

HEALTH HAZARDS OF ENGINEERING COMPOSITE MATERIALS USED IN MARINE TRANSPORTATION: EXPOSURE PATHWAYS, TOXICOLOGICAL RISKS, AND MITIGATION STRATEGIES

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ABSTRACT

Fiber-reinforced polymer (FRP) composites—primarily GFRP and CFRP—deliver corrosion resistance and weight savings in ships and marine systems, yet their lifecycle health hazards across manufacturing, operation, maintenance, fire events, and end-of-life are underexamined. This paper synthesizes occupational and public-health risks associated with resins (epoxy, vinylester/polyester), hardeners (amines), styrene monomer, fibrous dust (glass and carbon fibers), and smoke/toxic gases from composite fires, alongside microplastics released from coatings and FRP degradation. Drawing on experimental evidence of seawater aging in CFRP/GFRP single-lap joints (moisture uptake, mechanical changes), it is exposed pathways (inhalation, dermal, ingestion), health outcomes (neurotoxicity, dermatitis/sensitization, respiratory irritation, potential carcinogenicity for certain vitreous fibers), and practical controls (engineering, administrative, PPE) aligned with IMO/SOLAS fire-safety equivalence principles. It is proposed a risk-mitigation checklist for shipyards and operators and outline research gaps in dermal uptake biomarkers for epoxy systems and quantitative microplastic health risk from marine sources.

KEYWORDS: Composite Materials, Epoxy Resins, Health Hazards, Marine Transportation, Occupational Safety.

1. INTRODUCTION

Marine transportation has widely adopted FRP composites to reduce topside weight, limit corrosion, and enable novel structures—from hull shells and superstructures to gratings, ducts, and piping. This trend is well documented in recent marine composites reviews and applications across ships, offshore, and renewable marine energy.

While performance benefits are clear, health hazards emerge along the lifecycle: styrene exposure in polyester/vinylester open-mold processes,^[3,4]

dermal/respiratory sensitization to epoxy systems and amine hardeners;^[7,8] fibrous dust during machining/repair;^[10,11] smoke toxicity (HCN/CO and irritant gases) in fire events;^[18,19] and microplastics and additive leachates from marine coatings and FRP weathering.^[20,21]

Seawater exposure also alters composite interfaces (moisture uptake, matrix plasticization), affecting maintenance hazards and the propensity for debris generation.^[1–2] GFRP composite manufacturing process is explained in Fig. 1.^[25]

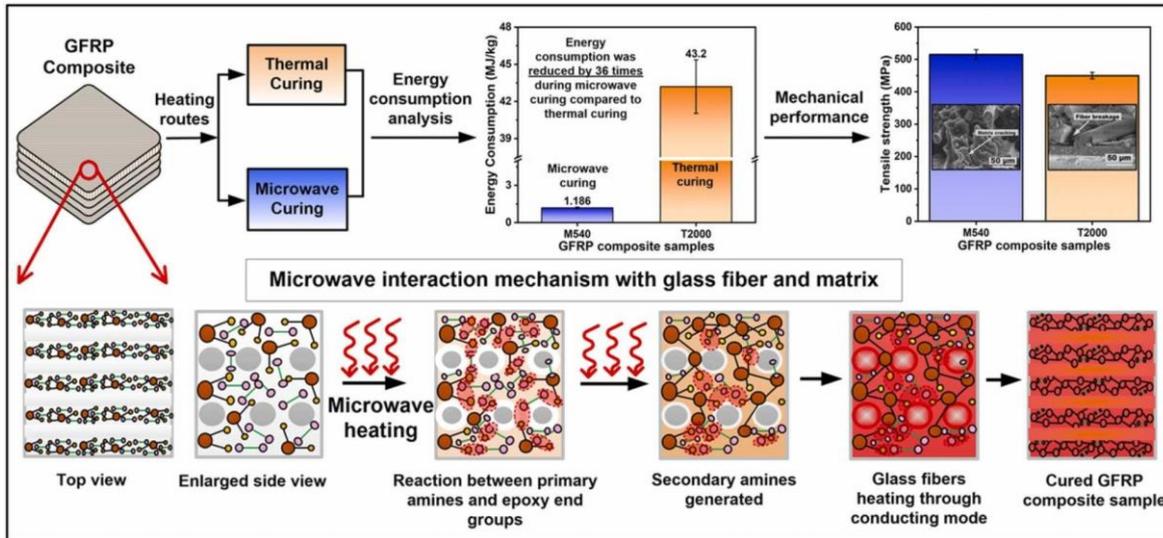


Figure 1. Composite manufacturing process of GFRP.^[25]

2. Exposure Pathways in the Marine Composite Lifecycle

Inhalation of styrene vapors (polyester/vinylester),^[3-5] aerosols, and solvent mixtures; dermal contact with resins and hardeners; potential ototoxic interactions with concurrent noise exposures.

Dermal/respiratory exposure to epoxy systems during bonding,^[7] coating repair, and adhesive joints; machining and sanding release respirable fibrous dust (glass or carbon) and matrix particulates; in-water cleaning of hulls releases microplastic particles.^[10] Exposure pathways in the marine composite lifecycle is represented in Fig. 2.

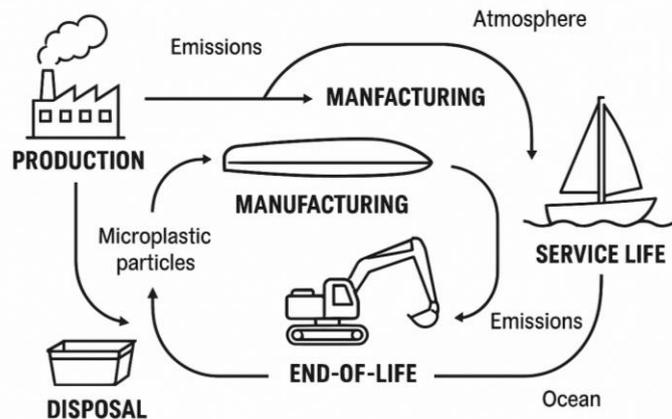


Figure 2: Exposure Pathways in the Marine Composite Lifecycle.

Composite fires yield dense smoke with CO/HCN^[18] and irritants; post-fire handling of charred FRP can release fiber fragments.^[16]

Thermal/mechanical processing can produce fine particulates and off-gassing; challenges of recyclability are being actively discussed in IMO FRP guidelines workstreams.

3. Material-Specific Hazards

3.1 Styrene (polyester/vinylester systems)

Short-term neuro-irritative symptoms (headache, fatigue, dizziness)^[3,6] and mucosal irritation; longer-term concerns include effects on peripheral nerves and hearing;^[7,9] regulation varies (OSHA PEL 100 ppm; modern OELs trending lower).

Historical and modern surveys in FRP boat plants show frequent exceedances of recommended limits in open-mold operations; closed-mold and non-atomizing equipment reduce exposures.^[18]

Integrated monitoring among FRP workers confirms exposure-response relationships using urinary mandelic/phenylglyoxylic acids biomarkers, with suggested operational thresholds.^[20,22] As illustrated in Fig. 3(a), fiber reinforcements are employed in the form of unidirectional (UD) prepreps, resulting in composites with anisotropic characteristics. These materials exhibit maximum strength and stiffness along the fiber direction, while their properties are significantly reduced in the transverse direction. In contrast, bidirectional (woven) prepreps, shown in Fig. 3(b), provide enhanced strength

and stiffness in both principal directions. For multidirectional fiber reinforcements, superior mechanical performance is achieved by stacking multiple

prepreg layers with varying fiber orientations, thereby creating a laminate with optimized properties.

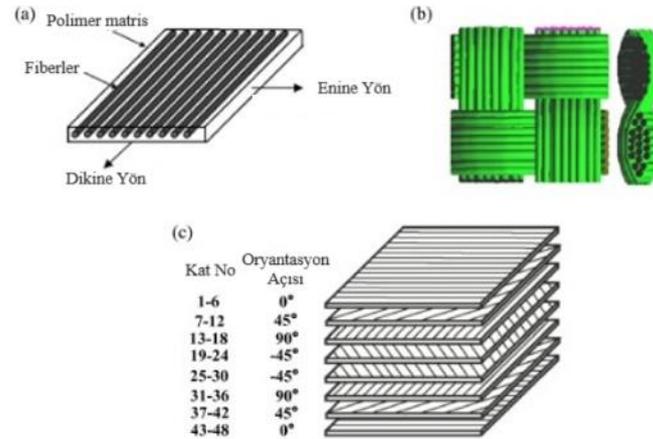


Figure 3: The most common application scheme for FRP composite structures: (a) unidirectional laminate (b) bidirectional laminate (woven layer) and (c) multidirectional laminate, semi-isotropic orientation sequence [0°/45°/90°/-45°]

3.2 Epoxy resins and amine hardeners (adhesives & coatings)

Epoxy systems are leading causes of occupational contact dermatitis; DGEBA resins, reactive diluents, and amine hardeners are strong sensitizers; airborne allergic contact dermatitis can occur.

Unreacted amines can remain in cured resins (particularly cold-cured systems), sustaining sensitization risk over time. Standard latex gloves may be inadequate—multilayer laminate or thick nitrile recommended; patch-testing with workplace samples is advised in clinical evaluation.

3.3 Fibrous dust (glass & carbon fibers)

Synthetic vitreous fibers (SVFs) can cause upper respiratory irritation; carcinogenicity varies by type—continuous filaments and most glass/rock/slag wools are Group 3 (not classifiable), while certain inhalable glass wool fibers and refractory ceramic fibers raise cancer concerns.

Machining CFRP can release WHO-respirable fibers under certain conditions (particularly pitch-based CF splitting), demanding local exhaust and containment; health guidance parallels mechanical irritation plus respiratory precaution.

University OHS guidance emphasizes PPE, ventilation, and dust control; NASA hazard documents outline controls for manufacturing, machining, and catastrophic failures of carbon structures.^[10-15]

3.4 Smoke and toxic gases in composite fires

Epoxy matrices are combustible; fires produce CO and HCN (“toxic twins”) and irritant gases that impair escape

and cause acute and cumulative health effects during overhaul.

Case reports from aerospace composite fires illustrate severe symptoms (eye/skin irritation, dyspnea) even post-extinction.

Recent materials research focuses on flame-retardant strategies and smoke suppression for CFRP, but marine adoption must address SOLAS non-combustibility constraints via alternative design equivalence.^[17-20]

3.5 Microplastics and additive leachates

Weathering and abrasion of marine coatings (polyurethanes, epoxies) and in-water hull cleaning release microplastics, with shipping potentially contributing thousands of tons annually; IMO flagged hull scrapings/coatings as microplastic sources.

Health considerations: MPs can carry PFAS, POPs, metals and exhibit bioavailability across trophic levels, raising ingestion/inhalation concerns; additive leaching (plasticizers, flame retardants) depends on partition and diffusivity parameters and weathering state.^[18-21]

4. Seawater Aging and Its Health-Relevant Implications

Experimental studies on single-lap bonded GFRP/CFRP joints indicate higher water uptake and greater modulus reduction in GFRP than CFRP over 1–3 months in seawater (23.5 °C, 3.3–3.7% salinity). Matrix plasticization and interfacial degradation alter fracture behavior and damage morphology (SEM), with implications for maintenance safety (fragile edges, fiber protrusions, dust upon repair). These findings align with Fickian/non-Fickian moisture diffusion behavior and underscore inspection and control of machining debris

after marine exposure.^[1-2] The dual-cartridge manual application gun and Loctite Hysol-9466 are shown in Fig. 4.



Figure 4: Bonding of composites with a dual-cartridge manual application gun and Loctite Hysol-9466.

5. Occupational Health Risk Mitigation: A Practical Framework

5.1 Engineering Controls

It is used non-atomizing spray, closed-mold processes, and local exhaust ventilation (LEV) with hood design optimized for gelcoat/lamination stations; verify capture velocities and airflow.^[4]

On-tool extraction for CFRP/GFRP machining; HEPA filtration; enclosure/negative pressure zones for cutting pitch-based CFRP prone to axial splitting is used.^[10]

It is applied IMO MSC.1/Circ.1574 alternative design methodologies when FRP elements are used; integrate fire modeling, smoke toxicity assessment^[6], and containment strategies.^[16,17,21]

5.2 Administrative Measures

Air styrene with full-shift sampling; biomonitoring via urinary MA/PGA; dermal tracer studies where feasible; maintain noise controls given styrene ototoxicity.^[16,17]

Most of the employers preferred mechanized IWC with debris capture; prohibit uncontrolled scraping that releases microplastics; manage wastes per port and environmental regulations.^[17]

It is maintained SCBA use until multi-gas monitors confirm CO/HCN clearance; implement overhaul protocols based on combined thresholds.^[16]

5.3 Personal Protective Equipment (PPE)

Multilayer laminate or thick reusable nitrile gloves; forearm protection; chemical-resistant clothing; eye/face protection; dedicated changing/wash stations.^[9]

Fit-tested were done by P3/N100 respirators (or powered air purifying respirators), sealed goggles, and protective garments with elastic cuffs to prevent fiber ingress.^[7,12]

6. Public-Health & Environmental Interfaces

Ports and coastal communities may experience low-level airborne dust or microplastic releases during repair and cleaning; biofouling cleaning policies and waste capture technologies can reduce loads; standardized analytical protocols for MPs in water/air are urgently needed to refine human exposure estimates.^[20,21]

7. Research Gaps

Dermal uptake kinetics and biomarkers for epoxy system components (beyond patch testing) in shipbuilding settings.^[7] Respirable CFRP fiber generation under varied machining and thermal scenarios, including pitch- vs PAN-based fibers and weathered, seawater-aged materials.^[10,11] Quantitative microplastic health risk models for ship-origin coatings, integrating capture efficacy during IWC and additive leachate toxicology in marine waters.^[16,18] Performance-based fire safety: harmonized marine protocols for smoke toxicity and HCN/CO monitoring to inform operational thresholds during overhaul under IMO equivalence.

8. CONCLUSIONS

Fiber-reinforced polymer (FRP) composites have revolutionized marine transportation by offering superior corrosion resistance, high strength-to-weight ratios, and design flexibility. However, these benefits come with significant occupational and environmental health challenges that must be addressed systematically. Key hazards include styrene exposure, which is linked to neuro-irritative symptoms and potential ototoxicity during polyester/vinylester lay-up processes;^[3,6] epoxy resin and amine hardener sensitization, a leading cause of occupational dermatitis;^[7-9] and respirable fiber and dust generation during machining, particularly for pitch-based CFRP, which can release WHO-classified fibers.^[10,11] Fire scenarios pose acute risks due to the emission of toxic gases such as carbon monoxide and hydrogen cyanide, often referred to as the “toxic twins,” which impair escape and overhaul safety.^[18,19] Furthermore, microplastic release from hull coatings and FRP

degradation introduces long-term ecological and human health concerns.^[20–22]

Seawater aging exacerbates these risks by altering composite interfaces, reducing mechanical integrity, and increasing susceptibility to damage during maintenance.^[1,2] To mitigate these hazards, a layered control strategy is essential: engineering controls (closed-mold processes, LEV), biomonitoring for styrene metabolites, disciplined PPE protocols, fire-safety design aligned with IMO guidelines,^[16,17] and microplastic capture during hull cleaning operations. Future research should prioritize dermal uptake biomarkers, fiber toxicity modeling, and standardized microplastic risk assessments to ensure sustainable and safe deployment of FRP composites in marine environments.^[23,24]

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