

Research Article

Development of Innovative Cargo Safety Systems for Vehicles

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Article Info	Abstract
Article History	The purpose of the study is to develop and evaluate the effectiveness of an innovative cargo fastening system using aramid fasteners to improve the safety and stability of cargo transportation. The research methodology included the analysis of existing solutions, the development of conceptual models, mathematical calculations, and the modelling of the system using three-dimensional models. In addition, this study paid special attention to the choice of fastening materials, such as aramid fibre, and analysed the strength characteristics of fasteners to ensure maximum safety of cargo transportation. As a result of the work conducted, an innovative cargo and object fixation system was created, which provides a high level of protection and safety for the cargo, allowing it to avoid damage and emergency situations during transportation. Notably, this system is able to effectively distribute the load and reduce the impact of inertial forces, ensuring stability and reliability during the transportation of goods of various types and sizes. An additional substantial advantage of this innovative solution is its versatility, which allows its successful use in various scenarios and conditions. The technical solution created is suitable for moving both light and heavy loads and can be effectively applied to various types of vehicles.
Received May 30, 2025	
Revised Jul 22, 2025	
Accepted Aug 06, 2025	
Keywords	
Fasteners	
Three-dimensional model	
Strength characteristics	
Inertial forces	
Transportation of objects	



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1. Introduction

Cargo transportation plays an important role in the economy, ensuring the delivery of goods and facilities anywhere in the world. Trucks and other vehicles are vital to the logistics chains that connect manufacturers and consumers. The efficiency and reliability of these transport systems depend on many factors, among which cargo safety occupies a prominent place. Cargo fastening and fixation systems should ensure their safety during transportation, by minimising the risk of damage and loss. Therefore, as traffic

volumes grow and the variety of goods increases, the requirements for security systems are continuously rising, which stimulates the development of new and more advanced technologies.

The problem of cargo transportation safety is especially acute in conditions of heavy traffic and an increasing number of transported goods. Dynamic loads and inertial forces, which occur during vehicle acceleration, braking, and manoeuvres, frequently expose loads [1, 2]. These factors can lead to displacement or damage to goods, which entails economic losses. Traditional fastening systems based on friction methods and simple mechanical elements often do not cope with the task of ensuring complete safety [3]. As a result, there is a need for innovative solutions that can effectively protect goods from all types of external influences. In this regard, the development of modern innovative cargo safety systems can close many existing shortcomings in this area. Such systems are able to provide a more uniform distribution of loads on fasteners, which increases the stability and reliability of cargo fastening. The use of advanced materials also allows for the creation of fasteners with high strength and minimal weight, which improves the overall efficiency of transport operations [4, 5]. Additionally, the integration of mathematical models and reverse engineering methods allows for more accurate calculation of the parameters of fastening systems, adapting them to specific operating conditions and types of cargo.

One of the key aspects of ensuring safety during cargo transportation is the reliability of fastening systems. In the study by Araslanova [6], it was noted that existing fastening methods often fail to prevent the displacement of goods during movement, which often leads to damage and loss of cargo. Dzhupbanov [7] also showed that the traditional materials used in fasteners do not provide sufficient strength, which causes frequent breakdowns and the need for regular replacement. Gorselanczyk and Kujawa [8] focused on the shortcomings in determining the optimal parameters of fastening systems that do not consider the specific requirements of various cargoes and transportation conditions, which leads to a decrease in the overall efficiency and safety of transportation. Thus, an integrated approach to the development of innovative cargo securing systems can eliminate existing shortcomings and improve the safety of cargo transportation.

Another important factor is the adaptability of fastening systems to different types and sizes of loads. In the course of the study, Maciossek [9] emphasised that many modern fastening systems do not have sufficient versatility for use with various loads, which increases costs and preparation times for transportation. In the study by Turanov et al. [10], researchers conducted an analysis of the effectiveness of fastening systems in conditions of intensive operation, showing that the lack of flexibility in the settings of fasteners leads to their rapid wear. Ma and Chen [11], in turn, established that a substantial amount of cargo damage is associated with the insufficient adaptability of fastening systems to dynamic loads, which leads to a violation of the integrity of the cargo. Nevertheless, the development of new fastening systems based on these factors, including the ability to quickly and easily adjust to different types of cargo and

operating conditions, can substantially improve the efficiency and safety of transport operations.

Furthermore, an important aspect is the introduction of new materials and technologies into the development of cargo-securing systems. A study by de O Lima et al. [12] investigated the possibility of using composite materials for fasteners, identifying their high strength and resistance to external factors. In the paper of Hsieh et al. [13], the authors presented important data on fastening mechanisms equipped with sensors for real-time condition monitoring, allowing for rapid response to changes in transportation conditions. In the study by Gnap et al. [14], the integration of automated fastener control systems capable of independently adjusting the tension depending on the vehicle movement parameters was considered. However, despite the successes achieved, existing developments do not consider an integrated approach to the design of fastening systems, including synchronising with the dynamic characteristics of vehicles. This report demonstrates the need to eliminate these disadvantages by creating a fastening system capable of adapting to different types of cargo and transportation conditions, ensuring a high degree of safety at all stages of transportation.

The purpose of this study was to develop an innovative cargo securing system that provides a high degree of safety and reliability during the transportation of various types of cargo. Tasks were set to achieve this goal, including the development of a conceptual model of a parallel mechanism with fixed and movable bases for optimal load distribution and minimising the effects of inertial forces. Another important task of the study was to create a three-dimensional model of the cargo fastening system and the transportation base, which allows for an accurate analysis of the interaction between the cargo and the vehicle in various operating conditions.

2. Materials and Methods

A method of analysis and design of parallel mechanisms used in robotics and mechanical engineering was chosen to solve the problem of developing a cargo safety system. The process is summarised in Figure 1.

The study analysed the main parameters of the cargo, including its length, width, and height, as well as the parameters of the cargo's location relative to the base. Using the reverse engineering method, a coordinate recalculation operation was developed to determine each of the attachment lengths based on the desired characteristics of movement and orientation of the load. This process was presented as follows (1):

$$V = KV', \quad (1)$$

where: V' – a vector that represents the cargo in the axial system of the cargo, describing the position and orientation of the cargo relative to its coordinate system; V – a vector representing the cargo in the coordinate system of the transport base, describing the position and orientation of the cargo relative to the coordinate system of the base on which it is located; K – the transformation matrix corresponding to the vector V (allows the transition from the coordinate system of the load to the coordinate system of the base, considering its position and orientation).

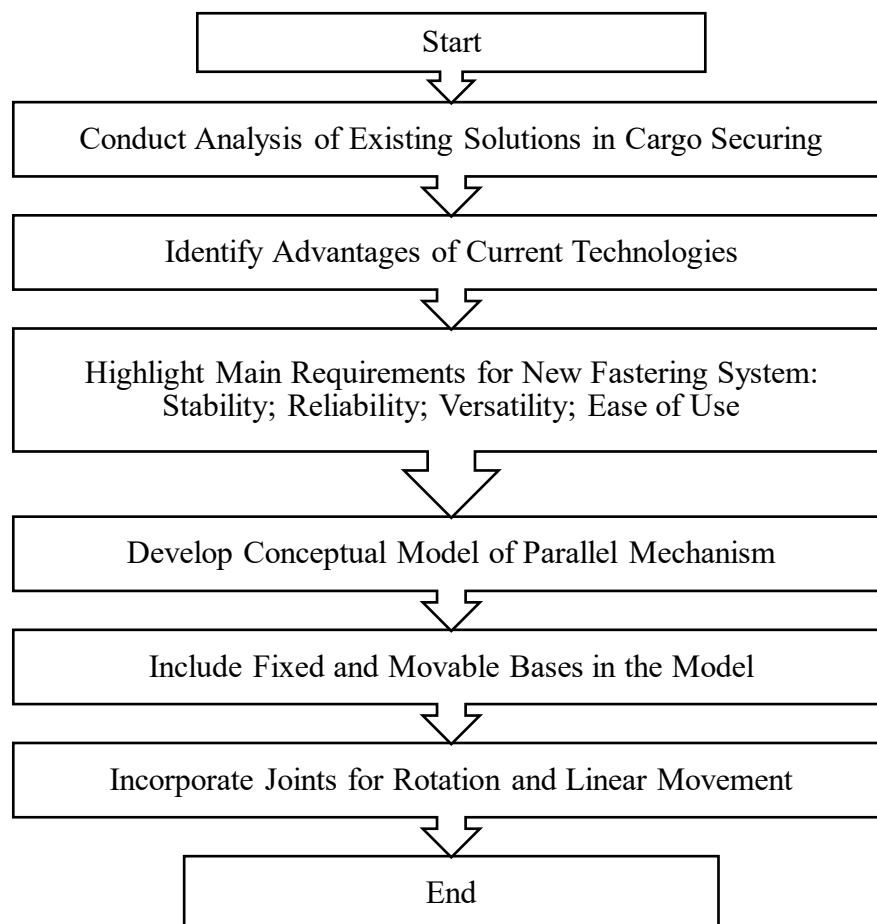


Figure 1. Methodology for Developing a Cargo Safety System

This transformation matrix K was represented as (2):

$$K = \begin{bmatrix} d_{11} & d_{12} & d_{13} & X_p \\ d_{21} & d_{22} & d_{23} & Y_p \\ d_{31} & d_{32} & d_{33} & Z_p \end{bmatrix}, \quad (2)$$

where: d_{ji} (for $i, j = 1, 2, 3$) – the elements of the transformation matrix reflecting the components of motion (determine the magnitude and direction of changes in the position and orientation of the object in three-dimensional space); X_p , Y_p , and Z_p – the components of the transformation matrix corresponding to rotation and displacement (each of the elements defines the corresponding motion along the X, Y, and Z axes).

Additionally, as part of the study, a method was developed to determine the length of an object's attachment in three-dimensional space using the O-XYZ orientation system. This method is based on a mathematical equation that allows accurately determining the distance from the attachment point to the origin, thereby ensuring the exact location of the attachment and guaranteeing the stability and safety of the system. Using the obtained values of the length of the fasteners, the corresponding characteristics of the fixation system were determined, which allowed ensuring the correct location and stable fixation of the object in space.

Special emphasis was placed in this study on the choice of fasteners and materials used in them to

ensure maximum safety and avoid potential emergencies during cargo transportation. For this purpose, fasteners made of Twaron aramid fibre (Teijin Aramid, the Netherlands) were selected. Considering the average value of the ultimate tensile strength of aramid fibre, the elasticity coefficient of fasteners made of this material was determined. In addition, the comprehensive analysis of the security system for cargo transportation also took into account the vehicle, which was a Dongfeng Sokon truck (China) (Figure 2), featuring a rated payload capacity of 1500 kg and a cargo bed measuring 2.26 metres in length, 1.44 metres in width, and 0.34 metres in height.



Figure 2. Dongfeng Sokon Truck, Source: [15].

The paper also considers a model of fastening a load with a certain length, based on which the magnitude of the tension force was calculated, which plays an important role in ensuring the stability and safety of the fastening system. After calculating the initial stress of the fastener, the next step was to determine its strength characteristics, which helped prevent a situation where the voltage exceeds permissible limits and leads to fastener failure.

3. Results

Cargo locking devices during transportation are designed to hold the upper and side parts of the cargo on a transport base to limit its mobility. This includes limiting linear movements along the X, Y, and Z axes, as well as rotational movements around them. Thus, the system prevents the cargo from shifting or tipping over during transportation. The principles of a parallel mechanism can be used to increase the efficiency and reliability of fastening, which is similar in structure to traditional cargo fastening systems. Parallel mechanisms are systems in which several joints work in a coordinated manner, ensuring stable retention of objects. They are used in robotics and mechanical engineering to create high-precision manipulators and platforms [16]. The introduction of parallel mechanism modelling in the cargo fastening system opens up new opportunities to improve the accuracy and reliability of fixation.

The parallel-type mechanism with six links includes a movable and fixed base and the links that

connect them [17]. The connection points $b_1 \sim b_6$ represent the attachment points on a movable base, while the points $B_1 \sim B_6$ indicate the connection points on a fixed base. These pairs of points serve as anchoring nodes for fasteners made of Twaron aramid fibre, which connect the load to the vehicle base and ensure stable fixation during transportation. In such a system, the mobile platform is relatively stationary due to the links that provide the necessary flexibility and stability of the structure. Each of the links has spherical hinges at the ends, allowing rotation in three directions, and a prismatic hinge in the middle, providing linear movement along one axis. This configuration provides a high degree of mobility and positioning accuracy for the movable base [18, 19]. The attachment points $b_1 \sim b_6$ on a movable base and $B_1 \sim B_6$ the fixed base serve as connecting nodes that allow the links to transmit movements and forces between these two bases. This allows evenly distributing the load and ensuring the stable functioning of the mechanism. The use of six links is necessary to fully constrain all six degrees of freedom (three translational and three rotational) of the cargo, thereby guaranteeing its spatial stability during transportation [20-22]. This mechanism's design enables its effective use in various applications that demand high accuracy and reliability.

Each of the six links in the parallel-type mechanism is composed of two types of mechanical joints: spherical hinges at the ends and a prismatic hinge in the centre. A spherical hinge, also known as a ball-and-socket joint, allows rotational movement in all three axes (X, Y, and Z), offering three degrees of rotational freedom. These joints enable the attached elements to pivot freely, which is essential for accommodating the complex orientations of the load during dynamic transportation. A prismatic hinge, in contrast, permits translational movement along a single axis. It functions similarly to a linear slider, allowing the link to extend or retract. This enables adjustments in the length of each link and contributes to the system's ability to compensate for changes in the cargo's position due to road vibrations or vehicle manoeuvres.

In this system, the prismatic hinge is in the middle of each link and works together with the spherical hinges to provide a total of six degrees of freedom. This configuration grants the mechanism the capacity to adapt dynamically to shifts in the load, maintain equilibrium, and preserve secure contact between the cargo and the base structure. Figure 3 illustrates the proposed cargo fixation system, where six identical links connect the movable and fixed platforms. Each link (denoted as l_1 to l_6) transmits force via these combined hinge types, ensuring that the system can both rotate and translate as needed to maintain load stability. The integration of spherical and prismatic hinges allows the mechanism to respond flexibly to changes in load geometry or external forces, ensuring high positioning accuracy and robust retention during transportation [23].

This study proposes a new version of the cargo safety system using a parallel mechanism model. In this variant, the movable base of the parallel mechanism is treated as if it were fixed. This approach is

justified by the fact that parallel mechanisms provide high stability and accuracy through the use of several links connecting movable and fixed elements [24]. In the new cargo fastening system, each link, which has spherical hinges at the ends and a prismatic hinge in the centre, allows even distribution of the load and securely fixes it, preventing its displacement and overturning. With this design, the fixed base of the parallel mechanism serves as a base for securing the load, ensuring its stability and safety. Six links connecting the fixed and movable bases allow the system to adapt to different types and sizes of goods, ensuring their reliable fixation regardless of the conditions of transportation [25]. This design significantly enhances transport efficiency and safety when compared to traditional friction-based fastening methods, which typically rely on tensioned straps, chains, or ropes pressed against the cargo through frictional contact with the vehicle surface. Such conventional systems depend on the coefficient of friction between the securing element and the load or platform to resist slippage and often require frequent retightening due to loosening caused by vibrations or dynamic loads. In contrast, the parallel mechanism provides a structurally integrated solution that maintains load stability through mechanical constraint and distributed force application (Figure 3).

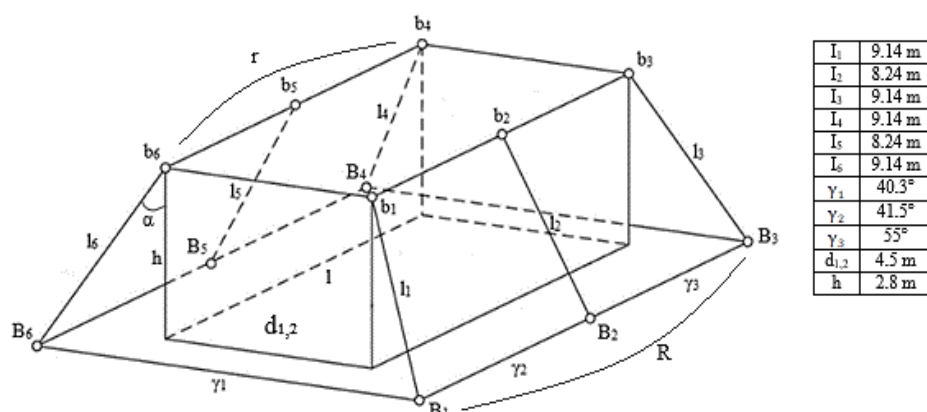


Figure 3. A Model of a Load Securing System Using a Mechanism with Six Parallel Joints

In Figure 3, the main parameters (dimensions) of the load include length (l), width (d), and height (h). Since the load and the base have identical mirror planes, the distances between them on each side are indicated as d_1 and d_2 . These distances are measured from the edges of the load to the edges of the base, ensuring an even distribution of the load during transportation. Each of the cargo fasteners is designated as l_1 , l_2 , l_3 , l_4 , l_5 , and l_6 . It is assumed that the fasteners l_1 , l_3 , l_4 , and l_6 have an equal length, designated as l' to simplify calculations and ensure uniform load distribution. The angles between these fasteners and the base are γ_1 , which ensures symmetrical tension and distribution of forces acting on the load. The fasteners l_2 and l_5 also have a similar length, designated as l'' , and the angles between these fasteners and the base are γ_2 . In the process of securing the load, the inclined tension of the fasteners is also considered. The angle γ_3 that forms between the attachment component shows how the inclined tension affects the fixation of the load, providing additional stability and preventing displacement when the vehicle is moving.

Based on the reverse engineering method of the system under consideration, it is possible to use the coordinate recalculation operation to determine each of the fastening lengths, which will allow systematically calculating the necessary fastening parameters based on the desired characteristics of movement and orientation of the load [26]. Any fastening element, regardless of whether it is on a load or a transport base, can be determined using the principles of spatial orientation [27]. Equation (3) can be used to do that, which allows obtaining the exact coordinates of each attachment point in a three-dimensional environment:

$$\begin{aligned} b_1 &= (b_{1x}, b_{1y}, 0) = (r \cos \alpha_2, r \sin \alpha_2, 0), \quad b_2 = (b_{2x}, b_{2y}, 0) = (0, d/2, 0) \\ b_3 &= (b_{3x}, b_{3y}, 0) = (-r \cos \alpha_2, r \sin \alpha_2, 0), \quad b_4 = (b_{4x}, b_{4y}, 0) = (-r \cos \alpha_2, -r \sin \alpha_2, 0), \\ b_5 &= (b_{5x}, b_{5y}, 0) = (0, -d/2, 0), \quad b_6 = (b_{6x}, b_{6y}, 0) = (r \cos \alpha_2, -r \sin \alpha_2, 0) \end{aligned} \quad (3)$$

as well as equation (4):

$$\begin{aligned} B_1 &= (B_{1x}, B_{1y}, 0) = (R \cos \alpha_1, R \sin \alpha_1, 0), \quad B_2 = (B_{2x}, B_{2y}, 0) = (0, d/2 + d2, 0) \\ B_3 &= (B_{3x}, B_{3y}, 0) = (-R \cos \alpha_1, R \sin \alpha_1, 0), \quad B_4 = (B_{4x}, B_{4y}, 0) = (-R \cos \alpha_1, -R \sin \alpha_1, 0), \\ B_5 &= (B_{5x}, B_{5y}, 0) = (0, -d/2 - d2, 0), \quad B_6 = (B_{6x}, B_{6y}, 0) = (R \cos \alpha_1, -R \sin \alpha_1, 0) \end{aligned} \quad (4)$$

where: r and R are the values of the radii of the curves of the upper faces of the cargo space and the transport base; α_1 – values determining the angles of direction B_1 , B_3 , B_4 , and B_6 ; α_2 – values determining the angles of direction b_1 , b_3 , b_4 , and b_6 .

The mathematical value denoting the length of the attachment can be represented in the O-XYZ orientation system using equation (5), which will allow accurately determining the distance from the attachment point to the origin in three-dimensional space, enabling the accurate determination of the location of the attachment and ensuring the necessary stability and safety of the system:

$$\begin{aligned} l_{1x} &= d_{11}b_{1x} + d_{12}b_{1y} + X_p - B_{1x} \\ l_{1y} &= d_{21}b_{1x} + d_{22}b_{1y} + Y_p - B_{1y}, \\ l_{1z} &= d_{31}b_{1x} + d_{32}b_{1y} + Z_p \end{aligned} \quad (5)$$

Thus, the equation that allows determining the length of the attachment can be represented as (6):

$$l_i = \sqrt{l_{1x}^2 + l_{1y}^2 + l_{1z}^2}. \quad (6)$$

where: $i = 1, 2, \dots, 6$.

By applying this equation, it is possible to determine the optimal fastening length depending on the required parameters and operating conditions. This step is especially important in design and engineering calculations, where accurate determination of the fixation length plays a critical role in ensuring the safety and reliability of the structure [28]. Using these mathematical equations, it is possible to calculate the length required to attach the object. This process involves substituting values from (5) to (6), resulting in equation

(7), which is important for ensuring the reliability and stability of the object attachment:

$$l_i = (d_{11}b_{1x} + d_{21}b_{1y} + X_p - B_{1x})^2 + (d_{21}b_{1x} + d_{22}b_{1y} + Y_p - B_{1y})^2 + (d_{31}b_{1x} + d_{32}b_{1y} + Z_p)^2, \quad (7)$$

The obtained values of the length of the fasteners, calculated using the equations described above, are presented in Table 1. Analysing this data helps to identify the required fastening lengths for specific operating conditions or design features, which is crucial for design and engineering calculations that accurately determine the fastening parameters necessary to ensure the system's reliability and safety [29].

Table 1. Parameters of fasteners of the cargo safety system

Mounting number	Length value, m
1	9.14
2	8.24
3	9.14
4	9.14
5	8.24
6	9.14

Based on the information received about the fasteners, it is possible to determine the appropriate characteristics of the fixation system. Thus, the angles γ_1 , γ_2 , and γ_3 , necessary for the correct installation and fastening of an object or cargo, can be calculated using equation (8), which will ensure the correct location and stable fixation of the object in space:

$$\begin{aligned} \gamma_1 &= \arcsin \frac{h}{l_6} \approx 40.3^\circ \\ \gamma_2 &= \arcsin \frac{d_2}{l_2} \approx 41.5^\circ, \\ \gamma_3 &= \arccos \frac{d_1}{l_1 \cos \varphi_1} \approx 55^\circ \end{aligned} \quad (8)$$

Special attention must be paid to the choice of fasteners and materials used during cargo transportation to ensure maximum safety and avoid potential emergencies [30]. As part of this study, fasteners made of Twaron aramid fibre (Teijin Aramid, the Netherlands) were selected for securing the load, the characteristics of which are presented in more detail in Table 2.

Table 2. Material characteristics for fasteners

Characteristics	The value of the parameter
Bending strength	3 GPa
Density	1.44 g/cm ³
Temperature resistance	250-300°C
The index of elasticity in tension	90-99%
Tensile strength	2.5-3.5 GPa
Type of fastener	Aramid fibre straps
Tensioner type	Tension strap

Aramid fibres are synthetic polymer materials created by polymerising aromatic amino acids (Figure 4). These fibres possess unique properties that make them exceptional materials for a variety of applications, including fastening systems for cargo transportation. One of the key characteristics of aramid fibres is their high strength. They have a unique molecular structure that provides high tensile strength. The rigid polymer chains in this molecular structure, highly orientated along the fibre axis, significantly enhance their mechanical properties [31]. The high tensile strength of aramid fibres allows them to withstand substantial loads without tearing or deformation, making them an ideal choice for creating fastening systems that ensure cargo transportation's safety.



Figure 4. Aramid Fibre-Based Cargo Fastening System, Source: [32].

Another important characteristic of aramid fibres is their resistance to wear and abrasion. Due to their high strength and resistance to wear, aramid fibres maintain their properties for a long time, ensuring the durability and reliability of fastening systems [33-35]. Applications that subject materials to constant friction and mechanical stress rely heavily on this resistance to abrasion. Additionally, the high chemical resistance of the material makes it resistant to destruction under the influence of various chemicals. This evidence chemical resistance is due to the stable molecular bonds within the aramid fibres, which are not easily broken down by most acids, bases, and solvents. This confirms the effectiveness of this material for use in the most challenging conditions of transportation of various goods and objects, including exposure to harsh environmental factors such as moisture, temperature variations, and chemical contaminants [36, 37]. Furthermore, aramid fibres exhibit excellent thermal stability, maintaining their structural integrity at high temperatures, which is essential for applications in extreme environments. They also have a low flammability, which adds an extra layer of safety in transportation scenarios where fire hazards might be a concern. The combination of these properties makes aramid fibres a superior material for ensuring the safety and reliability of cargo fastening systems under diverse and demanding conditions.

Taking the average value of the ultimate tensile strength of aramid fibre at the level of 3 GPa, the coefficient of elasticity of fasteners made of this material E is defined as (9):

$$E = 3000 \text{ MPa} * 1.44 = 4.32 \text{ GPa}, \quad (9)$$

Table 2 also demonstrates that the rate of return of elasticity of aramid fibre during stretching is in the range of 90-95%. The initial tension is set at 1.5% to increase the durability of the fastening system. For example, we consider a load attachment model with a length of l_1 equal to 9.14 m. According to calculations, the magnitude of the tension force F_1 , which plays an important role in ensuring the stability and safety of the fastening system, is (10):

$$F_1 = \frac{EA\Delta l_1}{l_1} = \frac{14.8 * 10^9 * 10^{-4} * 0.015 * 914}{914} \approx 22.64 \text{ kH}, \quad (10)$$

where: A – the cross-sectional area of the aramid fibre fastener; Δl_1 – the elongation of the fastener.

After performing calculations of the initial stress of the fastener, it is necessary to determine their strength characteristics. This will avoid a situation where this voltage exceeds the permissible limits and leads to the destruction of fasteners. A formula is used to calculate the strength of fasteners S_p for this, which is presented in the form (11):

$$S_p = \frac{S}{k_p k_r} = \frac{5000}{2 * 1} = 25 \text{ kH}. \quad (11)$$

where: S – the calculated load, that is, the maximum permissible force that the fastener can withstand; k_p – the safety factor, which considers the strength characteristics of the aramid fibre and provides an additional margin of safety; k_r – the dynamic force arising from vertical oscillatory accelerations acting on the system.

Notably, the value of the tension force F_1 experienced by the fastener during the initial tension process is less than the value of the ultimate strength parameter S_p , which is determined by the design load and considers safety and dynamic force factors. This indicates that the tension force applied to the fastening rope does not exceed its strength characteristics, ensuring its reliability and durability in operation. Thus, the initial tension of the fastener is within safe limits, which guarantees its safety and effectiveness during the fastening and transportation of cargo. A detailed understanding and calculation of these parameters is critical to ensuring safe transportation, as improper tension can lead to the rupture of the ropes, which in turn will lead to damage to the cargo or even emergency situations. After making sure that the value of F_1 is smaller than S_p , it can be stated that the selected initial tension parameters fully comply with the safety requirements and performance characteristics of the aramid fibre used in the fastening system.

When developing safety systems for cargo transportation, it is also important to conduct a comprehensive analysis of the entire system, including the vehicle, which plays a key role in the transportation process [38]. In this study, the Dongfeng Sokon truck (China) was selected as the vehicle. This choice is based on its manoeuvrability and load capacity, which makes it the best option for transporting goods under various operating conditions. The movement of the vehicle and its effect on the

fastening system are considered when creating a three-dimensional model, which allows for a more accurate assessment of the interaction between the load and the vehicle during transportation. Figure 5 shows the developed model of the cargo fastening system and the transportation base in three dimensions, using the Dongfeng Sokon vehicle as an example.

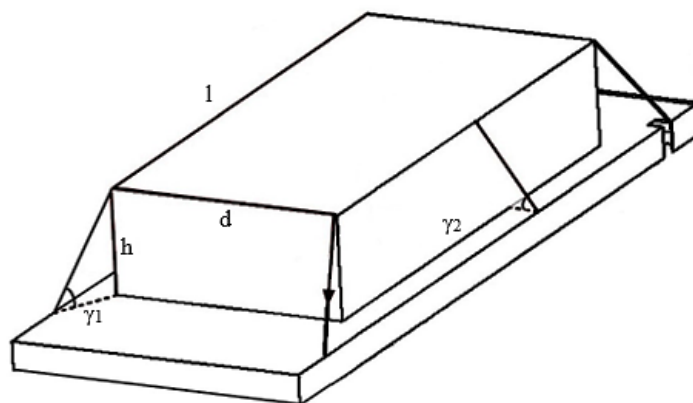


Figure 5. The Developed Model of the Cargo Fastening System and the Transportation Base

This cargo safety system consists of two main components: the model of fastening the object for transportation and the model of the base for transportation, which is used in the vehicle in question. In this detailed model, all parameters such as length (l), width (d), height (h), and angles (γ_1 and γ_2) displayed in Figure 5 correspond to those presented in the model in Figure 3.

This system has a number of substantial advantages. Firstly, it guarantees the safe and reliable fastening of the load on the vehicle. Due to specially designed fasteners and mechanisms, the system minimises the risk of displacement, falling, or damaging the cargo during transportation. This functionality is especially important for the transportation of valuable or fragile goods, where any damage can lead to serious financial losses. This system also provides a high degree of ease of use and time savings. It is designed with ease of installation and maintenance in mind, which allows quickly and efficiently conducting the processes of loading and unloading cargo. This feature increases productivity and reduces the time spent on cargo transportation, which is especially valuable in conditions of heavy freight traffic. Additionally, it plays an important role in improving road safety. By preventing possible emergencies related to improper fastening or the displacement of cargo, it helps reduce the risk of road accidents and protects road users.

Thus, the developed cargo security system represents not only an innovative technical solution but also an important step in ensuring the safety and efficiency of cargo transportation. It opens up new opportunities in the field of logistics and the transport industry, allowing for more efficient use of the possibilities of transporting various types of goods. The developed system demonstrates the potential for further improvement and application in a wide range of areas where safety and efficiency in transportation play a key role.

4. Discussion

In the course of this study, an innovative cargo securing system was developed that is capable of providing a high level of safety and preventing possible damage and unforeseen situations during transportation. It successfully solves the problem of minimising the impact of external factors, which guarantees the stability and reliability of cargo transportation under various operating conditions. In the study by Krzyżaniak et al. [39], various aspects of cargo safety systems during transportation were also investigated, which allowed a more profound understanding of how the fastening system affects cargo in various conditions of movement and the influence of external forces.

The paper of Vlkovský et al. [40] focused on the examination of special fastening methods aimed at improving the stability of large objects during transportation, which eventually contributed to the development of an approach that improved the efficiency and safety of goods. Nevertheless, this study stands out among the papers mentioned for its comprehensive approach to the analysis and optimisation of cargo securing systems. Unlike previous studies, which often address cargo fastening systems in isolation, this research offers a comprehensive solution by combining material innovation, mathematical modelling, and mechanical engineering principles. Specifically, it introduces a fastening system based on aramid fibres (Twaron), whose high tensile strength and resistance to external factors have been quantitatively incorporated into the design through detailed stress and tension calculations. Furthermore, the application of a parallel mechanism model with six degrees of freedom enables more precise load distribution and stability during dynamic vehicle movement, a feature lacking in most traditional systems. By integrating a three-dimensional coordinate transformation method and reverse engineering techniques, the proposed system adapts to different cargo geometries and vehicle types. These engineering advancements enhance mechanical reliability and reduce operational costs through faster installation and maintenance. Therefore, the study contributes novel, practical, and cost-effective solutions to cargo transportation safety, surpassing conventional friction-based methods in both adaptability and robustness.

The influence of external forces on cargo integrity, especially during dynamic events such as sudden braking or uneven road surfaces, has been examined by Lovska et al. [41]. Their work emphasised the significance of modelling dynamic loads and how they affect the cargo structure and its securing system. This study supports that emphasis and takes it further by implementing an engineered solution. The aramid fasteners used in this system were pre-tensioned by 1.5% of their original length. The resulting tension force, calculated through the modulus of elasticity of aramid fibres, falls below the material's ultimate tensile strength, confirming the system's ability to resist deformation during inertia-inducing manoeuvres.

The results also demonstrated that one of the important advantages of the developed system is its applicability in a wide range of operating conditions. The system was designed to accommodate various

cargo types and geometries, with adaptability to different transport scenarios achieved through the integration of a parallel mechanism and high-strength aramid fibre straps. While specific weight categories were not the primary focus, the system's structural configuration and material properties allow it to securely fasten both relatively small loads (e.g., compact goods with modest dimensions) and larger, heavier objects commonly encountered in industrial or construction logistics. This design flexibility makes the system suitable for use across sectors such as commercial freight, construction materials delivery, and equipment transport. Additionally, the straightforward fastening mechanism and the use of uniform attachment components support ease of implementation, helping reduce the time and cost associated with staff training and system setup, which in turn promotes broader adoption. A study by Khachatryan [42] examined the optimisation and versatility of transportation systems and outlined new directions for improving cargo movements across different industries. However, unlike the present study, Khachatryan's work did not examine specific engineering improvements aimed at enhancing fastening reliability under dynamic load conditions. In contrast, this research places greater emphasis on the integration of advanced materials and structural solutions, which collectively improve the safety and operational flexibility of the fastening system across varied transportation contexts.

The innovative cargo fastening system utilising aramid fibres presents several advantages over traditional fastening methods, such as ropes, belts, chains, and wires. Aramid fibres exhibit exceptional tensile strength, often around 3 GPa, allowing them to withstand substantial loads without deformation or tearing, whereas traditional materials like polyester, nylon, or polypropylene used in ropes and belts have lower tensile strengths and are more susceptible to wear and environmental degradation. Chains, while offering high strength, are significantly heavier and prone to corrosion, especially in chemically aggressive environments, and steel wires can suffer from fatigue and corrosion over time, reducing their lifespan and reliability [43]. Aramid fibres are much lighter than metal chains and wires, reducing the overall weight of the fastening system and potentially lowering fuel consumption and handling effort [44, 45]. They can be woven into various forms, such as straps and belts, allowing for flexible and adaptable fastening solutions that conform to different shapes and sizes of cargo, making them easier to handle and install compared to rigid metal fasteners. The high strength-to-weight ratio and resistance to environmental factors ensure that aramid fibres provide a reliable and safe fastening solution, reducing the risk of cargo damage or loss, and their low flammability adds an extra layer of safety in transportation scenarios where fire hazards might be a concern. Although the initial cost of aramid fibres may be higher, their durability and low maintenance requirements can result in long-term savings, whereas traditional fasteners may require frequent replacement due to wear and environmental degradation, leading to higher long-term costs.

The versatility of the system also implies its potential for application in various fields of activity. For instance, the system can ensure the safe transportation of building materials in construction, and it can

facilitate the movement of large-sized equipment in heavy industry. In addition, the advantage of the versatility of the developed cargo fastening system is also manifested in its ability to adapt to different types of vehicles. Such versatility means that it can be successfully integrated into trucks and other modes of transport, such as railcars, ships, or even aircraft, which increases its value and practical applicability. Melnyk [46] also focused on the possibility of integrating the cargo securing system with various types of vehicles, which, as a result, allowed for improved compatibility and reduced the risk of unforeseen situations during transportation. Notably, the study expands on these results by offering a more detailed understanding of the universality of the system. This study, which included the development of an innovative cargo securing system, demonstrated its successful adaptation for trucks, providing comprehensive conclusions about the system's applicability and increasing its value for operators and logistics companies.

Material innovation forms another critical component of this research. The use of Twaron aramid fibre as the primary material for fasteners introduces several advantages over traditional composites. Previous studies by Meng et al. [47] and Chauhan et al. [48] analysed composite belts and reinforced polymers for transportation purposes, noting their advantages in terms of flexibility and resistance to environmental stress. However, these studies lacked a focused analysis on specific fibres, like Twaron. In contrast, this work not only selects this material but also incorporates its physical properties into system calculations. For instance, Equation (10) calculates the tension force based on the cross-sectional area and elongation of the fibre, ensuring that the induced stress does not exceed the safety limits. Furthermore, Equation (11) includes a safety factor and dynamic force parameters to verify the robustness of the fastening system under real-world conditions.

In addition to mechanical strength, chemical and environmental resistance plays a key role in ensuring system longevity, especially in global transport contexts. Kaczmarczyk [49] underscored the impact of climatic variations on material fatigue and the importance of selecting materials with high tolerance to such changes. Similarly, Archetti et al. [50] surveyed the influence of fastening methods and materials on cargo safety across multimodal freight systems. This study complements these investigations by confirming that aramid fibres exhibit superior resistance to moisture, chemicals, and temperature variations. These qualities ensure minimal material degradation and reduce the frequency of system maintenance, thus improving cost-efficiency and operational reliability. By examining both environmental and mechanical resilience, this study demonstrates a more holistic approach than many existing materials-focused investigations.

Thus, the results of all the studies conducted in the field of vehicle cargo safety systems emphasise the importance of continuous development in this area. The analysis of various factors, such as the effectiveness of fastening systems and the use of new materials and design solutions, as well as the examination of their impact on the transportation process, plays a key role in ensuring the safety and

reliability of cargo transportation, which ultimately increases the level of safety and reduces risks during transportation.

5. Conclusions

As a result of this study, an innovative cargo securing system has been developed, which represents a substantial step in the field of cargo transportation. The developed fastening system has a high degree of safety, as it can prevent destruction and unforeseen situations during cargo transportation. The system effectively distributes the load while minimising the impact of inertial forces while the vehicle is moving. This ensures stability and reliability in the process of transporting goods of various types and sizes.

One of the key advantages of the developed system is its versatility and applicability in various operating conditions. The system can be used to transport both light and heavy loads, adapting to different types of vehicles. Due to this flexibility, it can be successfully applied in various industries, including logistics, heavy industry, and construction. In this study, the use of high-strength aramid fibre fasteners as a fastening material enabled the system to achieve high strength and reliability while maintaining minimal weight. This choice of material provided the opportunity to achieve an optimal combination of strength and lightness, which is a vital aspect in the development of efficient transport systems.

In general, the developed cargo securing system is an innovative technical solution that contributes to improving the efficiency and safety of cargo transportation. Its extensive functionality and reliability make it a promising tool in the field of logistics and transport. Notably, the study has certain limitations, including the lack of detailed testing of the developed cargo fastening system in practice. It should also be considered that the results of the study may be limited by the context of use and operating conditions, which requires additional verification in various conditions.

Areas for further research in this field may include the integration of new technologies into the proposed system, such as automated cargo management systems, and the investigation of their impact on the efficiency and safety of cargo transportation. It is also important to explore the possibilities of integrating the developed cargo securing system with existing infrastructures to ensure a more harmonious and safe movement of cargo vehicles, which will open up new ways to improve its functionality in various transport scenarios.

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

Funding: The authors declare that no funding was received for this research.

Declaration of Competing Interest: The authors declare they have no known competing interests.

Research Involving Human/Animal Participants: This article does not involve any studies conducted by authors on animals or human participants.

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