dunnage for transportation of a steel roll coil”. *International Journal of Modern Physics* 20(25-27): 3769-3774.
16. Lerher T. 2015. *Cargo securing in road transport using restraining method with top-over lashing*. Nova. New York. ISBN: 978-1-61122-002-5.
17. Loading guidelines. 2024. Section 2: Goods, *UIC International Unions for Railway.*
18. Loading guidelines. 2024. Section 1: Principles, *UIC International Unions for Railway*.
19. Nieoczyma A., J. Cabanb, J. Vrabelc. 2019. „The problem of proper cargo securing in road transport – case study”. *Transportation Research Procedia* 40: 1510-1517. DOI: 10.1016/j.trpro.2019.07.209.
20. Andersson N., P. Andersson, R. Bylander, S. Sökjer, P.B. Zether. 2004. *MariTerm AB. Equipment for rational securing of cargo on railway wagons*. VINNOVA. Report/Rapport VR. 2004:05. ISBN: 91-85084-07-7.
21. Olsen, A.A., F. Karkori. 2024. „General Load Securing Methods”. In: *Containerized Cargo Handling and Stowage. Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping*. Springer. Vol 22: 333-359.
22. Olsen A.A., F. Karkori. 2024. „Load Securing, Filling Materials and Use of Friction”. In: *Containerized Cargo Handling and Stowage. Springer Series on Naval Architecture, Marine Engineering, Shipbuilding and Shipping*. Springer. Vol 22: 361-392.
23. Olszewski Z., P. Krawiec. 2013. „Study of trailer lashing mechanical properties in terms of transport safety”. *Visnik Nacional Universitetu. CDS-archive. Lviv Politehnika* 777: 95-99.
24. Palúch S., Š. Peško, T. Majer, J. Černý. 2015. „Transportation network reduction”. *Transport Problems* 10(2): 69-74. ISSN: 1896-0596. DOI: 10.20858/tp.2015.10.2.7.
25. PKP Cargo S.A. Instruction on loading and securing freight shipments Ch-6. Annex to decision No. 19/2022.Ch-6. PKP CARGO S.A. Instruction on loading and securing freight shipments.

26. Rievaj V., J. Vrabel, F. Synak, L. Bartuska. 2018. „The Effects of vehicle load on driving characteristics”. *Advances in Science and Technology – Research Journal* 12(1): 142-149. DOI: 10.12913/22998624/80896.
27. *Rozporządzenie Ministra Infrastruktury z dnia 25 stycznia 2018 roku w sprawie sposobu przewozu ładunku*. Dz.U. 2018 poz. 361. [In Polish: *Regulation of the Minister of Infrastructure of 25 January 2018 on the method of transporting cargo*].
28. Ruifang M. 2009. „Simulation Analysis for Cargo Mechanical State during Transportation. Logistics. *The Emerging Frontiers of Transportation and Development in China*: 821-827. DOI: 10.1061/40996(330)117.
29. Zasady przewozu wojsk transportem kolejowym RON 9577 DU-4.4.1(B).2014. Warszawa. P:184. [In Polish: Rules for the transportation of troops by rail RON 9577 DU-4.4.1(B).2014. Warsaw. P:184].
30. Shtykov V. P. 2014.„The carrier's liability for failure to vehicles to transport cargo”. *Life Science Journal* 11(9): 292-294.
31. Skrucany T., J. Gnap. 2014. „The effect of the crosswinds on the stability of the moving vehicles”. *Applied Mechanics and Materials* 617: 296-301.
32. Turanov H., Y. Ruzmetov, I. Dobychin. 2019. „Fastening cargo on railway rolling stock”. *XII International Scientific Conference on Agricultural Machinery Industry*. *Conf. Series: Earth and Environmental Science* 403: 012206. DOI: 10.1088/1755-1315/403/1/012206.
33. Turanov K., E. Timukhina. 2008. „Analytical modeling cargoes displacement in wagon and tension in fastening”. *Transport Problems* 3(3): 69-76.
34. Turanov Kh.T., E.N. Timukhina, D.V. Volkov. 2007. „Loading capacities of flexible elastic fastening elements in cargo location with mass center displacement lengthwise the wagon”. *Urals Transport* 4: 25-35.
35. Turanov Kh.T., M.A. Khadzhimukhametova. 2008. „Mathematical modeling of cargo shift lengthwise the wagon under the action of longitudinal and vertical forces”. *Transport: Science, Engineering and Operation* 7: 27-31.
36. Vlkovský M., T. Ivanuša, V. Neumann, P. Foltin, H. Vlachová. 2017. „Optimizating cargo security during transport using dataloggers”. *Journal of Transportation Security* 10: 63-71. Springer. Science Business Media. DOI 10.1007/s12198-017-0179-4.
37. Defence24. Available at: https://www. Defence24.pl.
38. PKP Cargo. Available at: https://www.PKPCargo.com.
39. Zamecnik J., J. Jagelcak, S. Sokjer-Peterssen, T. Hvojnik, M. Lipka. 2017. „Influence of a lashing strap winding in tensioning ratchet on the results of the strength tests and cyclic loading tests according to the standard EN 12195-2”. *Communications. Scientific Letters of the University of Zilina* 19(2): 10-17. ISSN: 1335-4205.

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