Research Article

Evaluation of ROPS and FOPS Tests for Structural Integrity of Forklifts

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Abstract

This study examines the Roll-Over Protective Structure (ROPS) and Falling Object Protective Structure (FOPS) tests and their results for forklifts. The main focus of the study is the evaluation of the cabin safety of a forklift with a lifting capacity of 3.5 tons. Within this scope, the compliance of the protective structures with the international standards ISO 3471 and ISO 3449 has been thoroughly analysed. In the ROPS tests, the applied force and energy values under lateral, rear, and vertical loading conditions were calculated; the test setup, the applied loads, and the resulting deformations in the structure were investigated. Furthermore, in the FOPS test, the required energy levels were evaluated, and the results of the tensile tests conducted to verify the mechanical integrity of the fasteners (bolts) after the impact test were presented.

Keywords: ROPS, FOPS, forklift, protective structure, test, safety, requirement

1. Introduction

A forklift is a type of stacking machine designed to lift and transport loads from one point to another using an attachment located at the front of the vehicle. The area where the operator is seated and controls the forklift is referred to as the cabin. The cabin possesses various characteristics in terms of safety, ergonomics, and functionality. A closed cabin is a structure enclosed by glass panels and doors, designed to protect the operator from external factors such as dust, rain, and cold weather, making it suitable for both indoor and outdoor operations. In contrast, an open cabin design is generally preferred for indoor use.

Some of the key safety features of the cabin include the Rollover Protective Structure (ROPS) and the Falling Object Protective Structure (FOPS). The ROPS is a structural system intended to protect the operator in the event of a forklift rollover [4], while the FOPS is designed to safeguard the operator from falling objects [5].

The structural components of the cabin and chassis must be selected and designed to withstand the forces generated during a rollover or object impact. The design and selected materials must be verified through testing to ensure safety and reliability. The test procedures that validate these protective systems are specified in ISO standards. An illustration of the forklift examined in this study is presented in Figure 1 [3].

Figure 1: General View of Forklift.

2. Materials and Methods

The structural composition of forklifts can be classified into nine main sections: counterweight, elevator lift, exhaust system, electrical and preassembled component systems, hydraulic systems, powertrain system, cabin, chassis, and steering systems (Figure 2).

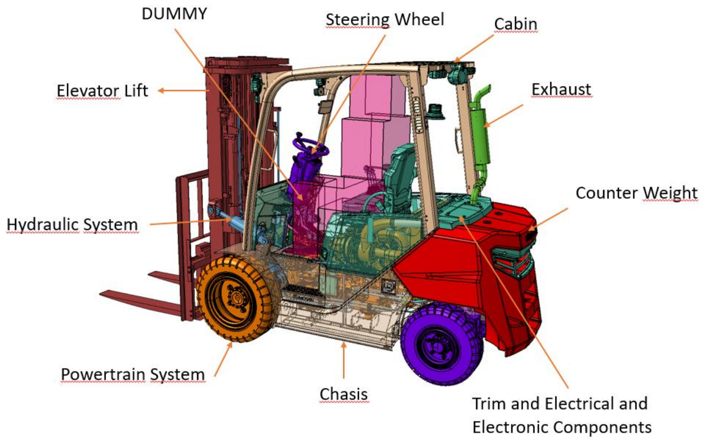

Figure 2: Forklift Subsystems and Components

In this study, a TÜMOSAN brand forklift with a lifting capacity of 3.5 tons was used. Some technical specifications of this forklift are provided in Table 1 below [1].

Table 1: Technical Specifications of the Forklift [1].

Features	
Power supply	Diesel
Load capacity (kg)	3500
Load center distance (mm)	500
Wheelbase (mm)	1750
Weight	
Forklift weight, unloaded (kg)	4820
Unloaded axle load, front/rear (kg)	1970/2900
Axle load, front/rear (kg)	7900/470
Dimensions	
Cabin total height from ground (mm)	2170
Total length (mm)	3900
Length to fork crown (mm)	2750
Total width (mm)	1250
Fork dimensions (thickness, width, length) (mm)	45/125/1200
Fork mirror width (mm)	1208
Turning radius (mm)	2450
Engine	
Engine power@speed (kW@rpm)	41@2500
Maximum torque (Nm@rpm)	190@1600

2.1. Deflection-Limiting Volume Characteristics of Protective Structures in Construction and Earthmoving Machinery (ISO 3164)

Safety is one of the most critical factors in the design of construction machinery. Machines used in sectors such as agriculture, construction, mining, and forestry are subject to various standards to ensure the protection of operators in the event of workplace accidents that may occur inside the cabin. ISO 3164 is an international standard that specifies the reference dimensions and test methodologies related to the testing of protective structures for such machines, including ROPS (Rollover Protective Structures) and FOPS (Falling Object Protective Structures) [6]. The dimensions of the dummy used in ROPS and FOPS tests are defined as the Deflection Limiting Volume (DLV) (Figure 3). All linear dimensions of the DLV shown in Figure 3 shall have a tolerance of ±5 mm. The accuracy of positioning the DLV's Seat Index Point (SIP) relative to the SIP of the seat on which it is installed shall be within ±13 mm in both the horizontal and vertical directions. The macro accuracy of rotation shall be ±1° [6].

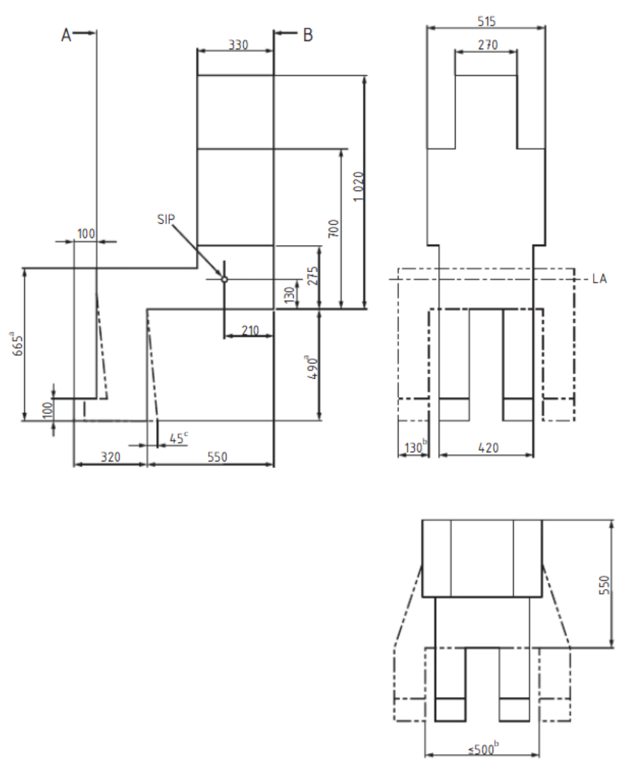

Figure 3: Dummy Dimensions Used in ROPS and FOPS Testing [6].

During the ROPS and FOPS tests of the cabin, in order to prevent the dummy from coming into contact with the applied forces from the lateral and rear directions, the dummy may be rotated 15° away from the direction of the applied force, while keeping the Seat Index Point (SIP) fixed, to move it away from the cabin [6] (Figure 4).

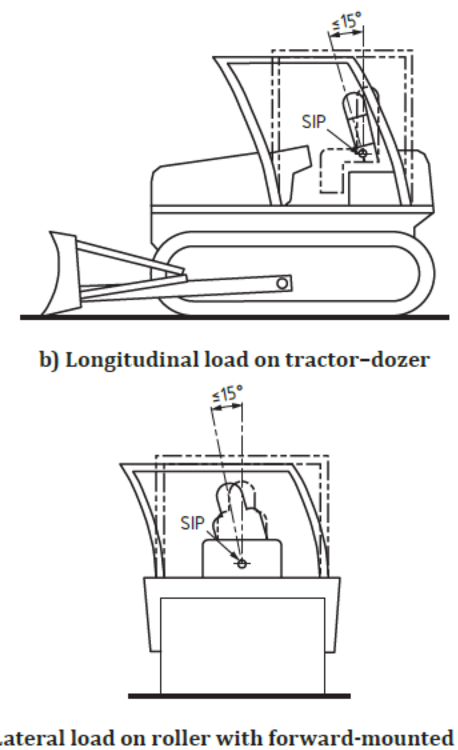

Figure 4: DUMMY's Return Based on the SIP Point [6].

2.2. Roll Over Protective Structures (ROPS)

When evaluated within the scope of ISO 3471:2008, forklifts may be classified among mobile machines that require Rollover Protective Structures (ROPS). This standard specifies the performance requirements and testing procedures for protective cabins or frames that must possess sufficient structural strength to ensure operator safety in the event of a rollover [4].

In this context, equipping forklifts with a ROPS that meets the requirements of ISO 3471 serves as an important measure to enhance operator safety.

2.2.1. ROPS Force Loads

The ROPS test loads are determined in accordance with ISO 3471:2008. The forces to be applied to the forklift during the ROPS test are calculated based on the unladen mass of the forklift, excluding any load attached to its lifting equipment. If the applied force exceeds the moment acting from the center of gravity of the forklift to the wheel rotation axis, the forklift may overturn in the direction of the applied load. The overturning behavior of the forklift can be tested according to ISO 22915[4].

The main difference between ISO 3471:2008 and ISO 22915 lies in their testing objectives. ISO 22915 evaluates the stability of forklifts under four different test conditions—both laden and unladen—according to their rated lifting capacity. In this test, the forklift is placed on a platform and tilted at specific angles and heights to determine whether it overturns under loaded or unloaded conditions. On the other hand, ISO 3471:2008 focuses on assessing whether the deformation of the protective structure (cab or frame) during a rollover would cause injury to the operator [4].

An important point to consider in ISO 3471:2008 is that the forces applied to the forklift must be calculated based on its own weight (mass), excluding the weight of any load corresponding to its lifting capacity. In Table 2, the mass of the forklift is denoted as M. The forces are applied sequentially in the lateral, longitudinal, and vertical directions. The energy corresponding to the applied lateral force must meet the required value; if the applied force does not achieve the target energy level, additional force must be applied until the required energy is reached. The relevant equations are provided in Table 2, in accordance with ISO 3471:2008 [4].

Table 2: Force and energy formulas to be applied to the ROPS structure according to the ISO 3471:2008 standard [4].

Machine mass m kg	Lateral load force F N	Lateral load energy U J	Vertical load force F N	Longitudinal load force F N
1) Crawler earth-moving machine: dozer, loader, pipelayer and trencher type				
$700 < m \leqslant 4\,630$	$6m$	$13\,000\,(m/10\,000)^{1,25}$	$19{,}61m$	$4{,}8m$
$4\,630 < m \leqslant 59\,500$	$70\,000\,(m/10\,000)^{1,2}$	$13\,000\,(m/10\,000)^{1,25}$		$56\,000\,(m/10\,000)^{1,2}$
$m > 59\,500$	$10m$	$2{,}03m$		$8m$
2) Grader				
$700 < m \leqslant 2\,140$	$6m$	$15\,000\,(m/10\,000)^{1,25}$	$19{,}61m$	$4{,}8m$
$2\,140 < m \leqslant 38\,010$	$70\,000\,(m/10\,000)^{1,1}$	$15\,000\,(m/10\,000)^{1,25}$		$56\,000\,(m/10\,000)^{1,1}$
$m > 38\,010$	$8m$	$2{,}09m$		$6{,}4m$
3) Wheeled earth-moving machine: loader, tractor-dozer, pipelayer, landfill compactor, skid-steer loader, backhoe loader and trencher type				
$700 < m \leqslant 10\,000$	$6m$	$12\,500\,(m/10\,000)^{1,25}$	$19{,}61m$	$4{,}8m$
$10\,0000 < m \leqslant 128\,600$	$60\,000\,(m/10\,000)^{1,2}$	$12\,500\,(m/10\,000)^{1,25}$		$48\,000\,(m/10\,000)^{1,2}$
$m > 128\,600$	$10m$	$2{,}37m$		$8m$
4) Tractor section of combined earth-moving machine: tractor scraper, articulated frame dumper				
$700 < m \leqslant 1\,010$	$6m$	$20\,000\,(m/10\,000)^{1,25}$	$19{,}61m$	$4{,}8m$
$1\,010 < m \leqslant 32\,160$	$95\,000\,(m/10\,000)^{1,2}$	$20\,000\,(m/10\,000)^{1,25}$		$76\,000\,(m/10\,000)^{1,2}$
$m > 32\,160$	$12m$	$2{,}68m$		$9{,}6m$
5) Roller [a]				
$700 < m \leqslant 10\,000$	$5m$	$9\,500\,(m/10\,000)^{1,25}$	$19{,}61m$	$4m$
$10\,000 < m \leqslant 53\,780$	$50\,000\,(m/10\,000)^{1,2}$	$9\,500\,(m/10\,000)^{1,25}$		$40\,000\,(m/10\,000)^{1,2}$
$m > 53\,780$	$7m$	$1{,}45m$		$5{,}6m$

The forklift is classified in the wheeled work machine category in the ISO 3471:2008 standard. The force formulas to be applied for this classification are as follows.

2.2.1.1. Lateral Load Force and Lateral Load Energy Calculate

The lateral force has been calculated as follows:

$$F_{lateral} = M \times 6$$

The lateral energy has been calculated as follows:

$$E_{lateral} = 12\,500\ (M / 10\,000)^{1,25}$$

2.2.1.2. Vertical Load Force Calculate

The vertical force has been calculated as follows:

$$F_{Vertical} = M \times 19{,}6$$

2.2.1.3.Longitudinal Load Force Calculate

The longitudinal force has been calculated as follows:

$$F_{Longitudinal} = M \times 4{,}8$$

2.2.2. ROPS Force Components and Positioning

In the ROPS test application, components are designed to distribute and transmit the point load exerted by hydraulic cylinders onto the cabin profiles. These components are used to prevent localized contact when they are mounted on the profiles.

The lateral loading component is a structural element designed to accurately and controllably transmit the force applied laterally to the cabin during ROPS testing. During loading, it prevents the force from concentrating at a single point, ensuring that the test is conducted in accordance with the standards.

Lateral load tests are a critical stage in evaluating whether the cabin can protect the operator in the event of a rollover, and the reliability of load transfer directly affects the accuracy of the test results.

In the ROPS test, the component applying the horizontal load should be positioned at the vertical center of the profiles. Horizontally, it should be located at one-third of the cabin length from the rear towards the force center. These components must be smaller than 0.8 times the cabin width. For box profiles, the contact surface should be flat; for omega profiles, a specially designed insert can be used to fill the cavity and provide proper load distribution (Figure 5) [4].

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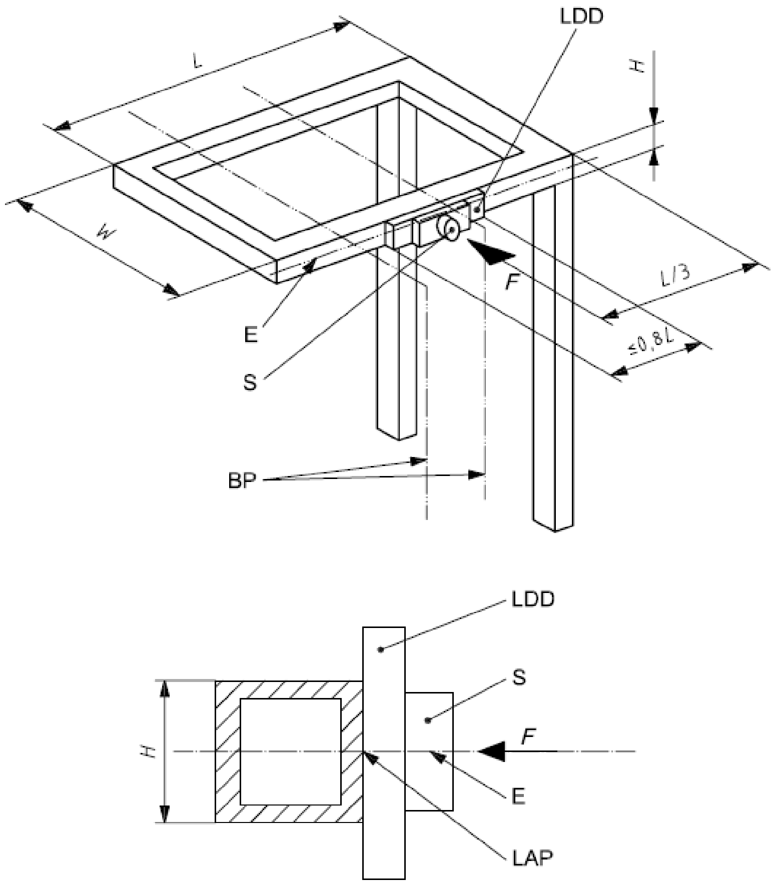


Figure 5: Positioning of the Lateral Force Component [4].

In the ROPS test, the component that applies the rearward force should be positioned properly on the upper rear profile surface. This component must not exceed 0.8 times the cabin width and should be centered on the profile. The applied force acts at the midpoint of this component (Figure 6) [4].

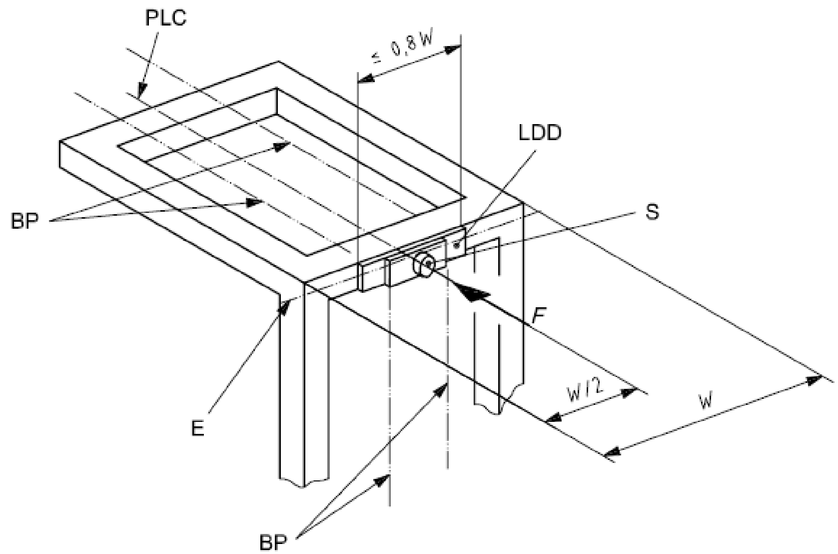


Figure 6: Positioning of the Rear Force Component [6].

In the ROPS test, the position of the vertically acting force component must be located at the intersection point of the centerline of the laterally acting force and the rearward acting force.

2.2.3. Installation of the ROPS Test Rig

The forklift to be tested for ROPS must be securely fixed onto the test platform. In this test, the forklift was anchored to the platform using brackets connected to the front wheel bolts and the rear axle bolts. The dummy was then mounted on the seat at the intersection point of the seat index point (SIP) of the forklift and the SIP point of the dummy, which served as the reference position (Figure 7).

Figure 7: The Forklift Fixed to Test Platform

The lateral force component is a specially designed structure that is typically mounted as a modular unit on the main loading plate. In its design, a sufficiently thick and rigid material is selected to ensure that the applied load is distributed over a wide surface area. This component is generally manufactured from high-strength materials such as S355 or ST52 steel, which minimizes possible deformations during testing. The force application component must not slip over the cabin profiles. Box sections are welded onto the plate where the load is applied, while the lateral force component is designed in accordance with the omega profile and positioned on the plate accordingly (Figure 8).

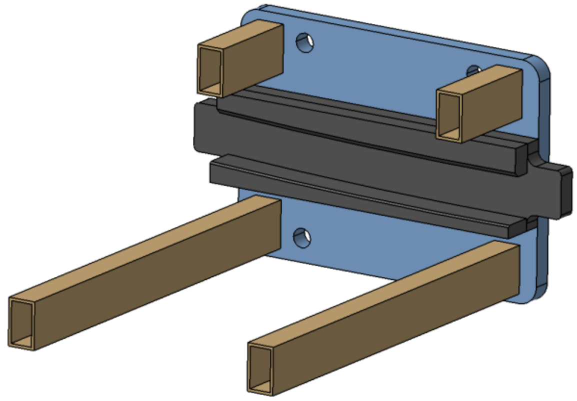


Figure 8: Lateral Force Component

The lateral force component is positioned as indicated in figure 6. (Figure 9)

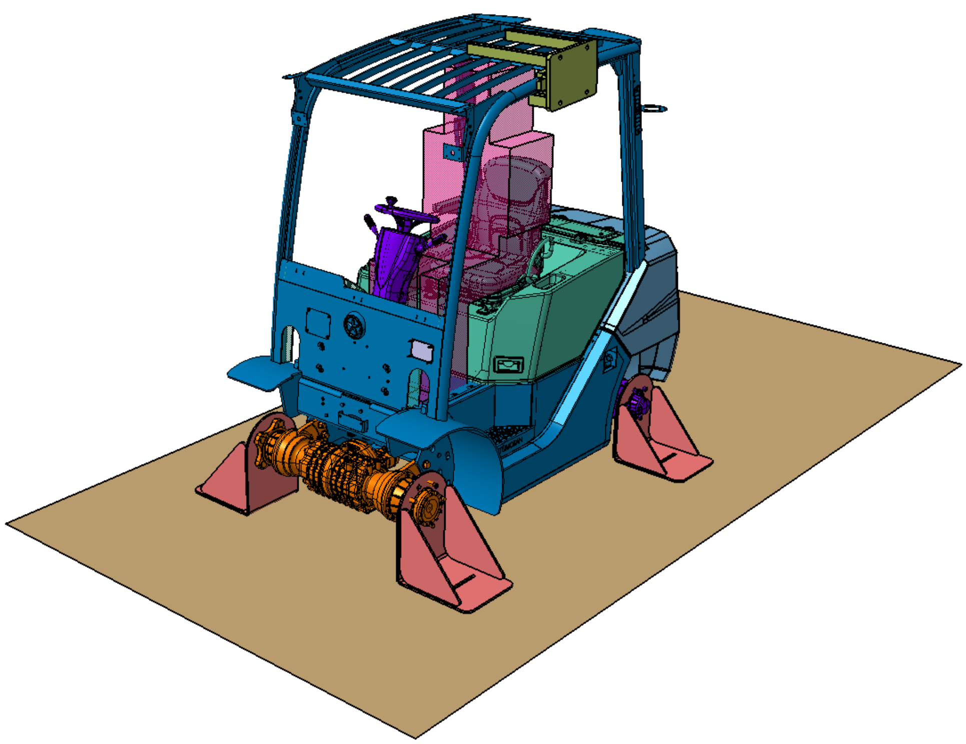


Figure 9: Positioning of the Lateral Force Component

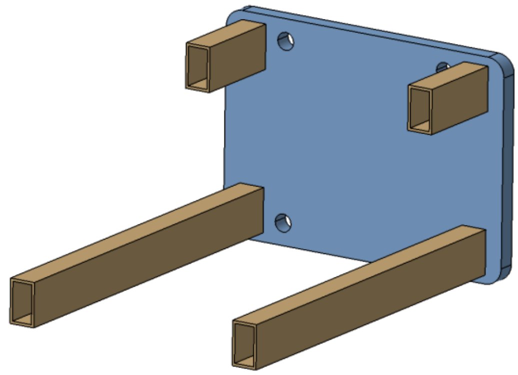


Figure 10: Rearward Force Component

The rear impact force component is a structural element used in the ROPS test to accurately transmit the load applied to the cabin from the rear. This component ensures uniform load distribution during testing and demonstrates the structural performance of the ROPS system in compliance with the specified standards. From a design perspective, it has a flat and rigid steel plate structure. During loading, the hydraulic cylinder or mechanical force application system is connected to this component, and the force is directly transmitted to the rear section of the cabin.

One of the most important features of this component is its ability to distribute the applied load over a wider area. Concentration of force at a single point may cause local deformations and lead to inaccurate test results. Therefore, the rear impact force component is designed to spread the load uniformly. Box profiles prevent the cabin from slipping downward along the rear frame, ensuring rigid and stable force transmission.

To enable the rigid and accurate transmission of the rear-applied force, the rear tail bracket was cut, and the plate was positioned as shown in Figure 11.

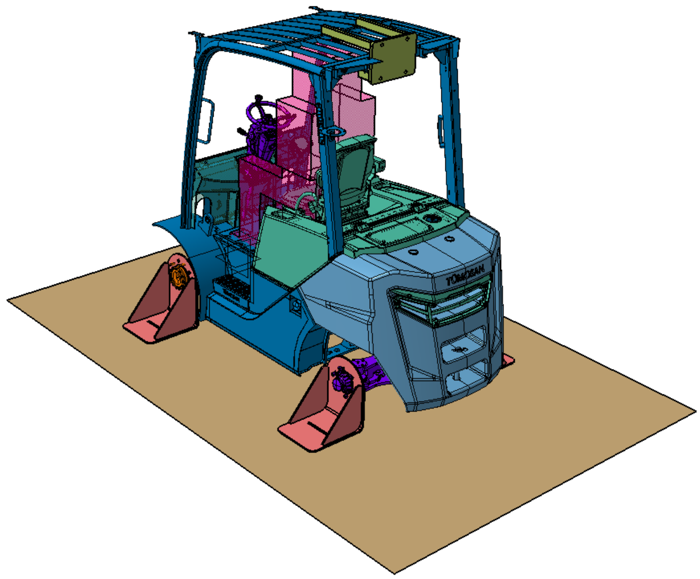


Figure 11: Positioning of the Rear-Acting Force Component

The vertical force component is a critical element designed to accurately and controllably transmit the load applied to the cabin from above during ROPS testing. This component is used to evaluate the vertical load-bearing capacity of the ROPS structure, which plays a key role in protecting the operator in the event of a rollover involving tractors or construction machinery. The vertical loading test is essential for determining the cabin's resistance to collapse and its ability to maintain a safe survival space for the operator.

The vertical force component typically consists of a thick plate made of high-strength steel, supported by structural profiles. In these tests, a structural element with an H-profile is commonly used. The flat surface of the profile is crucial for ensuring that the load is evenly distributed onto the cabin. If the force is concentrated on a small area, local collapse may occur, resulting in inaccurate test outcomes. Therefore, the surface of the vertical force component must be wide and rigid (Figure 12).

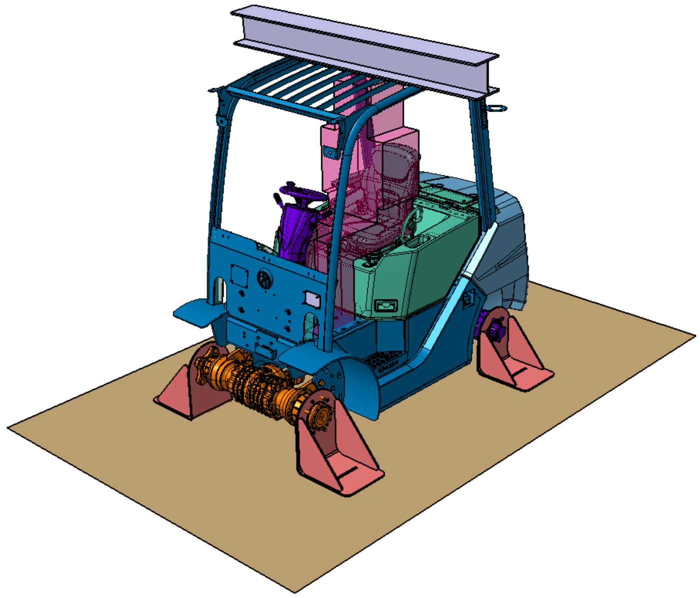


Figure 12: Positioning of the Vertically Acting Force Component

2.3.FALLING OBJECT PROTECTIVE STRUCTURE (FOPS)

Industrial machinery used in various sectors is equipped with multiple safety systems to ensure that operators can work safely under demanding conditions. Accidents caused by falling objects are particularly common in industries such as mining, construction, and forestry. Therefore, Falling Object Protective Structure (FOPS) systems have been developed to protect the operator's cabin from objects that may fall from above. For construction and heavy-duty machinery, a protective structure must be designed to ensure operator safety against falling objects. In this study, the preparation of the FOPS test area, the test implementation methods, and compliance with relevant standards are examined. The test area should be prepared in accordance with the ISO 3449 standard, and all evaluations should be conducted based on the procedures defined in this standard [5].

FOPS systems are classified into different levels according to their field of application and the loads to which they may be exposed. These systems are divided into two categories based on the impact energy levels applied during testing:

Level I: This level is tested by dropping a round object with an impact energy of 1365 Joules from a specified height. The dropped object may be made of steel, cast iron, or another solid material; however, it must be harder than the material it impacts. The test mass is 45 kg, and the spherical object must not exceed a diameter of 250 mm (Figure 13) *[5].*

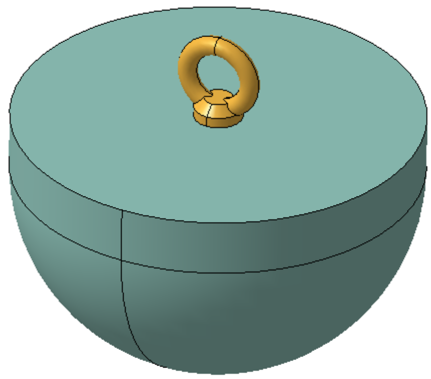


Figure 13: Example of a Launch Component Belonging to Level I

Level II: This level is tested by dropping a blunt-edged object with an impact energy of 11,600 Joules from a specified height. The dropped object may be made of steel, cast iron, or another massive material; however, it must be harder than the material it impacts. Level II applies to machines operating in environments where there is a high risk of large rocks, concrete blocks, or other heavy objects falling. It covers machinery used in building demolition, logging, and material handling operations (Figure 14) *[5].*

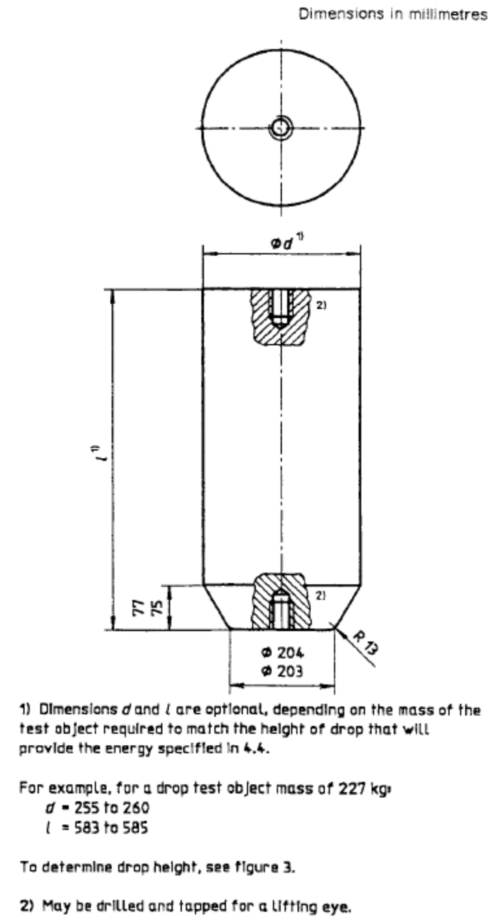


Figure 14: Launching Component for Level II [5].

In order to meet the energy requirements specified for both Level I and Level II, the height position of the dropped object can be determined using the following potential energy equation.

$$E_{potansiyel} = M \times G \times H$$

$E_{potansiyel}$: Potential energy based on height (Joules)
M: Mass of the falling object (kg)
G: Gravitational acceleration (m/s^2)
H: Height between the falling object and the FOPS structure (m)

FOPS systems are generally used in conjunction with ROPS (Roll Over Protective Structures). While ROPS protects the operator's cabin in the event of a machine rollover, FOPS provides protection against falling objects.

2.4. Setting Up the FOPS Test Arrangement

Construction and heavy industrial machinery may be exposed to falling objects in their working environments. To ensure operator safety in such incidents, Falling Object Protective Structures (FOPS) have been developed and are required to undergo standardized testing. Forklift structures must be designed to withstand the impact conditions defined in the ISO 3449 standard. The test area should be constructed on a flat and solid surface. A level ground ensures accurate measurement of impact forces. To minimize external environmental influences, the testing setup should be established either in an indoor laboratory or in an outdoor area with adequate safety precautions. Barriers, warning signs, and personal protective equipment should be provided to ensure the safety of personnel working within the testing area. Equipment and test procedures that comply with international standards such as ISO 3449 must be used. The structure to be tested should be securely fixed in place to prevent any movement during testing. It should be mounted on a test stand or directly on the vehicle chassis, using appropriate fastening elements to maintain stability throughout the test. The test apparatus must be designed to transmit the impact force directly and effectively. Care should be taken to maintain the required impact energy by adjusting the drop height according to the mass of the falling object. A remotely controlled hook system may be used to ensure that the impactor is released accurately from the desired position. To observe deformations on the structure, laser measurement systems or high-speed cameras can be utilized. All test data should be recorded and analyzed for evaluation. Proper preparation of the FOPS test area is crucial for obtaining reliable test results. The suitability of the ground surface, adequacy of safety precautions, and compliance of testing equipment with relevant standards are critical factors for a successful testing process. After the impact, the deformation of the FOPS structure must not result in any contact with the DUMMY. These procedures contribute significantly to maintaining occupational safety standards and maximizing operator protection (Figure 15).

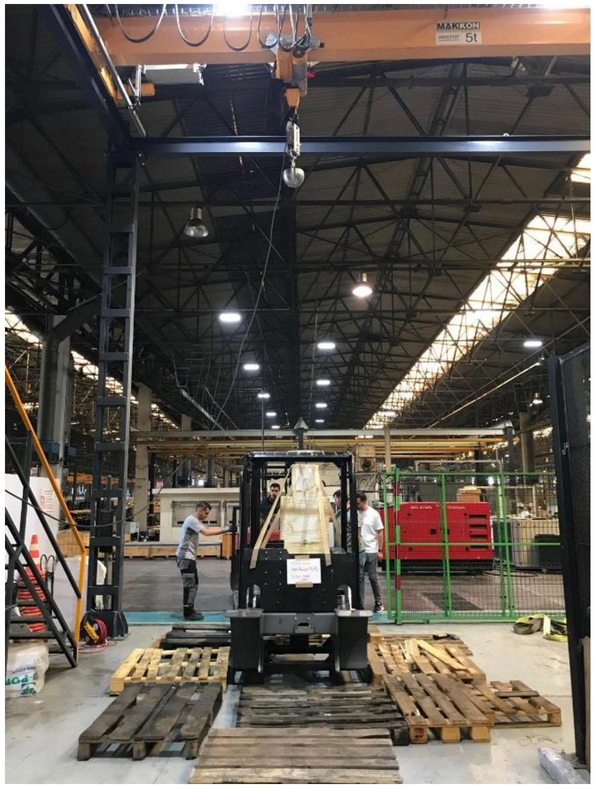


Figure 15: Preparation of the FOPS Test Setup

2.5. Connection Elements Between Cabin and Chassis

One of the fundamental structural components that ensures operator safety in construction machinery is the connection between the cabin system and the chassis. These connections must demonstrate high strength not only during the static operation of the machine but also under dynamic loads such as rollover, collision, or sudden impact that may occur in the field. In forklifts and similar types of machinery, ROPS (Roll Over Protective Structure) tests are conducted to evaluate such load scenarios, aiming to assess the structural integrity of both the cabin structure and the connections between the cabin and the chassis.

During the ROPS test, the cabin is subjected to controlled rollover or impact loads from specific angles. These loading scenarios directly transfer the applied forces to the bolts connecting the cabin to the chassis. The success of the test is not only dependent on the deformation capacity of the cabin frame but also closely related to the ability of the connection points to safely transmit the load without exhibiting fracture or loosening.

In this study, four M12×45, six M12×40, and six M12×35 carbon steel bolts of grade 8.8, used to attach the forklift cabin to the chassis, were examined (Figure 16). A grade 8.8

bolt has a minimum tensile strength of 800 MPa and a yield strength of 640 MPa, making it a suitable choice for industrial connections requiring medium to high strength.

Following the ROPS test, tensile testing was performed to determine whether the bolts sustained any structural damage. In this test, the fracture loads, elongation values, and failure modes of the bolts were evaluated, and the results were compared with the ISO 898-1:2013 standard [7].

Figure 16: Bolts used between the cabin and chassis.

ISO 898-1:2013 is an internationally recognized standard that defines the mechanical properties of fasteners, providing reference values for several critical parameters such as tensile strength, yield strength, hardness, ductility, and fracture mode [7].

The tensile tests were conducted using a universal testing machine. Each bolt was mounted to the testing apparatus with appropriate gripping fixtures, and an axial load was applied at a constant loading rate. Throughout the test, force–elongation data were recorded, and the maximum load at fracture (Fmax) as well as the fracture mode (ductile or brittle) were evaluated (Figure 17) [7].

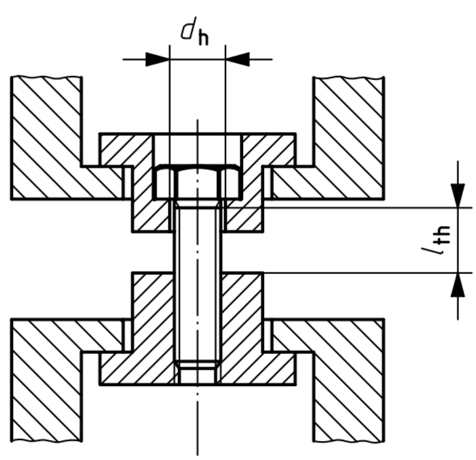


Figure 17: Test Sample Example for Bolts [7]

Although the bolts appeared to have no visible structural damage after the ROPS test, the tensile test results objectively determined whether they retained the mechanical integrity required to continue functioning effectively. Each bolt size group was evaluated separately, and the influence of length differences on load-carrying capacity was also examined. The tensile test concluded with the fracture of the bolt. The maximum tensile force is expressed as Fm. The yield strength is defined as the ratio of the maximum applied force to the cross-sectional area of the bolt.

3. Results

3.1. Conducting the ROPS Test

In this study, the design, engineering criteria, and occupational safety significance of Roll-Over Protective Structures (ROPS) and Falling Object Protective Structures (FOPS) were comprehensively examined. Based on literature reviews, experimental tests, and evaluations in accordance with relevant standards, it was determined that these systems play a vital role in ensuring operator safety. ROPS structures significantly increase the operator's chances of survival in the event of a tractor, forklift, or construction machine rollover, while FOPS systems protect operators against falling objects, particularly in construction sites, warehouses, and mining operations.

The forklift weight was considered as 4820 kg, as presented in Table 1. Taking into account the formula provided in Table 2;

$$700 < m < 10\,000$$

The mass M falls within these values. Therefore, by applying the formulas provided in the same row of Table 2, the longitudinal, lateral, and vertical forces, as well as the energy corresponding to the lateral force, were calculated as shown below.

3.1.1. Determination and Application of the Lateral Force

To perform the ROPS test, the forklift was fixed to the platform using brackets attached to the front and rear axle bolts, as shown in Figure 8. The DUMMY was then rotated around the SIP point at a maximum angle of 15 degrees along the force direction axis. (Figure 18)

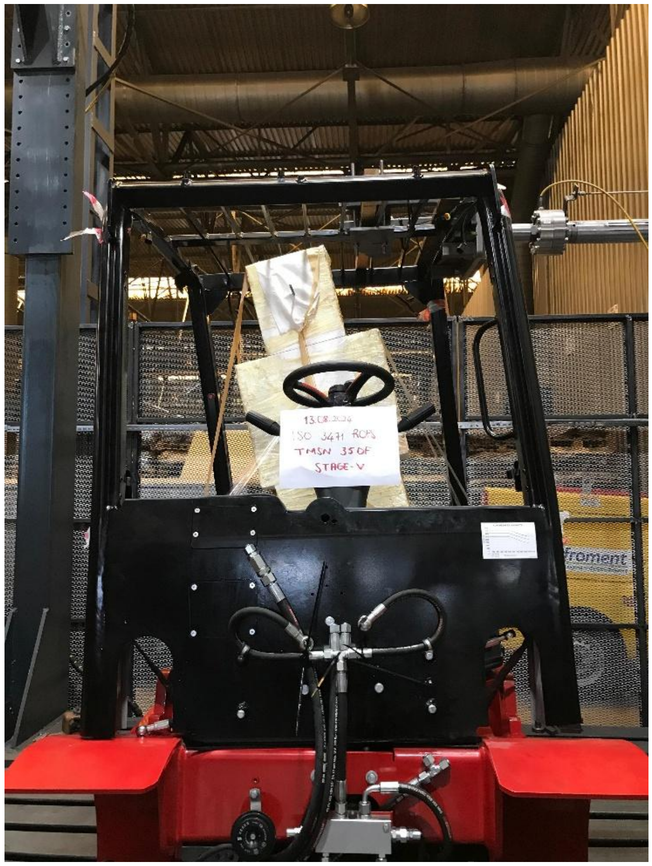


Figure 18: Lateral Load Force and Lateral Load Energy Loading

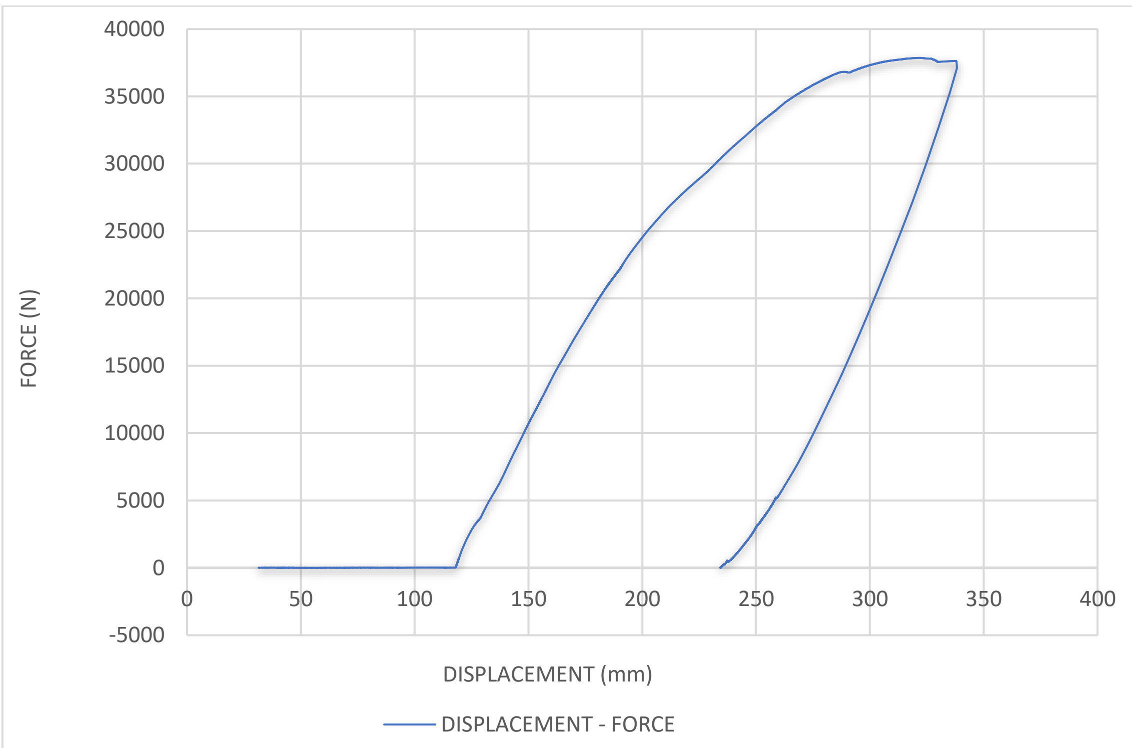
The ROPS structure of the forklift was mounted onto the platform as shown in Figure 9, and the formulas corresponding to this weight were calculated as below. A horizontal force was then applied, and it was observed that the corresponding energy was also absorbed. The relationship between force and displacement is shown in Graph 1, while the variation of force and energy is presented in Graph 2.

$$F_{lateral} = M \times 6 = 6 \times 4820 = 28\,920 \text{ N}$$

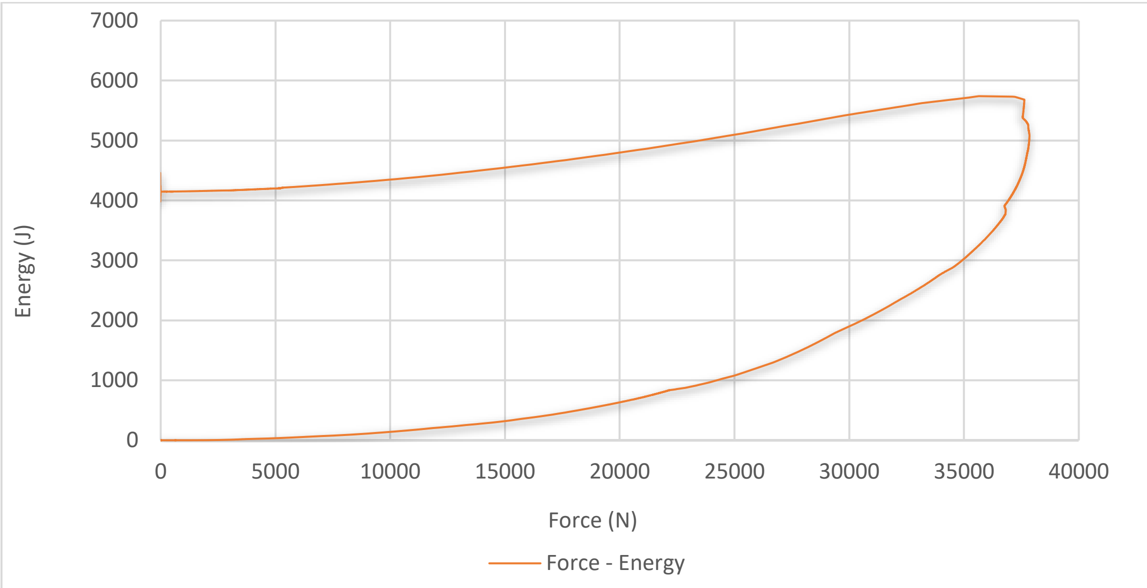
In order to ensure greater safety of the structure during the test, an additional 10% force was applied to the horizontal impact energy. The energy value corresponding to the applied force was calculated as follows.

$$E_{lateral} = 12\,500\ (M / 10\,000)1{,}25$$
$$= 12\,500\ (4820 / 10\,000)1{,}25$$
$$= 5020\ J$$
$$5020*1{,}1 = 5522\ J$$

More force was applied to achieve the required energy. A force of 35660 N was applied to meet the 5522 Joule energy requirement. The force applied in the horizontal direction was 23% greater than the required force. The ROPS structure displaced 218 mm in the direction of the horizontally applied force. The ROPS structure did not make contact with the DUMMY during its displacement.



Graph 1: Displacement by Horizontal Force.



Graph 2: Joule by Horizontal Force.

3.1.2. Determination and Application of Rear Force

In ROPS tests, a load was applied to the rear part of the structure. This force was applied to evaluate how the ROPS structure would perform in the event of a forklift rollover or an impact from the rear. During the test, it was checked whether the structure could protect the operator without deformation or while remaining within acceptable limits. The component for the rear-applied force was attached to the platform as shown in Figure 11. The part applying the rear force was connected to the force cylinder on the ROPS platform as shown in Figure 10 (Figure 19).

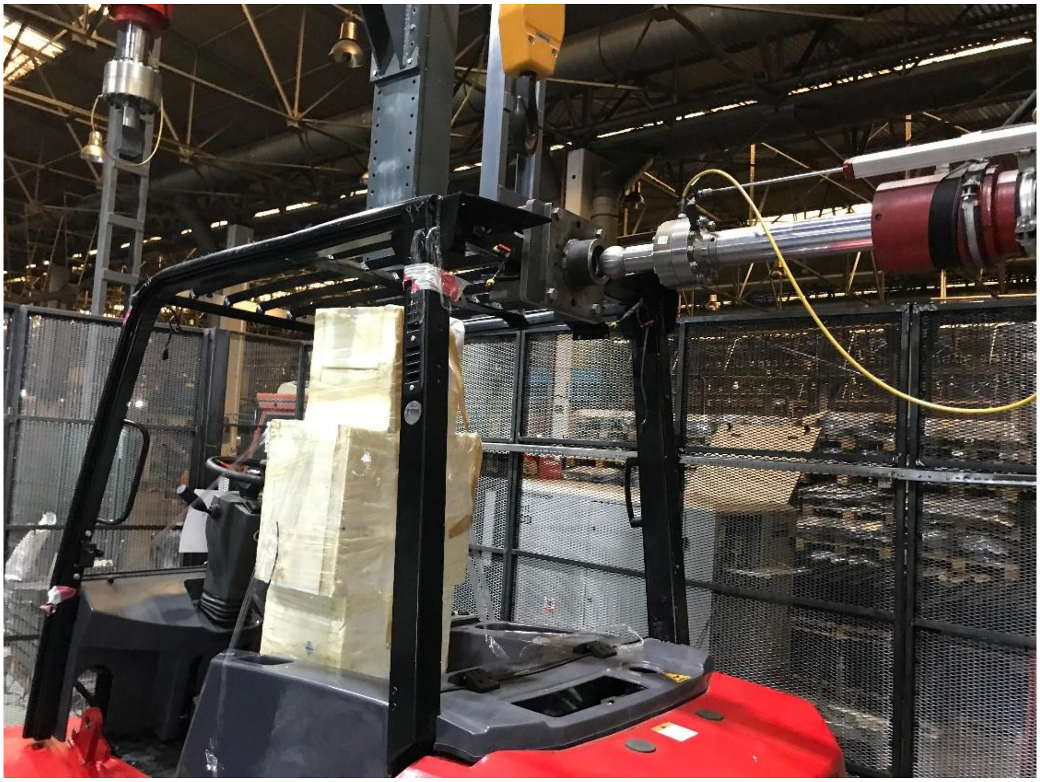


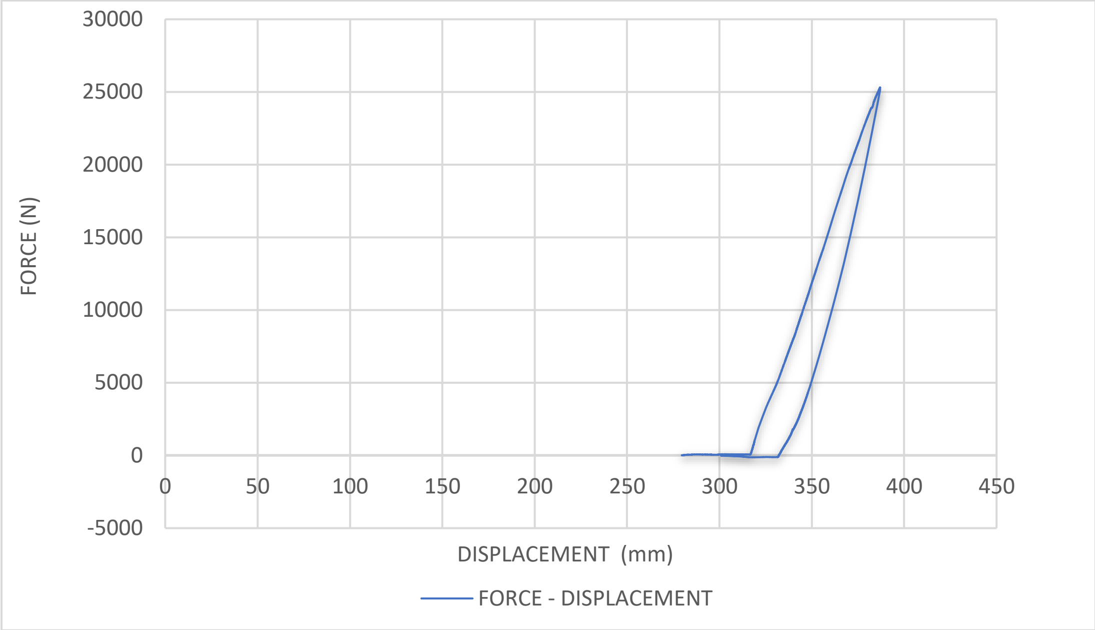
Figure 19: Longitudinal Load Force Loading

The rear-applied force in the ROPS test is a critical parameter used to evaluate the structure's durability and reliability. This test is conducted to ensure operator safety and to save lives in potential accidents. The dependence of the rear-applied force on the displacement is presented as shown in Graph 3.

The ROPS structure of the forklift was subjected to the rear-applied force, which was calculated using formulas derived based on the weight of the forklift, as shown below.

$$F_{Longitudinal} = M \times 4{,}8$$
$$= 4820 \times 4{,}8$$
$$= 23\ 136\ N$$
$$= 23\ 136 * 1{,}09 = 25\ 218\ N$$

During the test, approximately 9% additional force was applied in the rear direction to ensure the structure remained safer. The value of the applied force was calculated as follows. As a result of the tests, it was determined that under the applied force of 25,309 N, the forklift's rollover protective structure displaced by 107 mm. These values were evaluated within the limits specified in the relevant standards, and the test results demonstrate the structural performance of the ROPS.



Graph 3: Displacement Corresponding to the Rear-Applied Force

3.1.3. Determination and Application of the Vertical Force

The force applied from the top was applied vertically to the upper part of the ROPS structure. The main purpose of this test was to evaluate whether the ROPS structure could protect the operator in the event of a machine rollover or if a heavy object fell onto it. Forklifts operating in open or confined spaces are at risk of overturning or being struck by heavy objects. Therefore, it is crucial that the ROPS structure is resistant to forces applied from above. This test was set up on the platform as shown in Figure 12 (Figure 20).

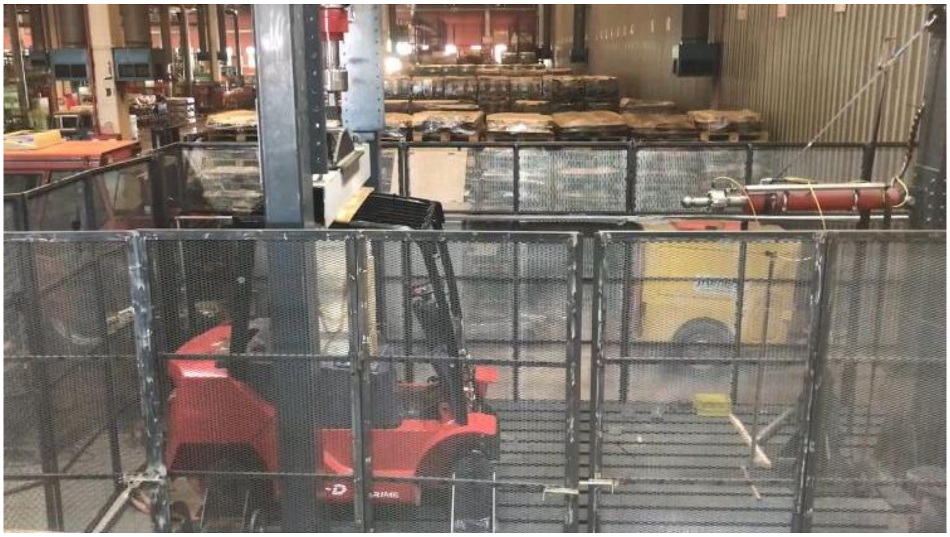


Figure 20: Vertical Load Force Loading

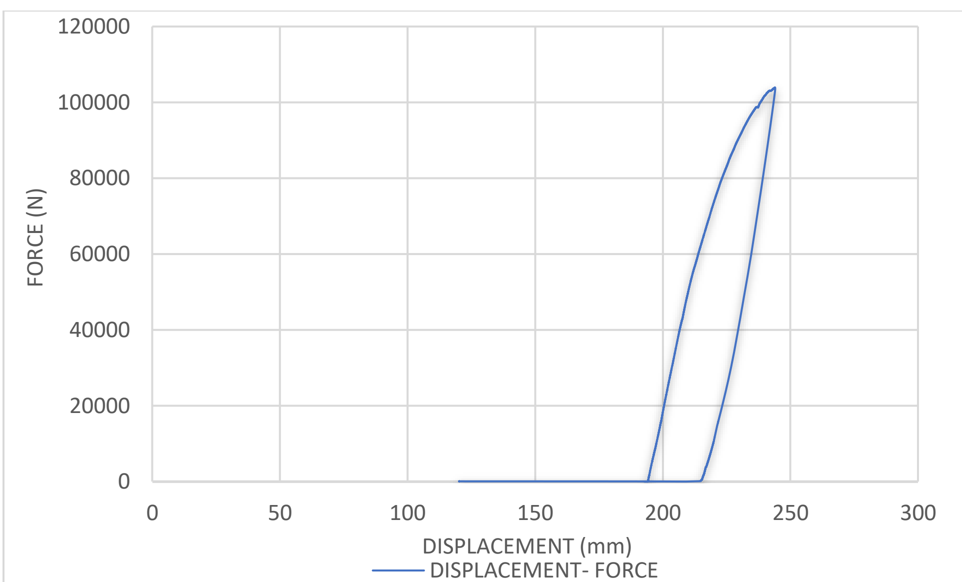
In the ROPS test, the force applied from the top was tested to evaluate the structural durability and stiffness of the ROPS, aiming to prevent rollover and impact accidents. The graph of the applied force versus displacement is shown in Graph 4.

The ROPS structure of the forklift was calculated using formulas derived based on the weight of the forklift, and the force was applied in the vertical direction.

$$F_{Vertical} = M \times 19{,}6$$
$$= 4820 \times 19{,}6$$
$$= 94\ 472\ N$$
$$94\ 472 * 1{,}1 = 103.923 N$$

The value of the applied force was calculated with a 10% increase, assuming that the structure would be safer if subjected to a force higher than the required value. As a result of the tests, a force of 103,923 N was applied to the forklift's rollover protective structure, and it was determined that the structure displaced by 50 mm under this load. The obtained data were evaluated within the limits specified in the relevant standards, and the test results demonstrate both the structural performance and the adequacy of the ROPS in terms of safety.

Accordingly, the effects of the applied forces on structural integrity were examined, and it was observed that the forklift's rollover protective structure provides the necessary strength within the established criteria.



Graph 4: Displacement Corresponding to the Vertically Applied Force

3.2. Implementation of the FOPS Test

Since the FOPS test follows a different standard than the ROPS test, it was conducted on a separate structure. During the test, the minimum height for Level I was calculated for the impactor using the following potential energy formula.

$$E_{potential} = M \times G \times H$$
$$1365 = 45 \times 9{,}81 \times H$$
$$H = 3{,}1 \text{ Meter}$$

The impactor must meet the Level I requirement specified in ISO 3449. Using the potential energy formula, the minimum height was calculated as 3.1 meters. The impactor was raised to the desired height with the help of a crane and prepared for release at the required moment using a remotely controlled hook (Figure 21).

Figure 21: Height Positioning of the Launch Part

During the test, the impact point of the weight can be determined using a laser or by attaching a string to the weight to mark its position on the cabin. Since there is a possibility that the weight may fall to the ground after hitting the cabin, wooden blocks were placed around it to prevent damage to the floor (Figure 22).

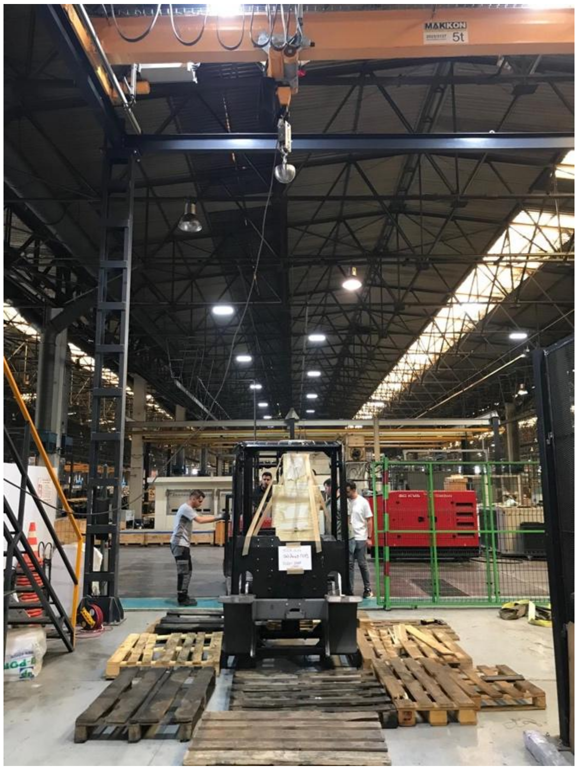


Figure 22: Safety Measures Taken for the FOPS Test

As the height increases, the potential energy also increases, which has a positive effect on safety. In the FOPS test, the weight was released from a height of 4 meters, resulting in an impact test with approximately 30% more potential energy compared to the standard test conducted from 3.1 meters. As a result of the test, releasing the weight from 4 meters caused a deformation of 28 mm in the structure (Figure 23).

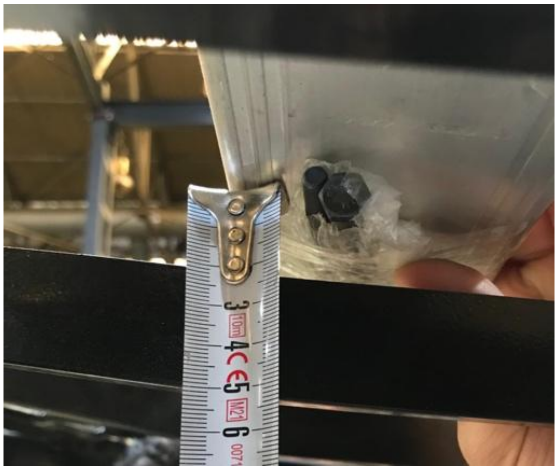


Figure 23: Deformation After the FOPS Test

The thrown impactor and the deformed parts did not come into contact with the DUMMY. The deformation resulting from the impact corresponded to the potential energy of the FOPS weight released from a height of 4 meters (Figure 24).

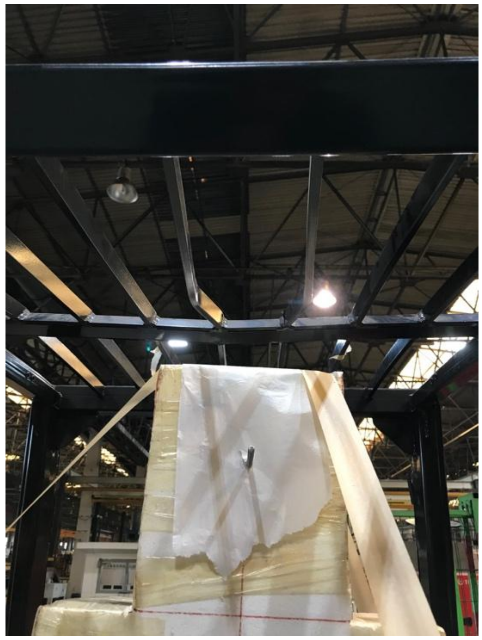


Figure 24: Deformation Resulting From the FOPS Test

3.3. Tensile Test of Bolts Between Cabin and Chassis and Results

In order to connect the bolt to the tensile testing machine, an intermediate fixture suitable for the upper and lower jaws of the machine is required. This fixture consists of three parts: the upper jaw holder, the threaded feed die, and the lower jaw holder. The bolt is attached to the lower jaw holder with a corresponding thread using the threaded feed die (Figure 25).

According to the evaluation conducted based on the ISO 898-1 standard, it was analyzed that the 8.8-grade bolts used in 16 connections between the chassis and the cabin still provided a safe connection after testing and did not experience any deformation that could affect their service life. Examination of the obtained graphs showed that all specimens exhibited linear elastic behavior initially, and after reaching the yield point, they entered plastic deformation and began to elongate. The fracture point met the ISO 898-1:2013 standard criteria, showing a minimum tensile strength of 800 MPa and a minimum yield strength of 640 MPa.

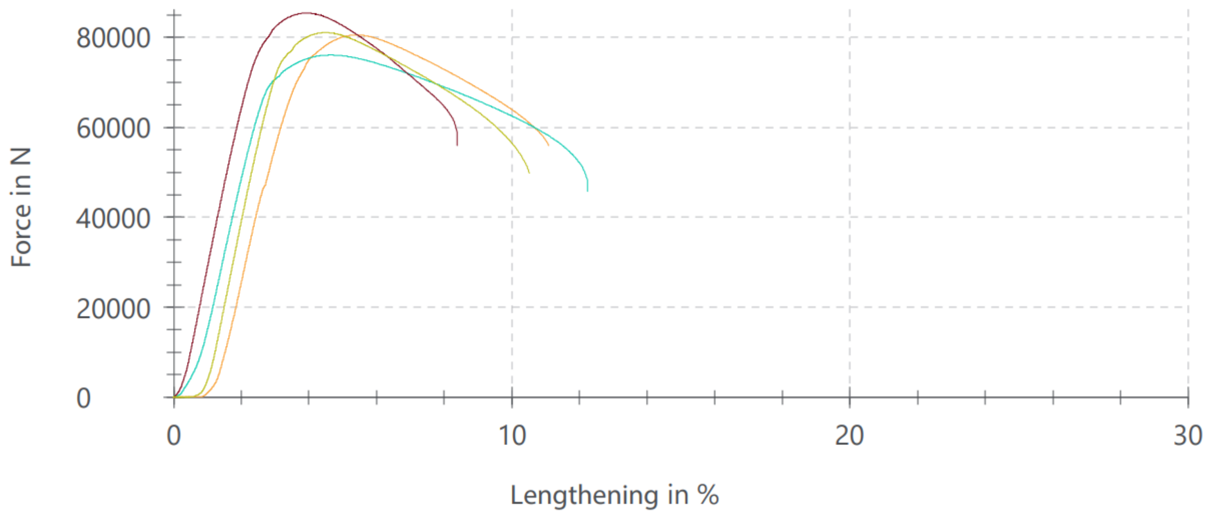
Figure 25: Preparation of the Test Specimen

3.3.1. Tensile Test Result of M12x45 Bolts

As a result of the test, all M12x45 bolts met the mechanical properties specified in ISO 898-1:2013 in terms of tensile strength, yield limit, and ductility. It was concluded that the fasteners maintained sufficient strength for safe use even after the ROPS testing.

Table 3: Tensile Test Results of M12x45 Grade 8.8 Bolts

Legend	No.	Specimen designation	$R_{p0.2}$ MPa	R_m N/mm²	F_m N	L_0 mm	L_u mm	R_B N	d_0 mm	S_0 mm²	A_{manual} %
	1	1. Sample	730	957	80537,62	45	49,1	55876	10,35	84,13	9,1
	2	2. Sample	808	905	76102,36	45	50	45811	10,35	84,13	11,1
	3	3. Sample	887	1015	85427,02	45	49,2	55879	10,35	84,13	9,3
	4	4. Sample	869	964	81072,16	45	50,1	49765	10,35	84,13	11,3



Graph 5: Force–Elongation Behavior of M12x45 Grade 8.8 Bolts

The obtained force–elongation curves indicated that the bolts exhibited ductile behavior under loading, and no sudden or brittle fractures occurred.

Figure 26: M12x45 Bolts Exhibiting Ductile Fracture After Testing

3.3.2. Tensile Test Result of M12x40 Bolts

The M12x40 bolts of grade 8.8, which provide the structural connection between the forklift cabin and the chassis, were subjected to tensile testing in accordance with ISO 898-1:2013. During the tests, the mechanical behavior of the bolts under axial loading was examined, and their strength, deformation, and fracture characteristics were evaluated based on the obtained results.

The experiments showed that all specimens initially exhibited behavior consistent with the linear elastic region at the beginning of loading, followed by plastic deformation upon reaching the yield point. During testing, the bolts demonstrated ductile behavior, breaking after significant elongation. This indicates that the material possesses high resistance to sudden and brittle fracture.

Table 4: Tensile Test Results of M12x40 Grade 8.8 Bolts

Legend	No.	Specimen designation	$R_{p0.2}$ MPa	R_m N/mm²	F_m N	L_0 mm	L_u mm	R_B N	d_0 mm	S_0 mm²	A_{manual} %
	1	1. Sample	766	839	70617,68	40	45,8	41904	10,35	84,13	12,1
	2	2. Sample	805	859	72278,16	40	45,1	44071	10,35	84,13	10,8
	3	3. Sample	830	908	76384,65	40	45,2	56934	10,35	84,13	7,01
	4	4. Sample	806	898	75238,14	40	45,3	58067	10,35	84,13	9,3
	5	5. Sample	791	886	73980,25	40	42,9	57238	10,35	84,13	8,1
	6	6. Sample	788	862	71980,42	40	44,9	49861	10,35	84,13	6,3

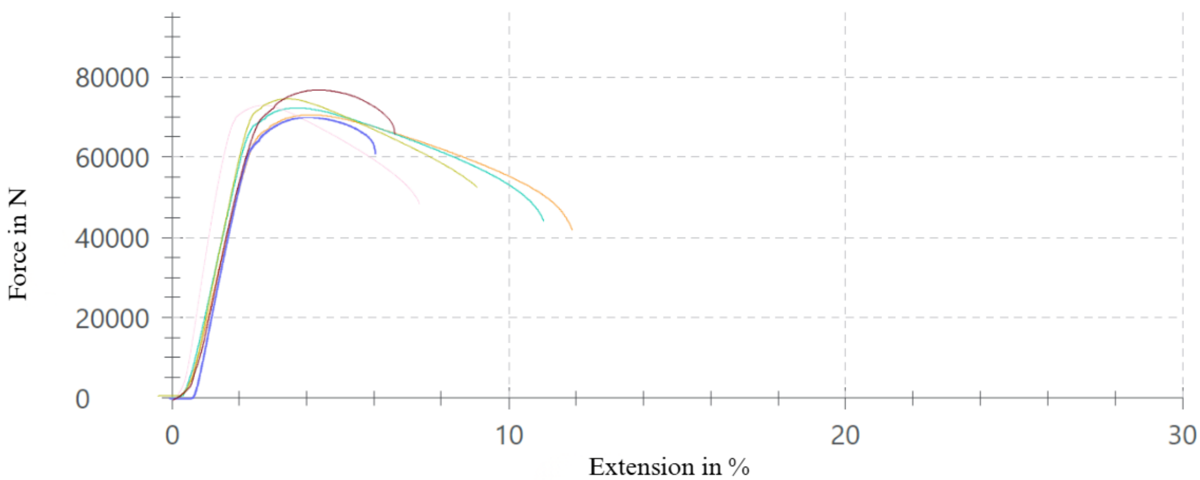


Figure 6: Force–Elongation Behavior of M12x40 Grade 8.8 Bolts

Figure 27: M12x40 Bolts Exhibiting Ductile Fracture After Testing

3.3.3. Tensile Test Results of M12x35 Bolts

The M12x35 bolts of grade 8.8, which serve in the connection between the cabin and the chassis, were subjected to tensile testing in accordance with ISO 898-1:2013. Within the scope of the study, the mechanical performance of the bolts under axial loading was evaluated in terms of strength, deformation, and fracture characteristics.

Table 5: Tensile Test Results of M12x35 Grade 8.8 Bolts

Legend	No.	Specimen designation	$R_{p0.2}$ MPa	R_m N/mm²	F_m N	L_0 mm	L_u mm	R_B N	d_0 mm	S_0 mm²	A_{manual} %
	1	1. Sample	721	856	71991,70	35	40	47851	10,35	84,13	14,3
	2	2. Sample	796	911	76670,54	35	38,35	66566	10,35	84,13	9,6
	3	3. Sample	829	907	76267,52	35	38,3	65510	10,35	84,13	9,4
	4	4. Sample	845	903	75950,81	35	39,9	53413	10,35	84,13	14,0
	5	5. Sample	798	895	75220,13	35	38,7	58335	10,35	84,13	10,0
	6	6. Sample	783	880	73971,25	35	39,8	50632	10,35	84,13	9,8

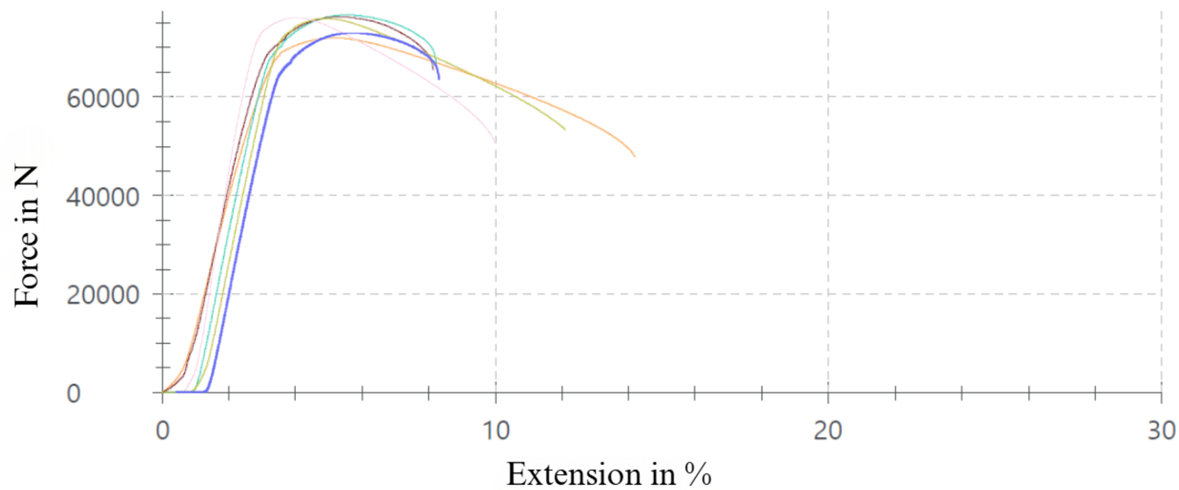


Figure 6: Force–Elongation Behavior of M12x35 Grade 8.8 Bolts

Figure 27: M12x40 Bolts Exhibiting Ductile Fracture After Testing

4. Discussion and Conclusion

The study demonstrates that the effectiveness of ROPS (Rollover Protective Structure) and FOPS (Falling Object Protective Structure) systems depends on multiple factors, including the strength of the materials used, structural design optimization, and compliance with relevant international standards (e.g., ISO 3471, ISO 3449).

This work comprehensively evaluated the structural durability and operator safety of a 3.5-ton capacity forklift through ROPS and FOPS tests conducted in accordance with ISO 3471 and ISO 3449 standards. The performed tests revealed that the designed protective structures maintain their mechanical integrity under rollover and falling object conditions while providing adequate safety levels.

The results indicate that the applied lateral, longitudinal, and vertical loads were successfully absorbed by the ROPS structure, and the deformation zones did not encroach upon the designated operator clearance zone (DLV). The maximum deformation values measured in each loading direction remained within the limits specified in ISO 3471, confirming that the cabin structure possesses sufficient strength and rigidity to protect the operator in the event of a rollover.

Similarly, the FOPS test showed that the upper protective structure withstood a falling object impact with a minimum potential energy of 1365 J, resulting in a deformation of 28 mm. This value is well below the interference threshold of the operator space, demonstrating that the cabin design also meets international safety standards under falling object conditions.

Table 6: ROPS Test Results

Load Direction	Horizontal	Longitudinal	Vertical
Calculate Force / Load	28920N /5020J	23136N	94472N
Applied Force / Load	35660N / 5522J	25218N	103923N
Decision	Fulfilled	Fullfilled	Fullfilled

Furthermore, tensile tests performed on M12x35, M12x40, and M12x45 grade 8.8 bolts used in the cabin-to-chassis connections confirmed that these fasteners retained their mechanical properties after ROPS and FOPS testing. Ductile fracture behavior was observed in the bolts, and the minimum tensile and yield strength requirements specified in ISO 898-1 were satisfied. This verifies that the connection points between the cabin and chassis can safely transfer loads even after testing.

Overall, the combined assessment of ROPS, FOPS, and fastener integrity tests confirmed that the forklift's protective systems provide a safe and durable structure for the operator. The study highlights the importance of integrating standards-based testing and material characterization into the design process to ensure safety. Future studies may focus on improvements such as geometric optimization of the cabin frame to further enhance both safety and performance.

5. Acknowledge

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