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Structural analysis and environmental performance of reusable military storage tents: Wind resistance and humidity control

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ABSTRACT

The article presents the results of the analysis of the effectiveness of storing system dedicated for special purpose equipment. Requirements for storage systems and effective techniques for protection against external factors that limit corrosion are described. A reusable storage tent was tested under varying weather conditions, with temperature and humidity resistance using the developed measuring equipment. The importance of the strength analysis of the tent structure exposed to the destructive effects of wind was indicated. Structural performance was investigated through numerical simulations of wind gusts reaching 120 km/h, conducted using the finite element method with the LS-DYNA software package. The simulations incorporated detailed modelling and material properties derived from the MatWeb database. The structural limitations of the tested tent are discussed as well as potential improvements are indicated.

Keywords: finite element method, strength analysis, storage, reusable cover.

INTRODUCTION

In recent years, tents have gained increasing popularity due to their versatility and adaptability to diverse operational scenarios. Their modular design and rapid deployment make them particularly valuable in emergencies, including natural disasters and military conflicts, where temporary infrastructure is urgently required [1]. These structures support various applications such as medical facilities [2], logistics hubs, and mobile storage units for military operations [3]. In addition to being cost-effective and environmentally adaptable, tents are accessible and easily configurable, which has contributed to their widespread adoption. They also serve as practical storage systems that offer protection for sensitive equipment from adverse environmental conditions.

The selection of this research topic is driven by the growing need for effective storage solutions to safeguard valuable military assets from environmental factors that accelerate material degradation. As the Polish Armed Forces continue to modernize their equipment inventory, there is increasing demand for storage systems that ensure long-term operational readiness while reducing maintenance efforts and costs. The ongoing conflict in Ukraine has further highlighted the importance of reliable storage infrastructure capable of withstanding a variety of climatic stressors [4]. Additionaly, the rising frequency of extreme weather events underscores the necessity of durable, wind-resistant shelters that also offer stable internal environments. The development of storage tents that fulfill both mechanical strength and environmental control requirements directly supports the Polish military's ability to preserve equipment condition, thereby improving defense readiness and logistical efficiency.

Despite significant advances in tent materials [5], frame construction technologies [6], and joint design [7,8], empirical validation remains essential—particularly regarding durability under challenging environmental conditions [9]. Properties such as energy absorption [10], resistance to punctures or structural damage [11], and mechanical performance under wind loads [12] must be examined in real-world contexts. Numerical simulations, especially finite element methods, provide a means to replicate complex load conditions, enabling a deeper understanding of structural behavior and facilitating design optimization. Such simulations assess tent strength, fatigue resistance, and load distribution across the structure, accounting for varying wind intensities and environmental parameters.

It is essential to distinguish between strength and resilience: the former refers to a structure's capacity to endure stress without failure, while the latter relates to maintaining functional performance over time under fluctuating external conditions. This distinction is critical in designing tents intended to provide prolonged protection against humidity, temperature variation, and wind. The integration of numerical modeling with experimental testing not only accelerates the design process but also ensures that the resulting storage solutions meet the rigorous demands of military applications [13].

The main objective of this study was to conduct a comprehensive analysis of the new version of the universal military equipment storage tent (NUPW II), focusing on two key aspects of its functionality. The first aspect is evaluating the tent's effectiveness in maintaining a controlled internal environment, with particular emphasis on humidity and temperature, which are critical for preventing corrosion of stored military equipment. The second aspect involves analyzing the structural strength of the tent under high wind speeds (up to 120 km/h) using the finite element method in LS-DYNA software. The research also aims to identify potential weak points in the tent's structure and propose possible improvements in materials and structural connections to improve its resistance to extreme weather conditions while maintaining effective environmental protection performance

STORING EQUIPMENT REQUIREMENTS

The primary objective in storing technical equipment is to preserve its properties and parameters, ensuring they remain intact without degradation. This imperative is driven by a rational approach to the utilization of specific equipment categories. According to the prevailing regulations in the Armed Forces of the Republic of Poland, stored technical equipment must meet specific criteria—it should be technically efficient, complete, and possess an appropriate reserve of resources, adhering to the standards of target operation after the warranty period [14]. It should be highlighted that the maintenance procedures are described in documents including instructions and guides related to particular groups or brands of equipment. Conservation is assumed as a technological operation, involving the use of materials to mitigate the adverse environmental effects on technical objects during storage.

It is important to recognize that storage itself comprises a set of organizational and technical measures. These measures are geared towards creating conditions conducive to maintaining military equipment in the required technical state during extended periods of inactivity. This involves specific activities related to storage, including maintenance, inspection of technical condition, and periodic assessments. It is crucial to underline that the effectiveness of storage or warehousing, is directly related with integration of the other elements in the technical equipment operation process. To meet this requirement, various storage methods are employed, ranging from cost-effective options (like lubricant-free and lubricant methods) to high-volume methods such as the dynamic storage method [15].

The management of equipment storage and its operations are integral components of the equipment life cycle. This life cycle encompasses all conceivable subsequent or interrelated stages in the life of the specialized equipment. These stages include scientific research and development, industrial design, production, utilization, repair, modernization, modification, maintenance, logistics, training, testing, withdrawal, and disposal. Block diagram of equipment life cycle is shown in Figure 1

In the context of these considerations, it is essential to highlight that the matter of equipment storage warrants attention right from the stage of scientific research and development. Addressing storage concerns at this early phase allows for the deliberate selection of a straightforward and efficient storage method ensuring reliability .

It should be underlined that the operation of technical equipment includes time intervals when the equipment is in use and when it is out of use during waiting phase. During these inactive intervals, environmental factors (such as weather and climatic conditions) can negatively affect the maintenance of the equipment's technical efficiency, posing a significant challenge

Figure 1. Phases of the life cycle of military equipment

for technical staff. Currently, the Polish Armed Forces utilize several methods for storing unused technical equipment: the lubricant method (S), the lubricant-free method (BS), and dynamic drying. The test results of these methods are shown in Figure 2.

Research carried out at the Military Institute of Armoured and Automotive Technology shows that a rational and effective storage method is using dynamic drying, where the essence is to limit the impact of negative factors on technical equipment. One of the many methods of protecting equipment against corrosion is to create an artificial environment that stops corrosion from occurring. In such an environment, the optimal parameters will be temperature and, above all, relative humidity, which should be maintained within the range of 40–60%. This method is dedicated primarily to large-sized equipment.

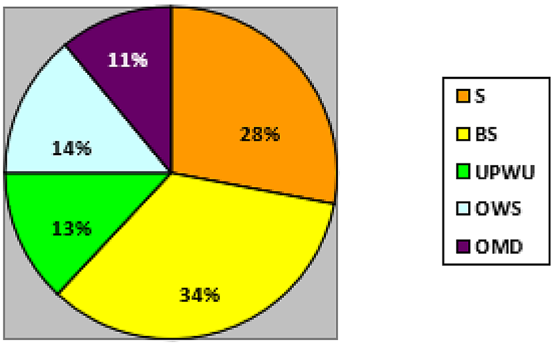


Figure 2. Storage methods used in the army based on survey carried out at Military Institute of Armoured and Automotive Technology during 2014–2023

UNIVERSAL REUSABLE STORAGE TENT

One of the suggestions for storing technical equipment is to use reusable covers. The Armed Forces use the method of storing technical equipment in universal, reusable covers, but 30 years have passed since its implementation. During this time, the Military Institute of Armored and Automotive Technology gained appropriate experience that allows to develop a new cover based on modern fabrics and new construction solutions (Figure 3). The essence of the structure is, among others:
- shape of the cover;
- linear dimensions;
- area and volume;
- type of material (fabric) used for the cover;
- type of material and shape of profiles used for the supporting structure;
- type and effectiveness of gas-tight locks and accessories, etc.;
- attaching the cover to the ground.

Figure 3. View of the new universal reusable storage tent

With regard to the operational properties that have a significant impact on the level of effectiveness of corrosion protection, cost reduction and improved organization of storage of technical equipment, the following should be mentioned:
- barrier and tightness against aggressive gases, water vapor, dust, etc.;
- a set of specific strength properties;
- usability, durability and reliability;
- complete lack of corrosive aggressiveness towards other system elements;
- resistance to propellants and lubricants (or other operating liquids) and possibly to fire;
- masking properties at the appropriate level.

The technological properties that determine the design of the reusable cover and its packaging technology are as follows:
- weldability of the multi-layer barrier material;
- ability to connect (welding, gluing, sewing, etc.) with other elements of the cover, especially zipper connections;
- susceptibility of all cover components to technological and necessary assembly seals;
- susceptibility to ongoing repairs by the user.

The covers used so far have the following features:
- material used for the cover coating:

a) surface weight: from 1981 - PVC Type SP-150 – 0.6 ÷ 0.7 kg/m²; since 1988 - PVC “Plawil” - 0.6 ÷ 1.0 kg/m²,

b) thickness: from 1981 - PVC Type SP-150 - 0.5 mm; since 1988 - PVC “Plawil” - 0.6 ÷ 1.0 mm.
- cover construction – none, use of a vacuum cover by creating an air negative pressure of approximately 0.01 atm (10 hPa).

The cover/tent for storing technical equipment shown in Figure 3 is made of PES+PVC fabric, the surface weight of which is 0.5 kg/m² and the thickness is 0.26 mm. Therefore, it is a lighter fabric than those previously used and previously presented. The supporting, frame structure was made of aluminum profiles and steel connectors, connected with screws. Profiles with a rectangular cross-section, depending on the configuration, had the following dimensions: vertical beams - 80 × 40 × 3 mm, and horizontal beams - 60 × 60 × 3 mm.

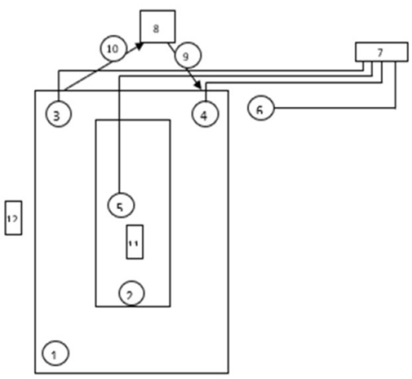
In addition, a device developed at the Institute is used to monitor the artificial environment. Due to the fact that the structure is similar to a tent, it is proposed to use the term “new universal reusable tent for storage” (NUNWUdP) [15].

TEMPERATURE AND HUMIDITY RESISTANCE TESTS

A comprehensive system was developed to monitor outdoor temperature and relative humidity, as well as the corresponding conditions inside the tent. The diagram of developed system is shown in Figure 4.

The test results in the form of temperature distribution and relative humidity, in the period from September 21, 2021 to December 29, 2021, were presented in Figure 5 and 6.

Using described above system, a series of tests were conducted to monitor the parameters both inside and outside the tent. The results confirm that the new universal, reusable tent for storage successfully fulfills the criteria associated with establishing and sustaining an artificial environment inside. This implies that significant technical equipment can be stored without being susceptible to corrosion. This study does not include statistical analyses as the environmental testing was conducted through continuous temperature and



1 - reusable tent shield,
2 – object,
3, 4, 5 i 6 - DHT-22 temperature and humidity sensors,
7 - universal temperature and humidity measurement module W-17/21
8 – dynamic dehumidifier
9 – air inlet
10 – air outlet
11 - environmental monitoring station inside the tent,
12 – environmental monitoring station outside the tent

Figure 4. Temperature and humidity measuring and monitoring system

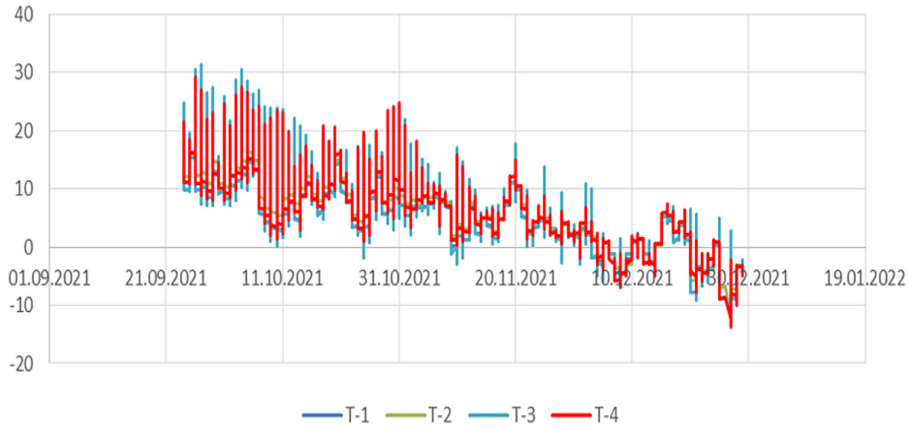


Figure 5. Temperature distribution in the analyzed object. Legend T-1, T-2, T-3 – corresponds to points 3, 4, 5 in Figure 6; T-4 – corresponds to point 6 in Figure 6

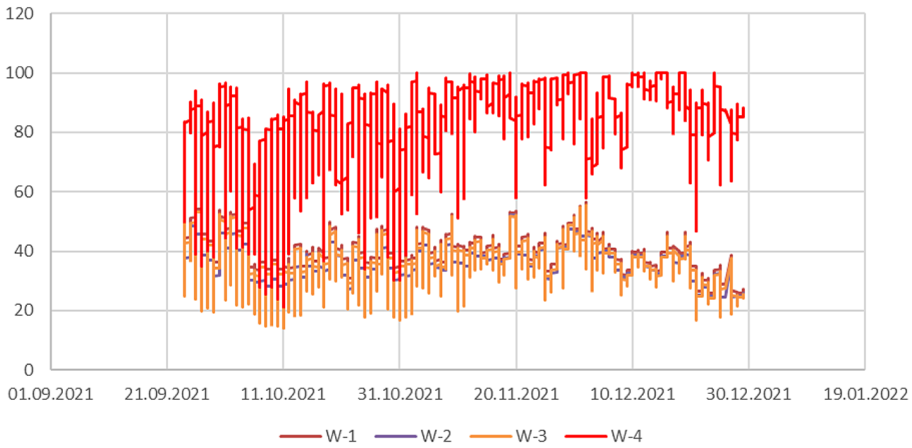


Figure 6. Humidity distribution in the test facility, Legend: W-1, W-2, W-3 – corresponds to points 3, 4, 5 in Figure 6, W-4 – corresponds to point 6 in Figure 6

humidity monitoring from September to December 2021, allowing observation of actual trends and seasonal changes rather than discrete samples requiring statistical analysis. For strength testing, advanced finite element modeling was employed using LS-DYNA software, based on established physical laws and material data from the MatWeb database, providing specific stress and strain values for defined wind load conditions. At the current preliminary design stage of the NUPW II tent, this research approach is more appropriate than statistical methods, which would become relevant only when comparing simulation results with physical tests of multiple prototypes.

TENT STRENGTH ANALYSIS

The tested tent was also subjected to a strength analysis. It consists of a canopy and a frame as shown in Figure 7. The tent frame is made as a spatial beam structure. It consists of profiles with a rectangular cross-section of 80 × 40 × 3 and 60 × 60 × 3 mm, which are used not only to transfer axial forces, but transfer all other forces and moments due to attaching the tent shell to the frame.

Numerical analyses were carried out using the Femap program, a simulation application utilized for creating, editing, and inspecting finite element models of complex products or systems. The moments of inertia were Izz = 2.82112E-7, Iyy = 1.25683E-6 and Izz = 3.71412E-7, Iyy = 3.71412E-7 (respectively). For the analysis, it was assumed that the profiles were made of aluminum alloy EN AW-6060 (PA38), the material properties are listed in Table 1.

The profiles used for the horizontal and vertical beams related to screwed system connections. Some of them are shown in Figure 8 and 9. According to manufacturer datasheet, the tent

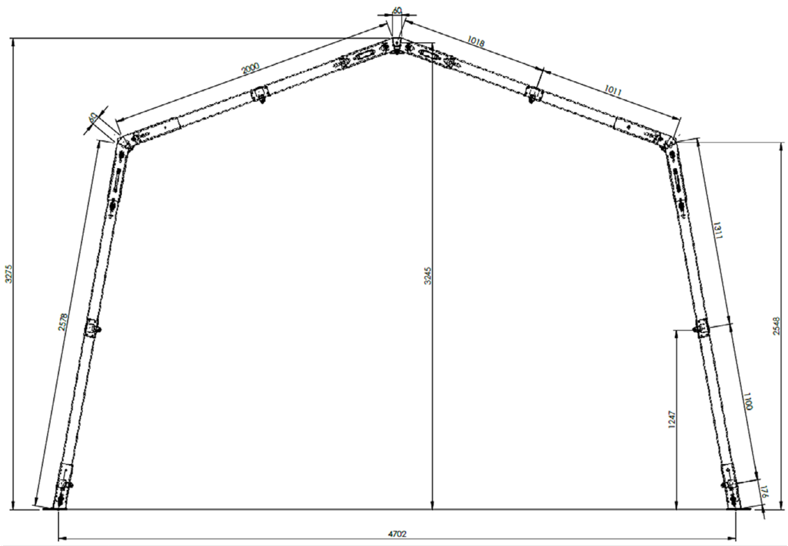


Figure 7. Dimensions of tent NUPWU II

Table 1. Material properties of used profiles

No.	Parameter	Value
1	Elastic modulus, E	69.5 GPa
2	Shear modulus, G	26.1 GPa
3	Poisson's ratio, υ	0.33
4	Tensile strength, R_m	240 MPa
5	Density, ρ	2700 kg/m^3
6	Strain rate factor, C	25 000
7	Strain rate factor,P	0.4

canopy is made of thin (2 mm) polyester (PES) coated with PVC and mass per unit area less than 400 g/m^2. The main functional features of the material used are flame retardancy, non-hygroscopicity, quick drying and resistance to discoloration. Mechanically, it is elastic and resistant to creases and fatigue. The material data of the PES analyzed in this work are based on available MatWeb database [16] and permanent reinforcements SRC

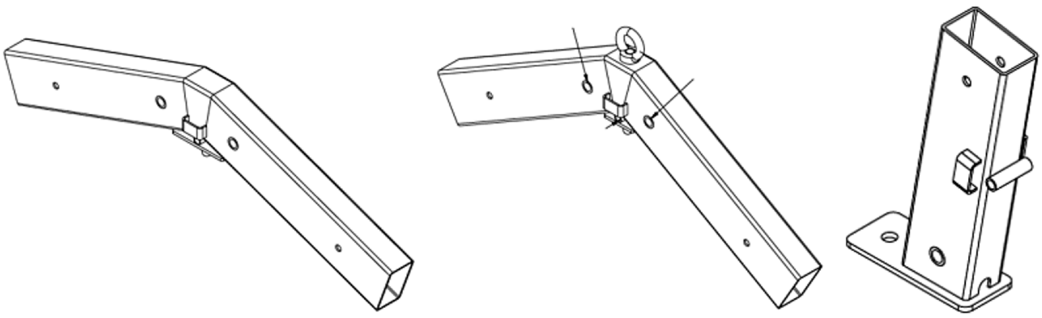


Figure 8. The vertical and horizontal beams connections to the frame

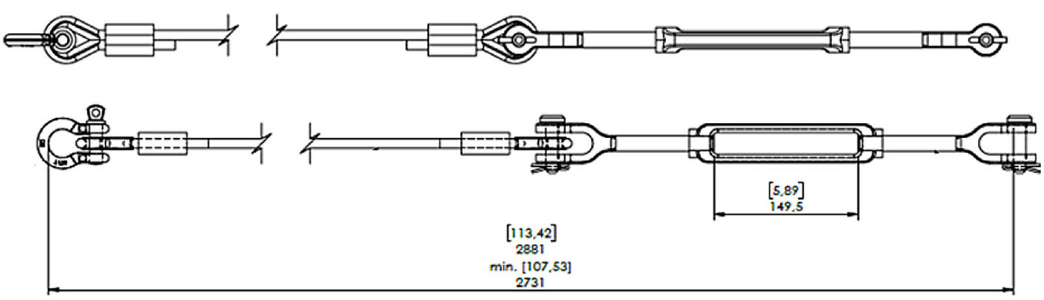


Figure 9. The vertical and horizontal beams connections to the frame

and SRP from literature [17]. Detailed parameters are presented in Table 2.

For illustration, an example of tent structure damages caused by wind gusts (recorded at the Military Institute of Armor and Automotive Technology during the Eunice storm) is shown in Figure 10. It should be underlined that this figure refers to a different object than analyzed in this paper.

The tent's mechanical strength was tested by simulating the load on its structure caused by gusty winds. This aspect, though infrequently discussed in the literature, appears to be highly significant. The impact of the wind was simulated by loading the tent surface with variable pressure (Figure 11). The relationship between wind speed v, and the pressure p and air density ρ in SI units, is expressed by a simple formula known from fluid dynamics (1).

$$p = \frac{1}{2} \times p \times v^2 \quad (1)$$

To adapt the above formula (1) to real conditions, the procedure described in the [18] standard was additionally used. The calculations also take into account other important factors such as: geographical zone PL (1, 2 or 3), terrain category (0, I, II, III or IV), height of the object above ground level and height of the object above sea level. Considering all described factors, the calculated wind pressure was slightly lower than the theoretical one. The calculations were made using available Euro Code calculators for 1. zone, IV category of terrain, 1.5 meters in elevation and a location 100 m above sea level. Related characteristics $p(v)$ are presented in Figure 11.

Table 2. Material properties of the tent canopy fabric

No.	Parameter	Value
1	Elastic modulus, *E*	4.36 GPa
2	Shear modulus, *G*	1.56 GPa
3	Poisson's ratio, *υ*	0.4
4	Tensile strength, R_m	100 MPa
5	Strain rate factor, *C*	2188
6	Strain rate factor, *P*	5.5

The numerical analysis was performed using the finite element method (FEM), using the LS Dyna environment from LSTC [19–20] installed on a multi-processor computing cluster. To model the properties of the canopy and frame profiles, the "PICEWISE_LINEAR_PLASTICITY" material model was used, which considers the linear plasticity of the material and the effect of speed on material properties (reinforcement) as well as the Cowper-Symonds equations of state expressed by the SRC and SRP coefficients.

The tent model was loaded with time-varying pressure (representing wind pressure) and gravitational forces (for g = 9.81 m/s2), acting on all elements with non-zero mass. Since the wind acts in an impulsive manner, it was assumed that the applied pressure follows the shape of the curve (Fig. 12), resembling a sinusoidal shape (without the wind suction effect, $p > 0$). Additionally, it was assumed that the pressure will reach the extreme (100%) pmax at the time points t = 1 s and t = 3 s and will have a value of 200, 300, 400 Pa (depending on the variant), corresponding to

Figure 10. Destruction of NUPWU I (former model) as a result of hurricane Eunice during February 17–18, 2022, with wind speeds reaching 100÷120 km/h

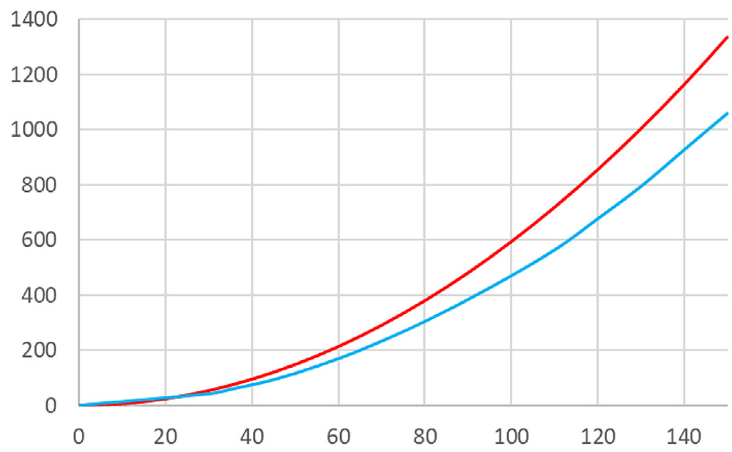


Figure 11. The dependence of wind pressure Pa on wind speed km/h calculated for the relationship (1) red line and for Eurocode-1 (blue line)

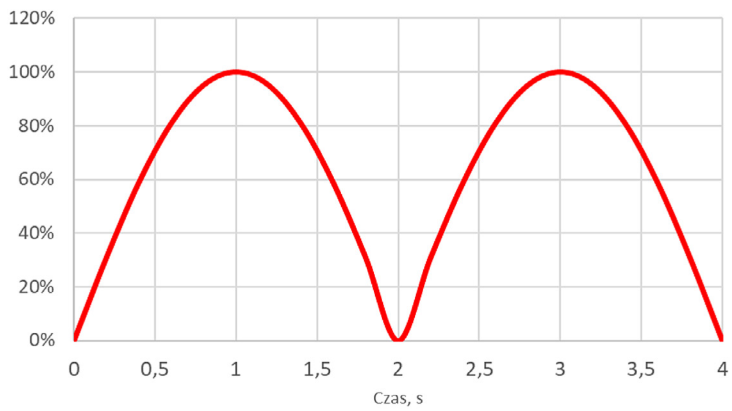


Figure 12. The applied model of the time course of pressure (relative values p/pmax)

a gust of wind with a speed *v* of approximately = 70, 80 and 90 km/h (depending on the variant). It was additionally assumed that the wind blew from the side and from the front and only these parts of the tent were subjected to the wind pressure load. The load model constructed in this way is shown in Figure 10

The tent shell is described with a mesh of flat finite elements of the SHELL element according to description in Figure 13.

In places of expected stress concentrations (narrows, holes, etc.), the density of element arrangement was increased accordingly. 50,000 elements and 50,000 nodes were used to build the

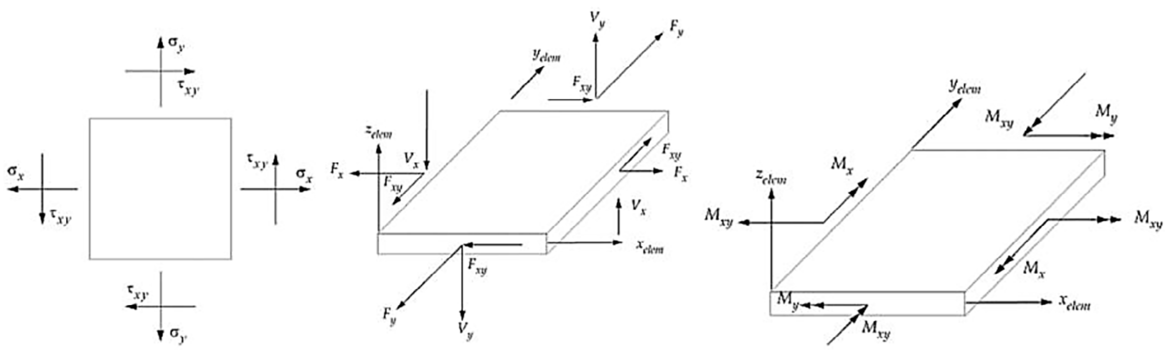


Figure 13. Stress and force vectors in the used shell element (QUAD4)

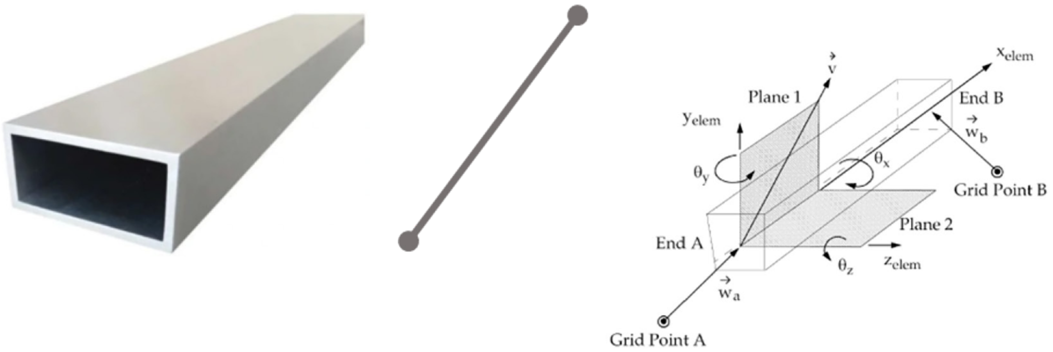


Figure 14. Modelling the frame profile using an element BEAM

mesh describing the tent shells. For the purpose of the analysis, the simulation considered fixing the tent canopy with four large pins, located at its corners. The frame profiles are described with a grid of 1-dimensional beam elements (Fig. 14). It is a bar element, in the simplest case, bent, and in general also stretched, compressed, sheared and twisted freely and not freely, and whose properties can be shaped in accordance with the selected bar theory [21], depending on the adopted position of the cross-section relative to the axis of the bent beam

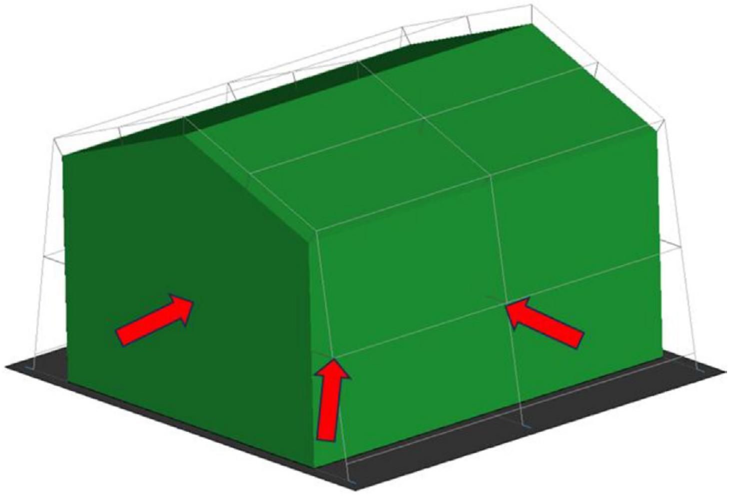


Figure 15. View of the tent model at t = 0 s (arrows indicate the assumed wind direction)

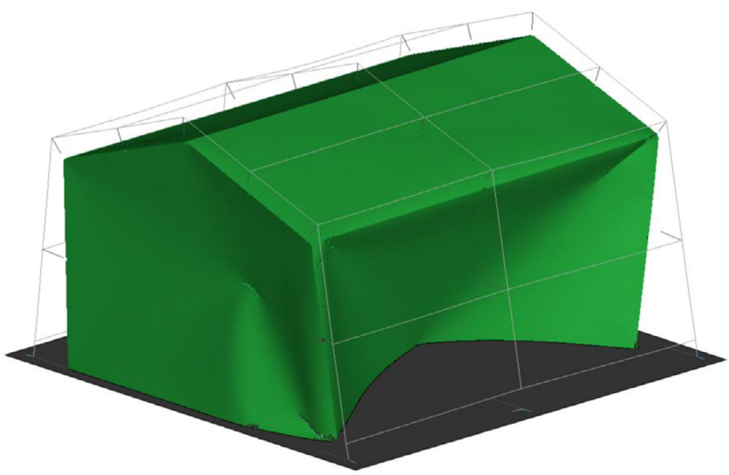


Figure 16. Deformations of the tent structure at t = 0.4 s for v = 90 km/h

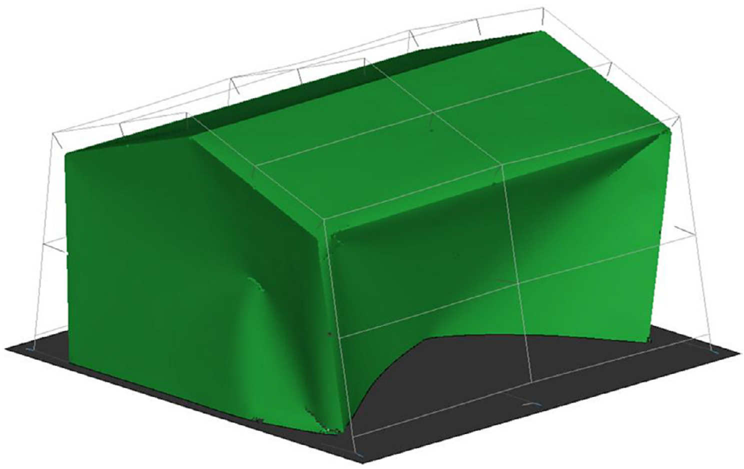


Figure 17. Deformations of the tent structure at t = 0.64 s for v = 90 km/h

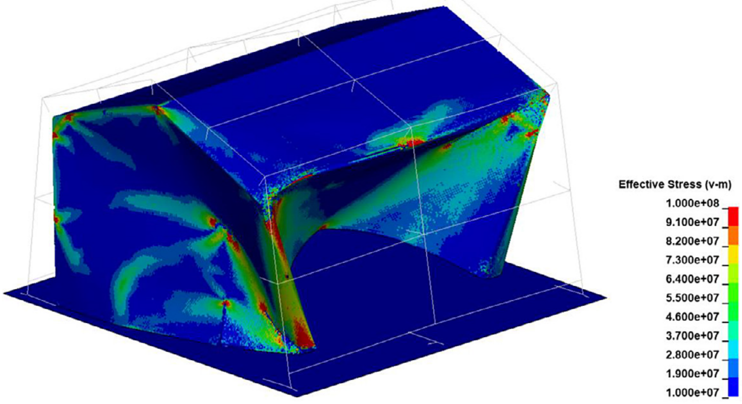


Figure 18. The beginning of the tearing of the tent canopy at t = 0.5 s for v = 90 km/h (red colour indicates extreme reduced stresses and tearing points in Pa)

Numerical calculations performed in the LS-Dyna environment were used as data source for the LS-PREPOST postprocessor [22]. In the deformation and destruction analysis, maps of reduced stresses (calculated according to the Huber-Mises-Hencky HMH energy hypothesis) generated for subsequent time moments were used. Fig. 15–17 shows an example of the increase of the deformation related to higher wind speed.

The analysis of reduced stresses also allowed us to trace the places and course of tearing of the tent canopy (Fig. 18).

CONCLUSIONS

In our research, we have investigated the new version, NUPW II, which represents a completely new tent structure compared to NUPW. This tent structure, currently in the design phase, has not yet undergone destructive testing but shows significant promise for military applications.

The analysis of the technical equipment storage system highlights its simplicity and effectiveness for storing military equipment, which is of paramount importance to the Polish Armed Forces as they continue to modernize their inventory. The developed system—including a tent, a dehumidifier, and an environmental monitoring device—ensures that equipment remains in optimal technical condition. The test results confirm that the tent successfully maintains relative humidity within the desired 40–60% range, which is crucial for preventing corrosion on the surface layer and aging changes in non-metallic materials.

A significant challenge faced by designers is the structural resilience against high wind speeds exceeding 100 km/h, a concern that has grown more relevant with increasing extreme weather events. An example of this vulnerability was demonstrated during the destruction of the supporting structure of a previous model during research at WITPiS in February 2022.

The examined tent structure performs well within wind speeds ranging from 70 to 80 km/h. However, higher speed winds can cause damage to the tent canopy and deformations in specific frame profiles. Finite element analysis using LS-DYNA software revealed that stress concentrations occur primarily at the connections between the frame and canopy, which become critical failure points during high wind events.

At the current preliminary stage of structural design, verification of the numerical model of the tent is not yet possible. Only the study of the real model will allow modification of the simulation assumptions made, such as boundary and initial conditions, material failure models, etc.

Based on analysis, we have identified potential improvements for the tent's durability such as strengthening the tent shell by thickening it or using a material with higher tear resistance. Moreover, reinforcing strap connections between the tent frame and canopy was recognized as crucial to prevent significant displacements of the tent frame and subsequent damage to frame profile connections. These improvements are essential for meeting the highest strength requirements needed by the Polish Armed Forces.

The carried-out strength analysis highlights the significance of performing numerical simulations before launching the production final design. The integration of both humidity/temperature performance and structural wind resistance testing provides a comprehensive assessment methodology for military storage tents that balances environmental protection requirements with structural integrity needs. This research directly contributes to enhancing the operational readiness of the Polish Armed Forces by ensuring their equipment remains in optimal condition despite challenging environmental conditions.

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