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Review article

Structural design parameters of laminated composites for marine applications: Milestone study and extended review on current technology and engineering

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ABSTRACT

The demand for the application of laminated composite materials is getting significant in the marine industry due to the advantages of use and life, maintenance, and efficiency of requirements and design over conventional materials. However, these materials are known to be highly susceptible to impact damage mainly due to out-of-plane impact events involving multiple interacting failure modes. The novel characteristics of the marine environment, such as extreme environments and long-term seawater influence, pose unique challenges to the resilience of these composites. Considering the expanding use of composite in complex marine structures and challenging marine environment conditions, this paper comprehensively reviews the composite research and development in marine applications to enable predictive models that can be safely used to achieve sustainable, efficient, robust, and safe design of marine engineering structures. The reviews cover the composite applications in the marine industry, novel marine characteristics for composite material, layering mechanism, material characterization, and damage mechanisms in composites due to various loading conditions in four different categories (delamination, matrix cracking, fiber breakage, and complete perforation), parametric joint method (vacuum and adhesive), and the failure criteria (debonding and interfacial delamination). This research brings valuable contributions in enriching the understanding and design of laminated composite structures by adopting the latest research trends. Applying advanced materials and numerical simulation has brought efficiency and effectiveness to analyzing laminated composite characteristics. Thus, this research opens new opportunities for further innovation and development in composite materials.

1. Introduction

The use of composite materials increased significantly in marine structures and the global industry, with an estimated growth rate of 5.8% per year. Composites are heterogeneous materials that combine two or more materials with different physical and chemical properties. Composite materials utilize the higher properties of fibers and matrix materials to achieve higher mechanical performance. The desirable properties such as high strength-to-weight ratio, corrosion resistance, design flexibility, low cost, durability, and chemical resistance of composite materials show that they are the best alternative to traditional homogeneous materials in marine applications [1].

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Most marine structural composites use E-glass fibers in an unsaturated polyester resin matrix. If higher stiffness is required and cost permits, structures can be fabricated using carbon fiber-reinforced epoxy resin. Different reinforcing materials and matrix types can be selected to meet the design requirements and end-of-life considerations for a particular application. As mentioned earlier, the matrix is the medium that transfers loads from the external environment into the reinforcing fibers, and if the matrix is a polymer (PMC, polymer matrix composite), two different products can be distinguished: thermoset resins, which are generally disposable (i.e., not easily recyclable) and thermoplastic matrix systems that can be recycled relatively easily. The main commercial groups of thermoset resins are phenolic, epoxy, unsaturated polyester, and vinyl ester resins. These materials are usually supplied in liquid resin form that can be solidified using chemicals and heat. The main thermoplastic polymers used as composite matrices are polypropylene, polyamide,

Regarding reinforcement, various fibers that can be used are generally classified into natural fibers (plant, animal, or mineral-based) and synthetic fibers (nylon, acrylic, aromatic polyester, polyethylene, aramid, glass, carbon). Boron, silicon carbide, stainless steel, aluminum, etc.). Glass, carbon, or aramid fibers are the most common choices and have very different mechanical properties [2].

Considering the desirable mechanical performance, the need for composites in marine applications continues to increase. One of the marine applications implemented in recent years due to environmental regulations imposed by the International Maritime Organization (IMO) is the need to reduce the weight of ships to improve the energy efficiency of the propulsion systems. This demand requires the application of materials with superior mechanical performance yet lighter than conventional metallic materials. Although composite materials have been widely used in specialized/small vessels, conventional steel materials are still the leading choice in medium/large vessels [3]. In recent decades, the use of composite materials as a new candidate in developing environmentally friendly and intelligent ships has increased in number and size. The aim is to create materials that effectively address every specification and characteristic requirement and mitigate adverse events such as unpredictable structural failures and faults.

Other new applications have also been proposed. There is a review of the design and analysis of reinforced thermoplastic pipes for offshore applications [4] and synthetic mooring ropes for marine renewable energy [5]. US Naval Base Mayport took delivery of the first set of fiber-reinforced polymer (FRP) composite "Camels" (Floating structures designed to separate large ships and mooring docks) for docked vessels [6]. Composite material also has a significant potential market for composites in marine renewable energy. Renewable Power Generation has deployed a commercial-scale second-generation marine power generation tidal energy turbine generating unit (TGU) in the Bay of Fundy on the Canada-US Border with a helical composite foil and a hybrid carbon/glass fiber reinforced composite direct drive shaft [7]. Additionally, three composite rotor blades, manufactured by AC Marine and Composites, have been installed on the AR1500 1.5 MW tidal power turbine generator in the Pentland Firth between the Orkney and Caithness Islands [8].

Additionally, variations on FRP have several advantages during construction, including the ability to consolidate parts, thereby reducing the number of sections, joints, and fasteners, providing significant weight reduction and improved stability by lowering the center of gravity, and facilitating more accessible application to complex shapes and combined curvatures. The "traceability" of composite materials makes them suitable for constructing submarine hulls, decks, and fairings [9]. However, designing the composite material for marine applications is complicated because many parameters determine the structural performance, including the loading responses (force, deflection, and energy absorption), loading types, and composite layering. For example, in the impact case, the performance is primarily affected by the impact resistance (to damage) and impact tolerance (residual properties) [10]. The fatigue failure mechanism is also more complicated than that of metallic materials [11]. The composite joint performance also depends on several factors, including the adhesive layer or composite adherend layer, the joint geometry, surface preparation, and manufacturing methods used for production.

Another impact on the marine environment is the effect of seawater on composite degradation [7]. Absorbed seawater significantly influences the mechanical properties of composite materials. Water molecules react with matrix polymer molecules, causing plasticization, which causes cracks in the matrix and voids in the matrix, which are potential starting points for fatigue cracking, delamination, and blistering. Several studies have shown that composites progressively lose stiffness and strength when exposed to water absorption, and the decrease is proportional to the apparent weight gain [12]. In recent decades, significant efforts have been made to combine the knowledge of experimental testing and scientific testing gained so far in the research field of marine applications of composite materials. However, there is room for extensive research into composites' long-term structural performance, sustainability, and material durability.

Considering the conditions above, the present paper reviews the composite application in the maritime field, covering the characteristics that must be possessed, applications of laminated composites, joining methods, layers of laminated composites, failure criteria, and characteristics of laminated composite materials. This review is made to support the development of the use of laminated composites in maritime applications by providing adequate knowledge of stress limit conditions, durability and service life, failure modes, fracture toughness, fire resistance, and other marine environment influence parameters for the efficient and sustainable design process of marine application structures in the demanding industrial sector.

2. Mandatory characteristic

As with laminated composite materials, especially laminated composites for maritime applications, every material must have main characteristics such as strength, durability, specific gravity, processability, and others. Materials that will be applied to the marine environment require quite different treatment than materials in general. To find data from testing a material applied in a marine environment, testing must also be able to adjust to sea conditions, especially from the level of salination from seawater. The main parameters that become characteristics that composite materials must consider when deciding whether a material is capable of are usually based on seawater resistance, strength and stiffness, fracture toughness, impact resistance, fatigue resistance, and corrosion resistance.

2.1. Sea water resistance

Resistance to seawater is a pivotal criterion for materials used in maritime applications due to the corrosive nature of saltwater, which significantly affects material properties. The capability of a material to withstand seawater's influence becomes crucial in evaluating its sustainability in marine environments. Several studies have explored the behavior of laminated composite materials under seawater exposure conditions. Ulus et al. [13]. We are investigating the seawater durability of Halloysite Nanotube Reinforced Epoxy/Basalt Fiber Hybrid Composites. This research aims to assess the impact of incorporating halloysite nanotubes (HNT) into epoxy (EP)/basalt fiber (BF) hybrid composites on seawater resistance, an essential parameter in assessing composite material durability. Their findings reveal that incorporating 2% by weight of HNT in EP/BF composites enhances mechanical performance post-immersion in seawater compared to composites lacking EP/BF addition.

In 2020, Keshavarz et al. [14] explored the addition of graphene nanoplatelets (GNPs) to fiber metal laminates (FML) to enhance their performance under marine conditions. FML, consisting of AL6061 and glass fiber-reinforced epoxy (GFRE), was tested with varying concentrations of GNPs in simulated seawater conditions. GNPs, nanometer-sized graphene sheets, are known to enhance material mechanical properties. The study demonstrated that incorporating 0.25% GNPs significantly reduced water absorption while slightly reducing flexural properties, modulus, and strain compared to samples without GNPs. A comparison of the percentage of GNPs addition to FML on water absorption resistance can be seen in Fig. 1.

Meanwhile, Calabrese et al. [15] examined the durability and mechanical stability of epoxy/glass-hemp hybrid composites under salt mist environmental conditions. Their research involved exposing samples to salt mist for up to 60 days to assess water absorption, which is crucial for material performance in water-exposed environments. The study revealed that composites' hydrophilic/hydrophobic behavior influenced water uptake and wettability, with glass fibers notably influencing water absorption stability. Flax-fiber composites exhibited significantly higher water absorption than glass-fiber composites, highlighting the importance of material composition. Additionally, incorporating glass fibers into flax laminate enhanced flexural strength by 90% and modulus by 128%, albeit lower than full glass laminates, showcasing the potential for enhancing mechanical properties in hybrid composites.

2.2. Specific strength and stiffness

The use of laminated composite materials in the maritime industry is due to their high strength and low weight combination. These materials are designed to bear dynamic loads derived from ocean waves, vibrations, and other external forces. The success of a ship structure primarily depends on the material's stiffness, which plays a vital role in ensuring dimensional stability. The stiffness is essential to ensure the structure continues performing without significant deformation or dimensional changes [16]. Although strength and stiffness are not necessarily opposites, they often have a complex relationship and depend on several factors. An increase in stiffness can precede an increase in strength, especially if the change is accompanied by an increase in the material's ability to absorb deformation energy without failing. However, this dynamic relationship depends on specific material properties and loading conditions [17]. Factors such as fiber orientation in the composite material, fiber volume fraction, internal structure of the composite, and proper manufacturing processes can be optimized to increase the strength and stiffness of the material without adding significant load. Overall, using composite materials in the maritime context requires a careful and holistic approach to ensure an optimal balance between strength and stiffness under diverse and challenging environmental conditions [18].

The strength and stiffness levels of a material can be known through testing. Previous strength testing was also carried out by Nadir et al. [19] who tested the flexural stiffness and strength values of laminated composite wood beams with the addition of Glass Fiber Reinforced Polymer (GFRP) reinforcement layers and compared them with Carbon Fiber Reinforced Polymer (CFRP). The testing provided parameters for the stiffness and strength of the composite material. This implies that stiffness and strength are crucial parameters to consider in the evaluation of the quality of a composite material. Fig. 2 shows the strength of CFRP and GFRP from the experimental results, where CFRP has a higher strength than GFRP.

2.3. Hight fracture toughness

Fracture toughness measures a material's ability to resist crack propagation. The higher the fracture toughness of a material, the more resistant it is to crack propagation. The harsh maritime environment conditions, including high waves, strong winds, and corrosion, pose a risk of crack initiation and propagation in laminated composites. Therefore, composites must exhibit high fracture toughness to prevent crack initiation and propagation, ultimately averting material failure [20]. Several strategies can be employed to enhance the fracture toughness of laminated composites. One approach is utilizing base materials with high fracture toughness. Additionally, reinforcing layers with high fracture toughness should be incorporated, such as the introduction of aramid fiber-reinforced layers, as demonstrated by Chen et al. [21]. Which incorporates aramid fiber reinforcement layers such as PI fibers into the composite structure. This study has shown that adding PI fibers significantly improves the interlaminate toughness of laminated composites. Furthermore, research findings indicate that adding carbon nanotubes (CNT) and short fibers can significantly enhance the crack resistance of epoxy-based steel laminates, thereby improving fracture toughness. In summary, practical strategies for improving the crack resistance of composite materials involve incorporating aramid fiber-reinforced layers, optimizing areal density in reinforcing layers and utilizing reinforcing materials such as CNT and short fibers.

According to Le Guen-Geffroy et al. [22], Fracture testing is essential in materials science and engineering for several reasons. Firstly, it allows for determining a material's resistance to crack propagation and failure, providing crucial information for designing and assessing the safety and

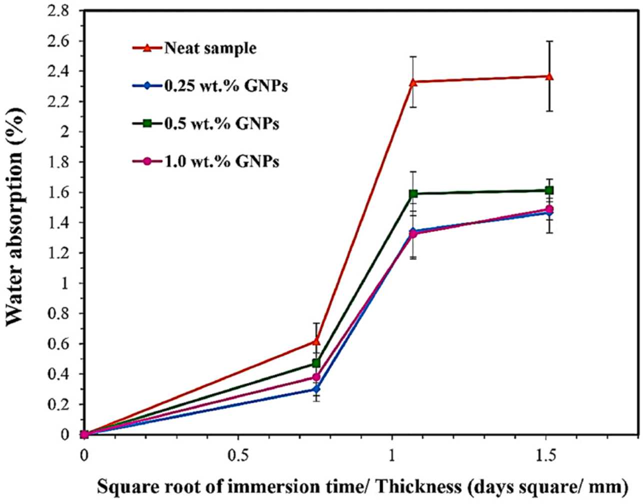


Fig. 1. Water absorption of the FMLs with GNPs as a function of the immersion time [14].

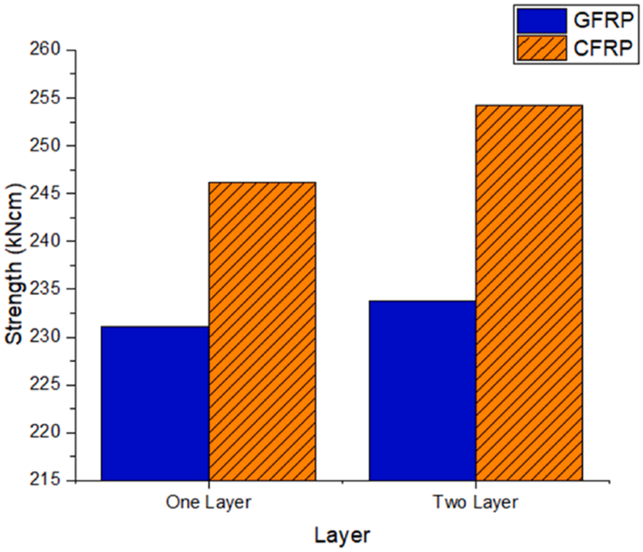


Fig. 2. Experimental strength of CFRP and GFRP (redraw based on data in Nadir et al. [19]).

reliability of structural components. Additionally, fracture testing aids in understanding the behavior of materials under different loading conditions, such as mode I test (crack opening under tensile loads) and mode II loading (in-plane shear) fracture, which is vital for predicting and preventing failures in real-world applications. Furthermore, studying the effects of environmental factors, such as seawater aging, on fracture properties can provide insights into composite materials' long-term durability and performance in marine environments. Research has been conducted by Le Guen-Geffroy et al. using the test method mode I and mode II fracture tests, as well as developing a standard test to measure mode II delamination resistance. The mode I fracture toughness was tested using the double cantilever beam (DCB) test method based on the ISO 15,024. The mode II fracture tests were performed using a mixed mode bending (MMB) test method, which combines a three-point bending end-notched flexure with a DCB test. Additionally, physically aged specimens were tested after being heated in an oven at 60 °C for three weeks to examine the influence of physical aging on energy release rate in modes I and II. The results showed that seawater aging decreased the energy release rate for mode I fractures by around 30%, leading to a decrease in mode II fracture resistance despite significant variability in the results. A comparison between the results of tests conducted with water and without water can be seen in Fig. 3. Physical aging was found to reduce the energy release rate for both mode I and mode II fractures. However, after seawater aging, the composite retained over 70% of its initial fracture properties.

To further develop composite materials, Di Boon and Joshi [23]. Wrote a review journal containing methods for improving laminated composites, especially at interlaminar interfaces and fracture toughness. The composite development emphasized in this journal is Fiber Reinforced Polymer (FRP) and Fiber Metal Laminate (FML) composites. This research focuses on research regarding methods for increasing Intralaminar Fracture Toughness (ILFT) in FRP-type composites using Carbon Fiber-Rainforced Polymers (CFRPs) and Glass Fiber Reinforce Polymers (GFRPs). Meanwhile, the laminate used is aluminum and titanium-based for the FML composite type. The study found that the FPR ILFT composite can be improved significantly through strengthening by increasing the thickness of the 3D composite. However, it is also necessary to consider that there must be a reduction in properties in the FRP field. For FML, anodization of the metal surface can promote composite-metal solid bonding.

2.4. *Excellent impact resistance*

The paramount requirement for composite laminates in maritime applications is outstanding impact resistance. These structures frequently encounter diverse loads, with impact loading emerging as a pivotal force capable of inflicting substantial damage. The preference for composite laminates in such applications is attributed to their lightweight nature and ample strength, which are tailored for specific functions. Impact resistance denotes a material or structure's capability to endure abrupt and high-energy impacts without succumbing to catastrophic failure. Consequently, the impact resistance of composite materials plays a vital role in safeguarding these applications' structural integrity and functionality [24].

Research has been completed by Castilho et al. [25] by carrying out impact tests. Impact testing is crucial because it assesses a material's or structure's ability to withstand sudden and high-energy impacts, essential for ensuring safety, durability, and performance in various applications. Impact tests involve striking a structure with an indenter or projectile to calculate impact energy and speed, providing valuable data on the material's behavior under dynamic loading conditions. This research is on marine sandwich composites, including the manufacture and flexure, quasi-static, and impact tests of a series of marine sandwich composites. The study used different core materials, such as PVC, Balsa Corecork NL10, and NL20, to produce a sandwich laminate with E-glass/polyester skins. The drop-weight tests were performed until the failure of the second skin. The results indicated that PVC and NL20 specimens showed predictability and repeatability of results, while NL10 presented different failure modes and higher absorbed energy. Additionally, the overall behavior of the PVC, Balsa, and NL20 specimens was well predicted by quasi-static tests. However, NL10 specimens' behavior changed dramatically from static to impact tests, increasing the absorbed energy three times. We can conclude that cork laminates have the potential for applications with impact requirements, with the downside of lower stiffness and higher weight.

In 2017, Hassoon et al. [26] conducted research on damage modeling in laminated composite under slamming impact water for naval application. This research focuses on the problem of slamming impact with damage to the composite structure implemented by inputting the user-defined material VUMAT into the finite element method using Abaqus explicit code to find the interlaminar damage for fiber-glass vinyl ester reinforce laminated composite panels based on Hashin criteria. This study found that the kinematic effect along the panel-water interface exhibits more excellent elasticity due to flexibility and local deadrise angle changes. As a result, this effect can significantly reduce the panel response at higher impact velocities, especially at the center and ends of the panel. Increasing the impact velocity leads to more stiffness degradation of the composite. In the present work for a flexible panel, the deflection in the center is 18.6 mm, which exceeds the allowable deflection of 9.04 mm. Matrix damage is the first damage that occurs in composite laminates. In repeated damping waves, matrix cracks start to occur and propagate toward the fibers for different layers of the laminated composite, then branching out in the interlayer zone to create delamination. These cracks can lead to fiber rupture, causing

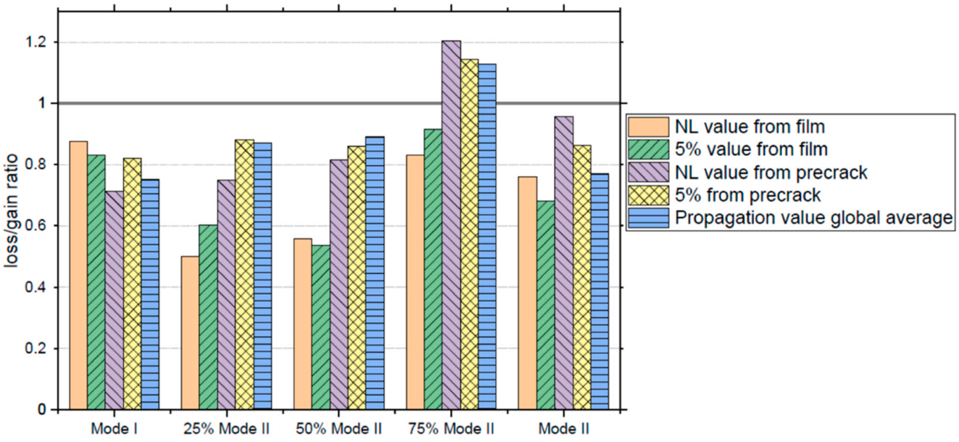


Fig. 3. Ratios of water-saturated/unaged fracture resistance values [22].

significant failures. From this study, the damage that occurred was observed in the matrix at the vulnerable parts to give attention to these locations. The damage can be seen in Fig. 4.

2.5. Hight fatigue resistance

Fatigue resistance, crucial for material longevity, refers to a material's capacity to endure repeated loading cycles without deterioration. The fatigue limit often quantifies this property, denoting the maximum stress level a material can sustain cyclically without failure. Elevated fatigue resistance is sought for enhanced safety, reliability, maintenance efficiency, weight reduction, and design versatility [27]. Various means can be pursued to Achieve high fatigue resistance, such as optimizing composite fiber orientation, as demonstrated in the study by Meng et al. [28]. Since mechanical structures are designed with predetermined service lifespans, assessing their resistance under cyclic stress conditions is paramount, particularly for Fiber Reinforced Polymer (FRP) composite materials. The investigation aimed to evaluate the bending fatigue behavior of laminated composites subjected to water ingress, employing both unidirectional (UD) and cross-ply (CP) laminates. These laminates were manually fabricated and subjected to bending tests conforming to ISO standards, followed by Finite Element Analysis (FEA) implementation. Experimental findings revealed that compressive delamination was the primary failure mode during bending fatigue. A comparative analysis of bending fatigue was conducted utilizing FEA, with the CP laminate exclusively modeled for the study.

Fig. 5 illustrates the progressive debonding observed in the 3D solid model during fatigue, wherein debonding elements form along the edges during fatigue crack propagation, exhibiting scaling and directional alterations.

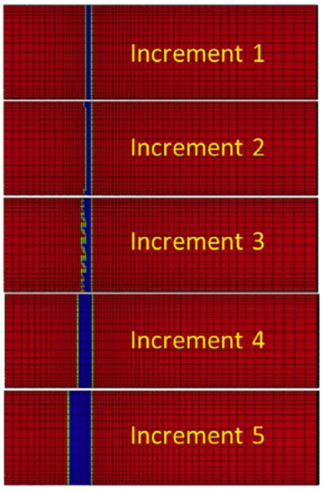
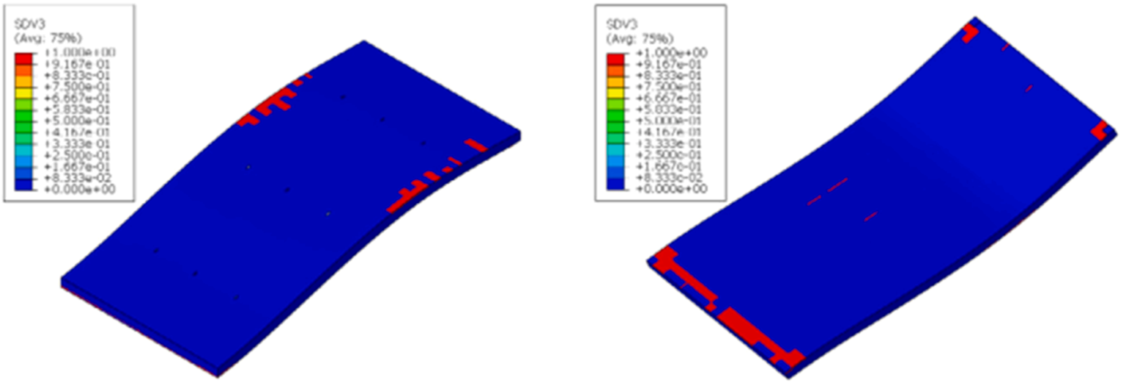


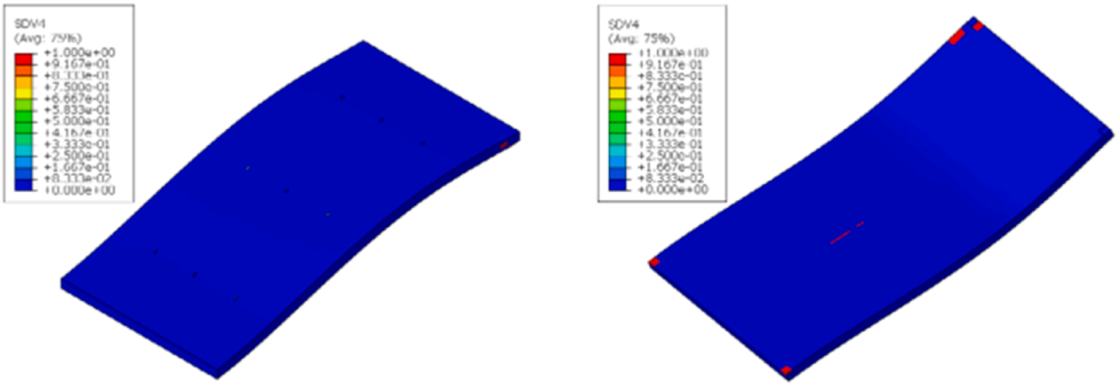
Fig. 5. Illustrated progressive debonding observed in the 3D solid model during fatigue [28].

This research found that the UD and CP laminates revealed different fatigue failure behaviors but a similar response to environmental effects. It was found that water degradation reduced fatigue performance: dry specimens survived at 80% UFS but failed at 90% UFS, while water-conditioned coupons survived at 65% UFS but failed at 80% UFS. The study of fatigue stiffness has shown that the fatigue failure modes were associated with bending conditions (3-point or 4-point bending), loading level, loading sequence, stacking sequence, and loading environments (dry and wet). Only an attempt to analyze the fatigue failure mechanisms by considering the practical conditions will lead to accurate results. FEA modeling unveiled the development of the 4-step buckling-driven delamination, in which the edge effect played an important role in fatigue crack propagation. Furthermore, the water ingress due to the



Top layer (matrix tension)

Bottom layer (matrix tension)



Top layer (matrix compression)

Bottom layer (matrix compression)

Fig. 4. Damage in semi-flexible panel [26].

capillary phenomenon significantly accelerated the crack initiation and propagation progress.

Siriruk and Penumadu [29] conducted experiments on the fatigue behavior of carbon fiber-vinyl ester composites affected by seawater using high X-ray tomography, which helps compare fatigue failure mechanisms. This study focused on the effect of seawater on the mechanical response of foam and facing materials individually and on sandwich structure collectively. It was found that the fatigue lifetime was reduced by 85%. Cyclic loading of samples exposed to seawater resulted in a 50% reduction in fatigue life. The results of high-resolution X-ray micro-tomography non-invasively dominated samples that experienced fatigue in the air were a combination of matrix cracks that fused parallel to the fibers and delaminate, as seen in Fig. 6. Exposure to water during dynamic loading significantly affects the fatigue life of carbon fiber-vinyl ester composites applied in marine technology.

The use of composite materials has also entered the military realm. Military ships are designed to have maneuverability, light hulls, and resistance to attack. This light hull can be achieved by using composite laminated material as the structure. Gargano et al. carried out research on resistance to attacks, mainly due to explosions [30]. Tests were carried out experimentally to determine the explosive blast response of the laminated material. Testing was conducted on carbon-polyester, glass-polyester, carbon-vinyl ester, and glass-vinyl ester laminated materials. During testing, the laminate material experiences dynamic loading due to shock waves with increased pressure and impulse, deformation, and damage. The test results found that E-glass laminate is more resistant to delamination cracking due to explosions than carbon fiber. Glass/carbon fiber laminates with a vinyl ester matrix have superior damage resistance than composites with a polyester matrix. The higher damage resistance is due to the higher bending strain energy capacity and interlaminar fracture toughness properties of laminates containing glass fiber or vinyl ester matrix.

2.6. *Corrosion resistance*

Because of their corrosion resistance, laminated composite materials are used in the maritime world. The corrosion process can cause damage to the material, such as decreased strength, life, and maintenance costs. Several factors, such as resin type, reinforcement type, and environmental conditions can influence the corrosion resistance of laminated composites [31].

Pan et al. [32] investigated carbon fiber-reinforced polymer (CFRP) corrosion behavior with magnesium layers without coating and with coating in a 3.5% NaCl solution. The results indicated that CFRP laminates with uncoated magnesium alloy experience the most severe corrosion (shown in Fig. 7). The Micro Arc Oxidation (MAO) coating on the magnesium alloy sheets significantly enhanced the corrosion resistance of CFRP/magnesium alloy laminates. MAO is an oxide layer formed on the surface of a metal when exposed to a low-intensity electric arc. In this study, MAO on magnesium plates theoretically improved corrosion resistance because MAO has a unique structure consisting of randomly arranged metal oxides. Furthermore, the results of this research indicated that the corrosion rate of laminates decreases with increasing immersion time.

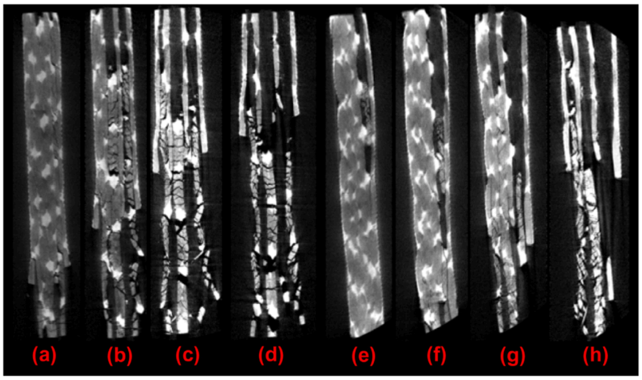


Fig. 6. X-ray tomography results of failed carbon fiber vinyl ester laminated composites under fatigue test. (a–d) unconfined dry specimen, (a) away from, (b, c) midway, and (d) near failure zone. (e–h) water-confined and wet specimens, (e) away from, (f, g) midway, and (h) near failure [29].

3. Applications

Composites are widely used in engineering practices such as aeronautics, automotive, marine, construction, and packaging due to their light weight, resistance to corrosion, high temperature and fatigue, and high specific stiffness and strength. Composites with vinyl ester and polyester resins are often used in marine applications. Another application of composites is as a floatation device material in seaplanes that mostly use fiber-reinforced polymer composites. In addition, composites are also used to develop marine energy conversion systems such as tidal turbines. This review will be used to develop buoyancy devices in seaplanes, marine renewable energy, and ships operating in the marine environment.

3.1. *Seaplane*

The seaplane can take off and land on land and water, making it suitable for missions at sea and wet areas. For operations in water, seaplanes are equipped with flotation systems such as pontoons or floats that provide buoyancy and stability when landing or taking off in water. Pontoons or floats that provide buoyancy in water must withstand impact loads because seaplane floats are designed to adapt to the water's surface. When landing in water, the float absorbs the force of landing and helps reduce the stress experienced by the aircraft. The float initially uses aluminum material for applications in the water environment and will be developed using composites due to the operation of the aircraft in the corrosive seawater environment. Therefore, it is necessary to know the effect of water and seawater on the properties of composites by reviewing papers that discuss this subject [33].

Many studies have addressed the effect of water and seawater on the properties of fiber-reinforced polymer composites, but none have been specific to seaplane applications. Most studies have been conducted by immersing composites in water and seawater. Although composites are lightweight, resistant to corrosion, high temperature and fatigue, and high specific stiffness and strength, studies have shown that prolonged immersion in water or seawater can lead to degrading their mechanical properties.

One of the things that needs to be known in developing seaplanes that will operate in water and seawater environments is the behavior of water absorption in float materials that can affect their mechanical properties. Another study by Fang et al. [34] indicated that water and seawater absorption in e-glass/polyester composites mixed with cadmium sulfide (CdS) QDs did not follow Fick's law. Mass loss occurs when the immersion time increases, which is associated with the leaching of unreacted monomers and hydrolysis of ester bonds. Studies on cadmium sulfide-modified polyester glass showed a decrease in tensile strength by 15.5% and 13.8% after immersion in water and seawater, respectively. In contrast, the tensile modulus was little affected by the immersion process. Water absorption results in the degradation of fibers and matrix and debonding between fibers and matrix.

Seaplanes maintain buoyancy by adjusting their weight and shape, as with the AG6000 seaplane made in China, which has a hull shape like the ship (see Fig. 8). Using composites is one solution to develop mechanical properties that support the design as a seaplane float material. Traditional type E glass fiber composites provide adequate strength at low cost and are suitable for interiors or small parts that do not have to bear heavy loads or stresses. Glass fiber has a lower tensile modulus,

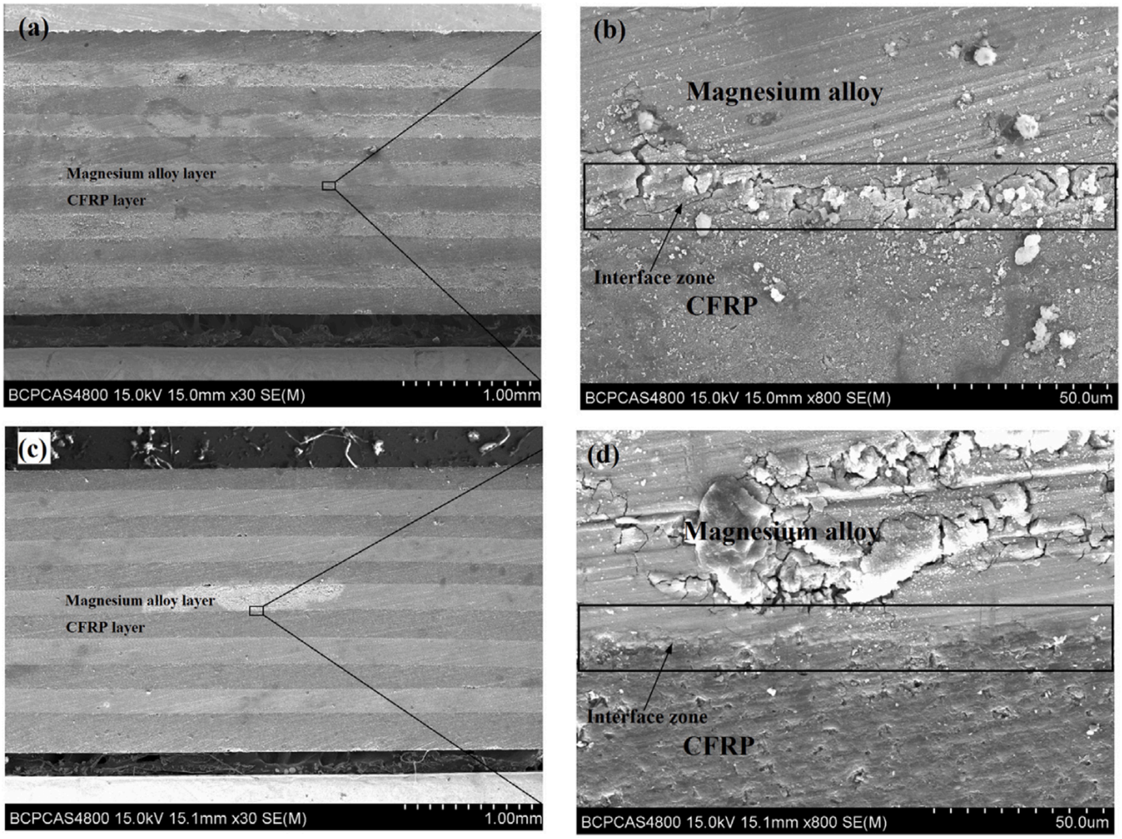


Fig. 7. SEM micrographs of side face for the FMLs after 30 min immersion: (a) and (b) CFRP/uncoated magnesium alloy laminates, (c) and (d) CFRP/coated magnesium alloy laminates [32].

Fig. 8. The Seaplane AG6000 [36].

higher strain to failure, can flex, and can withstand more strain without breaking. Meanwhile, more robust and lighter carbon fibers are starting to be used in applications where a small amount of flexibility in the inner structure of seaplanes is allowed due to their rigidity. On the other hand, carbon fiber has a higher price of about 8 to 10 times that of E-glass and a relatively low compression strength. Recently, hybrid composites containing carbon and glass fiber have better fatigue behavior in air and water than all-glass composites [35].

The hybrid composites often used in carbon-based seaplane hulls are carbon woven roving and e-glass woven fabric for glass/carbon hybrid composites and carbon woven roving and kevlar-carbon woven roving hybrid fabric for kevlar- carbon/carbon hybrid composites. The composite fabrication method for this seaplane hull uses the VARI method, which utilizes vacuum pressure from a vacuum pump to flow resin into the laminated fiber area. The tensile and compressive strength properties of the Kevlar carbon/carbon hybrid composite are slightly higher than those of the glass/carbon hybrid composite. As for the shear strength properties, both are relatively similar, which means that the two hybrid composite materials have a shear strength below the shear strength of aluminum. So, these two materials need to be improved in shear strength or applied to floating structures that experience shear loads below their ultimate shear strength [37].

3.2. Marine renewable energy

Nowadays, renewable energy is gaining a leading position (see Fig. 9) amid the depletion of fossil fuels and the desire to protect the natural environment. The development of energy generation devices requires the use of appropriate materials that have high durability on the one hand and are environmentally friendly on the other. The use of metals produced by metallurgical methods is limited due to their high weight and relatively low fatigue strength [38].

In the offshore renewable energy sector, there are various power generation methods, including offshore wind turbines (OWT), wave energy converters (WEC), and tidal energy converters (TEC). The Levelized Cost of Energy (LCOE) metric is commonly used in the renewable energy sector to evaluate the energy cost of different types of

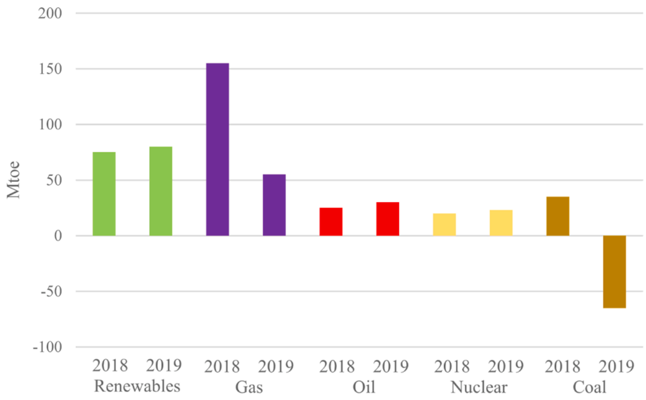


Fig. 9. Average annual change in energy demand by fuel (redrawn based on data in IEA reports [38]).

technologies. Eq. (1) for calculating Capital Expenditure (CAPEX), Operating Expenditure (Opex), and Energy Generation (Et) in the year (t) is used along with discount rate (r) and operational life (n) to calculate it. The composite reduces the CAPEX value when calculating the capital cost of design and the OPEX value when running and repairing. Thus, it is clear that reducing CAPEX or OPEX and/or extending the life cycle of offshore renewable energy assets will reduce LCOE [39]. Offshore wind farms have successfully done this in the last decade, as (shown in Fig. 10) which details the LCOE in the offshore industry between 2010 and 2020.

Currently, researchers are developing offshore renewable energy structures vulnerable to harsh environments with loading from wind, waves, and tides that cause fatigue damage in corrosive and erosive environments to improve design effectiveness. Benoit et al. A practical approach that has been found to improve engineering structures' mechanical and fatigue resistance is using Additive Manufacturing (AM) technology. Oak Ridge National Laboratory (ORNL) has investigated the structural nodes of the Vesta wind turbine. This investigation used composite and WAAM techniques to evaluate its potential to meet system requirements. WAAM is one of the most promising AM technologies for offshore renewable structures due to its ability to fabricate large and complex components in short lead times. DNV has therefore created the DNV-ST-B203 standard, an AM qualification standard for the oil and gas and related industries focusing on WAAM and Laser-Based Powder Bed Fusion (L-PBF) processes.

Teng et al. [40] applied composites for turbine blades in China. Polymers reinforced with pure carbon fiber were used to make spar caps, as shown in Fig. 11, for wind turbine blades, and polymers with glass fiber were used to make shells for blade components. They assessed the lie-cycle environmental performance of hybrid blades with carbon fiber-based pole covers, shells, and shear webs based on recycled carbon fiber composites. They indicated that the energy and carbon payback time for carbon fiber turbine blades was found to be 5–13% lower compared to incumbents in the market.

Statistical analysis and model calculation are used to evaluate the application of carbon fiber composites in large-scale wind turbine blades in China, and an analysis system scheme is provided to comprehensively evaluate the economics and energy efficiency of carbon fiber wind turbines. In marine applications, the potential kinetic energy found in tidal currents is a renewable energy source. Wherever efficient means of achieving this energy can be improved, tidal currents can be provided to meet the world's growing energy needs. The utilization of ocean current turbines for power generation is increasing, and horizontal axis ocean current turbines are one of the systems being developed for this purpose. Many types of hydrokinetic turbines, metal-based or composite, were considered and tested. The practice of composites in marine structures, particularly for offshore utilization, is beginning to emerge. Composite materials offer new prospects for the renewable marine energy industry. Furthermore, these structures may be subject to the impact of storms and seawater splashes (see Fig. 12) in the marine environment [41].

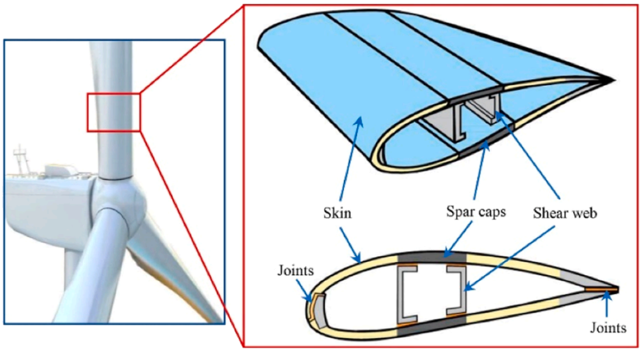


Fig. 11. Structural drawing of wind turbine blade [40].

Energy from tidal currents is generated by regular daytime or semi-diurnal cycles. One of the main advantages of tidal energy over other renewables, such as solar and wind energy, is that energy production can be predicted on a long-term scale due to the well-documented behavior of the tides. In addition, tides are much more constant than wind; therefore, their output is more a priori measurable. As mentioned, due to the high density of seawater (at least 800 times that of air), submerged turbines experience a significant workload compared to wind turbines.

Materials used must maintain a high level of strength and stiffness to withstand the corrosive seawater environment and require little or no maintenance, given the inaccessibility of deep-sea water areas. For these reasons, fiber-reinforced polymer composite materials, particularly Glass Fiber-Reinforced Polymer (GFRP) and Carbon Fiber-reinforced Polymer (CFRP), are attractive options for realizing tidal turbine blades. Designers generally prefer GFRP due to the trade-off between structural properties and low cost. CFRP offers high performance and lower weight (about 13% for the blade) compared to GFRP but at 7 or 8 times higher. For this reason, the use of carbon fiber composites is limited to the central part of the blade [42].

Blades also play an essential role in tidal turbines. Until now, blade manufacturing has focused on high-cost, low-volume prototype blades, as these have met the industry's needs. However, we must now consider producing higher volumes, such as OpenHydro company's 16m diameter, lower-cost blades, to generate more competitive and cleaner electricity. Flanagan et al. [43] Out-of-autoclave (OOA) technology has been developed to address these blade design challenges. The key to this application is a ceramic mold that reliably heats blades operating at temperatures above 200 °C. The combined use of epoxy powder and ceramic, heat-treated tooling enables one-shot consolidation of large composite structures such as tidal blades. EireComposites has patented this technology, which has produced a wide range of blade types.

The first large-scale turbine blades made of fiber-reinforced plastic

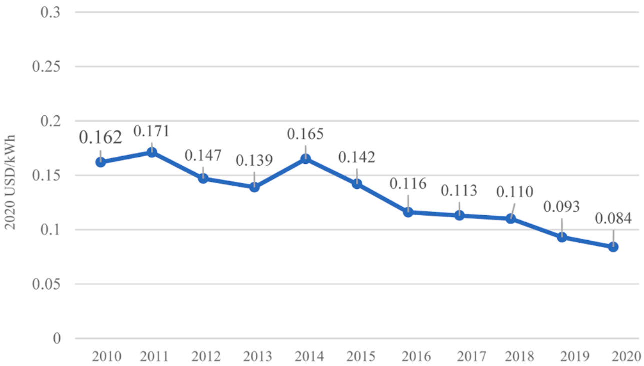


Fig. 10. LCOE Offshore Industry 2010–2020 (redrawn based on data in O'Neill et. al. [39]).

Fig. 12. Environmental degradation of composites for marine current turbine [41].

were produced by hand-laying out pre-preg. The main parts of the tidal turbine blades (i.e., upper and lower skins and box-section spars) were manufactured separately and then joined using adhesives at a very high production cost. The resin infusion process has been used to minimize costs, allowing a reduction in the number of components to be assembled and increased automation of the process.

The Airborne Composites company uses another technique to produce tidal turbine blades. They produced four-meter-long blades installed in the 500 kW CoRMAT turbine, developed by the European Marine Energy Center (EMEC) in 2014, using the VARTM 'one-shot' process. The VARTM "one-shot" process ensures higher production efficiency, eliminating the presence of additional material around the connector interface. The company has also developed a method to insert the insert at the blade root and connect it to the hub before resin insertion. Consequently, drilling operations on the realized composite are eliminated, and the laminate thickness is reduced. Some problems related to the quality of laminates and defects in the production part are still unresolved. For single laminates and sandwich structures, manufacturing defects include delamination, dry areas, non-wetted fibers, porosity, wrinkles, defects in fiber reinforcement, and fiber misalignment.

3.3. *Conventional ship*

The research focused on the use of resin composites in marine systems over the last decades, showing the possible advantages of multiple changes in materials, such as hulls, rudders, and bulbous and turbine blades, to name but a few. The paper presents recent developments in the above sectors, presenting advanced composite applications in naval vessels. When the boat is underway, the scaffold is supervised by the duty officer, who is supported mainly by a capable sailor on station duty. During basic movements, the skipper will often be carried on an extension enforced by a duty officer, a capable seaman in the bargain of a pilot, whenever required.

The production of innovative hull composite materials has marked a significant advancement in naval shipbuilding. Composite materials have been used primarily by the naval ship industry due to their superior properties. Low magnetic signature naval mine countermeasure ships are applications of composites that can detect mines before they detect them because their hulls are made of nonmagnetic materials or equipped with local degaussing systems, as seen in Fig. 13(a).

However, there are challenges in joining superstructures, as welding is not possible when joining composites and steel. Rivets are an ancient technology in this field, and hardly any bolts are used as they cause weight and require a lot of labor. Using bolts in composite superstructures would be detrimental to reducing the expected weight. The bolts would be in the order of 20% of the weight of the composite superstructure. One of the bonding capabilities of composites for shipboard use is bonding metals and plastics in uniting the entire superstructure with the bottom of the hull, as seen in Fig. 13 (b). As in the case of fire and the risk assessment that can occur, composite ships are proven to be safer in fire than steel ships. Composite structures do not conduct heat well, so they are inherently safer in small fires [44].

In 1973, the United Kingdom and the United States jointly developed HMS Wilton, the world's first GFRP (Glass Fiber Reinforced Polymer) mine-resistant ship, with a total length of 46.6m. In 1992, France also tested the Lafayette frigate, as seen in Fig. 14 (a), whose superstructure was designed with composite sandwich panels. This is because the superstructure on the ship, as the uppermost makes it when longitudinal deformation occurs on the hull, will give the superstructure a tremendous structural stress value and be at risk of damage. So, the role of composite sandwich panels on the superstructure is needed, which, in addition to the design needs of a strong deck, will also increase the weight, which causes the ship's center of gravity to increase and its stability to decrease. In 2016, the latest Zumwalt (DDG-1000) destroyer, as seen in Fig. 14 (b), was officially delivered to the U.S. Navy, with a total length of 183m, a draft of 8.4m, and a displacement of 14500t Its superstructure is made of composite materials, and the structure above the main deck is hidden inside the superstructure (Tang Composite materials here replacing traditional steel materials in the superstructure are used to not only reduce the weight and center of gravity of the hull structure but also improve the performance and maintain the strength of the ship structure itself [45].

Glass fiber-reinforced Polymer composite applications also play a significant role in the blade of the ship. The main propulsion system on the ship produces thrust by moving the fluid around it. This causes the need for structural strength on the propeller to be reviewed even better where the marine environment is harsh compared to air because the viscous force in water is much greater than the density of air. The large hydrodynamic loads make it subject to strict geometries driven by hydrodynamic design, which limits it to firm and rigid materials.

Recent research identified the composite behavior of glass fiber (GFRP) with carbon fiber (CFRP) in ship blades. Glass fiber (GFRP) composites absorb more energy than carbon fiber (CFRP) composites. Still, the choice of reinforcement type for marine blades usually also considers other factors such as specific strength, stiffness, and water absorption. This is where carbon fiber (CFRP) usually outperforms glass fiber (GFRP). However, various factors need to be reconsidered to get the appropriate composite requirement within the financing budget and long-term use of the blade on a more efficient vessel [46].

In addition to applications in blades, glass fiber reinforced polymer (GFRP) is the most common material used to manufacture ship structures in the hull. Its excellent performance and cost-effectiveness go hand in hand with the hull's need for outstanding characteristics that enable its flexible application. The design and manufacture of composite ship hulls is very complicated. Ship displacement, speed, division, and

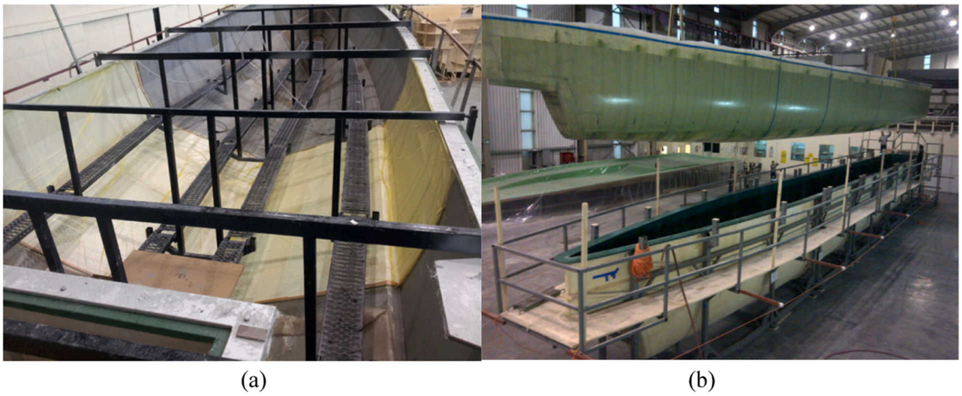

(a) (b)

Fig. 13. Composite hull on ship: (a) Molding a composite hull, and (b) Demolding a composite hull [44].

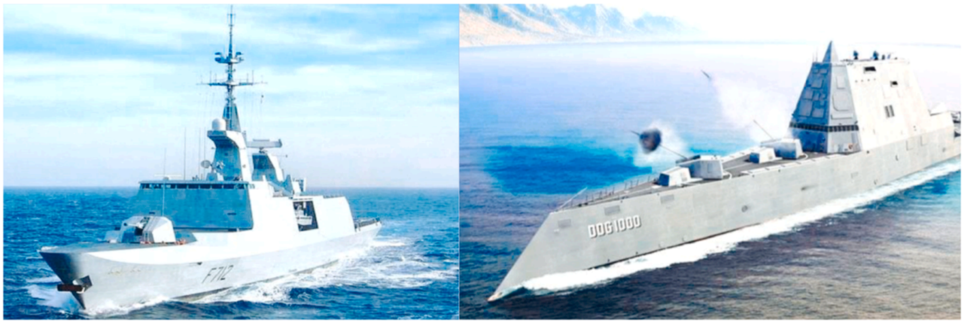

(a) (b)

Fig. 14. Composite Superstructure on the ship (a) Lafayette frigate, (b) Zumwalt (DDG-1000) destroyer [45].

other factors related to the main specifications of the ship, including stiffener spacing and design pressure, must be considered. The mechanical properties of these composite laminates are influenced by the fabric type, combination, and orientation of the fibers expressed in terms of the weight and volume fraction of the fibers and resin that make up the laminate. The need for low-weight hull structures such as fishing boats and yachts has reduced fuel consumption and operating costs and increased speed. Due to the application, the thickness of the composite hull plate varies greatly and can be set according to the size of the structure and the application. The laminate thickness for GFRP ships has a hull plate thickness of 10 mm or more. In the case of naval and coast guard vessels, the thickness may reach several tens of millimeters. Laminates are made from two raw materials and resin, so it is not easy to process composite hull plates to the required thickness [47].

In addition to fishing and leisure boats, the recreational boat industry uses glass fiber, the dominant reinforcing fiber in polymer matrix composites. As a result, the hulls of small boats are primarily manufactured through polyester resin laminates reinforced with mat-type glass fibers due to their low cost, ease of process, good mechanical performance, and resistance to the marine environment. In contrast, the low recyclability after end-of-life becomes an environmental issue.

In another study, natural fiber-reinforced composites (NFRC) have been used for various purposes because they have advantages over synthetic types, such as low density, low cost, biodegradability, minimal waste disposal issues, and environmental friendliness. Hybridization of natural and synthetic fibers in the same matrix is one of the promising strategies that can be used to address structural issues. Synthetic fibers have excellent mechanical and physical properties and compatibility with polymer matrices. They are also very effective in reducing the shortcomings of the natural type [48].

Therefore, applying natural fiber-reinforced composites (NFRC) has gained interest as an alternative to glass fiber-reinforced plastics (GFRP). Natural fibers such as jute, rattan, bamboo, and fique have several advantages, such as lower density, biodegradability, good damping properties, and high health safety over glass fibers. Moreover, their specific mechanical properties are comparable or close to those of glass fiber-reinforced polymers. The methodology is jute-fiber-reinforced-bioepoxy (JFRb) laminate with a vacuum infusion process cured at a specific temperature and followed by a soaking process to produce good water absorption quality. Applying this natural fiber composite is an achievement regarding mechanical properties, but the increase of layer thickness due to this natural fiber makes it heavier than that produced with GFRP. JFRb is one of the alternative applications of GFRP with consideration of its natural properties that are good for the marine environment in the manufacture of recreational boat crafts [49].

In addition to the realm of GFRP small ships, there are needs such as large ships that use aluminum as a consideration for better cost and the mechanical properties of aluminum that are needed in the characteristics of a ship hull structure. The most formidable opponent of aluminum is its high corrosion properties because when exposed to marine conditions containing chloride ions, the disruption of the passive layer initiates the formation of pits. Although pure aluminum alloys exhibit lower corrosion rates, they still suffer from pitting corrosion. Hence, the purity of aluminum is responsible for its pitting attack resistance.

The service life interval of ship hull protection should be one small repair period of 3 years according to the requirements of ship technical performance indicators. AA1050-H14 was found to have higher pitting resistance to lower cathodic intermetallic phases in the alloy. In this study, AA1050-H14 was used as the matrix material, and ZnO was used as the reinforcing material. The samples were processed in NaCl solution, where the composite material added ZnO was processed at a certain rpm to show the difference in anodic polarization results. The corrosion behavior of AA1050 can also be studied by treating the material with the friction stir technique. Selective alloying of AA1050 with ZnO with a rotation speed of 1000 rpm resulted in the highest corrosion resistance. Both polarization and corrosion resistance were obtained. Thus, the passivation application of certain substances hinders the initiation of pit spreading [50].

Laminate material often used in ship applications due to its cost-effective composite system is laminated wood. This laminate overlays multiple veneers in the longitudinal direction and is an alternative to solid or glue-laminated wood. Due to the limitation of large-diameter trees from plantation forests, the availability of large dimension columns and beams made from sawn timber from logs has decreased. Therefore, the research and development of laminated timber or veneer laminated timber (LVL) manufacturing is receiving more and more attention. Its water resistance, strength, dimensional stability, resistance to weathering, and durability make it a reliable choice for various projects. Be it boating, decking, or any other application that requires a durable and reliable material [51].

4. Laminate component layering

In general, the composite itself consists of 3 parts consisting of core, resin, and reinforcement [52]The composite core consists of several layers: polymer fibers, carbon fibers, aramid fibers, and metals such as aluminum and copper. Based on the matrix, composite materials can be classified into two types: metal matrix composites and non-metal matrix composites. Resin serves as a binder to bind the core and reinforcement parts. Resin can be divided into Orthophthalic and Isophthalic, both of which show good mechanical resistance and resistance to water permeability.

4.1. Metal matrix

Metal matrix is a matrix made of metal materials such as aluminum (Al), magnesium (Mg), titanium (Ti), copper (Cu), and nickel (Ni) [53]. The techniques used in composite development, especially for Metal Matrix Composite (MCM), are powder metallurgy, stir casting, spray atomization, squeeze casting, plasma spraying, and co-deposition.

Silicon carbide (SiC), aluminum oxide (Al2O3), and graphite (Gr) have commonly used particle reinforcements for MMCs. In maritime applications, matrix metals are used because they have high stiffness, strength, and corrosion resistance.

4.1.1. Metal matrix composite

4.1.1.1. Aluminium metal matrix composite (AMMC). Aluminum and its alloys are becoming the first choice for marine and offshore structures thanks to their superior mechanical properties, lightweight, and corrosion resistance. Aluminum Metal Matrix Composite (AMMC), which utilizes dispersion strengthening effects, can improve the performance of aluminum alloys. Improvements in strength, fatigue, corrosion, heat, and wear resistance can be achieved through the fabrication of AMMC. Several fabrication methods, including friction stir processing (FSP), are used to obtain the highest quality AMMC. Muribwathono et al. [54] reviewed various types of aluminum with different reinforced materials using the FSP manufacturing process. The FSP method provided several benefits, such as finer grains, zone homogeneity, compaction, densification, and homogeneity of the aluminum alloy with composite precipitates [55]. This review can guide the selection of optimal materials, especially AMMC alloys, for maritime applications still under development.

In 2023, Szymanski et al. [56] accomplished a study to develop a manufacturing method for aluminum alloys. Aluminum Metal Matrix Composite (AMMC) alloys reinforced with ceramic powders in sintered form have excellent abrasive properties, making them attractive materials in technology. However, AMMC alloys reinforced with ceramics face obstacles in the production process due to the low ability of the material to permeate into the ceramic, making it difficult to fill the initial shape of the ceramic. This research uses AlSi11 alloy reinforced with sintered Al_2O_3 and explores the method of making metal matrix composite through the casting process. This method is considered to have the potential to reduce time and cost significantly. However, this method requires further development and research to achieve optimal results.

4.1.1.2. Titanium metal matrix (TMM). In the research by Elanchezhian et al. [52], there are predictions for the potential use of titanium as a coating in composites. They combined grade 5 titanium alloy (Ti-6Al-4V) with a metal matrix alongside Kevlar and carbon fiber, with the aim of implementation in the marine industry, specifically in the hulls of Navy warships. This composite type combines strength, lightweight, and corrosion resistance advantages, making it an attractive option for marine structures.

4.1.1.3. Nickel metal matrix (NMM). Due to their outstanding mechanical strength, advanced mixture safety, and complex process control, nickel composites are increasingly used as critical materials in various applications. A specialty of these composite materials is their ability to withstand extreme working conditions, including high temperatures. Kumaraswamy et al. [57] have investigated the development of nickel as a composite, which provides an overview of the development of nickel composites. The results show that adding reinforcements, such as graphite, silver, and hBn, will improve the material's wear resistance. In addition, extending SiO2 on the reinforced nickel atoms can improve the hardness and durability of the material.

4.1.2. Sandwich composite

One widely used form of composite material is in the sandwich configuration. This is described as a differentiated composite using a multilayer structure consisting of one or more high-strength outer layers, referred to as skins, and one or more low-density inner layers, referred to as cores. The exact definition is still used with several variations of this type of structure. Composite sandwich panels with two relatively rigid surface sheets separated by a lightweight core are attractive to industries that greatly emphasize mass reduction. Sandwich panels are widely used in the transportation, aerospace, automotive, naval, and defense industries. These panels are notable for their high bending and shear resistance. As a result of the growing industrial interest in the use of sandwich panels in recent years, a large amount of research and development on the impact characteristics of sandwich composites has been carried out [58]. The laminated composite structure usually uses a sandwich structure. The structure can be classified into two layers: skin and core. Combining these two main layers can give the sandwich structure a balance of strength, stiffness, and weight.

4.1.2.1. Skin layer. Skin is the outermost layer of the composite laminate structure; the skin makes the main structural surface and affects the strength and stiffness of the composite material / Fiber Laminated Metal (FML) is a type of coating that is widely used as a skin or outer layer in the manufacture of sandwich structures, especially for maritime applications. FML is a composite structure that generally consists of thin high-strength alloy sheets, such as Stainless steel, Aluminum, Titanium, and Magnesium, which are alternately bonded with epoxy resin layers reinforced by fibers such as Kevlar, polyethylene, aramid, glass fiber, and carbon fiber. According to Kazemi et al. [59], FMLs are classified based on four main parameters: metal type, reinforcement type, number of layers, and layer orientation, as illustrated in Fig. 15.

In general, the thickness of the metal alloy layers in FML ranges from 0.3 to 0.5 mm, with predetermined reinforcing materials and resins. An illustration of the interlayer arrangement of FML with Titanium material and three different coating types can be found in Fig. 16.

Several studies on FML (Fiber Metal Laminate) with an aluminum metal layer have been conducted extensively, such as the one conducted by Liu et al. [60] who continued their research with different material variations to evaluate the impact response in sandwich panels with FML skin layers using aluminum alloy. This study used Al sheets and one plan woven E glass prepreg layer. The core used remained the same as the previous study: aluminum foam with the same density. The specimens varied in the order of skin layer buildup, skin thickness, core thickness, and total thickness. The experimental results show that increasing the thickness of FML skin can increase energy absorption during impact, compared with increasing the thickness of the foam core in the composite (see Fig. 17).

In 2022, Mirza et al. [61] conducted research using a skin layer of 2024-T3 aluminum with a composite layer of E-glass. This research aims to maintain the maximum strength of the composite material but with a thinner thickness. The layer stacking configuration used is 2/1, meaning two aluminum sheets and one composite sheet, with different layer thicknesses, namely 0.3 mm for the top layer and 0.5 mm for the bottom layer. The test results showed that thinning the top layer of the skin resulted in the maximum thinning of the part, while the bottom aluminum skin was thinned by 11.318%, 6.32%, and 13.6%, respectively. Using a thinner upper aluminum layer resulted in material cost savings and a reduction in the overall weight of the manufactured component.

4.1.2.2. Core layer. A core is an inner layer between two skin layers in a sandwich structure. It functions as a space or separator between the skins and provides additional thickness to the structure. The material used as the core also has many types and continues to grow. The core is usually metal foam for the composite metal matrix (CMM). The use of cores made from metal foam is intended to reduce the weight of the sandwich layer structure but still has the required strength. 2 previous studies have used aluminum foam cores. Aluminum foam is an aluminum material that has been processed and has a cavity-like foam that is lightweight but also has high resistance. Aluminum is widely used in maritime applications, especially in the manufacture of ship structures.

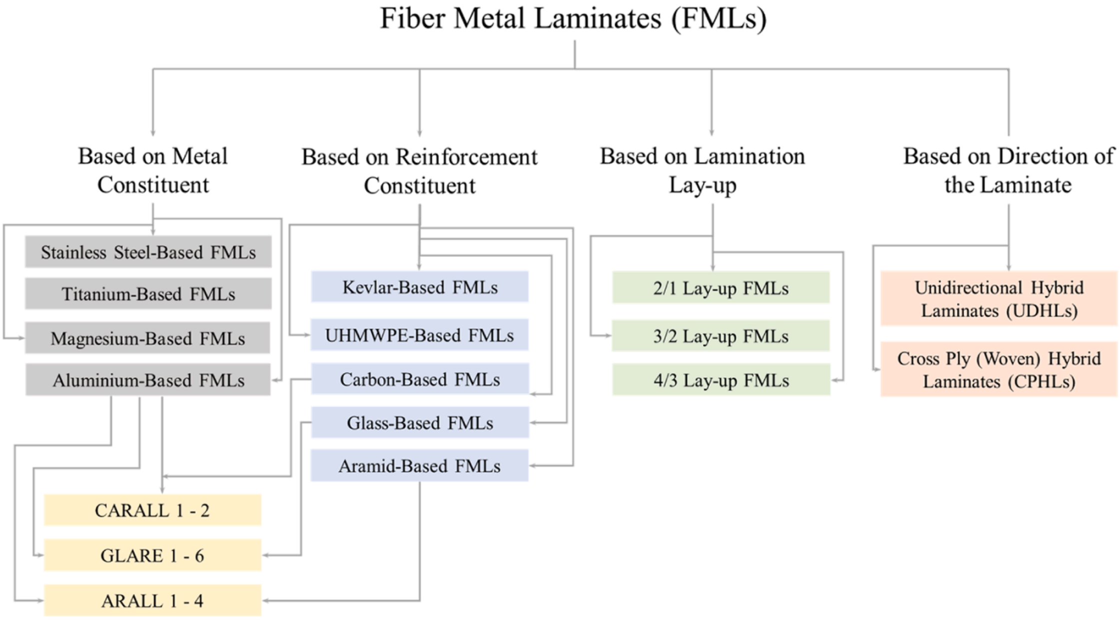


Fig. 15. Classification of FML [59].

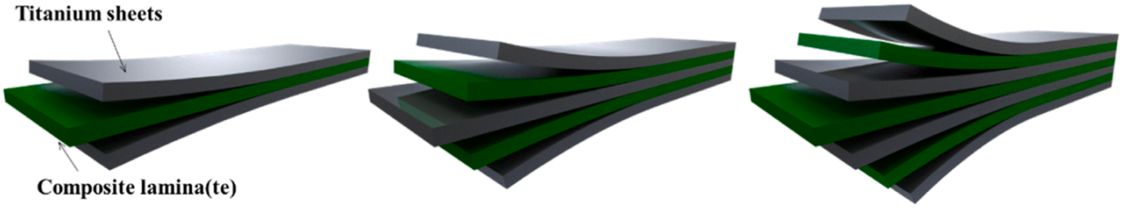


Fig. 16. Illustration of FML layer preparation with titanium material in 1, 3/2, and 4/3 lay-up configurations [59].

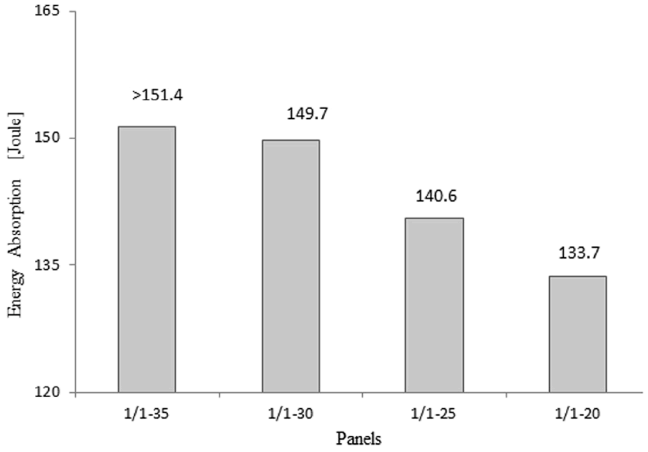


Fig. 17. Foam core thickness effect on energy absorption [60].

In 2016, Lamanna et al. [62] developed a composite sandwich core with aluminum syntactic foam as the core. Unlike aluminum foam, aluminum syntactic foam incorporates porosity in the foam structure through hollow particles dispersed in the matrix. This syntactic foam has good compressive loading resistance and is suitable for maritime applications constantly exposed to vibration. This study's aluminum syntactic foam core is A356 aluminum filled with alumina hollow spheres (Al_2O_3-HS). The carbon skin for the outer layer uses a simple wave pattern with a linear density of 0.193 kg/m^3. An illustration of the syntactic foam core layer can be seen in Fig. 18. This study aims to analyze the dynamic effects, and the experimental results are used to validate the theoretical analysis. The results showed agreement between the experimental results and the theoretical analysis.

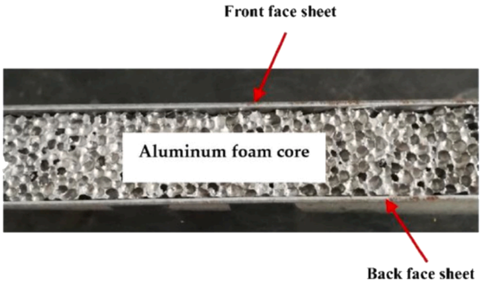


Fig. 18. Illustration of synthetic foam core layer with alumina hollow spheres [63].

A recent development in the core layer of sandwich structures is the development of metal rubber cores, which have been investigated by Xue et al. [64]. This study aims to analyze heat transfer in cylindrical shells. Metal rubber is a porous material with a particular network structure containing stretched and helical metal wires in the forming tool. It has high elasticity, strong damping ability, and is resistant to high temperature, weather, and corrosion. Sandwich cylindrical shell with metal rubber (SCS-MR) has great potential for applications in high-temperature environments as it overcomes thermal resistance issues, reduces vibration, and is lightweight. However, theoretical and experimental testing is needed to understand its characteristics better.

4.2. Non-Metal matrix

The matrix comprises non-metallic materials such as polymer (PMC), ceramic (CMC), or a mixture of carbon fiber and epoxy resin. It is used in maritime applications because it is lightweight, corrosion-resistant, and flexible, and its stiffness and strength can be adjusted based on the type of fiber used.

4.2.1. Skin layer

The skin layer of a laminated composite is the outermost component that requires high strength and impact resistance. Achieve strength comparable to metallic coatings, even when using a non-metallic matrix, is critical in its development. Its main advantage is its lightweight structure. Fiber Reinforced Polymer (FRP) is a commonly used material in maritime applications, with various reinforcing fibers such as Aramid, Carbon, Glass, and Basalt. FRP is used as the outer layer in laminated composite due to its proven strength and corrosion resistance. However, manufacturing composite coatings for maritime applications often entails high costs. To keep costs affordable, Kumar et al. [65] developed a hybrid composite made from carbon fiber and glass fiber (see Fig. 19). This research showed that hybrid composites have advantages over composites made from only one type of fiber, with lower water absorption and higher impact resistance. The hybrid composite with layers of glass, carbon, glass, glass, and carbon [GCG_2C] showed the best results in this study.

Adhesive resin is a crucial component in the outer layer of laminated composite that affects the material's overall strength. Proper resin selection is essential, as exposure to seawater can reduce the flexural and tensile strength of the composite. To compare the strength of composites, especially the adhesive, Spasova et al. [66] presented a study that compared the strength of composites with polyester resin matrix and vinyl ester resin matrix. The research involved two types of specimens: the first consisted of 6 layers of fiberglass, known as Fiber Reinforced Polymer Matrix Composite (FRPMC), and the second had a combination of reinforcing fibers from 3 layers of fiberglass and three layers of biaxial fiberglass, known as Biaxial Reinforced Vinylester Matrix Composite (BRVMC). The results show that BRVMC composites with biaxial fibers are more robust than FRPMC. This suggests that BRVMC is more suitable for marine environment applications than FRPMC, highlighting the positive influence of biaxial fibers on the strength of composite materials. Biaxial itself is a composite that uses two different fiber direction orientations, such as 0°/90° and 45°/-45° layers. Research conducted by Waqas et al. [67] were also proved that the layup angle or fiber orientation of each layer of composite material has a big influence on and can increase the strength of the material.

The strength of the composite layer can also be increased by adding additional components, such as new materials, to the fibers. Kumar et al. [68] added nano-TiO_2 particles, which are inorganic nanofillers intended to close the pores/voids in the composite to increase interface strength. The type of composite added with particles is the GFRP type, where the addition is made to the polyester resin mixture using a manufacturing method, more or less. It is known that adding 0.1% nano-TiO_2 can reduce the diffusivity of seawater. Adding 0.1% nano-TiO_2 in GFRP can increase flexural and interlaminar shear strength (ILSS).

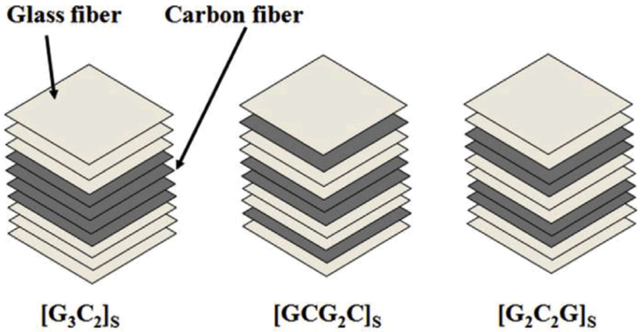


Fig. 19. Schematic diagram of the stacking sequence of the hybrid composite laminates [65].

4.2.2. Core layer

The core is the layer in sandwich structures, which plays a crucial role in determining the strength of non-metallic composites. The strength of a sandwich composite structure depends on the reliability of the core layer, which provides essential support for the entire structure. Typically, cores in non-metallic composites use fiber blends tailored to specific needs. Foam cores are becoming a common choice for composite contents, with adhesives such as polyvinyl chloride (PVC) distinguishing them from metal matrices. In the marine industry, the combination of fiberglass fibers with vinyl ester resin and PVC foam core has been commonly used for the manufacture of sandwich composites [69]. However, using foam cores in maritime applications requires further research as they tend to absorb seawater.

A study by Ding et al. [70] in 2018, the effect of PVC foam core aging in a marine environment was evaluated. Divinycell H80 PVC foam core was selected based on its strength and stiffness. The skin layer uses E-glass multi-axial fabric EKTI 200, which has been proven to have adequate strength. The results showed that water absorption in the composites was affected by the oscillating hydrothermal atmosphere and thermal cycling, with a decrease in stress strength as the aging time of the sandwich composite with PVC foam core increased. According to Balıkoğlu et al. [71], the performance of PVC foam cores can be improved through surface modifications. These modifications include making nets, grooves, and perforations on the PVC foam core. The results showed that modification in the form of making perforations in PVC foam core can increase the ultimate flexural strength. This is due to the ability of the resin component to enter and fill the shape of the perforations, which, in turn, increases the flexural strength of the composite. However, this change also has an impact on the weight of the resulting composite as well as the amount of resin used.

In addition to foam cores, core layers in sandwich composites are also developed in various structural forms, such as honeycombs, corrugates, Y-shapes, and others, specifically designed to dampen vibrations and absorb energy. Although their structure differs from foam cores, core layers of various shapes still have relatively similar capabilities. Research results by Mahesh et al. [72], on foam 81 and honeycomb cores showed that both have almost the same energy absorption capability. In 2018, using the hot-press molding method, Liu et al. [73] developed Y-shape cores from unidirectional carbon/epoxy with different layer variations, namely eight layers, 12 layers, and 16 layers. The Y-shaped core, whose geometry is customized to form the letter Y, is made of composite material with customized Y-shape geometry. The Y-shape geometry was set with fixed parameters for $h = 18$ mm, $H = 27$ mm, $e = 2$ mm, and $\propto = \pi/4$, as illustrated in Fig. 20. Differences in the thickness parameter t will result in variations in the density of the Y-shape core structure, as shown in Table 1. This study showed that the density parameter t in the Y-shape core will affect the sandwich composite material's energy absorption capability and mechanical strength. Increasing density or layer thickness increases energy absorption capability and overall mechanical strength.

Fiber Metal Laminated (FML) can use metal or polymer matrix materials. Natural fibers are essential to produce economical, recyclable, and environmentally friendly composite materials. Natural fibers have properties that are more resistant to abrasion and mold compared to synthetic fibers. Some natural fibers used in composite manufacturing include jute fiber, truss core, bamboo fiber, and sisal fiber. The use of sisal fiber in the core layer with an aluminum layer as skin (SiRAL) shows high tensile and flexural strength, so it has the potential to be developed as a cost-effective, multifunctional, and environmentally friendly structural application. Core characteristics, such as strength,

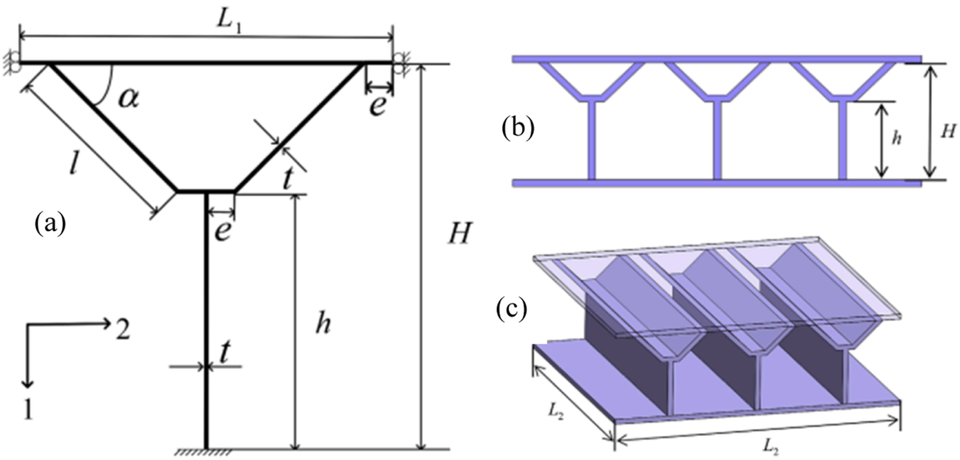


Fig. 20. Y-shape geometric (a) sketch of the unit cell; (b) Schematic cross-section; (c) Schematic 3D geometric model [73].

Table 1
Relative densities for sandwich structure fabricated from different layers of unidirectional carbon/epoxy prepreg [73].

Number of layers	8	12	16
Relative density	5.34%	7.95%	10.53%

stiffness, and weight [74].

The future development of core layers in composites is expected to be dominated by hybrid materials that incorporate natural fibers. Recent research by Afolabi et al. [75] examined hybrid composites using a syntactic foam composite core made from hollow glass microspheres (HGM) and epoxy resin. Although the use of natural fibers in the skin layer may slightly reduce the toughness of the composite, strength improvements can be made in the core. Previous studies have shown that HGM has sufficient strength to seal porosity and reduce weight. Hence, combining synthetic foam composite with HGM as core in sandwich composite with natural fiber hybrid skin is an attractive alternative. Thus, the physical and mechanical properties of Synthetic Foam Core (SFC) are expected to improve significantly. For applications in marine structures, hybrid composites with modified natural fibers in sandwich composites are expected to perform better than single fibers. In addition, using natural fibers is also considered to reduce production costs and support environmental sustainability.

5. Join method

Joining parts in maritime applications is crucial as it directly impacts the structure's lifespan and integrity. Marine structures located in coastal, offshore, and deep ocean waters routinely experience cyclic mechanical loads, including forces and moments resulting from environmental factors such as wind and waves and service factors like operations and machining [76]. An illustration of the loading on a cruise ship can be found in Fig. 21, which depicts the loading on a maritime structure as a whole. Particular attention should be given to the importance of the joining method in laminated composite structures. There are two main aspects in laminated composite joining: the joining between layers in one composite material and the joining between two or more different composites. The process of joining fibers in composites utilizes various methods, depending on the type of material used. The choice of adhesive material is a critical aspect in designing the joining of composite layers.

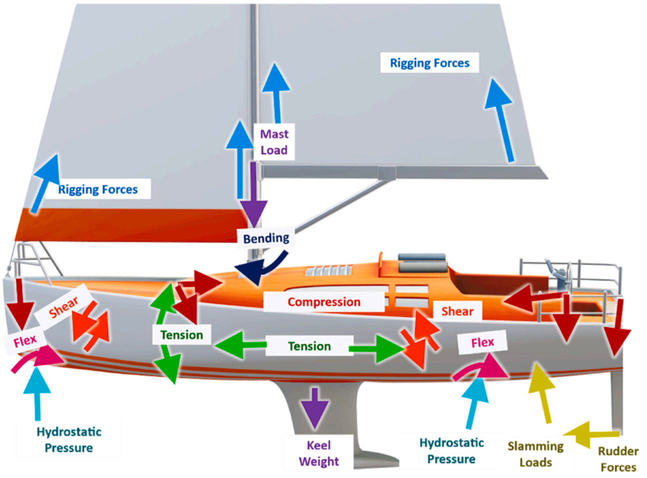


Fig. 21. Schematic illustration of various loads on a yacht [77].

5.1. Vacuum

Several methods combine laminated composite layers, namely hand lay-up, vacuum bagging, spray lay-up, pultrusion, resin transfer molding, filament winding, compression molding, injection molding, and thermoforming [78]. The vacuum method is the most effective in maritime applications because it produces products with optimal characteristics [77,78]. However, the hand lay-up process is often used in the marine industry for joining components using the over-lamination method due to its practicality and flexibility in certain situations [74]. This suggests that while the vacuum method excels in producing high-quality products, the hand lay-up process is more commonly used for specific applications where ease of use and adaptability are prioritized. Therefore, the research conducted by Kim et al. [79] compared the strength and durability of composites combined with hand layup and vacuum infusion methods. GFRP processed by vacuum infusion had greater average ultimate strength and modulus than GFRP samples processed by hand layup in tension and compression tests. This is mainly due to the higher fiber volume fraction of the vacuum infusion processed samples. In the punching shear test, the samples processed by vacuum infusion had greater values of shear strength and displacement versus thickness than the samples processed by hand layup due to the increased porosity in the hand layup. Modification by combining composites from hand layup and vacuum infusion (Hybrid) methods was carried out to obtain composites with excellent durability.

Several types of vacuum methods are used for joining composite layers. One of them is vacuum hot-pressing, used to connect Ti-Al laminated composite materials in tests conducted by Qin et al. [80]. The procedure of using vacuum hot-pressing on Ti-Al Laminated material is by stacking Al and Ti in the vacuum hot-pressing furnace alternately consisting of 5 Ti layers and 4 Al layers with different loadings (see Fig. 22). Al and Ti must have been cleaned before pressing to remove the oxide layer and contaminants. Once the foils are stacked in the chamber, a pressure of 5 MPa is applied with loading control at room temperature to ensure good contact between the foils. Then, the samples were heated in a 10–3 Pa vacuum chamber at 550 °C for 3 h while maintaining the pressure to allow diffusion bonding of the layers. Finally, the samples were cooled in a furnace to room temperature.

The vacuum method is also applied to connect laminated composite through the vacuum diffusion bonding technique. In general, laminated composites connected by vacuum bounding are dominated by metallic materials. Some studies, such as the one conducted by Wang et al., show the applicability of this technique in joining two different types of metals, such as CuW and Al. [81]. However, metallic materials such as Ni-base superalloys are also used for maritime applications because they are highly corrosion-resistant [82,83]. As an innovation, super-Ni/NiCr laminated composites, consisting of a super-Ni cover layer and a Ni80Cr20 sintered base layer, have been proposed. Jian et al. [84] described that incorporating this material with other composites requires a vacuum diffusion method that connects the TC4 material. Joining was carried out at 950 °C for 30, 60, and 90 min with the addition of interlayers to improve the strength of the joints. The results show that adding interlayers, such as Cu+Ti composites, can increase the maximum shear strength of the joint to 72.4 MPa for 90 min under vacuum conditions.

5.2. *Adhesive*

Composite materials are joined using a combination of mechanical fasteners and adhesives, with the choice of joining technique depending on the specific application and material properties. In aircraft applications, composites are typically joined using a combination of mechanical fasteners and adhesives. In contrast, in the automotive industry, composites are often joined with adhesives only. For composite joints, various mechanical fasteners such as rivets, pins, two-piece bolts, and bolted fasteners made of materials such as titanium, stainless steel, and aluminum are used.

An adhesive is a material that acts as an adhesive between two or more surfaces, allowing adhesion to the surface of its substrate. The ability of an adhesive to form a solid bond between two dissimilar materials not only enhances structural integrity but also provides optimal continuity of function in various applications. Adhesives come in many forms, from liquid to solid state, and are classified based on several criteria, including chemical composition, curing method, bond strength, and shape. The use of adhesives as joints in composite materials is justified by their ability to increase the strength of composite materials. Carefully selected adhesives can significantly increase mechanical strength, prevent cracking and fracture with even load distribution, adjust the thermal coefficient to reduce stress and deformation and dampen vibration. In addition, using adhesives also provides advantages such as weight efficiency, design flexibility, and efficient production processes. Choosing the suitable adhesive and understanding its functional advantages are crucial in improving the performance of composite materials [85].

In the adhesive method, an adhesive is applied to the surfaces to be joined and subsequently bonded together. Many examples support selecting appropriate adhesive joints for different types of mechanical loads [86]. Various types of joints, including single lap joints, double lap joints, tapered lap joints, shawl joints, butt joints, strip joints, double strap joints, tapered double strap joints, and stepped lap joints, can be applied to connect composite structures, as seen in the illustration in Fig. 23. The main advantages of using adhesive joints include superior fatigue strength and lightweight structure. Bonded joints feature lighter weight, more affordable cost, corrosion resistance, and sustainability against damage. No machining operations, such as drilling, are required for bonded joints. This type of joint offers greater flexibility and inhibits crack propagation in the adhesive layer, thus increasing its fatigue life.

Several factors affect the strength of the connection using this adhesive, ranging from the geometry of the connection, the adherend in the connection, the surface preparation of the adherend, the connection method, the type of adhesive, and the thickness of the adhesive.

5.2.1. *Adherend surface preparation*

One of the most sensitive aspects of making an adhesive joint is the surface preparation of the substrate. The bond’s quality depends on the adhesive’s quality and the preparation of the surfaces to be bonded. Sample preparation consists of cleaning the adhesive surface to remove grease or dirt that reduces the wettability of the adhesive and abrasive surface treatment (blasting) to remove contaminating substances, increase roughness, and chemically modify the surface to form polar groups that increase surface energy [88].

5.2.2. *Adhesive type*

Bound Joint Adhesive is increasingly being improved in terms of its load-bearing effectiveness to further streamline the connection time and reduce the cost. The Single Lap Joint (SLJ) is the easiest and most used joint. Usually, only one type of adhesive material is used, as in the research of Moya-sans et al. and Figueredo et al. [89]. Some studies try to develop adhesive joints with more than one adhesive material, also

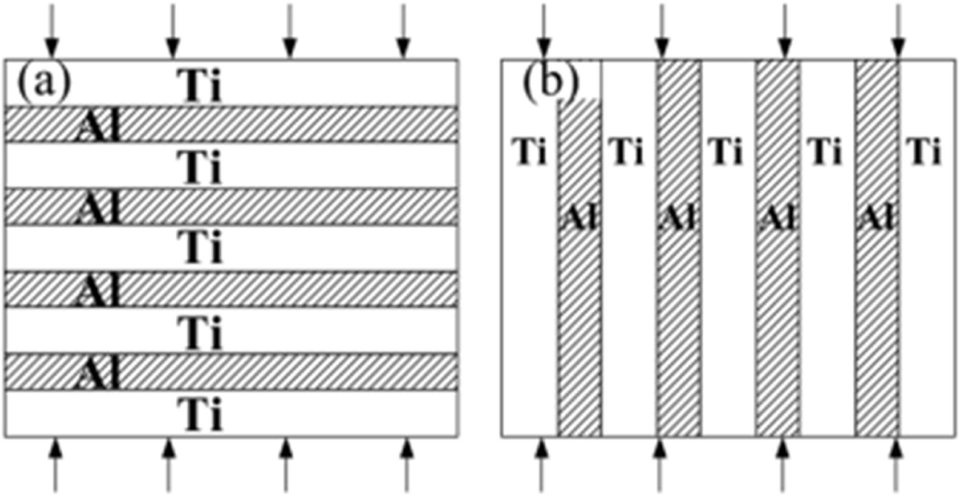


Fig. 22. Loading Configuration (a) morphology of the bonding interface of TI/Al laminated composite. (b) element distribution at the bonding interface [80].

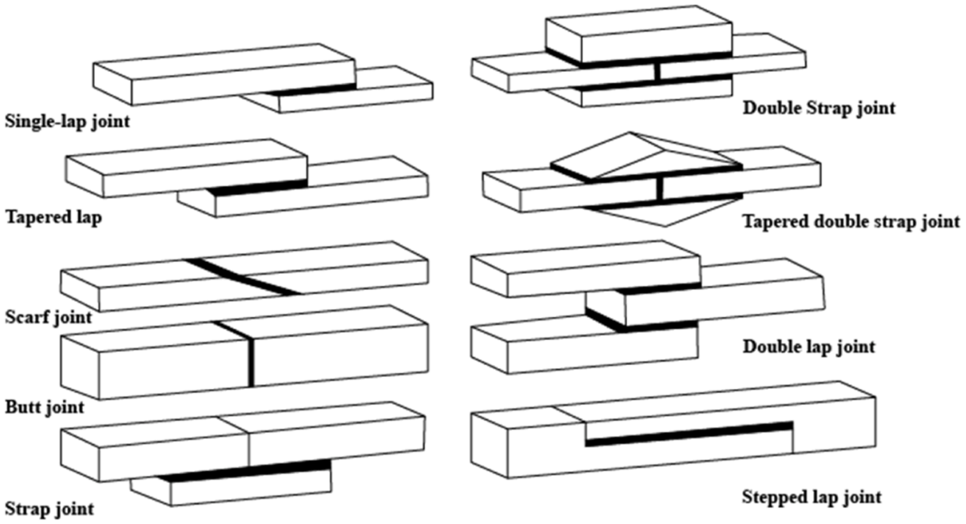


Fig. 23. Various types of adhesive-bonded joints (Redraw based on Jeevi et al. [87]).

called mixed adhesive joints, where two different adhesives (ductile and brittle) are used in one joint. Mixed adhesive joints are used to avoid the formation of non-uniform stress distribution in the joint. The study used Brittle adhesive at the center, and Ducktile adhesive was placed at the overlap. Where higher stress concentrations occur (see Fig. 24) [88]. The mixed adhesive design is an alternative for cases where there are significant differences in the properties of two different adhesives and where the joint must be in specific environmental conditions [90].

Jairaja and Naik [90] investigated multiple adhesive joint configurations, exploring two different overlap lengths of 20% and 40% for brittle adhesives (L_1/L). They used two types of adhesives, namely AV 138 (as brittle adhesive) and Araldite 2015 (flexural adhesive), in single lap joints with different adherents. The experimental results, illustrated in Fig. 25, revealed that a length ratio 0.2 provided the highest failure load in both brittle and flexural reference single-lap joints. In contrast, the configuration with a length ratio of 0.4 exhibited a lower failure load than the single lap joint using the flexural adhesive alone. In addition, a parallel numerical analysis was performed, which showed that using dual adhesive layers resulted in lower stress concentrations at the edge of the overlap (see Fig. 26). The mixed adhesive line with 20% brittle adhesive showed higher bond strength than the single adhesive joint using both brittle and flexural adhesives. In contrast, the mixed adhesive line with 40% brittle adhesive showed lower strength when compared to the flexural adhesive.

Alia et al. [91] developed a new adhesive material, polyurethane, specifically for maritime structures. This study evaluated the adhesive durability and joint performance under maritime conditions. These tests are essential because the mechanical properties of adhesives can change over time, especially when exposed to variable loads and the simultaneous effects of temperature and humidity. Therefore, specialized testing is required to ensure that adhesive joints can optimally maintain their function and mechanical performance in a maritime environment.

Before undergoing testing, a mathematical analysis of the forces acting on the test material using the cohesive law with various loading modes was performed to identify assumptions related to cracks in the material. The connection type used was a multi-cantilever beam (MCB), and the material tested was cold-rolled steel, as it is often used in maritime applications and has a uniform thickness. Its composition is similar to conventional carbon steel.

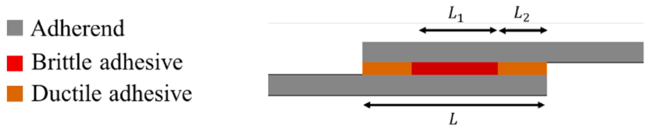


Fig. 24. Mixed adhesive joint [88].

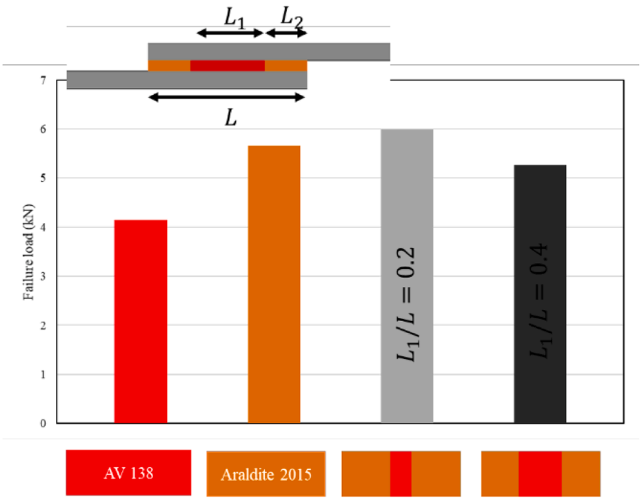


Fig. 25. Effect of length ratio on failure load in mixed adhesive joint [88].

The adhesive used consisted of two components (RE 11,820–9 and AXSON), and their properties are listed in Table 2. The tests included mode I shear stress and mode II normal stress for adhesive joints immersed in seawater. The results showed that the cohesive behavior of tangential stress was higher than that of normal stress, indicating that steel with polyurethane adhesive joints immersed in seawater exhibited optimal performance when exposed to shear stress (mode II). In addition, immersion in desalinated water favors the joints, especially when exposed to mode II normal stress and modes I and II tangential stresses. The low normal and tangential stresses of the joints in seawater indicate that the joints undergo a progressive degradation process.

5.2.3. *Joint geometry*

The shape of the joint affects its strength and geometry. Moya-Sanz et al. [92] conducted a study to determine the effect of the geometry of the materials bonded in adhesive joints, comparing the Single Lap Joint method with different geometry variations. Single Lap Joint is often used because of its simple geometry and structural efficiency. Five different geometries of Single Lap Joint were investigated: single lap

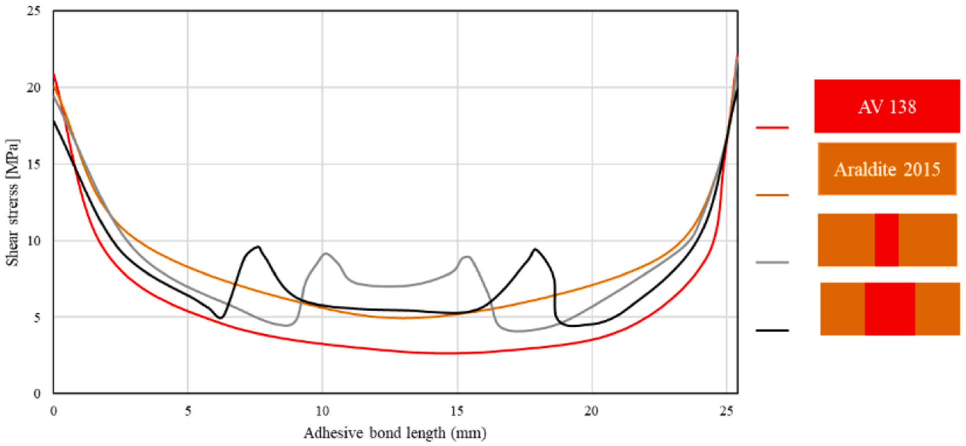


Fig. 26. Effect of length ratio on shear stress distribution in mixed adhesive joint [88].

Table 2
Properties of polyurethane adhesive [91].

	Polyurethane (RE 11,820 de AXSON©)
Tensile strength (MPa)	6
Elongation at break (%)	120
Viscosity at 25 °C (mPa s)	4500
Pot life at 25 °C (min)	10

joint as validation, adherend recessing, adherend chamfering, adhesive chamfering, and adhered you adhesive chamfering with the same slope. Configuration (1) is used as a single lap joint with different overlaps that differ (from 10 mm to 80 mm). Configuration (2) includes three recesses of the adherend (1.6, 1.2, and 0.8 mm), with recess lengths between 2.5 mm and 22.5 mm. In configurations (3) and (4), the adhesive and adhesive chamfer has an angle between 15° and 90°. The latter configuration considers the adhesive and adhesive chamfer together, with the same angles as in configurations (3) and (4). All cases studied show a total length of 240 mm. In configurations (2), (3), (4), and (5), the overlap length (Ls) is equal to 40 mm (see in Fig. 27)

The adherents were made of unidirectional carbon-epoxy pre-preg lay-up with a thickness of 0.15 mm on each ply and bounded with an epoxy adhesive Araldite 2015. In all study cases, the best depth/length relationship for improved mechanical strength was between 0.064 and 0.32. The most significant variation appears in the case of the most considerable recess depth, 1.6 mm, because it is geometrically most different from the reference configuration. The recess causes a peel stress peak in the adhesive at the point where the recess is created, but this peak does not limit the strength of the joint, as the peel stress peak at the end of the adhesive is much larger. It can be concluded that the most crucial parameter in joint strength, in our case, is the value of the recess depth and not its length. Recess depth was found to be responsible for reducing the peel stress peak due to the decrease in cross-section at the overlap end. It was also found that chamfering the adherents and adhesive at a 15° angle resulted in the highest failure load and reduced vertical displacement and peak peel stress. This configuration was identified as the most influential parameter governing the strength of the adhesive joint. The peak peel stress reduction in chamfering was attributed to a reduction in the eccentricity of the load and a gradual change of cross-section at the end of the overlap. Overall, the chamfering of adherents and adhesives was identified as the best option for improving the mechanical strength of single-lap adhesive joints in composite laminates [92].

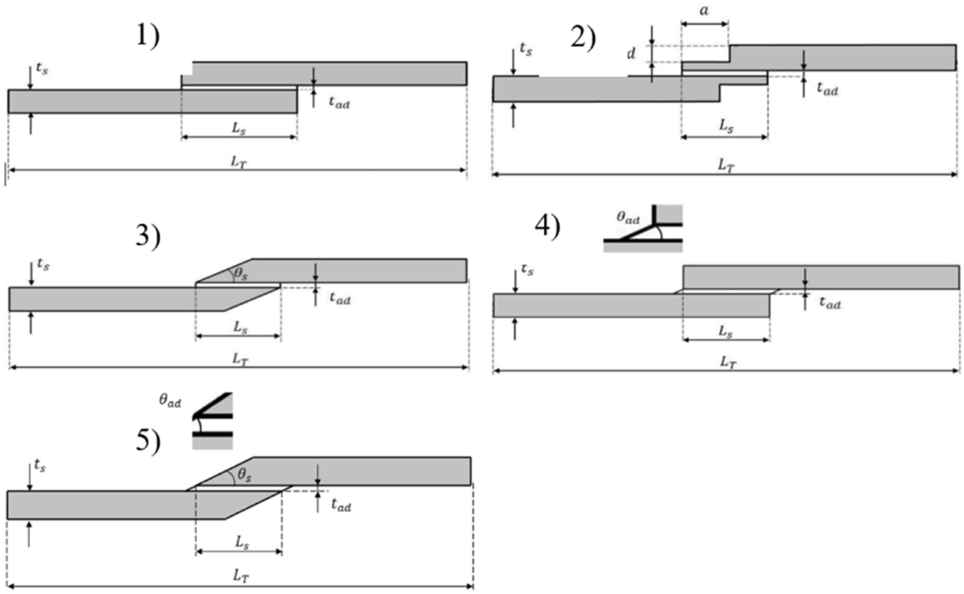


Fig. 27. Configurations joints: (1) Single-lap joint, (2) adherend recessing, (3) Adherend chamfering, (4) Adhesive chamfering, and (5) Adherend and adhesive chamfering [92].

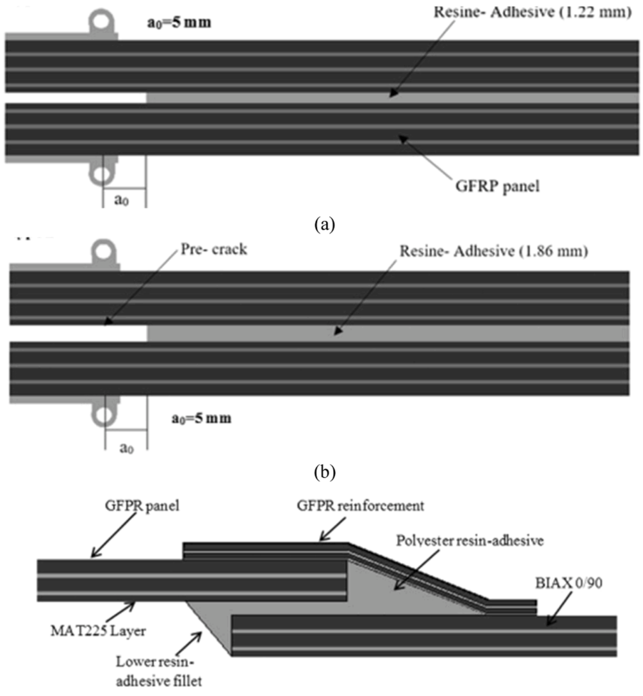
5.2.4. *Joint type*

Carvajal et al. [93] conducted a study in 2020 that investigated the utilization of adhesive as a joint in composite materials. This research focused on the strength of adhesive joints in high-speed craft, particularly on the impact fatigue applied to them. Composite joints are applied to connect single hulls and decks in several fast boat designs. The use of adhesive joints was chosen due to their proven advantages, such as better stress distribution, superior fatigue performance, and increased stiffness compared to conventional bonding methods [85]. This study used adhesive bonding on GFRP panels with two types of joints tested, Single Lap Joints (SLJ) and Double Cantilever Beams (DCB), with different adhesive thickness variations. Further illustrations can be found in Fig. 28.

The tests involved impact fatigue, constant amplitude, and quasi-static crack propagation tests. The test results showed that thinner-thickness DCBs produce higher GIC values. At the same time, thicker adhesives can increase the energy release rate (Glth) values under impact and constant amplitude fatigue conditions. According to the modified Paris law coefficients, increasing the thickness of polyester resin adhesive reduces the fatigue durability under impact fatigue and constant amplitude fatigue conditions. The growth rate of fatigue cracks mainly increases under impact fatigue, and the cyclic impact load can increase the crack propagation rate, especially in high-speed ships.

5.2.5. *Adhesive thickness factor*

The thickness of the adhesive layer significantly influences the quality of the joint. Figueiredo et al. [89] studied Double Cantilever Beam (DCB) joints using specimens made from carbon-epoxy precursors bonded with a thin layer of Araldit 2015 adhesive. The composite adhesive was made from unidirectional pre-preg (SEAL® Texipreg HS 160 RM; Legnano, Italy) with a layer thickness of 0.15 mm. The manufacturing process involved manually stacking 20 unidirectional layers, then curing in a hot plate temperature (130 °C) and pressure (2 bar). The thickness of the adhesive was varied (t_A) between 0.1 mm and 2 mm using the ENF test method, which applies a 3-point bending load to the specimen. This study also applied four reduction methods, namely the Compliance Calibration Method (CCM), Direction Beam Theory (DBT), Corrected Beam Theory (CBT), and Compliance-Based Beam Method (CBBM), to estimate the critical energy release rate (GIIC) and shear cohesive zone model law (CZM). In addition, this study involves numerical analysis with the inverse data fitting method to estimate the unique shear CZM law, which is used to predict joint strength. The results show that increasing the adhesive thickness (t_A) can increase the critical energy release rate (GIIC) to a certain threshold, after which the parameters stabilize, as shown in Table 3. This behavior is due to the expansion of the fracture process zone (FPZ) and the reduction of the adhesive's limiting effect. This study also highlights adhesive ductility's significance, where adhesives with high ductility properties can increase joint strength due to their ability to deform plastically and distribute stresses more evenly. These findings provide insight that adhesive thickness (t_A) plays an essential role in the fracture behavior and strength of adhesive joints, particularly in composite structures [89].



(a) (b) (c)

Fig. 28. Joints tested (a) Double Cantilever Beams adhesive 1.22 mm (b) Double Cantilever Beams adhesive 1.86 (c) Single Lap Joint [93].

5.3. *Future researches*

One of the challenges in joining using adhesives is the potential for delamination in the joint, which can result in reduced performance. Ramezani et al. [94] responded to this problem by developing research to strengthen Single Lap Joints (SLP). The approach involves strengthening the adherend by replacing the Carbon Fiber Reinforced Polymer (CFRP) layer with polymer on the adherend surface. Varying the thickness of the polymer layer and the metal inserted in the adherend also affects the joint's resistance to failure load and failure mode.

Using cohesive zone modeling, numerical analysis was performed for quasi-static and intermediate rate conditions. The results showed that adding aluminum and polymer can increase the failure load under quasi-static and intermediate load conditions. The increase was mainly observed under intermediate load loading conditions. Reinforcement of joints with aluminum or polymer at the adherend showed the highest load resistance when the reinforcement reached 25% in aluminum and polymer. This finding indicates that reinforcement with these materials can positively affect joint durability and performance, especially under intermediate loading conditions [95].

In the future, more research on connections will be carried out to find more detailed designs for connections. Experimental methods are tested to obtain data validation between various types of connections for marine energy composite structures [96]. Along with the industry's growth, research continues to be developed to explore the connection of composite materials used in the future, such as thermoplastic composites and recyclable resin systems. Future research can use numerical simulation or Finite Element Method (FEM) with data validation from experiments that have been carried out so that it is not too costly. Apart from the type of connection that continues to be developed, testing with more than 1 factor of safety parameters. The connection of the structure will be estimated to be stronger if, during testing, it is monitored by the Three Structural Health Monitoring (SHM) techniques, including Acoustic Emission (AE), Fiber Optic Sensor (FOS), and Digital Imaging Correlation (DIC) to assess connection damage during testing [97].

6. Material characteristic

Structures made of composite materials have a wide range of applications. The application of composite structures is increasing, especially in weight-sensitive applications, due to the high specific strength and specific modulus of fibrous composite materials. and specific modulus of fibrous composite materials. Laminated composites allow the designing of structures with the desired strength and stiffness in every direction. Behind the advantages of laminated composite structures such as plates and shells, stresses in out-of-plane stresses appear in these structures, especially near the edges, and lead to complex 3D stress states in these structures under simple loads such as tensile, bending, twisting, and fatigue, which can lead to delamination and local failure in these

Table 3
G_{IIC} [N/mm] as a function of t_A for all data reduction methods [89].

t_A [mm]	Method	1	2	3	4	5	6	7	8	Average	St.Dev.
0.1	CCM	–	–	3.099	2.699	2.363	3.381	*	2.370	2.782	0.403
	DBT	–	–	3.090	2.556	2.457	3.329	3.287	2.669	2.898	0.351
	CBT	–	–	3.036	2.423	2.317	3.034	2.978	2.606	2.732	0.297
	CBBM	–	–	3.093	2.721	2.832	3.181	3.109	2.611	2.925	0.214
0.2	CCM	*	5.030	*	4.796	5.568	4.021	5.106	4.644	4.861	0.474
	DBT	5.282	5.295	5.071	4.800	5.179	4.769	4.941	4.890	5.028	0.196
	CBT	5.482	5.127	4.972	4.049	4.594	4.752	4.518	4.553	4.756	0.409
	CBBM	5.589	5.339	5.009	4.618	4.860	5.508	4.713	4.839	5.059	0.347
0.5	CCM	6.861	6.975	5.715	7.166	6.012	6.748	*	6.341	6.545	0.497
	DBT	6.108	7.703	7.242	7.354	6.927	6.356	6.935	7.599	7.028	0.530
	CBT	6.159	7.488	6.389	7.477	6.798	6.107	9.192	7.217	6.728	0.558
	CBBM	6.595	7.802	7.096	7.855	7.002	6.652	6.552	7.716	7.159	0.522
1.0	CCM	–	–	10.298	12.055	10.867	9.025	9.499	–	10.349	1.064
	DBT	–	–	10.995	10.963	9.115	9.847	8.548	–	9.894	0.977
	CBT	–	–	9.756	10.129	9.138	9.407	8.972	–	9.498	0.447
	CBBM	–	–	10.702	10.336	9.253	10.10	9.837	–	10.047	0.488
2.0	CCM	10.85	–	10.26	8.036	–	–	8.534	8.811	9.301	1.075
	DBT	9.192	–	9.797	7.770	–	–	8.644	10.23	9.128	0.867
	CBT	7.909	–	7.996	8.468	–	–	10.97	7.062	8.483	1.328
	CBBM	10.50	–	10.57	10.50	–	–	10.22	9.942	10.348	0.237

structures. Usually, the classical shear deformation theory cannot predict the complex 3D stresses in the structures. Predicting the 3D stress state of composite structures such as plates and shells is one of the research interests in mechanics. Shells are one of the research interests in the mechanics of mechanics, and various analytical and numerical methods are presented for modeling and predicting complex 3D stresses in composite structures. Analytical solutions for predicting interlaminar stress in the general case have yet to be found, and many numerical and approximate technical methods have been presented for three decades. Torsion, Tensile, bending, and fatigue of laminates due to torsion, as well as out-of-plane and in-plane stresses, are studied for various ply arrangements [98].

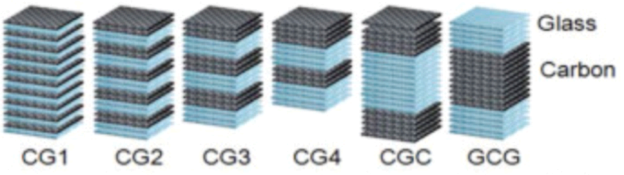
6.1. Tensile

Submarines have recently been used as navigation and research tools to explore the deep sea and to perform more specific functions such as search and rescue missions or submarine cable repairs. Since the development of submarines, many different materials, including wood, steel, and composite materials, have been tried. Davies studied titanium materials for bow construction. Manned deep-sea submarines that can reach depths of 6000 m (Nautile, France, Shinkai, Japan, MIRs, Russia, Alvin DSVs, United States) use composite materials such as glass-reinforced composites to reduce tensile forces and titanium alloys for the submarine.

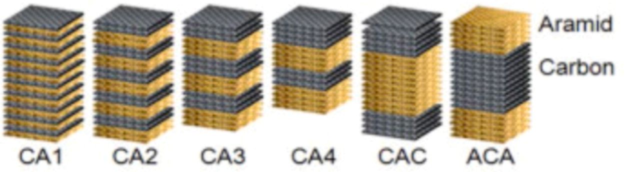
The nature of loading in the uniaxial tensile test differs from the three-point bending test. For example, the stress and strain during tensile testing will be homogeneous in the elastic region during loading, assuming no localization effect. In contrast, in a bending test, when a specific part of the sample is in the tensile mode, other parts of the sample will be subjected to compression; it also takes on the shear component of the stress. The above reasons may lead to lower flexural properties compared to Tensile properties. Brittle materials are susceptible to defect populations, so they tend to have lower tensile properties than flexural properties [99].

Recently, research efforts have been devoted to producing hybrid composites. The appearance of hybrid composites can be adjusted through various manufacturing factors, generally fiber type and fraction, fiber orientation, stacking sequence, laminate shape, and manufacturing process. Composites with the same reinforcing fiber can have different properties depending on the choice of lamination structure. For example, the combination of fiber pair laminates shown in Fig. 29 (a) and (b) is called 'pairing'. Standard processing technologies such as autoclaving, liquid composite molding, pultrusion, tape lay-up, filament winding, and sheet molding compounds have been used to manufacture high-performance composites suitable for industrial applications [100].

To determine their mechanical properties, tensile tests were conducted with dumbbell-shaped tensile specimens cut to the size specified in the ASTM D638 standard, shown in Fig. 29(c), on six CG and CA-type



(a) Laminating structure of carbon and glass fabric



(b) Laminating structure of carbon and aramid fabric

(c) Tensile test

Fig. 29. Laminating structure of hybrid composites [101].

composites. As described above, CG and CA materials are two hybrid composites combining glass or aramid fibers with carbon fibers. Fig. 30 illustrates the main tensile properties of carbon/aramid fiber (CA), shown in Fig. 30(a), and carbon/glass fiber (CG) composites, shown in Fig. 30(b).

The mechanical properties measured by the tensile test, namely ultimate tensile strength (UTS), modulus of elasticity, energy per unit volume, and elongation with different lamination methods, are shown sequentially from the top of the graph. On the left side of this graph, the mechanical properties of carbon fiber (C), aramid fiber (A), and glass fiber (G) composites are shown for comparison with hybrid composites. Samples ACA and GCG, laminated at the center of the carbon fiber, are superior in strength and stiffness to samples CAC and CGC. This shows that the lamination order governs the tensile properties even though the same materials are used [101].

6.2. Notch

One of the commonly used composites for building and repairing in various fields of the marine industry is glass fiber reinforced chopped strand mat (CSM) polyester composites, which have been previously discussed for their cost advantages as well as applications in marine fields such as ship hulls, seaplanes, and others. Composite laminates are usually exposed to intentional and unintentional indentations during application. Therefore, notch testing is required to meet the structural needs of assembly, joining, and forming. Generally, composite materials are susceptible to all types of notches because they cause a considerable reduction in strength, efficiency, and stability due to stress concentration. Abdalrahman describes a methodology on three variable notch shapes, with the composite using a mixture of CSM fiberglass of various shapes and sizes, as shown in Fig. 31.

Abdalrahman et al. [102] results showed that three variable notch shapes were tested by ASTM D30391 with a capacity of 100 KN and considered with SEN. This demonstrates the resistance of notched CSM-reinforced polyester composites to tearing during application. Numerical models of three Tensile specimens with the proposed SEN shape and the exact size of 10 mm, as shown in Fig. 32, were simulated in ANSYS/workbench. Figure to balance between analysis time and accurate prediction of results.

The simulated tensile test was run to obtain the point and value of the maximum stress concentration at the notch zone and the stress distribution along the minimum section of the notched specimen. Fig. 33 shows the corresponding numerical and experimental NTS results. In addition, the stress distribution along the specimen width of 20 mm from the notch tip is deduced numerically, as plotted in Fig. 34.

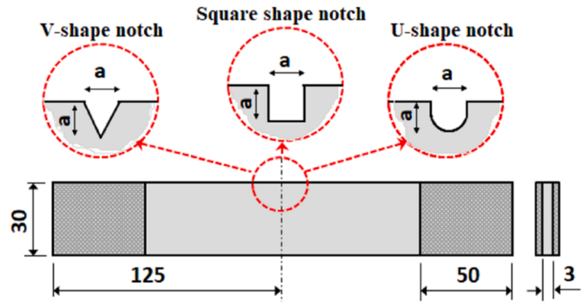


Fig. 31. Geometry of the tensile SEN specimens[102].

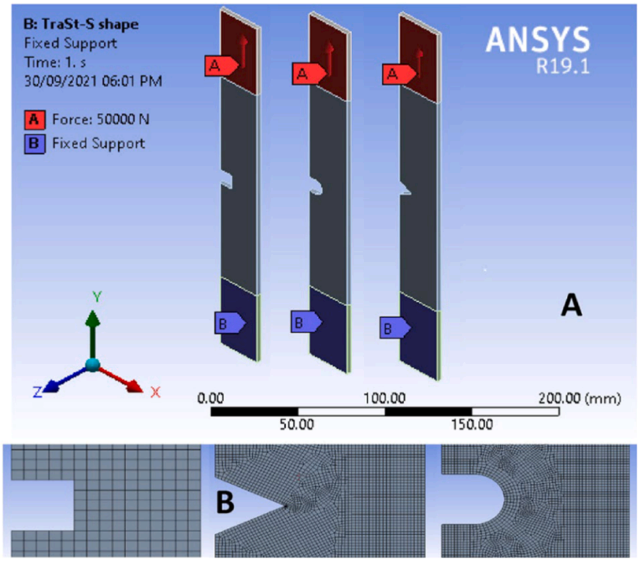
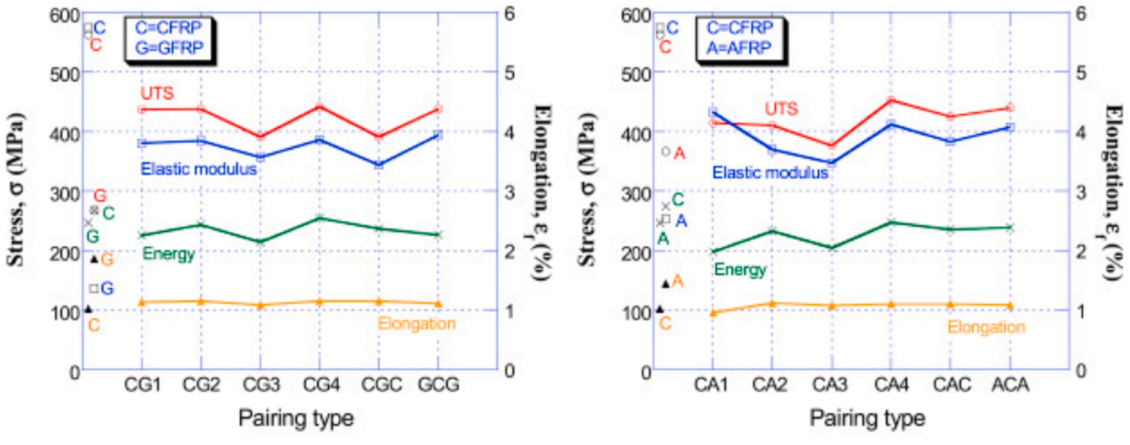


Fig. 32. (a) Numerical models of the notched test specimens, (b) Meshing of the test specimens around the notches [102].

6.3. Bending

Composite materials have been a competitive alternative to traditional metallic materials for some time due to their lower density, higher stiffness, higher strength, and better fatigue resistance than steel or aluminum. These properties allow composites to be prime candidates for structural applications.



(a) CG-hybrid (b) CA-hybrid

Fig. 30. Tensile properties with the structure of hybrid composites [101].

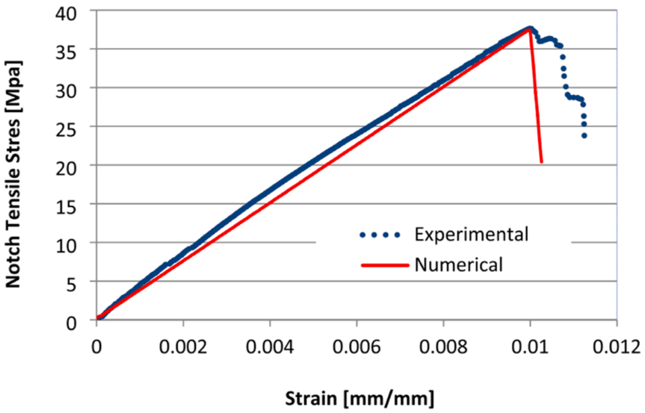


Fig. 33. The experimental and numerical notch tensile stresses (V-notch of 10 mm size at 0.053 s−1 strain rate) [102].

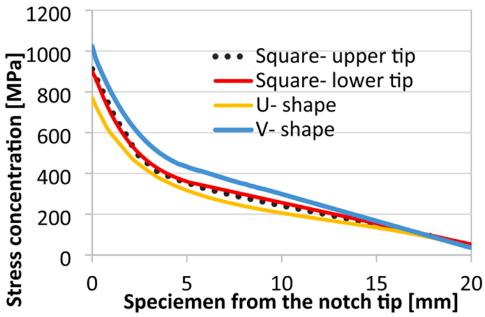


Fig. 34. Stress concentration along the specimen width from the notch tip [102].

One example of an assessment for material properties is using a three-point pedestal flexure test to predict the stiffness of anisotropic composite plates in flexure studied by Azzam and Li [103]. The results showed that the flexural behavior of composites depends on several factors, such as fiber orientation, laminate stacking, surface waviness, and molding temperature. Many studies have been conducted regarding the flexural properties of these composite laminates.

Traditionally, marine propellers were crafted from metal. However, the advent of composite materials has revolutionized this field. These flexible composite marine propeller blades, a product of this innovation, boast a unique feature-load-dependent blade deformation. This allows for a high degree of customization, reducing load variations, delaying the onset of cavitation, and enhancing propeller efficiency by passively adjusting the blade shape. Static bending tests were conducted on the composite laminate under loading to understand this unique behavior. The experimental setup is depicted in Fig. 35.

A Carver model 3912 hydraulic ram press with a maximum ram stroke of 5.125 inches (0.130175 m) was used to load the center of the free end of the laminated plate. A model LCCB-100 load cell with a maximum load of 100 lb (444.82 N) was used to measure the applied load, and an A4Tech webcam was used with a National Instruments DAQ 9239 pattern matching module and LabVIEW Vision Development to detect and record tip twisting and displacement. LabVIEW reads and records the load cell output as well as the x and y location of the free edge of the test sample using the LabVIEW Vision Development Module [104].

Wu et al. [105] studied the bending stiffness of braided composite tubes and energy absorption capacity by conducting three-point bending tests to analyze the whole process from initial elasticity to progressive damage to overall failure. The results show that the flexural energy absorption of the tube structure can be significantly improved by adequately selecting the braiding angle and proper stacking sequence in multi-layer braided tubes. The energy absorbed by the material during static and dynamic loading causes damage, such as fiber rupture, laminar and interlaminar cracking, delamination, and matrix cracking. Therefore, it is crucial to study the mechanical behavior of composites. Specific energy absorption (SEA) has been adopted to evaluate the energy absorption ability of different structures. It is defined as the absorbed energy EA, the area under the load-deflection plot divided by the mass of the test piece.

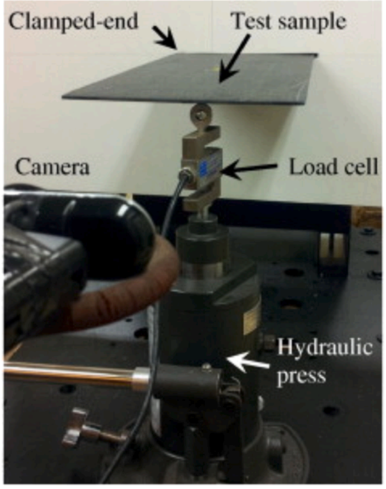


Fig. 35. Experimental structural setup test [104].

Farrokhabadi et al. [106] experimentally and numerically studied the behavior of a new multi-layer sandwich panel under flexural loading. For different corrugated core geometries (rectangular, trapezoidal, and triangular), energy absorption, specific absorption energy (mass-energy unit), and contact force are among the parameters investigated. The experimental results showed that the multi-layer sandwich composite panel not only improves the strength of the structure under three-point bending loading but also significantly increases the absorbed energy by increasing the contact force and displacement until complete failure. They found that the dominant damage and failure mechanisms during the loading process of sandwich panel specimens are delamination, matrix cracking, fiber breakage, global bending, local indentation, core bond release, and crushing and buckling of cell walls and face sheets. The results show that sandwich panels with rectangular-shaped corrugated cores absorb more energy and have higher specific energy than others.

6.4. Torsion

Thick laminates require more complex analysis methods in calculating torsional stiffness due to non-trivial through-stresses near their free edges. These through-thickness stresses become particularly relevant in analyzing thick laminated rectangular plates of finite-width receiving torsional loads applied to a single longitudinal axis. An accurate and pragmatic method of calculating torsional stiffness for thick laminated rectangular plates of finite width, consisting of any number of layers arranged in any laminate stacking sequence, was found. The aim is to do so in a manner conducive to practical engineering applications (e.g., in industry). Based on the Saint-Venant torsion theory mentioned above, it is assumed that the laminated plate of interest is long compared to its width and that its long edge (which is parallel to the axis of the applied torsional moment) is free of any applied torsional traction or moment (see Fig. 36) [107].

Torsion in thin-walled composite beams with open cross-sections is experienced in exploitation. Therefore, it is essential to evaluate the behavior under this type of loading. Analytical solutions for the torsion

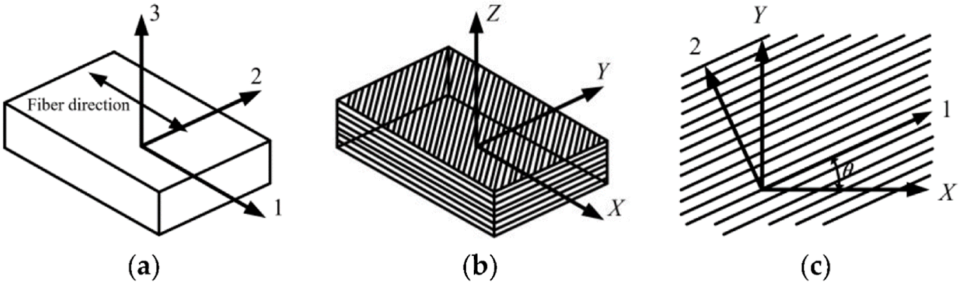


Fig. 36. Lamina and global laminate coordinate systems [108].

of thin-walled laminated composite beams with open cross-section under the influence of shear are presented. Beams with symmetrical cross-sections are considered. Based on Vlasov's classical thin-walled beam theory, the torsion theory with shear influence is adapted for thin-walled laminated composite beams with orthotropic and symmetrical arrangement.

The corresponding analytical models for stress and displacement analysis are presented. Supported and clamped beams subjected to uniformly distributed couples, acting on the cross-section planes, are analyzed. Solutions for stresses and displacements are obtained in closed analytic form. The distribution stress expressions concerning the longitudinal and cross-sectional curvature coordinates are obtained. It is proved that the beam undergoes torsion due to shear effects caused by cross-pairs of planes of cross-section and bending due to shear in a plane orthogonal to the plane of symmetry. If the cross-section has two axes of symmetry, the beam will only be subjected to torsional shear forces [109].

6.5. Thermal

Composites are used not only for their structural properties but also for thermal stability. Synthetic glass and carbon fiber are high-performance reinforcements for various applications that require more strength. Researchers aim to investigate the mechanical and thermal properties of laminates embedded in polyester. Nurazzi et al. [110] investigated the effect of alkali treatment and hybridization of fibers and glass fibers on the thermal properties of the composites with unsaturated polyester. The fibers were treated with 1% sodium hydroxide (NaOH) solution for 1 h. The composites were pre-peeled by hand through a lay-up process with a matrix reinforcement ratio. This experimental study investigated the flexural behavior of CFRP laminates and discovered their flexural properties under the influence of elevated temperatures. For this purpose, various CFRP specimens were prepared and tested, using the three-point bending test method as presented in Fig. 37, at different temperature levels from room temperature to 90 °C [111].

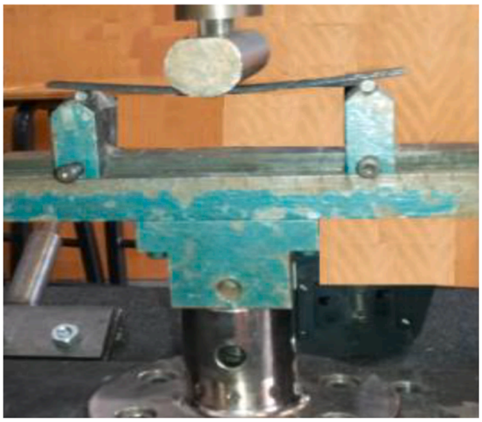


Fig. 37. Three-point bending test on the Instron 3367 machine [111].

The results show that the laminate's peak flexural load, modulus, and strength decrease consistently with increasing temperature. The laminate also became slightly more flexible, and a significant loss occurred in its flexural modulus when the temperature increased from 75 °C to 90 °C. The reduction in the flexural behavior of CFRP is attributed to the thermal softening of the epoxy polymer matrix whenever it approaches Heat Distortion Temperature (HDT). The CFRP specimens' durability test results at each specific temperature level are illustrated as load-deflection curves in Fig. 38. The CFRP material lost 60% of the peak load (flexural load resistance) at approximately 4 N/ °C from 500 N to 198 N. It is also shown that the flexural behavior was elastic, and the load drop was abrupt for all CFRP specimens tested over the temperature range from room temperature to 75 °C.

Thus, it can be concluded that the effect of temperature is quite significant, although the fibers on the outer surface dominate the flexural properties. The laminate loses properties constantly whenever the specimen temperature approaches the HDT of the epoxy component. Choosing the proper epoxy with the appropriate HDT is essential to design CFRP laminates that work at elevated temperatures and provide high thermal degradation resistance.

6.6. Fatigue

Many engineers and researchers know that metals experience fatigue, and there is a misconception that composites will not experience fatigue. However, more and more published reports and evidence show that composites also exhibit a form of service degradation called "fatigue." A simple description of this "fatigue" phenomenon is that the load-bearing capacity of a material decreases over time (load) under repeatedly applied macroscopic loads or displacements. In this way, the material will collapse at a much lower monotonic strength than normal [112]. The main characteristic of fatigue is the three phases shown in Fig. 39, which can be schematically shown by the crack growth rate curve usually obtained in standard fatigue fracture experiments in the

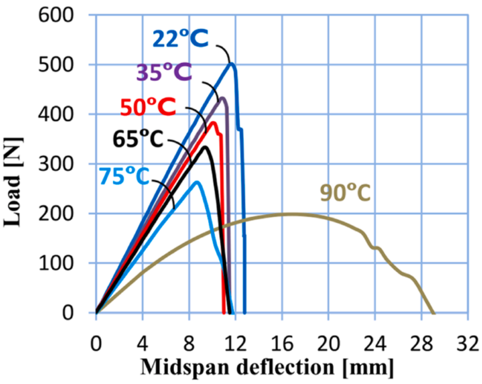


Fig. 38. Load-displacement curves of the CFRP specimens at different test temperatures [111].

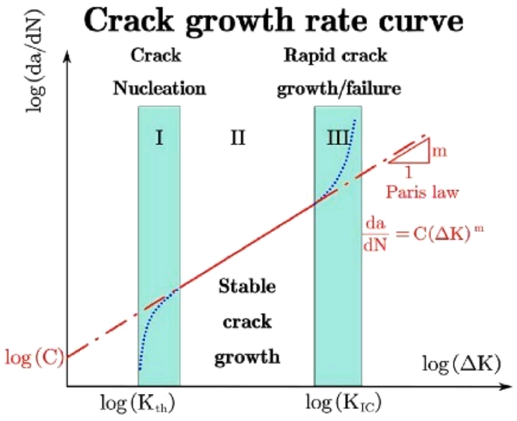


Fig. 39. Crack growth rate curve [113].

figure above. When a component is subjected to fatigue loading, the first stage is microcrack eruption, primarily controlled by the so-called fatigue threshold.

In addition, fatigue phenomena are usually classified according to their load life, as in the Wöhler curve (see Fig. 40), which is divided into three regions corresponding to each fatigue cycle. This was an early approach to studying fatigue phenomena in isotropic solids. Since the focus of this phenomenon is generally on the fatigue rather than the crack propagation, it can generally be done using numerical methods such as the finite element method (FEM) [113].

Critical distance theory (TCD) states that critical distance is a function of material properties through the (squared) ratio between tensile strength and fracture toughness. The critical distance is determined empirically (although a theoretical dependence on fracture toughness is suggested) through a fitting procedure to predict the effects of sharp notches and circular holes. Distance is a material property that represents the model input. Under monotonic loading, TCD has been successfully applied to estimate notch effects in long fiber composites. Since the TCD approach relies on critical spacing, which is a material constant, it may not be suitable for small-sized elements, where critical spacing exceeding the dimensions of the structure is required. The Wohler curve for plain (unnotched) specimens can be used as a representation of the variation of critical stress with the number of cycles to failure [114].

In marine turbine applications, the fatigue life prediction methodology (Fig. 41) presented for composite blades includes (a) quasi-static mechanical testing of the self-produced composites to determine orthotropic elastic engineering strength constants/parameters, (b) fatigue testing of the self-produced composites under realistic conditions (i.e., combined influence of seawater environment and cyclic loading) with the aim of fatigue characterization of the composites in terms of S-N data and fatigue failure modes, (c), incorporating BEMT-FEM to calculate the blade-fluid force distribution (tangential/thrust) and to predict the strain field on the tidal turbine blade and finally (d) model the fatigue damage accumulation based on constant lifeline diagram using Goodman's relationship approach. This methodology is applied here to representative horizontal axis tidal turbine blades modeled in FE software (ANSYS) using material properties determined from laboratory mechanical tests using the methodology described in previous work [115].

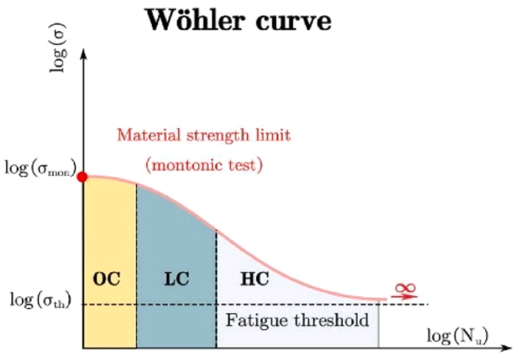


Fig. 40. Wohler or S-N curve [113].

7. Failure criteria

7.1. Failure mode

Composite fracture analysis case studies are used to demonstrate the failure modes of composites caused by their geometry, architecture, loading conditions, and environment. In general, the failure modes of composites are categorized into three groups: interlaminar, intralaminar, and translaminar failures. Interlaminar collapse refers to delamination between layers of different composite layers, intralaminar collapse occurs between fibers of the same layer, and translaminar collapse refers to the failure of reinforced fibers in cleavage, bending, and shear. Fig. 42 illustrates the potential failure modes of laminated composites. In the following sections, the different failure modes of laminated composite structures are analyzed in detail [116].

7.1.1. Matrix failure mode

The most common type of matrix failure mode is called matrix cracking. Matrix cracking can occur due to pre-existing fabrication faults or during loading. Stress concentration forms at the tip of the transverse crack at the layer level, which acts as a crack initiation site for matrix cracking, also called delamination. Therefore, the vertical extension of the transverse crack tip results in stress redistribution and causes delamination at the layer interface, as shown in Fig. 43. Therefore, the overall characteristics of the composite at the laminate level are compromised and may lead to early failure of the composite through other layers.

Being highly localized, matrix cracks are often difficult to detect; therefore, under fatigue loading conditions, they can trigger more detrimental delamination failures. Similarly, matrix cracking starts at the bottom surface during impact on a flexible target and spreads upward, forming a delamination plane. In addition, cracks in the matrix often cause damage to the delamination plane and contribute to the large area of cracks in the composite laminate. Therefore, it is essential to detect the matrix crack state and its development in real time to estimate the remaining useful life of the composite laminate. Corbetta et al. performed predictive maintenance of CFRP composite laminates using a particle filter-based Bayesian framework for matrix crack prognosis. The proposed prognostic methodology successfully predicted CFRP laminates' damage growth and fatigue life. A matrix crack growth evaluation technique using the Lamb wave-based automatic method was proposed by Liu et al. Experimental and simulation results verified the usefulness of the proposed model for quantifying matrix crack severity [119].

7.1.2. Interlaminar failure mode

Interlaminar failure is one of the most common and critical failure modes in laminated composites. It is caused by the lack of reinforcing fibers in the thickness direction and excessive interlaminar or out-of-plane stresses that weaken the layer interface and result in the progressive separation of adjacent layers. This failure mode is significant under direct or induced compressive loading through flexural or complex loading conditions. Interlaminar failure modes are dominated by fiber-matrix debonding, fiber bridging, and delamination (see Fig. 44)

The fiber-matrix interface's shear strength for debonding exceeds the constituent bonds' adhesion strength. As a result, interface failure occurs, and a weak interface is formed between the fiber and the matrix. Another important interlaminar failure mode is the bridging or bonding

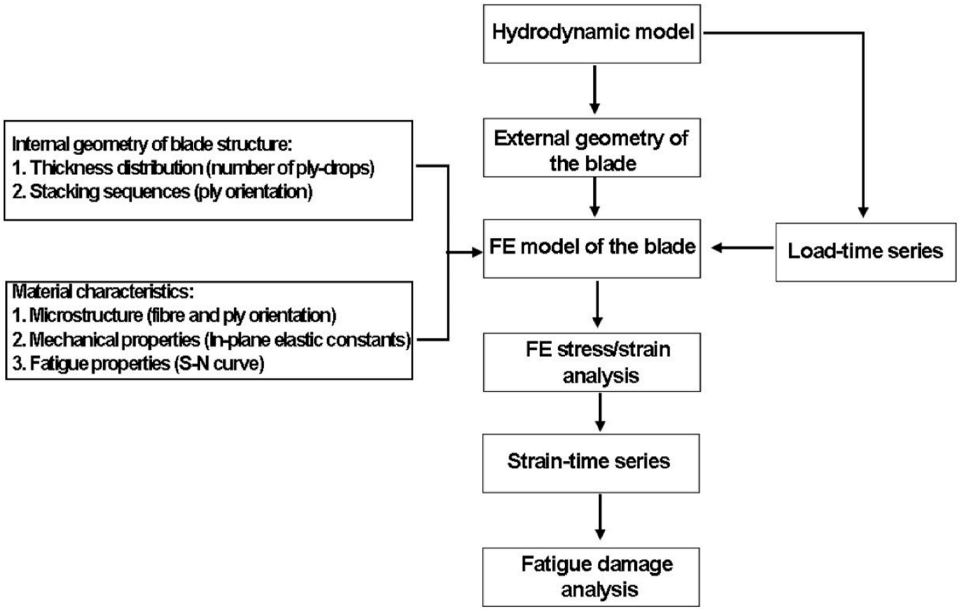


Fig. 41. Methodology flowchart for fatigue life prediction of composite tidal turbine blade [115].

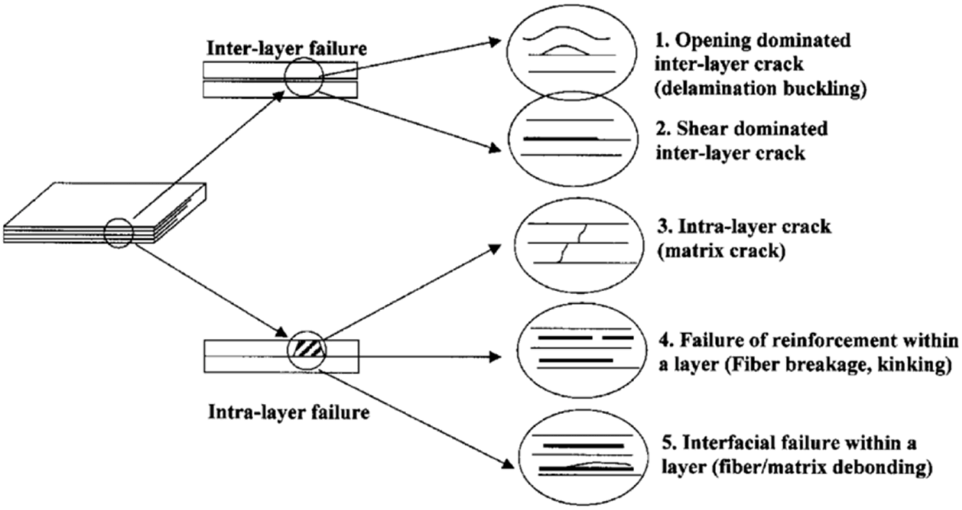


Fig. 42. Possible failure modes for layered materials based on material constitution [117].

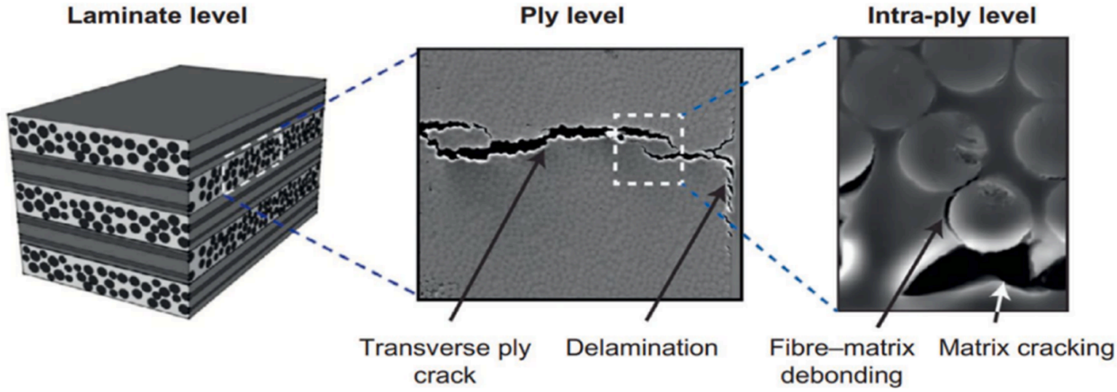


Fig. 43. Hierarchical nature of damage in a composite from intra-ply-level damage at the microscale to delamination at the macroscale [118].

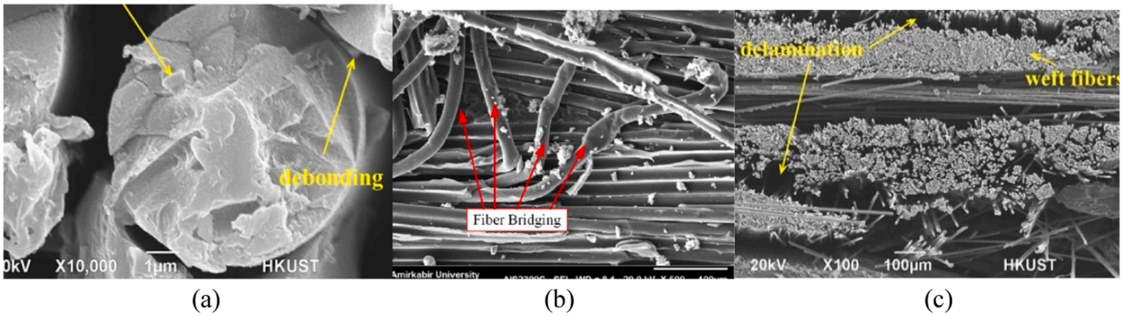


Fig. 44. Interlaminar failure mode: (a) Debonding [118], (b) Fiber bridging [120], and (c) Delamination[118].

zone caused by I-mode (opening mode) fracture in composite laminates. The degree of fiber bridging depends on the constituents of the laminate and its processing conditions, such as humidity and temperature, while bridging tends to increase as the crack length increases [121].

Delamination is the most critical damage due to its adverse effect on reducing load-bearing capacity. This failure is of great concern in classic fiber composites reinforced with carbon and glass fibers. The most common cause of the delamination process is the lack of sufficient binder and insufficient penetration in bonding the composite fibers. Advanced composite laminates are particularly susceptible to delamination due to their low interlayer shear and tensile strength. The onset of delamination damage in composite laminates is related to the critical strain energy release rate or fracture toughness.

Delamination may occur due to imperfections during the manufacturing process or the influence of external factors during the working life of the composite laminate, such as foreign body impact at sea. Inadequate curing methods cause irregular stresses in different areas, causing delamination defects. Delamination failures also often occur due to interlaminate stresses, which usually correspond to the lowest thickness strength. This is because laminates do not have a fiber-reinforced thickness in the middle of two adjacent layers, so the structure must rely on the brittle matrix to transmit loads in this direction [122].

Using machine learning, Elenchezhian et al. [123] studied the classification of various crack modes, including fiber bridging. They derived physical insights from labeled data and classified unlabeled data into corresponding crack modes. The machine learning-based crack modes were validated with composite theory. A simulation-based approach to predict the fracture behavior of composite laminates involving fiber bridging also agreed with experimental data. Delamination is one of the most critical interlaminar failures, controlled by matrix fracture, and occurs due to bond release between layers with different orientations. In recent years, concentrated efforts have been made to detect delamination in composite laminates using machine learning and deep learning techniques. One such effort was to use three machine learning algorithms (Linear Regressor, Random Forest Regressor, and XGB Regressor) with a two-regressor architecture to predict the delamination area and X, Y coordinates for a four-layer laminate structure. They concluded that the delamination location was best predicted by linear regression. In addition, a combination of finite element analysis (FEA) and machine learning for delamination detection in non-destructive vibration was investigated. The proposed approach improves the ability of natural frequency tests to measure delamination in laminated composites. They proposed an artificial neural network to predict delamination in smart composites using low-frequency structural vibration. A convolutional neural network (CNN) was incorporated to distinguish healthy and delaminated conditions, and the results showed 12 cases of delamination and one healthy case with a classification accuracy of 90.1%.

7.1.3. Fiber failure mode

Another failure mode for composite laminates is fiber failure, characterized by inclusions or voids located within the fiber rather than on its surface, contributing to the gradual failure of the composite laminate. Fiber failure mainly affects the tensile strength and modulus of composite laminates, especially when fiber defects are present in a large enough concentration. Complex loading, such as a combination of flexural and axial loads, can also cause fiber fracture. Further load increases cause the fibers to be pulled out of the matrix, and the load-bearing capacity of the broken fibers drops to zero. Fig. 45 illustrates the fractography of carbon fibers pulled out in a laminate structure [124].

On the other hand, fiber break-out is the most undesirable failure in composite laminates. The fiber, as the load-carrying constituent of the composite, bears all the load and, in case of fiber failure, breaks near the fracture surface. During this failure, little or no bond release is observed, and the failure occurs at the maximum load-carrying capacity of the composite laminate. Fig. 46 shows the rupture of a hybrid hemp/fax composite laminate.

To investigate these types of failure modes, Huang et al. [126] proposed a probabilistic model to determine the fibers' fatigue deformation behavior and failure mechanism. However, more efforts are needed to predict the exact failure modes of composite laminates under various simple and complex loading conditions.

7.2. Failure mechanism

This section describes the sequence, accumulation, and interaction of defects in laminated composites. Tao et al. [127] used Lamb wave velocity to propose a technique for characterizing fatigue damage in composite materials using basic damage mechanisms. The fatigue damage was evaluated by low-frequency Lamb wave S0 mode and Young's modulus of axial laminates. In this study, the stiffness information was used to obtain the information. Fig. 47 shows the normalized stiffness area depiction of the composite material under fatigue loading during its lifetime.

Here, cyclic and time-dependent deformation contributes to stiffness degradation and is observed in stage 1. The Characteristic Damage State

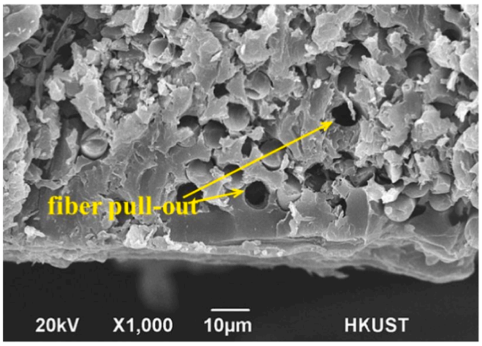


Fig. 45. Fiber pull-out [118].

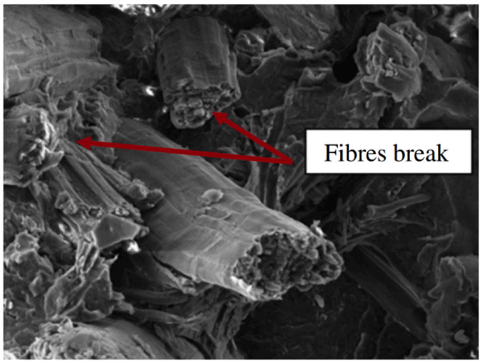


Fig. 46. Fibers break [125].

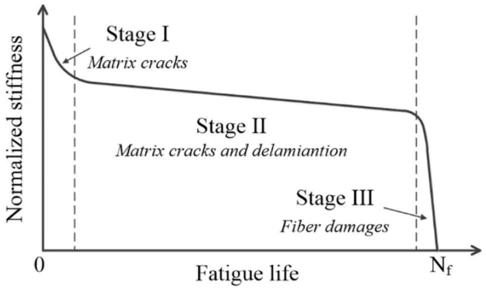


Fig. 47. A typical trend for composite stiffness degradation [127].

(CDS) in the Non-Interactive Scheme (NIS) is an ideal transition point. The gradual stiffness degradation reflects the Stage I evolution of transverse matrix cracking, which abruptly stops when it reaches CDS. Elenchezhian et al. [123] correlated various states of global stiffness, residual strength, and damage accumulation in composite materials. It is shown that damage begins with the formation of micro-cracks in the matrix, which then transforms into the detachment of fiber bonds from the matrix. These matrix cracks appear at various positions along the material until CDS occurs when the material is full of micro cracks. Up to CDS or stage 1, there is a significant decrease in global stiffness and an increase in damage; however, the remaining strength remains unchanged. After that, secondary cracks propagate at the specimen's free edge, initiating edge delamination. Before the end of Stage 2, the remaining strength decreases along with the same increase in damage growth. Once Stage 3 begins, secondary cracks grow rapidly, leading to a sudden decrease in strength and material failure.

7.3. Study of simulation-based models

The use of composites in constructing high-speed vessels, mine countermeasure vessels, and various sub-sections of large naval vessels is well known. FRP composite materials are also used in submerged pressure hull construction due to their high strength-to-weight ratio compared to metals and other alloys. Fiber-reinforced composite structures are made from composite laminates using different layout configurations and manufacturing techniques. Several layout configurations, layer orientations, and material systems may result in an optimal composite structure design.

The literature contains studies on composite plate optimization using genetic algorithms (GA) and numerical analysis. These studies have used composite failure criteria such as Tsai-Wu, Hashin, Maximum Stress, and Puck failure criteria as constraints and material weight minimization, deflection minimization, buckling load maximization, material minimization, and load carrying capacity maximization as objective functions [128].

A common approach in a numerical framework for composite materials is to first model the initiation of damage modes through failure criteria. The commonly used failure criteria for fiber-reinforced composite materials are stress and Puck failure criteria [129]. Here are the modified stress failure criterion damage modes shown by Eqs. (1)–(8)

Tensile failure of fiber

$$\sigma_{11}/X_t = 1, if \sigma_{11} > 0 \tag{1}$$

Compressive failure of fiber

$$\sigma_{11}/X_c = 1, if \sigma_{11} < 0 \tag{2}$$

Tensile failure of matrix

$$\sigma^{max}/Y_t = 1, if \sigma^{max} \geq 0 \tag{3}$$

$$\theta^{\mathrm{T}}_{\mathrm{m}} = \frac{1}{2}\, arctg\left(\frac{2\sigma_{23}}{\sigma_{23} - \sigma_{33}}\right) \tag{4}$$

Compressive failure of matrix

$$\sigma^{\mathrm{min}}_{\mathrm{m}} \Big/ \mathrm{Y}_c = 1,\ if\ \sigma^{\mathrm{min}}_{\mathrm{m}} \geq 0 \tag{5}$$

$$\theta^{\mathrm{C}}_{\mathrm{m}} = \frac{1}{2}\, arctg\left(\frac{2\sigma_{23}}{\sigma_{23} - \sigma_{33}}\right) + 143^{\circ} \tag{6}$$

Shear-Out of fiber-matrix

$$\sigma^{\mathrm{max}}_{\mathrm{S}} \Big/ \mathrm{S}_{12} = 1 \tag{7}$$

$$\theta_S = arctg\left(\frac{\sigma_{13}}{\sigma_{12}}\right) \tag{8}$$

The Puck criterion for various failure modes in fiber composites is shown by Eqs. (9)–(13)

Failure of fiber in tension

$$\frac{1}{\varepsilon_{1T}}\left(\varepsilon_{1t} + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) = 1 \tag{9}$$

Failure of fiber in compression

$$\frac{1}{\varepsilon_{1C}}\left(\varepsilon_{1t} + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) + (10\gamma_{12})^2 = 1 \tag{10}$$

Failure of matrix in transverse tension

$$\sqrt{\left(\frac{\tau_{12}}{S_{21}}\right)^2 + \left(1 - \mathrm{p}^{+}_{\mathrm{vp}}\frac{\mathrm{Y}_t}{S_{21}}\right)^2 \left(\frac{\sigma_{22}}{\mathrm{Y}_t}\right)^2} + \mathrm{P}^{+}_{\mathrm{vp}}\frac{\sigma_{22}}{S_{21}} + \frac{\sigma_{11}}{\sigma_{11D}} = 1 \tag{11}$$

Failure of matrix in moderate transverse compression

$$\frac{1}{S_{12}}\left(\sqrt{\tau^{2}_{21} + \left(\mathrm{P}^{-}_{\mathrm{vp}}\sigma_{22}\right)} + +\mathrm{P}^{-}_{\mathrm{vp}}\sigma_{22}\right) + \frac{\sigma_{11}}{\sigma_{11D}} = 1 \tag{12}$$

Failure of matrix in large transverse compression

$$\left(\left(\frac{\tau_{21}}{2\left(1 + \mathrm{P}^{-}_{\mathrm{vv}} S_{12}\right)}\right)^2 + \left(\frac{\sigma_{22}}{\mathrm{Y}_c}\right)^2\right)\frac{Y_c}{(-\sigma_2)} + \frac{\sigma_{11}}{\sigma_{11D}} = 1 \tag{13}$$

where, ε_{1T} and ε_{1C}Note the unidirectional layer collapse strain in tension and compression, respectively. The terms ε_1 and E_{f1}Note normal strain and Young's modulus, respectively. The term ν_{f12} is Poisson's ratio; $m_{\sigma f}$ refers to the average stress magnification factor for fibers in the x_2 direction. σ_{11} and σ_{22} I Note normal stress; γ_{12} and τ_{21} I Note shear strain and stress in the elastic symmetry direction, respectively, and S_{21}refers to the transverse and parallel shear strength of the unidirectional layer. The term refers to the angle-dependent fracture plane parameter and σ_{11D} indicates the stress value for linear degradation [130].

In the cohesive model, the quadratic nominal stress-failure criterion is used for damage initiation, and the 'BK criterion' based on the fracture mechanism of Benzeggagh and Kenane, is adopted for delamination development, as shown by Eqs. (14)–(16)

$$\left(\frac{\sigma_{3T}}{S_{3T}}\right)^2 + \left(\frac{\sigma_{32}}{S_{32}}\right)^2 + \left(\frac{\sigma_{31}}{S_{31}}\right)^2 \geq 1 \tag{14}$$

$$G_{IC} + \left((G_{IIC} - G_{IC})\frac{G_{II}}{G_T} + (G_{III} - G_{IC})\frac{G_{III}}{G_T}\right)\left(\frac{G_{II} + G_{III}}{G_T}\right)^{\eta_{BK-1}} \geq G_T \tag{15}$$

$$G_T = G_I + G_{II} + G_{III} \tag{16}$$

where G_I, G_{II} and G_{III}refer to the strain energy release rates in modes I, II, and III, respectively. The terms G_{IC}, G_{IIC}, and G_CNote the critical strain energy release rate. The term η is a semi-empirical exponent and describes the initiation and progression of delamination. The terms σ_{3T}, σ_{32}, and σ_{31}note the tensile stress and shear stress in the out-of-plane direction, respectively. S_{3T}, S_{32}, and S_{31}refer to the out-of-plane tensile and shear strengths, respectively. The material degradation model is a commonly used damage progression criterion for the numerical framework of fiber-reinforced composites [131].

Li et al. [132] studied the assessment of failure criteria (Hashin, Puck, Hou, etc.) and damage evolution laws (equivalent strain, equivalent displacement) for damage initiation and propagation (matrix failure, fiber damage, ply failure, delamination) in laminated composites under low-speed impact. The model was implemented in Abaqus through user-defined subroutines. Fig. 48(a) shows the accumulation, and Fig. 48(b) shows the evolution of the matrix and matrix tensile—compression concerning time for the proposed approach.

Wang et al. [133] proposed a strain rate-dependent three-dimensional damage model for initiating and evolving damage in laminated composites subjected to low-speed impacts. Fig. 49 shows the model implementation workflow.

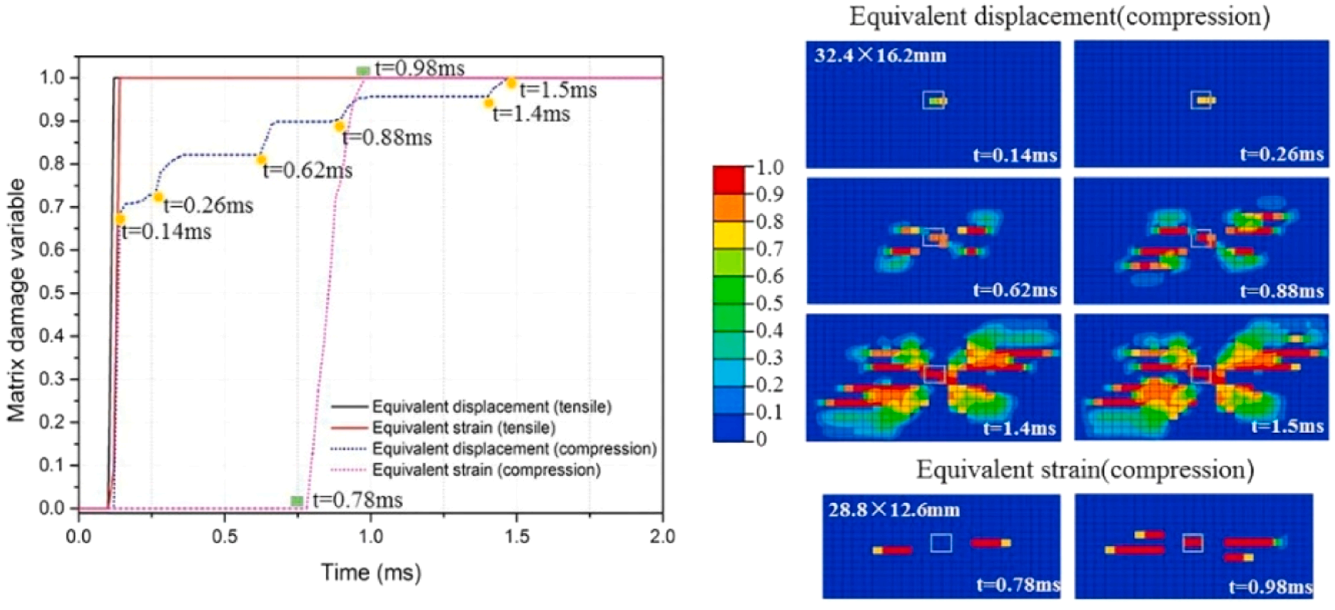
Naderi et al. [134] investigated the effect of ply thickness on damage initiation and propagation of thin-layer carbon fiber composites under stress using a micromechanical model. The composite laminate with [0/90/0] orientation was represented by a Representative Volume Element (RVE), as shown in Fig. 50, with four different 90° ply thicknesses. The tensile loading results show the suppression of matrix cracking with the 90°-layer thickness reduction. Therefore, high-speed results for damage evolution were obtained using the combined 3D computational micromechanics and augmented finite element method (AFEM).

Unfortunately, probabilistic physics-based predictive models for predicting the degradation of laminated composites are limited in the published literature due to these materials' orthotropic and complex failure characteristics. The following may be potential future research directions for the diagnosis and prognosis of laminated composites [136–145]:

- Hybrid physics and data-driven diagnosis and prognosis techniques to account for the complexity of laminated composites through adequate data in different phases of damage onset and propagation.
- Development of a common framework for prognosis and health management of laminated composites to accommodate different stacking sequences, fiber types, matrix materials, thicknesses, loading, and boundary conditions.
- Cross-domain knowledge transfer to bridge the gap between measurement-based and mechanics-based finite element models [146–156] for the early stages of onset and propagation of damage in laminated composites.
- Synergy of micro and macro models for physics-based diagnosis and prognosis of composite materials [157–164].

8. Conclusions

To determine the applicability of composite materials in marine applications, it is essential to understand the properties of the various types of laminated composites used, especially under extreme marine environmental conditions. This is particularly relevant in seaplane hulls requiring optimal water resistance during landing and take-off. The effectiveness of using composites in marine renewable energy projects and determining the appropriate laminate composition for different types of vessels is also an important focus. The strength and suitability of



(a) (b)

Fig. 48. Comparison of (a) matrix damage variable profile (obtained from the element at the center of the backside for tensile damage, the element at the center of the impact side for compression damage), and (b) matrix compression damage contours for models with different damage evolution methods [132].

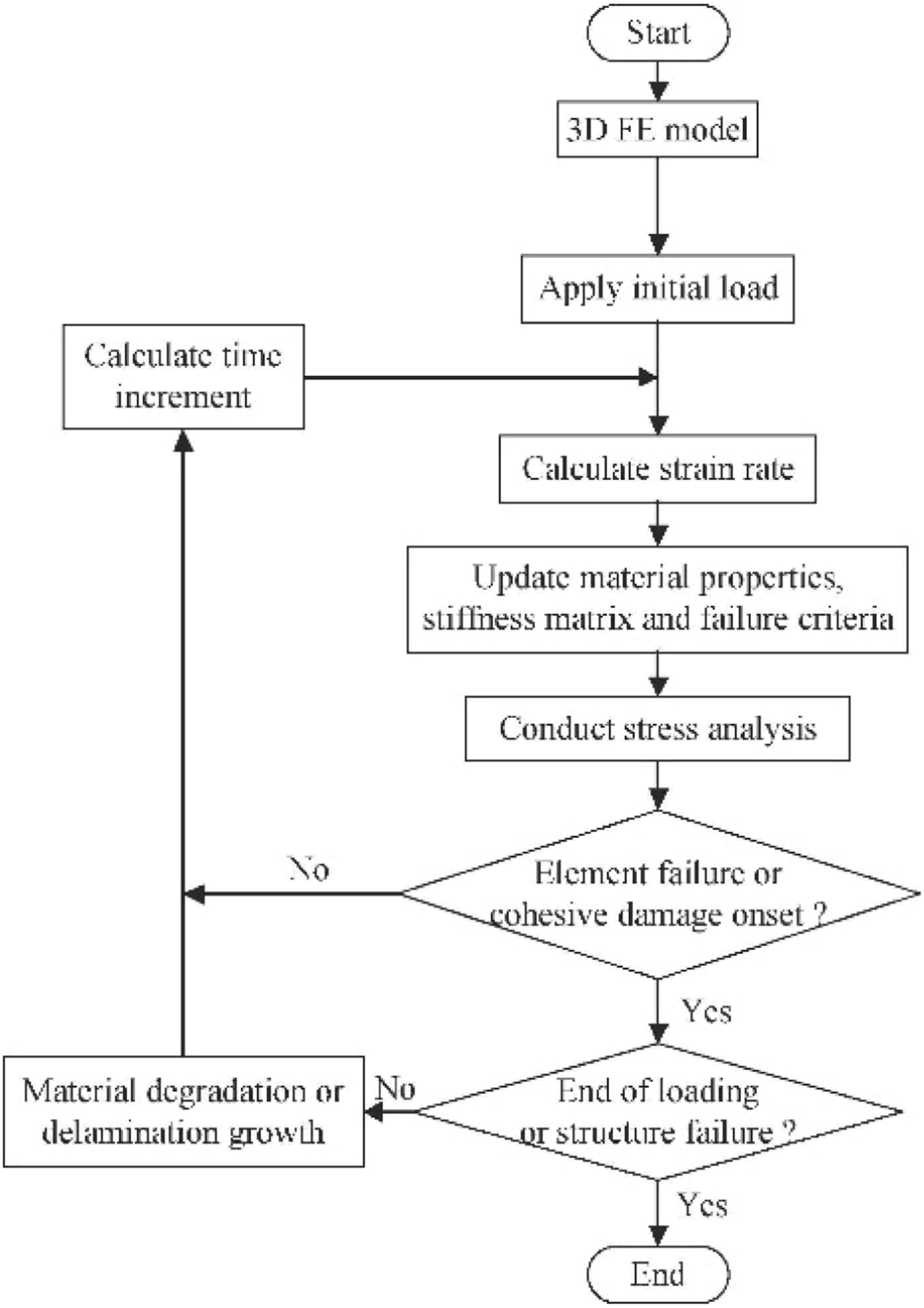


Fig. 49. Simulation flowchart of the strain-rate-dependent damage model [133].

laminated composite materials depend highly on the constituent components, with parameters continuously developed to improve durability against extreme conditions. The use of natural fibers as the core is also being developed for better manufacturing cost efficiency. Composite joining with adhesive considers variations in joint type, shape, adhesive type, and adhesive thickness, which directly affect the strength and durability of the joint. Recent research has also led to the use of thermoplastic polymer materials and environmentally friendly materials. Extreme marine conditions demand basic tests such as tensile, bending, torsion, and fatigue tests on composite material specimens to develop a suitable laminate formula. Once the formulation is obtained, various failure criteria must be considered as basic rules in designing laminated composite materials for marine applications before direct application. Adequate knowledge of stress limit conditions, durability and service life, failure modes, fracture toughness, fire resistance, and other marine environment influence parameters is essential for an efficient and sustainable design process for marine application structures in this demanding industrial sector. Therefore, studying one of the most critical parameters affecting composite materials' mechanical properties in marine applications is essential.

CRediT authorship contribution statement

Daffa Putra Islami: Writing – original draft, Investigation, Formal analysis. **Aldi Fahli Muzaqih:** Writing – original draft, Investigation, Formal analysis. **Ristiyanto Adiputra:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Aditya Rio Prabowo:** Writing – review & editing, Validation,

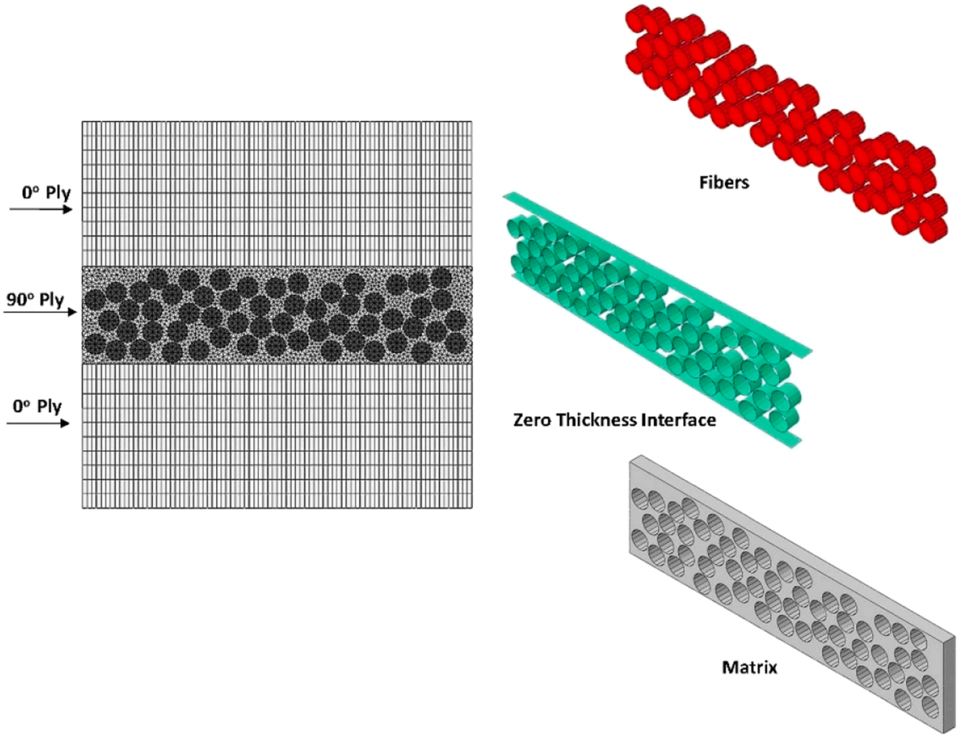


Fig. 50. Finite element model for RVE with 30 μm thick of 90° ply ($n = 1$) [135].

Supervision, Funding acquisition, Conceptualization. **Nurman Firdaus:** Software, Project administration, Data curation. **Sören Ehlers:** Conceptualization, Validation. **Moritz Braun:** Methodology, Validation. **Martin Jurkovič:** Software, Methodology. **Dharu Feby Smaradhana:** Visualization, Data curation. **Hermes Carvalho:** Visualization, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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