Iterative development of flexible textile composites for naval emergency shuttles in oil spill recovery

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ABSTRACT – REZUMAT

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Maritime oil spill accidents should not be regarded as irreversible disasters, as hydrocarbons are recoverable and economically valuable resources that, when efficiently processed, can be reintroduced into the economic value chain. Currently, five principal strategies are employed to mitigate hydrocarbon pollution: natural biodegradation, transfer to storage barges, in situ combustion, dispersion within the water column, and surface concentration followed by recovery. This paper focuses on the fifth strategy – concentration and recovery of hydrocarbons from the water surface – by presenting an iterative development approach for two composite materials intended for use in a naval emergency response unit. This unit is specifically engineered to improve the efficiency of hydrocarbon collection, concentration and recovery during maritime spill incidents, particularly under emergency conditions. The composite materials comprise a textile matrix structure made from 100% polyester yarns, obtained through a weaving process and subsequently coated with polyvinyl chloride (PVC) to enhance mechanical durability and resistance to water and oil. To optimise the structural performance of the composites in marine environments, textile engineering methodologies were applied, including advanced Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) tools.
This research highlights the critical role of the textile structure and the intrinsic properties of polyester fibres, including their tensile strength, flexibility, and chemical resistance to oil, saltwater, and ultraviolet (UV) degradation. An iterative design methodology supported by virtual prototyping was employed to evaluate how textile construction techniques – such as weaving and coating – affect the deployment of the composite material's overall mechanical performance and suitability for deployment in emergency oil spill response operations.

Keywords: *marine pollution, oil spill recovery, functional textiles, composite materials, naval emergency unit, computer-aided design (CAD), computer-aided engineering (CAE)*

Dezvoltarea compozitelor textile flexibile pentru unități navale de intervenție destinate recuperării hidrocarburilor din poluări marine

Accidentele maritime de poluare cu hidrocarburi nu trebuie considerate dezastre ireversibile, întrucât acestea reprezintă resurse recuperabile și valoroase din punct de vedere economic care, printr-o procesare adecvată, pot fi reintegrate în lanțul valoric. În prezent, cinci strategii majore sunt utilizate pentru atenuarea poluării cu hidrocarburi: biodegradarea naturală; transferul către barje de stocare; arderea in situ; dispersia în coloana de apă; precum și concentrarea la suprafață urmată de recuperare.
Prezenta lucrare se concentrează asupra celei de-a cincea strategii – concentrarea și recuperarea hidrocarburilor de la suprafața apei – prin propunerea unei metodologii iterative de dezvoltare pentru două materiale compozite destinate utilizării într-o unitate navală de intervenție de urgență. Această unitate este proiectată în mod special pentru a crește eficiența proceselor de colectare, concentrare și recuperare a hidrocarburilor în cadrul incidentelor de poluare marină, în particular în condiții critice de urgență. Materialele compozite investigate sunt constituite dintr-o matrice textilă obținută prin țeserea firelor de poliester 100%, ulterior acoperită cu policlorură de vinil (PVC), pentru a conferi rezistență mecanică crescută, impermeabilitate și protecție împotriva hidrocarburilor. Optimizarea performanțelor structurale ale acestor compozite în medii marine a fost realizată prin aplicarea metodologiilor de inginerie textilă, cu utilizarea instrumentelor avansate de proiectare asistată de calculator (CAD) și de inginerie asistată de calculator (CAE).
Lucrarea evidențiază rolul critic al structurii textile și a proprietăților intrinseci ale fibrelor de poliester – rezistența la tracțiune, flexibilitatea și rezistența chimică la hidrocarburi, apă sărată și radiații ultraviolete (UV). O metodologie de proiectare iterativă, susținută de prototipare virtuală, a fost implementată pentru a evalua modul în care tehnicile de obținere și finisare ale structurilor textile – precum țeserea și acoperirea – influențează performanța mecanică globală a materialelor compozite și compatibilitatea utilizării lor în operațiuni navale de intervenție de urgență în cazul poluărilor marine cu hidrocarburi.

Cuvinte-cheie: *poluare marină, recuperarea hidrocarburilor, textile funcționale, materiale compozite, unități navale de intervenție de urgență, proiectare asistată de calculator (CAD), inginerie asistată de calculator (CAE)*

INTRODUCTION

Oil spills have long-lasting and dramatic impacts on marine ecosystems, threatening biodiversity and harming marine life. Such incidents may arise from a variety of sources, including tanker accidents, offshore drilling platforms and routine maritime operations. Although the precise quantification of global oil inputs into marine environments remains challenging, studies estimate that approximately 35% of marine pollution originates from tanker traffic, while an additional 45% is attributed to industrial discharges and offshore extraction activities. Crude oil and petroleum products contain volatile organic compounds (VOCs) that readily evaporate, contributing to atmospheric pollution and exacerbating the overall environmental burden [1–3]. Several physical factors affect the behaviour of oil spills once they reach the water surface. These include surface tension, which influences the spread of oil, specific gravity (which changes as lighter components evaporate), and viscosity (which determines the oil's tendency to remain in place) [4–6].

Two principal strategies are employed in the development of materials and systems for effective oil spill response: oil concentration and recovery [7]. *Concentration* is commonly facilitated by the use of floating barriers, such as booms, which serve to confine and limit the dispersion of oil on the water surface. Recovery operations, on the other hand, involve various types of equipment, including booms, skimmers, and sorbents, that are designed to extract and collect the contained oil [8, 9]. The design of these recovery systems typically integrates critical components such as a freeboard to prevent oil from splashing over, flotation elements to ensure buoyancy, and support structures to maintain stability during operation. Once captured, the oil is pumped into storage tanks for subsequent transport and disposal [10–14].

Various types of composite textile structures are employed in the fabrication of flexible oil containment tanks designed for emergency response in maritime disaster scenarios. These materials are selected based on their ability to withstand harsh environmental conditions and to perform accordingly. Common configurations include: (a) polyester (PES) fabrics coated with polyvinyl chloride (PVC) or thermoplastic polyurethane (TPU); (b) polyester or polyamide fabrics vulcanised with rubber and coated with an external layer of Hypalon® to enhance resistance to abrasion and puncture; and (c) polyester fabrics coated with ethylene-vinyl acetate (EVA). Each material combination is tailored to ensure mechanical robustness, chemical resistance, and operational reliability under demanding field conditions [15–17].

The primary advantage of these composite structures lies in their enhanced resistance to a range of aggressive environmental and chemical stressors, including exposure to petroleum products, extreme temperatures, ultraviolet (UV) radiation, high-salinity seawater, industrial detergents, and, where applicable, various chemical agents.

This study investigates technologies for oil spill concentration and recovery through the conceptual design of a naval emergency shuttle, an innovative, floating, collapsible unit intended for rapid deployment in the immediate aftermath of a spill. The proposed shuttle is required to be lightweight, compact, and portable, with the ability to function effectively in strong sea currents while facilitating efficient oil collection and temporary storage. The design process critically considers the physicochemical properties of petroleum hydrocarbons, such as volatility and solubility, which influence material selection and structural integrity [18–22]. To meet these performance criteria, an iterative development approach was employed to engineer a flexible composite material based on a textile matrix. The research emphasises the optimisation of key material properties, namely flexibility, mechanical durability, and resistance to the harsh marine environment, for application in naval emergency shuttles [23–26]. Leveraging advanced digital design tools, this work aims to enhance the operational performance and overall effectiveness of oil spill response and recovery systems.

MATERIALS AND METHODS

In the design and development of a flexible composite material with a textile matrix for the proposed naval emergency transport unit, several key functional characteristics were taken into account to ensure its effectiveness in oil spill response scenarios. The naval emergency shuttle was required to:

- operate efficiently under moderate sea state conditions, corresponding to a minimum of Force 4 on the Beaufort scale (wind speeds of 11–16 knots and wave heights of approximately 1.0–1.5 m), during oil spill recovery operations;
- support transport and storage, with a minimum speed of 2 knots for the vessel-shuttle assembly;
- enable rapid deployment within a maximum response time of one hour, in conjunction with conventional oil spill recovery equipment such as vessels, booms, and skimmers;
- possess a hydrodynamic configuration that ensures stability and secure storage of recovered oil;
- incorporate additional design features to facilitate oil clean-up and phase separation;
- lightweight, compact, and highly portable to allow for ease of transport and deployment in emergencies.

Designing the naval emergency shuttle

Based on the defined operational requirements, a specialised structure for the naval emergency shuttle was developed. The design consists of the following primary components: 1 – central unit: a right circular cylinder structure forming the above-water freeboard, intended to concentrate the spilled oil and prevent wave-induced splashing; 2 – fine prow: a truncated conical element positioned at the front, equipped with

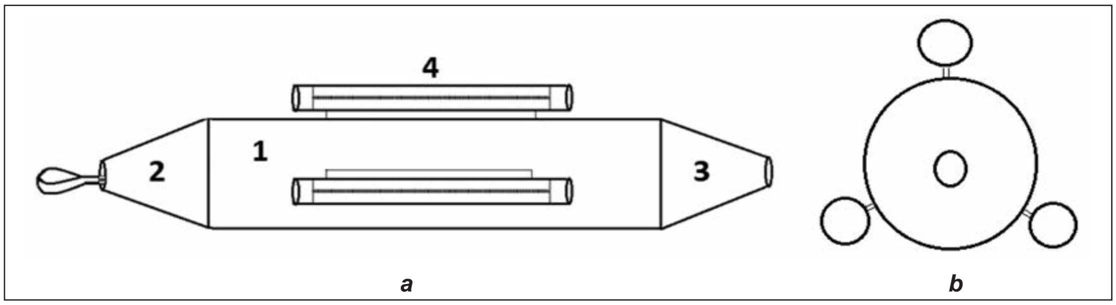

Fig. 1. Naval emergency shuttle design: *a* – frontal view; *b* – lateral view

Table 1

COMPONENT CHARACTERISTICS AND SUBASSEMBLIES				
Subassembly	**Shape**	**Dimensions (mm)**		
		Height/Length	Bottom diameter	Top diameter
Central unit	right circular cylinder	1800	600	
Fine prow/Stern	truncated cone	400	600	200
Floating structures	right circular cylinder	1200	150	

an anchoring eyelet; 3 – stern: a similarly shaped truncated cone, positioned at the rear for hydrodynamic balance and directional stability; 4 – floating structures: three right circular cylinders, aligned longitudinal along the central unit to provide buoyancy and support. These elements are illustrated in figure 1, which presents both the frontal and lateral views of the shuttle configuration.

The manufacturing process of the naval emergency shuttle involves the precise assembly of these components using a reinforced stitching technique, which ensures structural integrity while preserving the defined geometry and functional dimensions outlined in table 1.

Incremental development of the flexible composite materials with a textile matrix

To meet the specific requirements of the naval emergency shuttle – intended for the collection, concentration, and recovery of hydrocarbons from the water surface – two tailored composite materials based on PVC-coated polyester fabric were developed:

- CM1 (composite material 1): used for the central unit and the floating support;
- CM2 (composite material 2): used for the fine prow and stern.

The incremental development and optimisation of these composite structures were achieved using specialised CAD–CAE (Computer-Aided Design and Engineering) software tools. This digital approach enables detailed structural analysis and material adaptation according to the operational stress loads and marine environment constraints.

To generate the 3D models required for the structural analysis, the following steps must be completed:

a) 3D simulations and modelling

The Generative Structural Analysis module was used to define the model and to visualise the components of the shuttle, before the numerical simulation. Each subassembly was independently modelled in 3D, as illustrated in figure 2.

b) Geometry discretisation

The 3D models were discretised into finite elements using linear tetrahedral elements (four nodes, one Gauss point, three degrees of freedom per node). A meshing tolerance of 0.01 mm was applied to ensure high fidelity of the model geometry before simulation, as shown in figure 3.

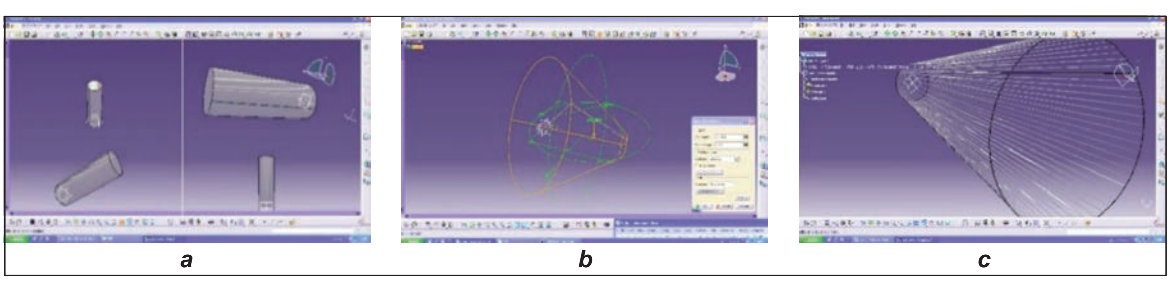

Fig. 2. 3D simulation of the naval emergency shuttle design:
a – central unit, *b* – thin prow and stern; *c* – floating structures

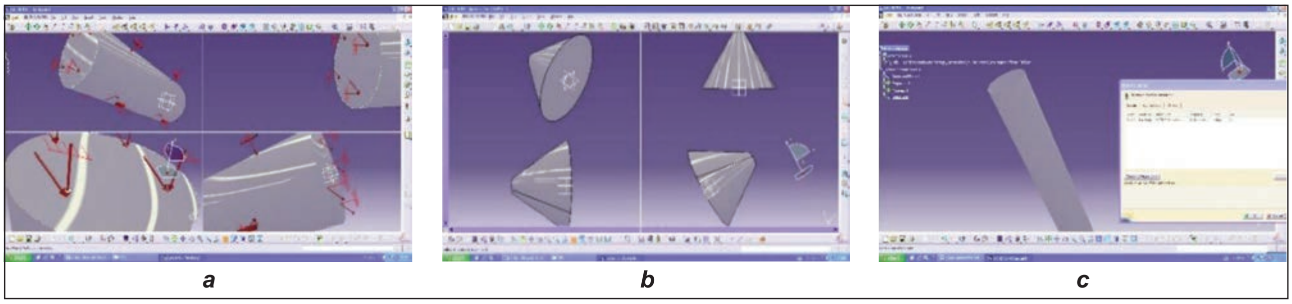

Fig. 3. Geometry discretisation: *a* – central unit, *b* – thin prow and stern; *c* – floating structures

RESULTS AND DISCUSSIONS

Structural models analysis

The structural behaviour of the naval emergency shuttle components was evaluated using finite element simulations conducted within the Generative Structural Analysis environment. The models were solved using the integrated solver, and deformation results were analysed through section-plane visualisation (Cut Plane Analysis). The internal deformation of the composite material subassemblies ranges from 0.0 to 10.5 mm, confirming that the structural integrity of the system is maintained under operational conditions corresponding to sea states of up to Beaufort 6 (figure 4).

In particular, the central unit showed a maximum displacement of 25.3 mm under simulated load. Despite this higher deformation, the structure remains within safe operational limits, without risk of collapse, validating its suitability for open-sea intervention scenarios.

Von Mises stress analysis

The results of the von Mises stress analysis for each subassembly are summarised below:

- Central unit: Stress value ranged from 0 to 2.13×10^8 N/m^2, remaining well below the value of the admissible stress limit of CM2 (3.45×10^{10} N/m^2);
- Fine prow and stern:
  Fine prow: 6.96×10^7 to 5.38×10^9 N/m^2;
  Stern: 6.41×10^5 to 4.96×10^7 N/m^2;
  Both remain below the admissible limit of CM1 (9.45×10^9 N/m^2).
- Floating structures: Stress values ranged from 0 to 1.27×10^7 N/m^2, also below CM1's resistance threshold, ensuring structural stability under operational marine conditions (figure 5).

Principle stress (main stress tensor)

The analysis of principal stress values further confirmed the material's structural adequacy:

- Central unit: range of -5.21×10^8 to 4.92×10^8 N/m^2 (below CM2's threshold);
- Fine prow and stern:
  Fine prow: -7.68×10^9 to 5.51×10^9 N/m^2;

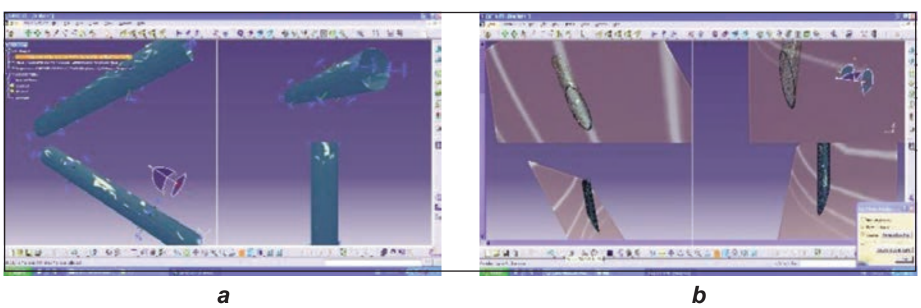

Fig. 4. Structural simulation- Deformation of floating structures:
a – multi-view visualisation; *b* – sectional view (Cut Plane Analysis)

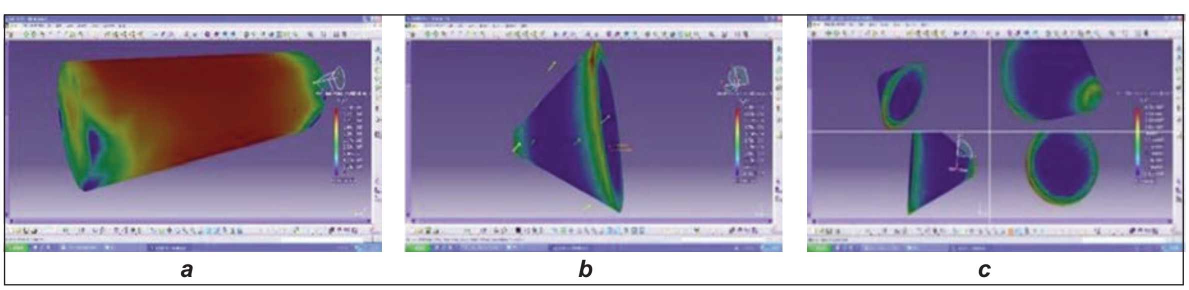

Fig. 5. Von Mises stress distribution during operational displacement: *a* – central unit; *b* – fine prow; *c* – stern

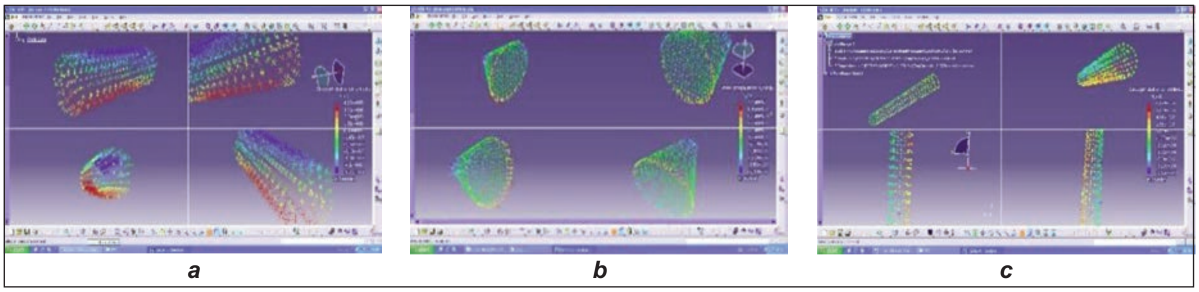

Fig. 6. Principal stress (main stress tensor) distributions: *a* – central unit; *b* – stern; *c* – floating structures

Stern: –0.25 × 10^7 to 7.75 × 10^7 N/m^2;
Both remain under the value of the admissible resistance of CM1.

- Floating structures: range of –1.13 × 10^7 to 8.62 × 10^6 N/m^2, within CM1's admissible limits (figure 6).

The results validate the structural resilience of the composite materials under simulated marine stresses, confirming the suitability of both CM1 and CM2 for use in the naval emergency shuttle.

Material testing and experimental validation

The developed composite materials were also subjected to physical-mechanical testing to characterise their performance. The test results are presented in table 2, and a demonstration model was tested in real operation conditions (figure 7), in order to validate the Iterative development of the flexible composite materials with textile matrix.

Finally, a demonstration model of the shuttle was tested under realistic conditions to validate the integrated system's design and material performance (figure 7).

Fig. 7. Demonstration model of the naval emergency shuttle

CONCLUSIONS

The conducted research demonstrates that the design and development of a rapid intervention naval unit for oil spill recovery necessitate the use of high-performance flexible composite materials capable of withstanding dynamic mechanical loads and harsh open-sea conditions.

The incremental development of the two composite material variants was supported by advanced Computer-Aided Design and Engineering *(CAD-CAE) tools*. Structural modelling and analysis were carried out using the Generative Structural Analysis module, with internal deformations assessed using Cut Plane Analysis. These enabled the precise simulation of operational stress conditions.

The simulation results showed that the deformations ranged from 0.0 to 10.5 mm for most subassemblies, confirming the structural integrity of the shuttle even under sea states up to Beaufort 6. For the central unit, the maximum deformation recovered was 25.3 mm – still within safe operational limits, ensuring no risk of structural collapse under severe agitation.

In conclusion, the composite materials developed through this research meet the functional, mechanical, and environmental requirements for a rapid-deployment naval shuttle intended for oil spill concentration and recovery. Their performance has been validated through both numerical simulations and field testing, confirming their suitability for high-risk marine intervention scenarios.

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Table 2

PHYSICAL-MECHANICAL CHARACTERISTICS OF THE COMPOSITE MATERIALS

Characteristics	CM1 (floating structures and central unit)	CM2 (fine prow and stern)
Fibre composition (%)	PVC-coated 100% PES	PVC-coated 100% PES
Mass (g/m^2)	850	1800
Breaking strength (N, warp/weft)	2100/2100	4400/3300
Elongation at break (%, warp/weft)	28/30	16/24
Tear resistance (trouser) (N)	230/132	450/300
Tear resistance (wing) (N)	140/105	350/250

REFERENCES

[1] European Parliament and Council, *Directive 2000/60/EC on establishing a framework for community action in the field of water policy*

[2] IOGP, *Environmental fates and effects of ocean discharge of drill cuttings and associated drilling fluids from offshore oil and gas operations. Report 543*, 2016

[3] Directive 2004/35/EC of the European Parliament and of the Council of 21 April 2004 on environmental liability about the prevention and remedying of environmental damage (Environmental Liability Directive)

[4] World Ocean Review, *WOR 5 – Coasts. A Vital Habitat Under Pressure 2019, Cap 1 – Coastal Dynamics*, 2019, 93–102

[5] European Commission, *Draft BREF for the Management of Waste from the Extractive Industries (MWEI BREF)*, 2016

[6] World Health Organization, *Chemical releases caused by natural hazard events and disasters*, Geneva, 2018, 16–28

[7] International Maritime Organization (IMO), *Code for the construction and equipment of mobile offshore drilling units (MODU Code)*, 2010

[8] BS / ISO, *BS EN ISO 15156-1:2015. Petroleum and natural gas industries. Materials for use in H2S-containing environments in oil and gas production. General principles for selection of cracking-resistant materials,* 2015

[9] European Commission, *Best Available Techniques Guidance Document on up stream hydrocarbon exploration and production*, 25 February 2019, 124–193

[10] United Nations Office for Disaster Risk Reduction, *Sendai Framework for Disaster Risk Reduction 2015–2030*, Geneva, 2015

[11] United Nations Environment Programme/Office for the Coordination of Humanitarian Affairs, *The cyanide spill at Baia Mare, Romania: before, during and after*, Geneva, 2002

[12] McIlhagger, R., Quinn, J.P., McIlhagger, A.T., Wilson, S., Simpson, D., Wenger, W., *The influence of binder tow density on the mechanical properties of spatially reinforced composites. Part 2 – Mechanical properties*, In: Composites: Part A, 2008, 39, 334–341

[13] Ratna, D., Chongdar, T.K., Chacraborty, B.C., *Mechanical Characterisation of New Glass Fiber Reinforced Epoxy Composite*, In: Polymer Composite, 2004, 25, 165–171

[14] Kim, H.S., Pourdeyhimi, B., Abhiraman, A., Desai, P., *Characterization of Structural Changes in Nonwoven Fabrics During Load-Deformation Experiments*, In: JTATM, 2000, 1, 1, 1–6

[15] Markleen, *Oil-Spill-Response/ Storage Tanks*, 2024, Available at: https://markleen.com/ [Accessed in August 2024]

[16] Nautic Expo, *Hydrocarbon tanks_Desmi*, 2024, Available at: https://www.nauticexpo.com/ [Accessed in August 2024]

[17] Pongsathit, S., Chen, S.-Y., Rwe, S.-P., Pattamaprom, C., *Eco-friendly high-performance coating for polyester fabric*, In: Applied Polymer Science, 2019, 48002, 1–8, https://doi.org/10.1002/app.48002

[18] Hallal, A., Younes, R., Fardoun, F., Nehme, S., *Improved analytical model to predict the effective elastic properties of 2.5D interlock woven fabrics composite*, In: Composite Structures, 2012, 94, 3009–3028

[19] Scardino, F., *An Introduction to Textile Structures and Their Behavior*, Textile Structural Composites, Composite Materials series Vol. 3, eds. Chou T.W. and Ko F.K, Elsevier, 1989

[20] Gibson, L.B., Cumiskey, S., Macosko, C.W., *Compaction of Fiber Reinforcements*, In: Polymer Composites, 2002, 23, 307–318

[21] Gu, H., *Tensile behaviours of woven fabrics and laminates*, In: Materials and Design, 2007, 704–707

[22] Wan, Y.Z., Wang, Y.L., Dong, X.H., Cheng, G.X., *Comparison of Mechanical Performance and Fracture Behavior of Gelatin Composites Reinforced With Carbon Fibers of Different Fiber Architectures*, In: Polymer Composites, 2001, 22, 111–117

[23] Ali, A., Ali, B., Mehmet, K., Seçgin, K., *Evaluation of the mechanical properties of chopped carbon fibre reinforced polypropylene, polyethylene, polyamide 6, and polyamide 12 composites*, In: Industria Textila, 2023, 71, 2, 175–183, https://doi.org/10.35530/IT.074.02.202214

[24] Karahan, M., Ari, A., Karahan, N., *Clusters analysis in technical textiles and composite materials sector: a regional case study,* In: Industria textila, 2024, 75, 6, 729–741, https://doi.org/10.35530/IT.075.06.202424

[25] Ruan, F., Wang, H., Xia, C., Yang, Q., Zou, L., Xu, Z., *Flexural and impact performance of Kevlar/basalt fabric interlayer hybrid curved composites*, In: Industria Textila, 2024, 75, 1, 49–56, https://doi.org/10.35530/IT.075.01.202313

[26] Toma, D., Popescu, G., Popescu, A., Olaru, S., Salistean, A., Badea, I., *Protective clothing system for interventions in emergency situations*, In: Industria Textila, 2023, 74, 1, 121–129, http://doi.org/10.35530/IT.074.01.1839

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