THESIS

Houssam Bakkali

Hungarian University of Agriculture and Life Sciences

Gödöllő Campus

Mechanical Engineering

Design of a roof structure connecting containers

Internal supervisors:

Prof. Dr. László Kátai

Prof. Dr. István Nagy

Prepared by:

Houssam Bakkali

GFLWNQ

Gödöllő

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INTRODUCTION

The growing demand for flexible and movable infrastructure solutions has prompted advancements in the design of retractable and portable structures. This thesis focuses on the design of a retractable roof system for field containers that will be moved often between fields. The problem that will be tackled in this thesis is designing a roof system that won't be permanently fixtured to any exterior support, it will rely solely on the containers, therefore it won't obstruct the movement of the containers and won't require any special equipment's to be transported.

The significance of this work arises from its applications in a wide range of industries, including agriculture, logistics, and temporary housing. Mobile containers are frequently subjected to unpredictable external conditions, so providing them with a lightweight, yet robust roof that can retract and deploy with no effort could significantly improve their performance. Furthermore, this technology may lessen the logistical and operational obstacles associated with traditional roofing technologies, hence increasing field operations efficiency.

The primary purpose of this research is to design and simulate a roof mechanism capable of expanding and retracting without requiring additional Ground support structure. The mechanism must be small, simple to use, and durable enough to survive weather conditions such as wind and rain. To do this, the study will investigate existing retractable structures such as stadium roofs, mobile shelters, and container-based designs, offering information on materials, mechanical systems, and design standards.

Key research questions guiding this study include:

What are the best materials and structural designs for a retractable roof system on mobile containers? How can the roof system retain stability without ground support while remaining compact and portable? What mechanical methods can ensure that the mechanism operates smoothly and reliably under a variety of field conditions? How can weatherproofing and load-bearing capability be optimized for mobile applications?

Throughout this research, I hope to develop a solution that will respect all the boundary conditions that we face, such as mobility, durability, and ease of use. The roof design will be refined using simulations to ensure that it fits both the practical and environmental requirements of mobile container use.

Previous study on retractable structures, such as those seen in sports stadiums and shelters, can help us better grasp the challenges and solutions associated with this type of construction.

This thesis will provide a thorough examination of materials, mechanisms, and design configurations that meet the unique needs of the mobile containers in question. Finally, the goal will be to create a retractable roof system that does not interfere with the containers' mobility while still providing weather protection.

CHAPTER ONE: LITTERATURE REVIEW

Introduction to the literature review

The development of retractable roof systems for mobile structures has piqued the interest of many engineers, particularly those working in industries that demand adaptable, weather-resistant, and movable infrastructure. This literature study delves into key concepts and improvements in the design and construction of such systems, focusing on the materials, mechanisms, and structural frameworks that support retractable and mobile roofing solutions. Understanding the materials and mechanisms involved in movable and retractable systems becomes increasingly important as companies seek to provide durable, functional, and easily deployed solutions.

To provide context for this analysis, many types of buildings were investigated: retractable roofs in sports stadiums, movable shelters, and container-based construction technologies. Each provides a unique perspective on the structural requirements, design issues, and mechanical solutions for sustaining and moving massive, unsupported spans. Sports arenas, for example, use well-established retractable systems that can endure environmental pressures, whereas transportable shelters prioritize portability, ease of installation, and lightweight construction. Container-based structures, which are commonly employed in temporary settings and mobile applications, highlight critical aspects for modular design, structural strengthening, and integration with existing mobile forms.

Furthermore, this research investigates essential industry standards, including Eurocode 1 (which covers environmental loading conditions) and Eurocode 9 (which gives requirements for aluminium and lightweight alloy constructions). These rules are critical for ensuring that the design meets safety, load bearing, and durability standards, especially in outdoor situations where wind and load factors are important considerations. Examining these criteria enabled the identification of important computations and structural characteristics that are critical to the project's success.

The next sections combine knowledge from various domains to assess the materials and mechanisms that make retractable roof systems possible, safe, and efficient. This analysis lays a solid foundation for creating a retractable roof that is both movable and structurally sound, providing vital assistance for the project's design phase.

1. Retractable roofs

Retractable roofs are architectural, and engineering systems designed to provide flexible coverage by allowing sections of the roof to move or fold away. These systems are often employed in structures like sports stadiums and swimming pools to offer both protection and openness as needed. The design of retractable roofs can vary significantly, incorporating different mechanisms and materials.

A lot of Sports Arenas around the world employ Retractable roofs as a solution to various issues, such as upkeeping the grass, heating, and cost of operation of the stadium.

We will be looking at multiple Sports arenas that have retractable roofs, which materials they used, Mechanisms and functionality.

1.1. Sports Arenas

Figure 1: Close Mercedes-Benz retractable roof

Source: [https://www.mercedesbenzstadium.com/news/a-time-lapse-of-the-roof-closing-at-mercedes-benz-stadium]

The Mercedes-Benz Stadium in (ATLANTA, USA) opened in 2017 as a replacement for the Georgia Dome.

The roof is a very complex piece of architecture that took quite some time to get functional to it full capacity, the design had to be modified because of the heavy load, and therefore all of the driving motors and actuators had to be modified to match the new loads and stresses.

The stadium's roof is built of 27,500 tons of steel, 3,500 of which form the roof petals. When it opens and shuts, each petal moves independently but all at the same time, creating the optical appearance of a camera lens.

The roof opens by moving eight "petals" that Slide open in a straight line, each one of the moving cantilever pedals move approximately 60meters to the centre of the stadium direction they are powered by eight mechanized “boogies” that drive the petals along the inner rail and are attached to the outer rail by six roller mechanisms.

In the closed position the eight petals lock together to form a watertight seal, and each petal structure is covered with air filled ETFE pillows. (“The Roof at Mercedes-Benz Stadium Closes for the First Time | Mercedes-Benz Stadium News”, n.d.)

1.1.1. Materials

1.1.1.1. Ethylene Tetrafluoroethylene (ETFE)

Ethylene Tetrafluoroethylene (ETFE) is a fluoroplastic known for its excellent properties, including high resistance to heat and chemical stability. It is commonly used in various applications due to its flexibility, light weight, and cost-effectiveness (Drobny, 2015) (Moreno et al., 2019). ETFE's technical specifications include a high onset temperature of degradation, which can be enhanced from 381.5 °C to 459.4 °C when mixed with inorganic polyoxides like aluminium polyphosphate and metakaolin, resulting in improved structural stability and mechanical properties such as an increased elastic modulus from 0.4 GPa to 1.6 GPa and tensile strength from 23 to 27 MPa (Shaulov et al., 2021). Additionally, ETFE can be processed into nanofibers using CO_2 laser supersonic drawing, achieving a degree of crystallinity of 54% and an average diameter of 0.303 µm, which is influenced by factors such as laser power and melt flow rate (Suzuki & Hayashi, 2013). In architectural applications, ETFE foils are integrated with organic photovoltaic cells to create energy-efficient building elements, offering benefits like semitransparency and low environmental impact. These foils can be configured to optimize energy performance and illumination comfort, as demonstrated in studies conducted in Barcelona and Paris (Moreno et al., 2019).

Figure 2 Single layered "ETFE" Roof

Source: [https://www.architonic.com/en/product/koch-membranen-single-layer-etfe-roofs/20178473]

A prime example of ETFE being used in a construction project is the Allianz Football stadium.

The Allianz Football stadium opened in 2005; The stadium is designed as a curved shell by The Swiss architects Herzog & de Meuron.

The façade of the building is made from 2,874 rhomboidal inflated ETFE foil panels and it is considered the biggest membrane shell in the world covering the 66,500 m² area which is the roof and façade.

According to Allianz Arena official website, Data about the ETFE foil panels:

"Thickness: 0.2 mm, Weight: 350 g/ m², Longitudinal/transverse tensile strength: 52/52 N/mm²,Longitudinal/transverse tensile stress at 10% elongation: 21/21 N/mm²,Longitudinal/transverse elongation at breaking point: 600/600 %,UV permeability: 95%,Visible light permeability: 93%,Colour: transparent (roof area), translucent white (rest of façade),1,380 non-standard panels, Total area: 7.6 to 40.7 m²,Length: approx. 3 to 10 m, maximum width: 1.9 to approx. 4.6 m, Maximum diagonal length: approx. 17 m, Fans keep the panels inflated at a constant pressure of 0.035 bar (maximum possible pressure 0.08 bar),In case of snowfall, 12 pressure-monitoring points ensure the correct pressure adjustments to allow for snow up to 1.6 m, Lifespan approx. 25 years, non-flammable, exceptionally resistant to heat and cold, self-cleans with rain,19 panels at the 51.41 m level can be opened to ensure proper ventilation. , Each of these special hydraulic panels can carry up to 8 t and has a wind pressure resistance of 22 t, The panels are non-loadbearing."

As we can see ETFE is a very versatile material that can be used in many construction projects, and it is an important material to keep in mind while selecting a material for this thesis work.

What is important to us in this case study is the Mechanical properties of each material.

Properties of "ETFE":

Mechanical	
Elongation at Break, %	100 - 300
Flexural Modulus, Gpa	0.8 - 1.4
Hardness Rockwell M	1 - 10
Hardness Shore D	70 - 75
Strength at Break (Tensile), MPa	45
Strength at Yield (Tensile), MPa	42
Toughness (Notched Izod Impact at Room Temperature), J/m	999
Young's Modulus, GPa	0.8

Table 1 Mechanical properties of "ETFE"

Source: [https://omnexus.specialchem.com/selection-guide/ethylene-tetrafluoroethylene-etfe-plastic]

1.1.1.2. PTFE-coated fiberglass

Polytetrafluoroethylene (PTFE) is a thermoplastic with very appealing properties, such as low friction coefficient, good flammability resistance and high chemical resistance.

The mechanical properties of the PTFE fabric are influenced by the Fibers and the woven method (Weaving is a method of textile production in which two distinct sets of yarns or threads are interlaced at right angles to form a fabric or cloth), with a slight effect observed from changes in strain rate; specifically, tensile strength increases slightly with higher strain rates while strain at break decreases. Additionally, the fabric maintains consistent mechanical properties across a temperature range of 20°C to 70°C, leading to the proposal of a temperature reduction factor for design purposes (Zhang et al., 2010)

1.1.1.3. Aluminium 6061

Aluminium 6061, a widely used alloy, is renowned for its excellent formability, corrosion resistance, and mechanical properties, particularly after heat treatment which involves precipitation hardening through the formation of β" precipitates (Meyer et al., 2023). The alloy's mechanical performance is further enhanced under cryogenic conditions, where it exhibits increased yield stress, ultimate tensile strength, and elongation at failure due to reduced thermal assistance and increased dislocation resistance (Jin et al., 2024). It strength and durability preserves the structural integrity of these structures while maintaining a relatively light weight.

Therefore, it is mostly used when the boundary conditions are loads, strength, and Ease of handling and manufacturing.

Mechanical properties of ALUMINIUM 6061:

Properties	Metric
Tensile strength	310 MPa
Yield strength	276 MPa
Shear strength	207 MPa
Fatigue strength	96.5 MPa
Elastic modulus	68.9 GPa
Poisson's ratio	0.33
Elongation	12-17%
Hardness, Brinell	95

Table 2 Mechanical properties of Aluminium 6061

Source: [https://www.azom.com/article.aspx?ArticleID=6636]

1.1.1.4. Steel Alloy

Steel alloys are engineered materials that use various elements to enhance properties such as strength, toughness, and wear resistance. The composition of steel alloys can vary significantly depending on the intended application. For instance, a steel alloy designed for structural purposes includes elements like carbon, silicon, manganese, and vanadium, which contribute to its reinforcement and toughness while maintaining low manufacturing costs

(Hongguang et al., 2021). In contrast, a steel alloy workpiece used for press hardened steel components contains higher chromium and silicon content and features a unique surface imprint pattern to achieve desired surface roughness and mechanical properties (Qi & Yang, 2020). For welding materials, steel alloys are formulated with high chromium and vanadium content to ensure high hardness and compatibility with iron base materials

Mechanical properties of the relevant Steel alloys:

Material	Condition	Yield Strength [ksi]	Ultimate Strength [ksi]	Elongation %	Elastic Modulus [psi]	Density [lb/in^3]	Poisson's Ratio
AISI 4130	Hot Rolled	70	90	20	29e6	0.283	0.32
	Stress Relieved	85	105	10			
	Annealed	55	75	30			
	Normalized	60	90	20			
AISI 4140	Hot Rolled	90	120	15	29.7e6	0.283	0.32
	Stress Relieved	100	120	10			
	Annealed	60	80	25			
	Normalized	90	120	20			
ASTM A242		46	67	18	30e6	0.282	0.3
ASTM A302	Grade A	45	75	15	29e6	0.282	0.29
	Grade C	50	80	17			
ASTM A514	Quenched & Tempered	100	110	18	29e6	0.283	0.3
ASTM A517	Grade F	100	115	16	29e6	0.280	0.29
ASTM A533	Class 1	50	80	18	29e6	0.282	0.29
	Class 2	70	90	16			
	Class 3	83	100	16			
ASTM A572	Grade 50	50	65	18	30e6	0.283	0.3
ASTM A588		50	70	18	29.7e6	0.280	0.28
ASTM A633	Grade E	55	75	18	29.7e6	0.280	0.28
ASTM A656	Grade 50	50	60	20	29e6	0.282	0.29
	Grade 60	60	70	17			
	Grade 70	70	80	14			
	Grade 80	80	90	12			
	Grade 100	100	110	12			
ASTM A710	Grade A	80	85	20	29.7e6	0.280	0.3
HY-80		80	---	18	29.7e6	0.280	0.3
HY-100		100	---	16	29.7e6	0.284	0.3

Table 3 Mechanical properties of Steel alloys

Source: [https://mechanicalc.com/reference/material-properties-tables]

Steel alloy is used mostly because of its versatility the material can be adjusted based on the use, making it very good for a wide range of applications ranging from construction and automotive to aerospace and tool manufacturing.

1.1.2. Mechanisms

There are several mechanisms used to operate retractable roofs in sports arenas, they range from sliding tracks to rolling systems, a brief study of the mechanisms could give us an overview of which mechanism to use depending on our boundary conditions.

1.1.2.1. Telescopic panels

Sections of the structure that extend or slide over one another to change forms, the structures that use telescopic panels are usually adjustable to the needs of the user.

The key mechanisms in telescopic panels are:

Sliding tracks: these tracks guide the movement of the panels both in retraction and extension, the tracks ensure smooth movement and alignment.

Interlocking panels: The panels are designed to overlap one another, to ensure the full coverage of the area when fully expanded.

Rolling systems: In case of heavier loads in larger telescopic panel systems, rolling mechanisms are used to facilitate the movement, the use Sliding tracks and Rolling systems is ultimately dependent on the distribution of loads.

Actuators: The telescopic panels systems are often powered by Electrical/hydraulic actuators.

This ensure that the system is either automated or semi-automated.

These systems are rarely manual due to the high forces needed to move the panels or the inaccessibility to the system.

1.1.2.2. Drive systems:

Electric Motor-Driven Systems: are the most used type of system in retractable roofs, these motors can power various types of mechanisms such as gears, pulleys, and Ball-Screw mechanisms to move the retractable roof.

Electric motors can handle heavy loads, with precise controls, Electric Motor-Driven systems can be easily controlled for automation and pre-programming the opening and closing sequence and requires low maintenance to operate.

Hydraulic drive systems: utilise pressurised fluids such as Hydraulic fluid to generate mechanical power, hydraulic drive systems are most effective to move larger retractable roofs due to it high power.

The draw back with Hydraulic drive systems is that it requires a lot of maintenance and careful sealing to prevent the Hydraulic fluid from leaking.

There is no reason to use hydraulic drive systems in retractable roofs unless you are working with large loads.

2. Mobile shelters

Mobile shelters are essential in providing temporary housing solutions during emergencies, such as natural disasters and wars, where rapid deployment and adaptability are crucial. The mechanisms of mobile shelters often involve transformable structures that can be quickly assembled on unprepared sites, ranging from small tents to large warehouses, depending on the application and size requirements (Gengnagel & Burford, 2006). These shelters must be lightweight and easy to transport, often utilizing prefabricated or standard materials to ensure cost-effectiveness and quick assembly (Oliveira & Campos, 2019). The materials used in these shelters are critical for their protective capabilities, with advancements in chemical and biological barrier materials like butyl rubbers and fluorinated polymers enhancing their resistance to various threats (Donahue, 2006). Additionally, deployable structures, such as those using torque force for rapid assembly, offer sustainable and efficient solutions without the need for external energy sources (Álvarez-García & Domínguez, 2023). The design of these shelters must also consider the hierarchy of demand, ensuring that distribution and resettlement are both rapid and accurate, addressing the complexity of evacuee needs (Geng et al., 2021). Ultimately, the goal is to create flexible, modular systems that provide adequate living conditions while being adaptable to different terrains and climates, ensuring a good quality of life for displaced individuals in temporary settings (Oliveira & Campos, 2019).

Mobile shelters are designed with three main characteristics in mind, Mobility, transportability, and deployment ability.

Mobile shelters are often transported and deployed in remote areas and fields, these structures share a lot of similarities with the topic in hand, that’s why it is important to take a look at the materials and mechanisms used in These mobile structures.

Materials:

-*Lightweight aluminium Frames such as Aluminium 6064*: These materials are used because of their resistance to corrosion and lightweight which makes this material perfect for Mobile Structures.

-*PVC coated fabrics*: Polyvinyl chloride also known as PVC is the world’s third-most widely produced synthetic polymer of plastic, it is used in construction such as pipes doors and windows.

It is a very durable, flexible and weatherproof solution, The issue lies in the environmental damage of polyvinyl chloride aka “vinyl”.

PTFE-coated fiberglass: as mentioned earlier PTFE-coated fiberglass

Mechanisms:

The mechanisms in Mobile shelters can range from various lightweight mobile structures, But the ones that are mainly used in the industry are:

-Collapsable Frames: which are frames that can collapse and shrink in size for easy transportation, and when deployed they can be extended and adjusted to the needed size of the operation.

-Tensioned fabric roofs: it’s a cover of fabric that is tensioned by rigid frames, or fixtures that allow the fabric to be pre-shaped and pre-tensioned to withstand environmental loads.

3. Container-Based Construction Designs

Container-based construction designs have gained significant popularity due to their modularity, cost-effectiveness, and sustainability. These designs utilize shipping containers as building modules, which are overwhelming the market due to global trade imbalances, particularly between Asia and North America, leading to a big surplus of containers that are economically viable for construction use (Kyselov & Lisova, 2022). The basic nature of containers allows for rapid assembly and disassembly, making them ideal for temporary structures such as emergency hospitals, as demonstrated during the COVID-19 pandemic with the construction of Wuhan Huoshen Mountain Hospital (Zhaorong & Zhili, 2023). The seismic performance of container buildings can be enhanced by adopting a box form composite structure, which significantly increases rigidity and yield strength compared to traditional container structures (Zhaorong & Zhili, 2023). Furthermore, container buildings align with sustainable development goals by repurposing decommissioned containers, thus reducing waste and promoting recycling (Cao & Zeng, 2022) (Pereira-de-Oliveira et al., 2021). However, challenges remain, such as the need for improved integration of design systems and standards between the construction and container manufacturing industries (Su et al., 2022).

Container-based Construction has gotten very popular in recent years due to the price and convenience of using containers, it's cheaper, quicker, and in some cases more versatile than traditional construction, Containers are typically made from weathering steels.

Weathering steels are specialized alloys designed to form a protective patina of rust, which enhances their resistance to atmospheric corrosion compared to conventional steels. This patina, primarily composed of ferric oxyhydroxides like goethite, is facilitated by alloying elements such as copper, chromium, and nickel, which promote the densification of the corrosion product layer, thereby enhancing the steel's protective qualities (Lin et al., 2024) (Lottes & Sitek, 2024). The use of uncoated weathering steel (UWS) in bridge construction began in the mid-1960s, offering a cost-effective corrosion protection system with low maintenance and life cycle costs, provided the environment allows the patina to form properly (Lottes & Sitek, 2024). However, the effectiveness of weathering steels is compromised in environments with high chloride ion concentrations, such as marine atmospheres, where the formation of akageneite and lepidocrocite can degrade the protective layer (Lin et al., 2024)

Weathering steels, such as ASTM A847, A588, A242, A606, and COR-TEN, have greater corrosion resistance to conventional carbon steel due to the formation of a protective oxide film on the metal's surface, which slows down future corrosion.

Physical Properties

Weather resistant steel	Standard	Tensile Strength MPa	Yield Strength MPa	Elongation in 2 inches (min.) %
CORTENA	US steel	470-630	355	20
IRSM 41-97	Indian Railways	480 min	340 min	21
ASTM A 588	ASTM	485 MIN	345 min	21

Table 4 Mechanical properties of relevant weathering steels

Source: [https://2.imimg.com/data2/NC/GW/MY-1913761/corten-a-steel-weather-resistant-steel.pdf]

4. Euro standards and regulations

4.1. Eurocode 9 – Design of aluminium structures (EN 1999-1-1)

Standards and equations relevant to the structural design of aluminium components are provided by *Eurocode 9 (EN 1999-1-1)* for the design of retractable roof mechanisms utilizing aluminium (or other lightweight alloys).

4.1.1. Design of Structural Members

Eurocode 9 contains formulas for estimating the load-carrying capacity of aluminium members under several load types, including axial, bending, and shear loads. Section 6.2 contains formulas for axial forces.
Bending: Section 6.3 contains equations for bending resistance, which is significant for horizontal stresses such as wind.
Shear: Section 6.4 contains shear resistance formulae for situations in which the roof may experience shear forces.

4.1.1.1. Axial Loads

Members are subjected to axial loads (tension and compression) when extended or retracted. Eurocode 9 offers design methods to calculate axial load capacities and prevent failure due to excessive stress:

$$N_{t,Rd} = \frac{A \cdot fo}{\gamma M}$$

- A: Cross-sectional area of the member.
- fo: Yield strength of the aluminum alloy used.
- γM: Partial safety factor for the material (commonly 1.1 for aluminium but varies based on alloy and application).

4.1.1.2. Bending Loads

Bending stresses arise from forces perpendicular to the length of structural members (like roof beams). The bending resistance calculation is essential to avoid bending failure under load conditions, such as wind or snow on the roof. Eurocode 9 provides bending moment capacity formulas for aluminium beams:

$$M_{Rd} = W \cdot fo/\gamma M$$

where:

- W is the section modulus of the beam.

4.1.1.3. Shear Loads

Shear capacity is vital for elements like bolts, which hold the retractable parts together, and beams subjected to lateral forces. Eurocode 9 uses a shear resistance equation for aluminium members:

$$V_{Rd} = A \cdot fv/\gamma M$$

Where:

- fv is the shear strength of the aluminium.

4.1.2. Buckling and Stability Considerations for Long Spans

Buckling resistance is critical in unsupported spans, such as retractable roof panels, to prevent collapse. Aluminium parts are prone to buckling under compression, especially telescoping sections. Eurocode 9 specifies axial buckling resistance for columns or beams under compressive loads:

$$N_{d,Rd} = \chi \cdot A \cdot fo/\gamma M$$

Where:

- χ: Buckling reduction factor, based on slenderness (depends on the length and cross-sectional properties of the member).
- $\lambda\ slenderness\ ratio$: Calculated based on the member's length, radius of gyration, and material properties. High slenderness ratios may require reinforcement.

Lateral-Torsional Buckling: For long beams, the Eurocode recommends calculating lateral-torsional buckling (where a member bends and twists under load), especially critical in structures without side supports.

4.1.3. Design of Connections and Welds

Connections play a vital role in the structural integrity of retractable roofs, where mechanisms and roof panels need to move but remain secure under load. Eurocode 9 covers both bolted and welded connections:

-Bolted Connections: Shear and tensile strength of bolts must be calculated:

$$F_{v,Rd} = A_b \cdot f_b/\gamma M$$

Where A_b is the effective bolt area, and f_b is the designated tensile strength of the bolt material.

-Welded connection: Aluminium weld strength equations ensure that welded joints can handle loading without failure. Welds should be designed to avoid heat-induced weaknesses, common with aluminium.

4.1.3.1. Shear stress in weld throat

For fillet welds, the strength is based on the effective throat area of the weld, as it is generally the weakest point. The shear resistance of the weld throat can be calculated as:

$$F_{v,Rd} = \frac{A_\omega \cdot f_{v\omega}}{\gamma M}$$

Where:

- $F_{v,Rd}$: Design shear stress of the weld.
- $A_\omega = a \,. L_\omega$: Effective throat area of the weld, where "a" is the effective throat thickness (often take as $(0{,}7. s)$ for fillet welds, and "s" the length of the weld leg, and "L_ω" is the length of the weld.
- $f_{v\omega}$: Design shear strength of the metal used in the weld usually calculated as $0{,}6$.
- γM: Partial safety factor for the weld material (typically 1,25).

4.1.3.2. Normal Stress in Welds

If tensile or compressive forces are applied to the weld along its length, the normal stress must also be considered:

$$F_{n,Rd} \frac{A_\omega \cdot f_y}{\gamma M}$$

Where:

- $F_{n,Rd}$: Design tensile/compressive resistance of the weld.
- f_y: Yield strength of the aluminium alloy.
- A_ω: Effective throat area of the weld.

4.1.3.3. Combined Stresses in Welds

When both shear and tensile stresses are applied on the weld, we have to ensure that the overall stress does not exceed the permitted limits. Eurocode 9 employs an interaction formula to evaluate the combined stress:

$$\left(\frac{\sigma_n}{f_y}\right)^2 + \left(\frac{\tau_v}{f_{v\omega}}\right)^2 \leq 1$$

Where:

- σ_n: Normal stress in the weld.
- τ_v: shear stress in the weld.

This interaction equation assures that the weld stays within safe stress limits even when subjected to tensile and shear loads. Proper stress calculations based on Eurocode criteria will help to ensure the retractable roof structure's structural integrity and safety.

4.1.4. Deflection and Serviceability Limits

Deflection is critical for structures such as retractable roofs to prevent excessive sagging due to self-weight, wind, or snow loads, which could impede function. Eurocode 9 establishes deflection restrictions based on span length:

$$\delta \leq \frac{L}{250}$$

where L is the span length of the roof beam.

This deflection limit guarantees that the roof remains within acceptable deformation limits for continued functionality, particularly for moving components.

4.2. Eurocode 1 – Wind Actions (BS EN 1991-1-4)

4.2.1. Basic Wind Pressure Equation

The primary wind pressure equation as stated in Eurocode 1 is as follows:

$$p = q_{ref} \cdot c_e \cdot c_p \cdot c_{dir}$$

Where:

- p: design wind pressure on the structure's surface.
- q_{ref}: Reference wind pressure, calculated from the reference wind speed
- c_e: Exposer factor, relative to the height and terrain.
- c_p: pressure coefficient, relative to the structure's geometry and exposer to wind.
- c_{dir}:Directional factor, accounting to predominant wind direction at the terrain in question. (Gulvanessian & Menzies, 2000)

4.2.1.1. Reference Wind Pressure q_{ref}

The reference wind pressure serves as the starting point, which will be modified by additional coefficients to account for structure-specific characteristics and site exposure.

To determine q_{ref} Eurocode1 provides us with the following equation:

$$q_{ref} = 0{,}5 \cdot \rho \cdot V_{ref}^2$$

Where:

- ρ: Air density
- V_{ref}: Reference wind speed, usually taken from local meteorological data. (Gulvanessian & Menzies, 2000)

4.2.1.2. Exposer factor c_e

The exposer factor c_e changes the reference wind pressure to the specific terrain, topography and height above sea level.

Eurocode 1 has a categorization for terrain types, and it goes as follows:

- **Category 0**: Sea or coastal areas with no obstacles.
- **Category I**: Flat, open terrain with minimal obstructions (e.g., fields).
- **Category II**: Open terrain with low obstacles (e.g., farmlands).

- **Category III**: Suburban or urban areas with buildings.
- **Category IV**: City centres with large buildings.

Wind pressure increases with height; therefore Eurocode 1 specifies height-dependent variables for each terrain category. The exposure factor changes with roof height from ground level, especially if the roof expands vertically during deployment. (Gulvanessian & Menzies, 2000)

4.2.1.3. Pressure Coefficient c_p

The pressure coefficient reflects how the roof's geometry influences wind pressure distribution. Values are based on:
Pressure coefficients vary depending on whether the roof is flat, sloping, or curved.
Position (open or closed): Retractable roofs with varied configurations (completely or partially open) require adjusted values since wind impacts vary depending on openings and surface orientation.
For a flat roof, the pressure coefficient may be -1.0 to -0.7, indicating negative pressure (lift) on the surface.
A gabled roof would have positive values on the windward side but negative values on the leeward side.
The internal pressure coefficient is also relevant in open layouts because wind enters through apertures and causes additional pressures within the structure. (Gulvanessian & Menzies, 2000)

4.2.1.4. Load Combinations and Partial Safety Factors

Eurocode 1 provides precise instructions on how to combine wind loads with other loads (such as self-weight and snow loads) to provide a safe design under combined loading situations. For instance, consider the wind load combination Q_ω combined with permanent loads G (like the roofs self-weight) is:

$$\gamma_f \cdot G + \gamma_f \cdot Q_\omega + \psi \cdot Q_s$$

Where:

- γ_f:Partial safety factor for wind (usually between 1.0 and 1.5).
- G: permanent load.
- Q_ω: Wind load.
- Q_s: Snow load, if applicable.

- ψ: Reduction factor to account for the reduced likelihood of simultaneous maximum loads.

This equation guarantees that the structure is constructed for both expected and exceptional situations, which is critical for movable or retractable designs that may encounter varied wind loads in a variety of field settings. (Gulvanessian & Menzies, 2000)

Conclusion of the literature review

To sum up, this literature analysis has provided a thorough basis for building a retractable roof for mobile containers by outlining important insights from current retractable structures, mobile shelters, and container-based constructions. By thoroughly examining sports arenas, we have found that retractable roofing systems in sizable spaces require great adaptability to endure environmental pressures like wind, snow, and other dynamic loads in addition to prioritizing structural robustness. Sports arena mechanisms and materials provide real-world examples of how retractable systems might be built for longevity and effective retraction—features that are directly relevant to the moveable roof system design of this project.

The research of mobile shelters provided a unique perspective, focusing on flexibility, simplicity of movement, and quick construction and disassembly—all of which are critical characteristics for a structure that will be transported frequently. Mobile shelters, which are frequently deployed in emergency and wartime settings, highlight the significance of lightweight, modular designs that are simple to construct while maintaining stability. Incorporating these insights guarantees that the roof is highly portable and adaptable to repeated field relocations, both of which are essential needs for this project.

The review of container-based construction gave useful information on the structural integration of roofing systems with container shapes. This field emphasised the need of modular construction, reinforcement techniques, and load distribution, particularly when dealing with enormous spans not supported by ground-based columns. The materials and methods utilized in container construction, such as strengthened steel alloys and corrosion-resistant coatings, highlight the importance of durability and weather resistance in outdoor and mobile applications. The knowledge gained from container-based constructions will assist ensure that the roof is not only sturdy and durable, but also optimized for long-term, repetitive usage in a variety of situations.

Furthermore, the incorporation of important standards, notably Eurocode 9 and Eurocode 1, provides the engineering framework that will lead the structural analysis and safety requirements for this project. Eurocode 1 has proven helpful in understanding wind activities on mobile and temporary structures by providing critical equations and guidelines for load calculations, deflection limits, and safety considerations. Eurocode 9 has a material-specific focus, particularly on aluminium alloys, and provides crucial calculations for structural integrity, joint design, and material limits under stress. By following to these guidelines, the project can exceed industry safety requirements, guaranteeing that the roof design is both strong and in accordance with recognized engineering methods.

Additionally, The study of materials and mechanics related to retractable roof systems and movable container structures has revealed critical concerns for designing a mobile roofing structure. From high-strength alloys to lightweight composites, the analysis emphasizes the significance of selecting materials that balance durability, weight, and environmental resistance. The use of weather-resistant alloys, notably aluminium and steel with protective coatings, has emerged as critical for transportable buildings exposed to varying environmental environments and potential corrosion. Furthermore, modern polymer and composite materials have the potential to be used in components that require both flexibility and durability, lowering the overall weight of the structure while retaining structural integrity.

In terms of mechanisms, the review identified numerous viable alternatives, ranging from telescopic tracks to foldable and sliding systems, that allow for quick retraction and deployment while requiring minimal structural support. Telescopic mechanisms, which are often employed in sports stadiums and container-based designs, offer a compact and practical option for smoothly extending or retracting enormous roof spans. Smooth-sliding or roller-bearing systems can improve movement while reducing friction, which is crucial for long-term operation. Furthermore, foldable truss designs, which combine strength and compactness, can help provide stability over unsupported spans, particularly given the roof's frequent relocation requirements.

By combining high-strength, corrosion-resistant materials with robust yet lightweight mechanisms, the design will meet both functional and operational needs. The chosen materials and mechanisms are not only capable of supporting the structural demands of a mobile, retractable roof but also ensure ease of maintenance, longevity, and adaptability. This approach aligns with the project’s goals of creating a practical, mobile, and reliable roof system, setting a solid foundation for the next phases of design and simulation.

In conclusion, our literature review combined knowledge from a wide range of structures and standards, resulting in a comprehensive grasp of the needs, challenges, and best practices for developing a retractable roof system. The discoveries from sports stadiums, movable shelters, and container constructions have paved the way for a versatile, long-lasting, and efficient design. With Eurocodes providing a rigorous framework for safety and stability, this project is now ready to go on to the detailed design and simulation phase, where these insights will be used to build a practical, mobile, and robust retractable roof solution for mobile containers.

CHAPTER TWO: METHODOLOGY

1. Design method

This project's methodology takes a structured design and evaluation approach, beginning with the development of important boundary conditions. This includes identifying the dimensions, functional needs, and projected loads, such as wind and snow, to guarantee that the retractable roof can satisfy operational expectations in a variety of field situations. Based on these parameters, a suitable mechanism will be selected to sustain the roof's movable and retractable function in the absence of ground support.

The next step is to create an initial design model with Autodesk Inventor. This design will make basic assumptions regarding materials, load distribution, and structural components. Once the basic model is completed, it will be assessed using calculations that verify its ability to withstand the stated loads under Eurocode standards, such as EN 1991-1-3 for snow loads and EN 1991-1-4 for wind loads, as well as the weight of the roof itself.

The findings of these computations will be used to inform ongoing improvements. This entails altering essential aspects such as material selection, cross-sectional dimensions, and reinforcement methods to create a strong and functional roof structure that can support loads consistently while achieving a target load limit. This iterative design and evaluation process will continue until all structural, functional, and safety requirements are met.

This methodology will allow for a systematic exploration of design alternatives and adaptations, ensuring the final solution meets the necessary standards and performance requirements for field deployment.

2. Software's used

In this thesis, Autodesk Inventor will be used as the primary design and simulation software to model and analyse the retractable roof system. Inventor's robust suite of tools will allow for precise design, detailed simulation, and stress analysis, ensuring that the retractable roof mechanism meets all functional and structural requirements. This application facilitates the creation of accurate 3D models, assembly simulations, and performance testing, which are essential for verifying the roof's durability, mobility, and reliability in various deployment conditions.

In addition to the design process, ANSYS will be used for detailed simulations of the retractable roof system. This powerful simulation tool allows for comprehensive analysis of structural stresses, load distribution, and material performance under various environmental and operational conditions. ANSYS enables the verification and optimization of the design, ensuring that it meets industry standards for safety, durability, and functionality in mobile applications.

3. Design Specifications and Dimension Setting

The first step in developing the retractable roof system is to define accurate dimensions limits and boundary conditions that match the planned container specifications and functional needs.

3.1. Establishing Container Constraints

- Container Dimensions: The foundation construction consists of two transportable containers, each measuring 609 cm long, 240 cm wide, and 240 cm high. These dimensions specify the region over which the retractable roof will need to function. Given that the roof must span both containers, the extension mechanism should have enough reach to give full coverage while also being flexible to minor differences in container positioning when deployed in the field.
- Roof Coverage Requirements: The two retractable roofs minimum coverage between the two containers is 350 cm. This guarantees that the roof completely closes the gap and protects against environmental variables such as rain and sunlight, even if the containers are only separated by a little distance.

3.2. Setting Dimensional Boundaries for the Roof Mechanism

- Extension and Retraction Limits: The system's design must consider the limits of its fully extended and retracted states. In the retracted state, each piece should collapse without exceeding the container's width, preserving the container's mobility profile. In the extended state, each piece should achieve its maximum coverage while remaining secure and without bending under strain.
- Weight Distribution and Structural Load: The roof's design must account for the weight of each segment, ensuring that the structure can support itself without putting excessive stress on the container walls. This is crucial to keeping the containers stable during transit or heavy winds.

3.3. Movement and Clearance Requirements

- Movement and clearance: the movement should be a simple transitional movement to not complicate the system, the clearance should be at minimum 175 cm while fully extended and the dimensions of the moving element should be accounted for within the limits of the container.

3.4. Attachment and Locking Mechanism

- Fixed Attachment Points: The roof will require attachment points within each container to ensure solid anchoring. These points must be strong enough to support the roof's weight and endure environmental stress.
- The roof will require a locking mechanism in both its retracted and extended states to ensure stability and security. This locking device will keep the roof from accidently moving, particularly in high-wind situations. The locks will be positioned so that they are easy to operate while still being secure enough to hold the roof parts in place.

3.5. Environment and Safety Requirements

- Wind and Load Resistance: Because the roof is mobile, it must be able to withstand wind forces as specified in BS EN 1991-1-4: Eurocode 1, which sets specifications for wind actions. This includes calculating the wind load based on the roof's predicted area and ensuring that the design remains stable and safe.
- Weatherproofing and Durability: this limits us to materials that are weather resistant such as aluminium, polymer coated Fibers and weathered steels.

By specifying the roof precisely, the design not only fits functional requirements but also provides dependable and safe operation in a variety of deployment scenarios. These criteria consider crucial elements including load-bearing capability, weather resistance, and structural stability, all of which are required for a roof that will be deployed and retracted on a regular basis in various field locations.

This strategy improves the roof's resilience to external pressures like as wind, rain, and temperature fluctuations, as well as ensuring that the materials and mechanisms are appropriate for these different situations. Setting comprehensive settings for the roof's extension and retraction operations also allows for controlled and smooth operation, which reduces wear on moving parts and contributes to the system's overall durability. The design also includes safety elements, such as secure locking mechanisms, to prevent inadvertent movement during use or transport.

Together, these meticulously set criteria allow the telescopic roof to provide consistent, reliable shelter and coverage, improving the system's functioning and lifetime. This attention to detail during the design phase not only meets urgent practical needs, but it also reduces maintenance requirements, resulting in a strong, field-ready system that can endure the pressures of frequent relocation and use.

And now after setting up these boundary conditions we must choose a mechanism that would deliver the necessary movement.

CHAPTER THREE: PRACTICAL CASE

1. Mechanism selection

While choosing a fit mechanism we must keep in mind the nature of the retractable roof top. our structure in the extended position would be supported from one end only.
Therefore, our mechanism should be able to withstand the deadload of the roof, it own weight and the live loads of the environment and should be able to deliver the transnational movement with ease.
First step in identifying the right mechanism is to define our structure.

1.1. Cantilever structure

A cantilever system is a structural element or framework that stretches horizontally and is solely supported on one end. Unlike simply supported beams or trusses, which have supports at both ends, a cantilever extends outward from a fixed point and relies on internal structural forces (mainly bending moments and shear forces) to maintain stability and resist displacement under load.

1.1.1. Key Characteristics of our Cantilever Systems

- Support at Only One End: The cantilever's fixed end bears the full load and resists bending, shear, and torsional stresses.
- Horizontal Projection: The free end of the cantilever spreads outward, usually without further support, making it an ideal structure for regions requiring open, unsupported space.
- Bending Moment Distribution: Because the cantilever has only one fixed end, bending moments are greatest at the fixed support and diminish along its length to the free end.

Example of a cantilever roof:

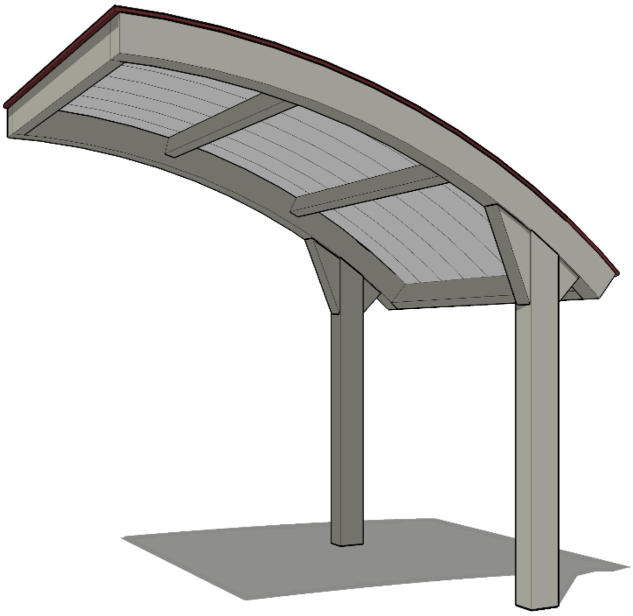

Figure 3 Roof Cantilever Carport

Source: [https://www.pngwing.com/en/free-png-niris]

As shown in Figure 6 the roof is merely supported from one end, it relies on it internal forces to have an equilibrium.

2. Heavy duty telescopic drawer slides

Heavy-duty telescopic drawer slides are strong sliding mechanisms that can withstand large loads. They are commonly used in industrial, commercial, and specialized home applications where durability, load bearing, and smooth operation are required. These slides are designed to endure severe loads, hard handling, and repetitive usage, making them perfect for applications such as manufacturing facilities, workshops, transportation, and high-load storage systems.

- A telescopic slide is a set of metal profiles that slide on ball bearings housed in ball cages.
  It has opening and closing brakes and allows weights weighing several tons to slide smoothly.
  Here are the specifics of an industrial "C" slide:
  - The fixed section is known as the "outer beam".
  - The moveable section fixed to the drawer is known as the "inner beam".

- The component that allows for extra extension is known as the "intermediate beam" (up to two beams).

➢ For a high performance “I” shaped slide:

Each flat beam is called a “inner beam”, one being fixed and the other mobile The central I is the intermediate beam (not the fixed part!)

Figure 4 Super extension telescopic slider

Source: [https://chambrelan.com/drawer-slides/drawer-runner/super-extension/]

As shown in figure 7 it is a super extension telescopic slider made by “Chambrelan”, super extension sliders can extend up to 150% the original length but when fully extended the load they can support declines significantly, therefore it can experience bending and/or buckling.

2.1. Features of Heavy-Duty Telescopic Drawer Slides

➢ **High Load Capacity:**

- Heavy-duty telescopic slides can support loads ranging from 100 to 1000+ kg, depending on the model and material. This strength enables them to support huge, heavy drawers, platforms, or panels that must extend and retract smoothly.

➢ **Extension Types:**

- Partial Extension: Only extends a portion of the total slide length, suitable for applications where full extension is unnecessary.

- Full Extension: Allows the entire drawer or platform to extend, offering full access to contents.
- Super-Extension: Extends beyond the full length of the slide, often up to 150% of the closed length, providing maximum access in tight spaces.

➢ **Material Composition**:

- Heavy-duty slides are frequently constructed from hardened steel, stainless steel, or aluminium alloys for strength and corrosion resistance. Some models also use unique coatings to increase longevity and prevent rusting in tough conditions.

➢ **Ball Bearing or Roller Mechanisms**:

- These slides often employ high-quality ball bearings or rollers to provide smooth operation even under large loads. Ball bearings are commonly used in heavy-duty applications due to their weight distribution and low friction.

➢ **Lock-in/Lock-out Mechanisms:**

- Locking mechanisms ensure that the drawer or platform remains firmly in place when completely extended or retracted. This is particularly beneficial in transit or mobile areas to prevent slipping while moving.

2.2. Advantages

➢ Durability: These slides are resistant to wear and tear thanks to their high-quality materials and construction, even under the most demanding conditions.

➢ Load Capacity: Can safely handle heavy loads, which is critical in both industrial settings and mobile environments.

➢ Smooth Operation: Ball bearings or rollers allow for easy and smooth sliding, reducing wear and extending slide life.

2.3. Considerations for Selection

Load requirements: we must calculate the dead load based on the material, and the live load (wind, snow if applicable) then we can choose from the catalogue a telescopic slider well above the loads, while also keeping in mind the safety factor.

Length and extension: we are limited with the boundary conditions so the maximum length of the telescopic slider cannot be more than 240 centimetres, and the extension should cover a minimum of 175cm.

Environmental Conditions: we should Select materials and finishes based on exposure to moisture, chemicals, or extreme temperatures, especially in outdoor conditions.

Based on the importance of mobility and resilience, bear loading capabilities and cantilever structural design, telescopic sliders are by far the most fit mechanism for the necessary application.

Since we don't know our exact loads at this stage of the design, we will take the parameter that we know already which is the extension minimum value that is 175cm and we can use that in the industrial catalogue to pick a telescopic slider that is well above our minimum.

A telescopic slide is a set of metal profiles that slide on ball bearings housed in ball cages. It has opening and closing brakes and allows weights weighing several tons to slide smoothly. Here are the specifics of an industrial "C" slide:
- The fixed section is known as the "outer beam".
- The moveable section fixed to the drawer is known as the "inner beam".
- The component that allows for extra extension is known as the "intermediate beam" (up to two beams).

2.3.1. Selecting the telescopic drawer

Looking through "Chambrelan" catalogue of their standardized telescopic sliders, if we set up the extension length as 2000mm which is the maximum and that leaves us with multiple sliders, but what's common between all of them is that the maximum load that they can take is 1000kg per pair.

Closed length	Extension	Load per pair on major axis	Deflection	Load per pair on minor axis	Deflection	Weight	
2000 mm ~ 78 3/4 "	2000 mm ~ 78 3/4 "	1000 kg ~ 2205 lbs	17 mm ~ 0 5/8 "	240 kg ~ 530 lbs	45 mm ~ 1 3/4 "	79,738 kg ~ 175 lbs	See more

Table 5: E1020 Drawer slide - Steel - Full Extension specifications

Source: [https://chambrelan.com/guide/e1020/]

As you can see in table 2 from the catalogue the closed length of the mechanism is 2000mm which well within our 240 cm length, the extension is 2000mm which is well over the needed extension 175cm, we are not concerned about loads on the minor axes nor deflection on that axis, the weight per single drawer is 79,738kg which is very acceptable, and won't cause unnecessary loads on the container walls, the deflection on the major axis usually happens if the load applied is relatively close to the maximum load, so to avoid that we are going to place a safety factor of "2" to account for live loads as well as dead ones.

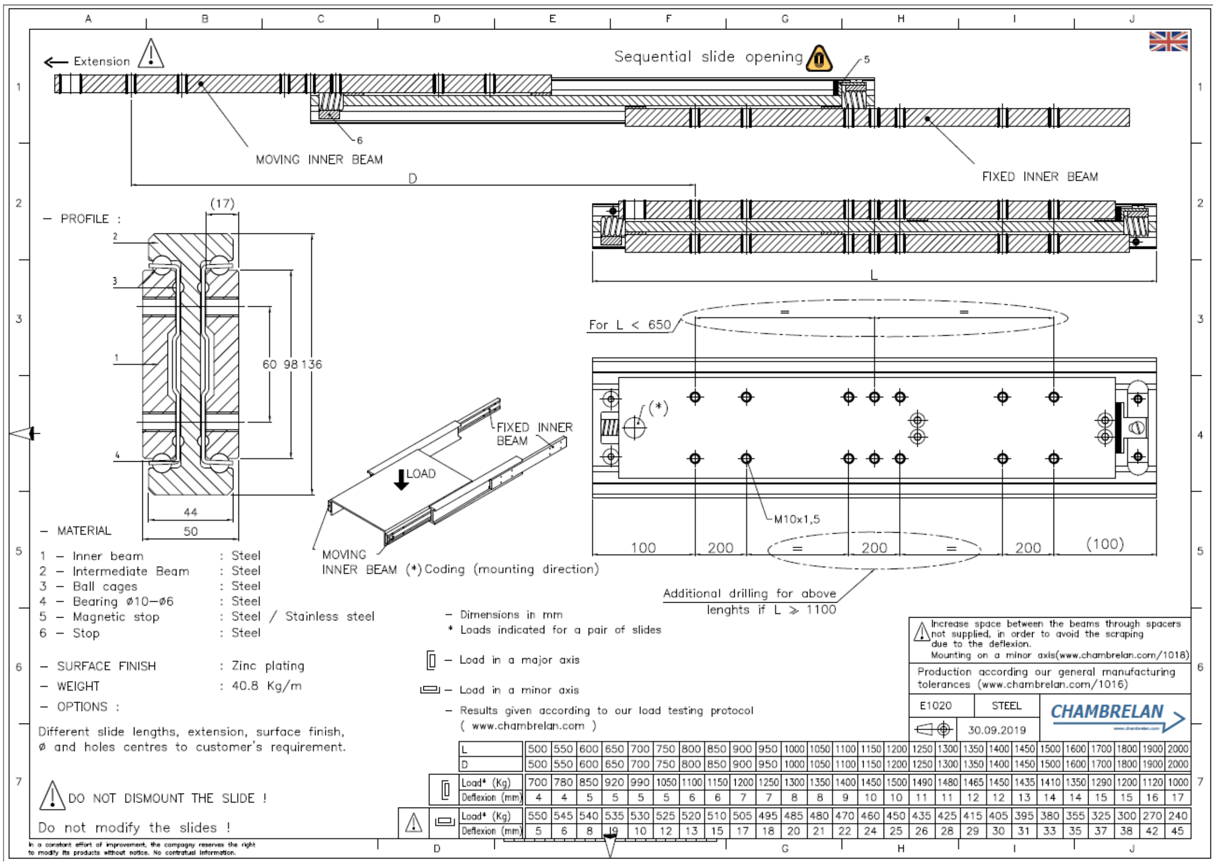

Figure 5 Technical sheet of E1020

Source: [https://chambrelan.com/wp-content/uploads/product/E1020/fiches/E1020.pdf?v=1730456639]

In figure 5 we are given all the specific dimensions and loads for our mechanism the screws that we are going to use are M10x1,5, since L is larger than 1100mm in our case we will be increasing the number of holes to 14 with the recommended dimensions.

Since the placement of the screws and the dimensions are given by the manufacturer, we only must figure out which material to use in the screws based on our load.

We will start by making an initial design of a flat roof with our specific dimensions.

3. Initial design

We will start by making a simple initial design, so basically a flat roof with the needed specified dimensions using “inventor” to design and ANSYS to simulate.

The roof dimensions: 2,000 mm width x 5,500 mm length (2,0 m x 5,5 m)

We will make this initial design out of aluminium 6064.

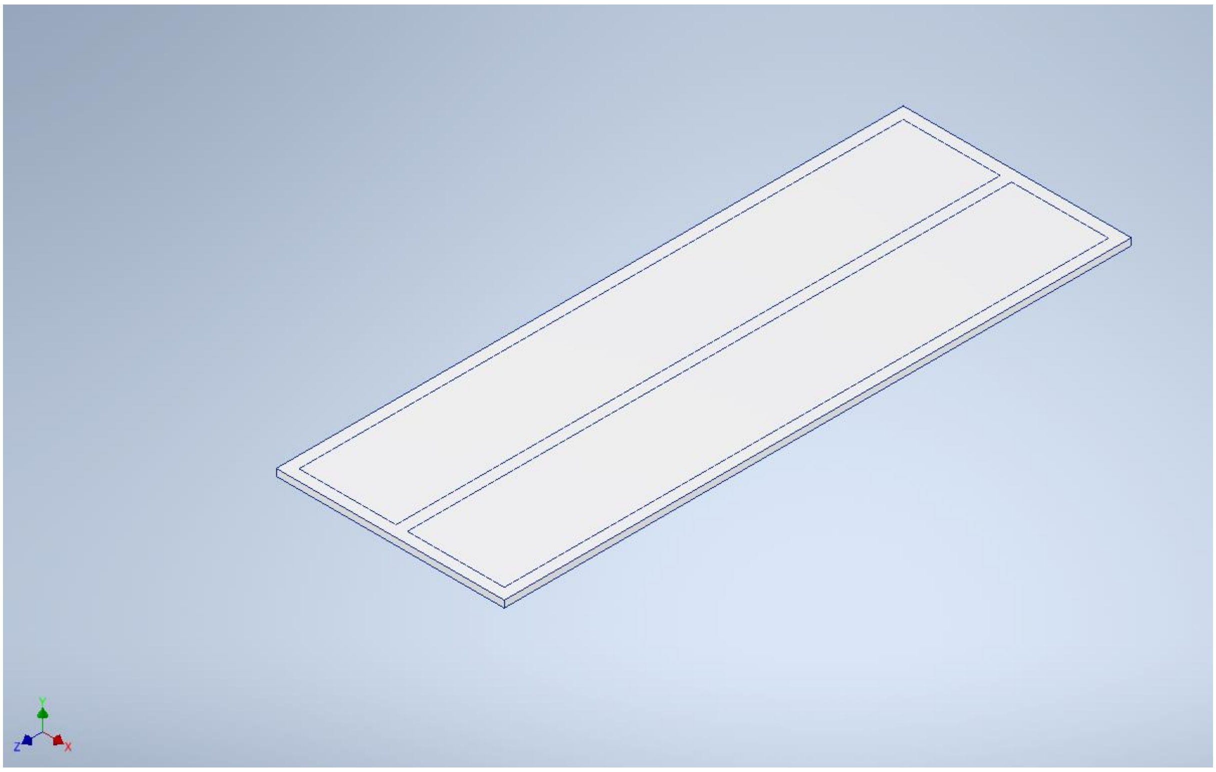

Figure 6: Initial design from inventor.

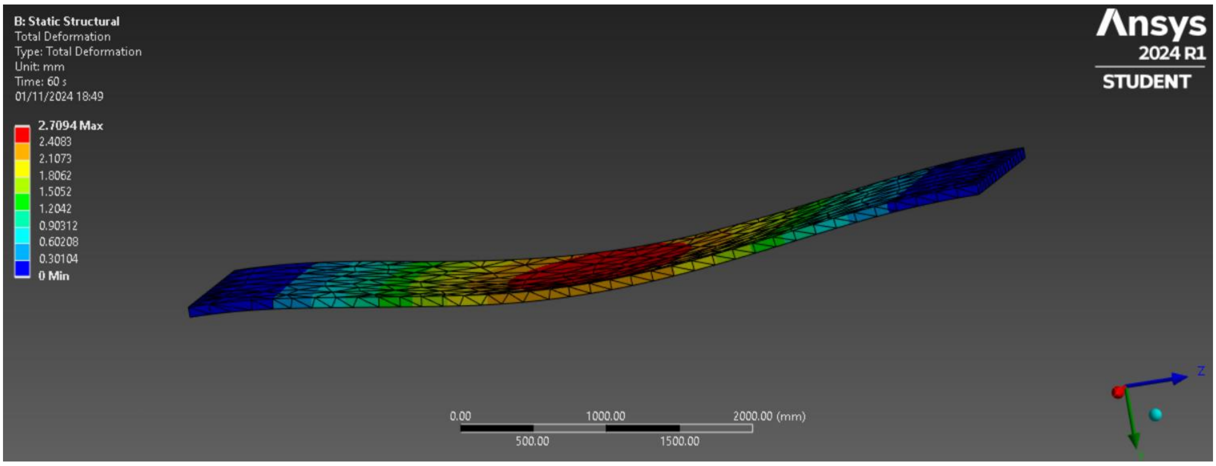

Figure 7 simulation in ANSYS under air pressure and self-load

As shown in figure 6 and figure 7 this is the initial design, I ran a simulation for the design in ANSYS using statical structures, the constrains were from the sides matching the chosen mechanism, and the loads were self-weight and atmospheric pressure, The simulation time was set as 60s.

The design performed very well under these conditions showing a maximum deformation of only 2,7mm at the centre line of the roof.

To further evaluate the design, we must consider the live loads that the roof will be subjected to.

The initial design made of aluminium 6064 weight roughly 395,361 kg.

3.1. Snow Load Calculation

According to Eurocode 1:

-Snow load on the ground (s_k), depends on the snow zone, Hungary's snow load varies by region, typically between 0,7KN/m² and 1,5KN/m².

- let's assume an average of 1,25kN/m².

$$s = s_k \cdot C_e \cdot C_t$$

s_k: snow load on the ground in our case 1,25kN/m².

C_e: exposure coefficient (typically 1 for open areas).

C_t: thermal coefficient (typically 1 if the roof is not heated).

Solving the equation, we will get S= 1,25 kN/m².

The total snow load on the roof would be:

$$total\ snow\ load = s \cdot\ Area\ of\ the\ roof = \frac{1{,}25kN}{\mathrm{m}^2} \cdot\ (2\,m\ \cdot 5{,}5\,m) = 13{,}75kN$$

3.2. Wind load calculation

Basic wind speed in Hungary given with Eurocode 1 database is between 24 and 26 meters per second.

The wind pressure (q):

$$q = 0{,}5 \cdot \rho . v^2$$

Where:

ρ: air density (assumed as 1,25kg/m^3).

v: basic wind speed (taking 25m/s for Hungary)

$$q = 0{,}5 \cdot 1{,}25 \cdot 625 = 390{,}625\ N/m^2$$

Wind load on the roof:

We are going to take in the worst-case scenario where the roof is perpendicular to the wind's direction:

$$Wind\ load = q \cdot AREA = 4{,}29\ kN$$

Total Design Load

Combining the dead load (weight of the roof), snow load, and wind load:

1. **Dead Load** (roof weight): $395.361kg \approx 3{,}88kN$
2. **Snow Load**: $13{,}75kN$
3. **Wind Load**: $4{,}29kN$

Total load would be: 21,92 kN

Even though the calculations given by the Eurocode 1 account for extreme weather conditions, the total load is still a bit higher than we would like it to be.

we must change our design to lower the deadload, snow load and wind load.

3.3. Curved design

A curved design based on the Eurocode 1 guidelines performs better than a flat design under wind and snow loads.

Therefore, I created a curved roof design made of corrugated aluminium as the top section, reinforced from the side by two aluminium plates that will be joined to the top section and to our telescopic mechanism with screws.

To offer additional support to the top section, curved beams are connected horizontally to the top section with screws and the beams are welded to the aluminium plates.

The beams are hollow inside, with a thickness of 20mm from all sides.

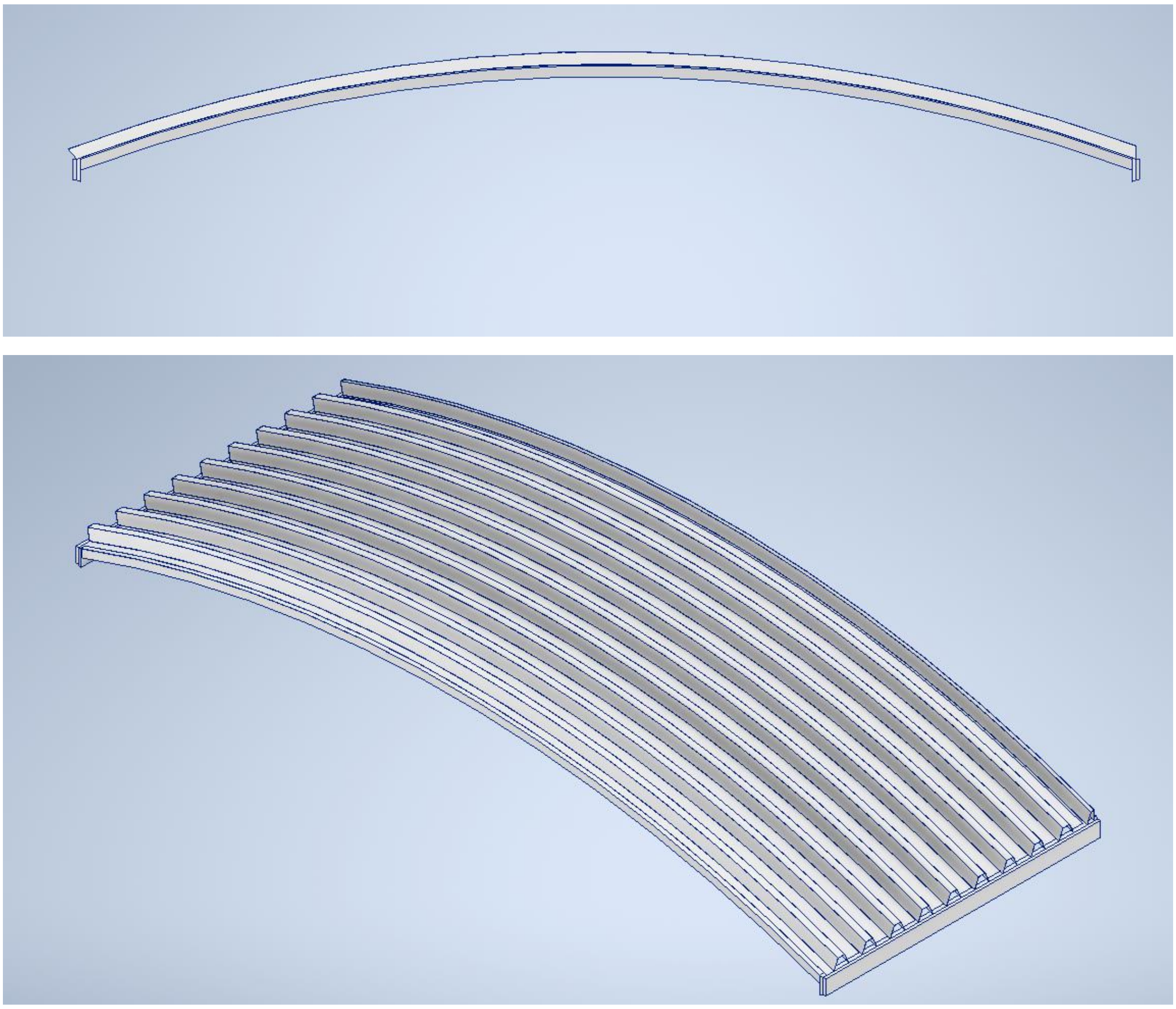

Figure 8: curved roof design made of corrugated aluminium

3.3.1. Deflection calculations

Known data:

-Elastic modulus of aluminium: 69 GPA

-Width: 100mm

-Depth: 65 mm

-Thickness: 20 mm

-Length of the beam: 5500mm

Let us calculate the deflection on the support beams.

First, we must calculate the moment of inertia, we will use the hollow beam formula.

For a rectangular hollow beam:

$$I = \frac{(0{,}1 \cdot 0{,}065^3) - ((0{,}1 - 0{,}04) \cdot (0{,}065 - 0{,}04)^3)}{12}$$

$$I = 2{,}210416667.10^{-6}\ m^4$$

Next step is to use the maximum deflection equation:

$$\delta_{max} = \frac{5 \cdot \mathfrak{w} \cdot L^4}{384 \cdot E \cdot I}$$

The maximum deflection is given to us by the euro code, deflection in aluminium support beams in roof structure shouldn't exceed $\frac{L}{250}$, which is 22 in our case.

So, by re-arranging the equation we can calculate for $\mathfrak{w}$ the uniformly distributed load.

$$\mathfrak{w} = \frac{22 \cdot 384 \cdot I \cdot E}{5 \cdot 5{,}500^4}$$

$$\mathfrak{w} = 0{,}28161 N/mm$$

We will multiple it by the length of the beam which is 5500mm and we will get the value 1548,88N.

Since we have 4 lengthwise support beams to an equally distributed force, we should multiple our force by 4.

We will get the value 6195.536644N.

We must calculate the force on the support on the width.

The moment of inertia will be the same.

Using the same principle of maximum deflection $\frac{L}{250}$, with the new length which is 2000 mm, we will get the value 8.

We apply it on the same equation:

$$\mathfrak{w} = \frac{8 \cdot 384 \cdot I \cdot E}{5 \cdot 2000^4}$$

$$\mathfrak{w} = 5{,}856 N/mm$$

We multiply it again by the length of the support beam and we will get the following value:

11713.43647N

This doesn't account for the maximum load of the mechanism which 9806.65N with a deflection of 17mm

As per the Eurocode, this means that our structural design is within the set safety of deflection.

The total weight of the design is 320kgs.

3.3.2. Snow Load Calculation

According to Eurocode 1:

-Snow load on the ground (s_k):

$$s = s_k \cdot C_e \cdot C_t$$

s_k: snow load on the ground in our case 1,25kN/m².

C_e: exposure coefficient (typically 1 for open areas).

C_t: thermal coefficient (typically 1 if the roof is not heated).

Solving the equation, we will get S= 1,25 kN/m².

We must account for the shape coefficient for curved roofs, which is 0,8 in this case.

Therefore S=1 kN/m²

The total snow load on the roof would be:

$$total\ snow\ load = s \cdot Area\ of\ the\ roof = \frac{1kN}{\text{m}^2} \cdot (2\,m \cdot 5{,}5\,m) = 11kN$$

3.3.3. Wind load calculation

Basic wind speed in Hungary given with Eurocode 1 database is between 24 and 26 meters per second.

The wind pressure (q):

$$q = 0{,}5 \cdot \rho\,.\,\nu^2$$

Where:

ρ: air density (assumed as 1,25kg/m^3).

ν: basic wind speed (taking 25m/s for Hungary)

$$q = 0{,}5 \cdot 1{,}25 \cdot 625 = 390{,}625\ N/m^2$$

Wind load on the curved roof:

We are going to take in the worst-case scenario where the roof is perpendicular to the wind's direction:

We are going to factor in the shape coefficient which is given as 0,7

$$Wind\ load = q \cdot AREA \cdot 0{,}7 = 3{,}14\ kN$$

Total Design Load

Combining the dead load (weight of the roof), snow load, and wind load:

1. **Dead Load** (roof weight): $320kg \approx 3.14kN$
2. **Snow Load**: $11kN$
3. **Wind Load**: $3{,}14kN$

Total load would be: 17,28 kN

Changing the shape of the roof and the structure have managed to lower the total load greatly, but it is still not low enough to be supported solely by our mechanism of choice.

we are going to replace the corrugated aluminium top section with a polymer coated Fiber such as PTFE coated fiberglass.

Whilst keeping the base structure as aluminium.

PTFE coated fiberglass weight ranges based on the manufacturer it typically ranges from 0,5 to 1,5 kg/m^2

We are using aluminium 6061 with a 1 mm thickness in the top section of the roof

The density of aluminium 6061 is:

$2700 \text{kg}/m^3$

If we multiple it by our thickness:

$2700 \text{kg}/m^3 \cdot 0{,}001m = 2{,}7 \text{kg}/m^3$

So, using PTFE coated fiberglass would help us cut in half the weight of the top section while maintaining all the functional properties of the roof.

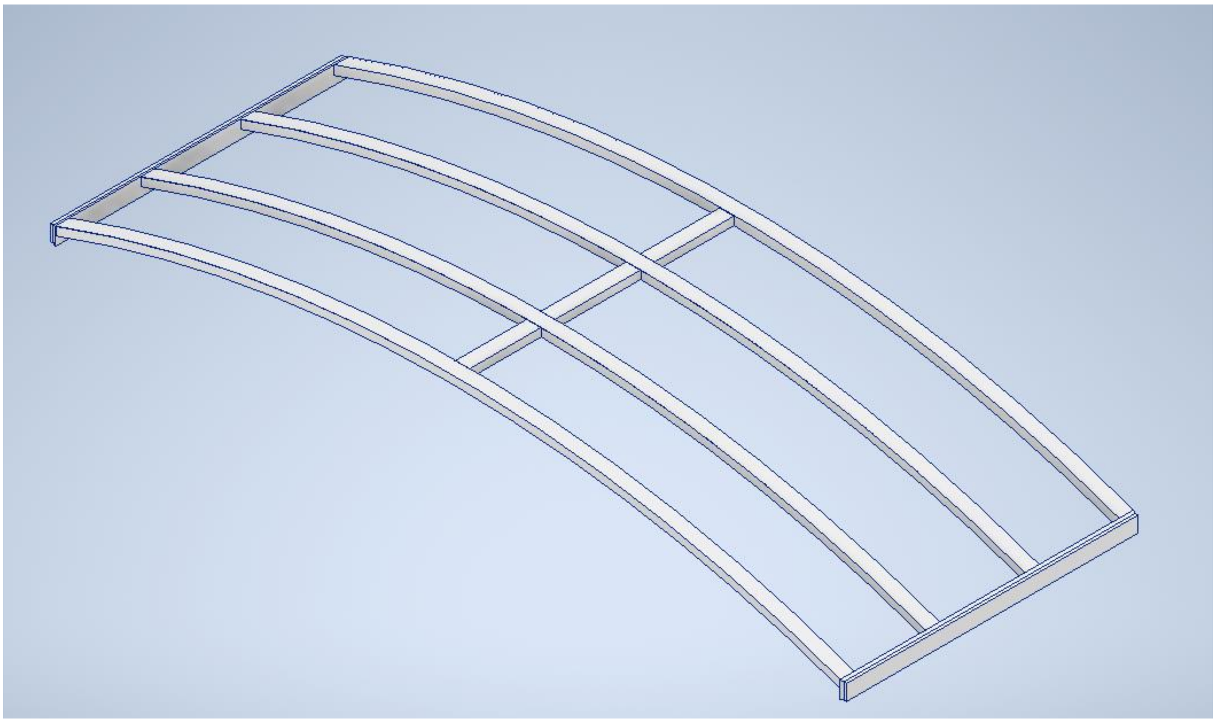

Figure 9 the roof frame design

The top section of the roof weighs approximately 100kg as obtained from “inventor” therefore if we change the top section to PTFE coated fiberglass our deadload will be 50kgs lighter than before, that will lower our overall load.

And for fixing the coated fiberglass to the aluminium frame we can use stainless steel panhead screws with washers, using stainless steel pan head screws combined with washers helps distribute the load and prevents the PTFE fiberglass from tearing or distorting under load. The washers can also protect the fiberglass from direct contact with the screw head.

Our load would still be well over 1kN; therefore, we need to find another solution for extreme weathers.

4. Fixture of the mechanism with the container

The mechanism needs to be set up on its major axis so it can deliver the most efficient performance with the lowest deflection, therefore the simplest solution for us to use would be to integrate two “L” shaped plates on both containers to lock in place the mechanism to the roof.

From the dimensions of the mechanism we can get that the fixed part has a height of 98mm, and the mechanisms width is 50mm.

Just for safety margins and for the mechanism to fit nicely into the L shaped plate we are going to set the height of the L shaped plate to 158mm and the width to 72mm now all that is left is to calculate the thickness of the L shaped plate and the material.

We need a material that can be resistant to corrosion and still offer great mechanical properties; therefore, we will select stainless steel as the base material for the L shaped plate.

And since we are working with M10x1,5 screws as recommended by the manufacturer of the mechanism and as pre-drilled in the telescopic sliders.

Typical clearance for M10 screws is 1 to 1,5 times the diameter for soft materials such as aluminium and 1,5 to 2 times the diameter for harder materials such as stainless steel.

Therefore, we set the thickness of our L shaped plate to 22mm.

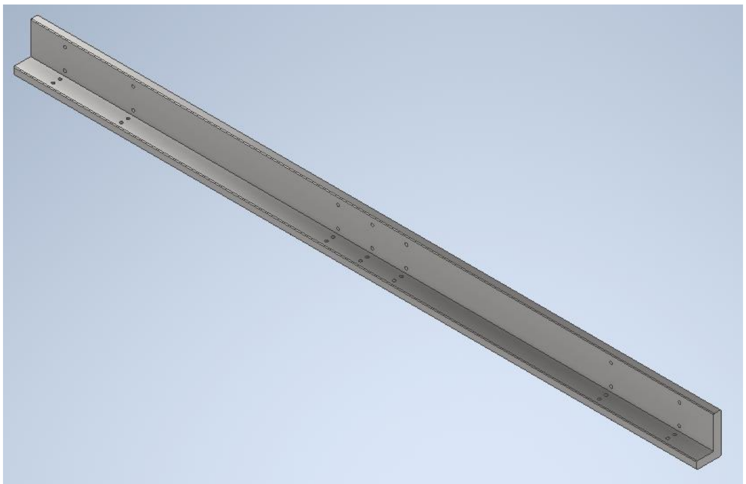

Figure 10 "L" shaped connection

We must calculate the necessary control equation to verify if the screws can handle the loads and forces in the system.

Shear control calculations:

$$\frac{\tau_{applied}}{\tau_{allowable}} \leq 1$$

$\tau_{allowable}$: Allowable shear stress (taken as 0.6 times the material yield strength for common metals)

Since we have M10x1,5 screws we are going to use the minor diameter to calculate the area.

For M10x1,5 the minor diameter is 8.376mm

$$\tau_{applied} = \frac{F_{shear}}{A_s}$$

Where:

F_{shear}: shear force on the screw

$A_s: Shear\ area\ (for\ threaded\ screws, we\ use\ the\ minor\ diameter)$

$$A = \frac{\pi d^2}{4} = 55{,}101 mm^2$$

Force per screw is the total force divided by the number of screws, if we have 10kN total equally distributed on each side and we have 14 screws per side, therefore our F would be equal to 375,14N per screw.

$$\tau_{applied} = \frac{357{,}14}{55{,}101} = 6{,}481\ N/mm^2$$

For A2-grade stainless steel, the ultimate shear strength typically falls around 300 N/mm², and using a safety factor 2, the allowable shear stress would be around 150 N/mm².

Since our shear stress is well below the allowable shear stress it is safe to say that the screws will handle the shear stress.

Tensile control calculations:

The Total updraft force as calculated is 3,14Kn.

Diving it by the number of screws which is 14, we will get the value: 224,3 N.

Which is the tensile force acting on each screw in case of the worse scenario updraft wind.

This value is very low compared to the yield strength of stainless-steel Grade-A2.

After calculating both the tensile and shear forces on the screws holding the mechanism to the L shape connection.

We can safely say that the screws can handle both the max allowable vertical load and wind loads.

5. Locking mechanism

5.1. Retracted locking

For the locking mechanism when the roof is not in the extended state, the manufacturer offers a detent pin solution that can come with the product to stop it from accidently extending.

Figure 11 example of detent pin

Source: [https://lifting.com/ball-detent-pin-014x112.html]

5.2. Extended locking

And for the locking of the system in the extended state two toggle clamps would be mounted on the side of roof where it connected to the telescopic drawer, and they can be manually locked when the two roofs are in proximity.

Figure 12 example of adjustable toggle clamps

Source: [https://www.amazon.com/CUKAYO-Stainless-Adjustable-Latches-Capacity/dp/B0BVJ82ZJS]

6. Movement of the roof:

To facilitate the manual extension and retraction of the retractable roof, a simple yet effective mechanism is proposed, consisting of a hooked stick paired with a ring mounted on the roof structure. This solution enables users to move the roof without the need for complex or motorized systems, aligning with both functional requirements and ease of operation.

The hooked stick features an ergonomic rubber grip for easy gripping and greater comfort during operation. The hook end is designed to securely latch onto the ring on the roof, giving users the leverage they need to manually extend or retract the roof safely. The ring, which is firmly attached to the roof structure, is designed to withstand the stresses required for smooth operation, even under normal environmental loads.

To extend or retract the roof, the user hooks the stick onto the ring and pushes or pulls depending on the desired movement. This simple approach provides precise control over roof movement while minimizing physical effort on the operator. This technology also allows for progressive expansion and retraction, providing the flexibility to modify the roof according on current weather conditions.

7. Proposed solutions for the roof under extreme loads

7.1. First solution

To meet the issues given by harsh weather conditions such as blizzards, heavy snowfall, and high winds, practical techniques must be considered to lower the imposed loads on the retractable roof without jeopardizing the design's general integrity and performance. One efficient technique to mitigate the impact of snow and wind loads in such conditions is to temporarily reduce the roof's expanded area. Unlike permanently limiting the roof area, this technique adheres to the design's primary boundary conditions by allowing the roof to attain its full potential when weather permits.

In adverse weather conditions, the roof should only be extended 1.2 meters to ensure safety. This constrained extension greatly minimizes the exposed area, minimizing the surface area where snow can build, and wind can apply force. To ensure safe use, the 1.2-meter restriction should be properly indicated on the roof structure, with the marker visible and sturdy enough to survive outside circumstances. Furthermore, user awareness is critical;

operators must be educated and trained to recognize this limit and the reasons for it. This ensures that the roof's extension is regulated under harsh weather conditions, reducing the risks associated with excessive loading.

7.2. Second solution

In circumstances where the roof must be fully extended despite adverse weather conditions, a strong plan for managing snow and ice accumulation on the surface is critical for maintaining structural integrity and avoiding hazardous overload. While full extension is not recommended in such situations, installing a heating system and following regular cleaning procedures might assist to reduce the risks.

A heating system might be built into the retractable roof structure, designed to evenly transfer heat throughout the roof surface, melting snow and preventing ice formation. This can be accomplished with embedded heating devices, such as electrical heating cables or mats designed expressly for outdoor use. The heating system should be flexible to meet different weather intensities and energy-efficient, activating only when the roof is fully extended in harsh conditions. Furthermore, an automatic temperature sensor might be placed to activate heating when temperatures dip below freezing, ensuring consistent protection against snow and ice formation.

In addition to the heating system, a human or automated cleaning program should be designed to remove accumulated snow or ice from the rooftop while in operation. This could include regular human clearance by designated staff or an automated system that uses mechanical brushes or low-power jets to clear the surface of snow, preventing accumulation while the roof is in use. This cleaning mechanism should be strong yet delicate enough to avoid damaging the roofing material, especially if the surface is comprised of polymers or coated fiberglass, which are more susceptible to abrasion.

By implementing these preventive measures, the roof system can remain functional and safe even in full extension during adverse weather conditions. However, it is critical to emphasize that these actions are secondary precautions, and reducing the roof extension remains the primary recommendation for ensuring optimal load management.

8. Final assembly:

Final assembly from inventor after assembling all the necessary parts, L shaped connector the mechanism and the roof.

An orange box is used as a simplification of the container, the box has 1 to 1 dimension as the container.

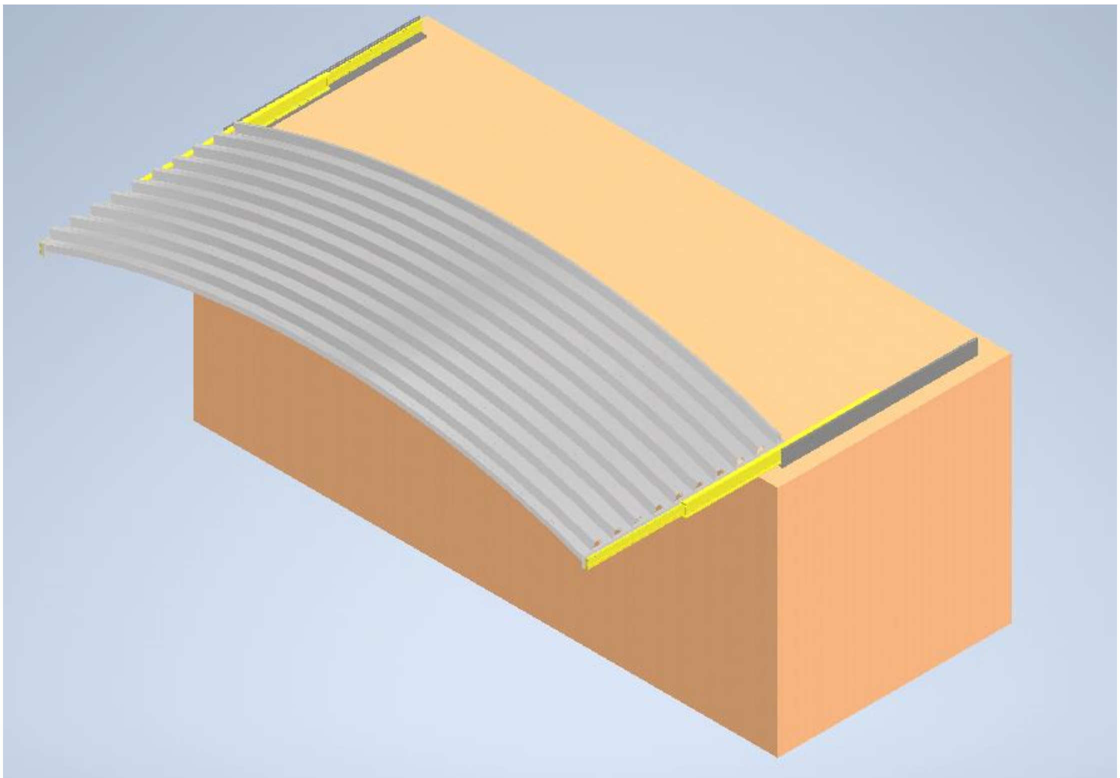

Figure 13 home view of the final assembly

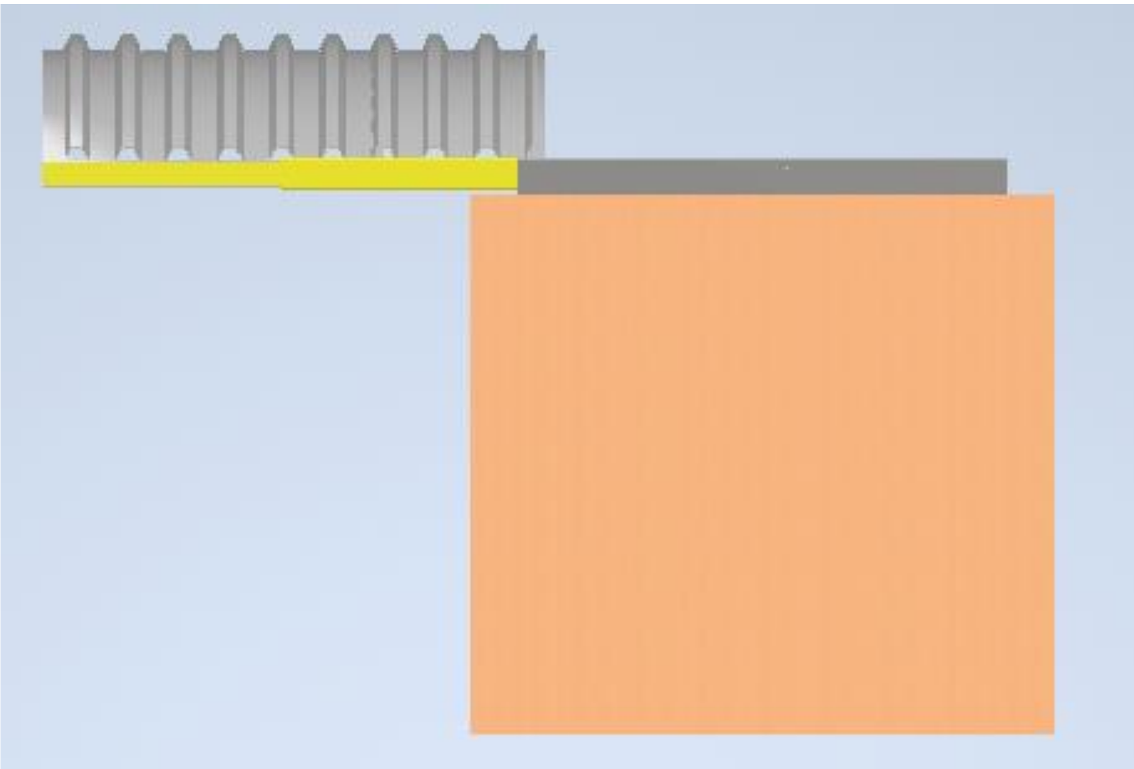

Figure 14 side view of the total assembly

CONCLUSION

This thesis focused on the design and implementation of a telescopic retractable roof system optimized for mobile container applications, addressing the major requirements of durability, mobility, and adaptation to changing weather conditions. A detailed analysis of sports arenas, transportable shelters, and container-based buildings, as well as a thorough review of Eurocode requirements, provided crucial insights into the project's ideal materials, structural considerations, and load-bearing mechanisms.

In developing the design, multiple solutions were explored to ensure the roof system could meet structural and functional requirements while remaining within acceptable load limits. Solutions such as reducing roof dimensions, choosing lightweight but durable materials like PTFE-coated fiberglass, and avoiding operation under extreme weather were incorporated to manage the roof’s load without compromising safety or functionality. The use of a heavy-duty telescopic drawer system, secured with toggle clamps, offered both ease of deployment and reliable locking, fulfilling the operational needs for quick and stable extension.

Calculations based on Eurocodes 1 and 9 gave crucial instructions for dealing with snow, wind, and dead loads, as well as precise component selection, particularly for structural parts and fasteners, to ensure stability and integrity under maximum predicted loads. The final design, which has a self-supporting curving corrugated aluminium roof structure supported by vertical telescopic sliders and strong L-brackets, strikes a good mix between strength and lightweight mobility.

This retractable roof design is a practical and scalable solution for mobile container applications, addressing both structural performance and user needs through material selection, efficient load distribution, and mechanical locking mechanisms. Future research could focus on weight optimization and deployment automation to improve user convenience and adaptability.

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