FRP-based reinforcement coatings of steel with application prospects in Ships and Offshore Structures: A review

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ABSTRACT

The goal of the presented paper is to discuss the latest research on novel FRP-based anti-corrosion structural coatings (i.e. enhancing structural capacity and strengthening the coating layer), leading to discussion about application prospects for ships and offshore structures. In the marine environment, structures constantly face corrosion and fatigue cracks. When these factors are combined with high operational and wave loads, it might cause a structural collapse. Recently, polymer composites have been studied for possible reinforcement, especially for steel structures in civil engineering. If such composites could be applied for marine structures as novel-type coatings, it is important to assess their effectiveness in halting corrosion and strengthening structures against various mechanical failure modes. The review of research on the fatigue, tensile, buckling, and debonding properties of fibre-based structural coatings is given and summarised. Most research has been focused on carbon fibre reinforced composites. Resins matrices other than epoxy, behaviour on corroded steel, ply orientation, and pre-stress level are still untapped adequately. Similarly, structural coatings containing another types of fibres than carbon and their hybrids are still insufficiently examined. Thus, although such research direction is promising, the need for future research is highlighted and given in detail.

KEY WORDS

Corrosion; Structural coatings; Reinforced Steel; FRP composites; Marine structures; Retrofitting

Abbreviations

WCO – World Corrosion Organization

GDP – Gross Domestic Product

GNPs – graphene nanoplatelets

NPs –nanoplatelets

ECR – epoxy coated reinforcement

RPC – resin pre-coating

FRP – fibre reinforced polymer

CFRP – carbon fibre reinforced polymer

GFRP – glass fibre reinforced polymer

BFRP – basalt fibre reinforced polymer

AFRP – aramid fibre reinforced polymer

Tg – transition temperature

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CNT – carbon nanotube

CFS – carbon fibre sheet

SCF – short carbon fibres

RAN – Royal Australian Navy

1. Introduction

The development of materials used for the marine industry including shipbuilding and offshore structures is extremely important from the safety and economic point of view. Steel and steel alloys are mainly used for these applications. Steel's low cost and excellent mechanical properties (hardness, toughness, tensile strength, yield strength, elongation, plasticity) make it suitable for a wide range of industrial uses, from the military to the domestic. On the other hand, steel is very corrosive, especially in humid environment. Various damage occurs in aging steel structures, of which corrosion is the most common among numerous factors. Due to the corrosive nature of seawater, corrosion and fatigue, which is fastened in corrosive environment, are the leading causes of structural damage in ships (Guedes Soares and Garbatov 1999).

Marine environment corrosion causes approx. 30% of marine structures failure, requiring repair or replacement (Radhamani et al. 2020). The financial penalties on failures, outages, and repairs are added on the top of the already high costs to which the effects of corrosion on vessel, structural, and equipment operations contribute (Mardare and Benea 2017). The World Corrosion Organization (WCO) estimates that corrosion causes an annual loss of around $2.4 trillion (or 3 percent of world GDP) (Velázquez et al. 2014). Additionally, up to 47% of structural incidents were possibly caused by corrosion (Bhandari et al. 2015). Costs associated with direct corrosion of marine structures in the United States was expected to reach $2.76 billion annually by 2022 (Yan et al. 2022), which is approx. 25% of US naval annual budget (Gold Standard Corrosion Science Group 2023). It is estimated by the NACE International IMPACT that corrosion costs of the US economy amount to $2.5 trillion annually (Bowman et al. 2016; Gold Standard Corrosion Science Group 2023). Using current corrosion management methods, the cost of repair of our aging infrastructure is close to $2 trillion (Bowman et al. 2016). Corrosion reinforcement in China costed about $2 trillion by 2021 (Li, Wang, et al. 2022), or around 1.2% of the country's GDP. Nevertheless, the sky-high rising costs of maintaining and repairing the equipment of this industry (such as ship hulls, offshore renewable energy platforms, and subsurface oil and gas facilities) are a major drawback. It is estimated that maintenance costs account for 20%-40% of all operating costs in the marine industry (Li, Xu, et al. 2022). Using more corrosion-resistant materials and using optimal corrosion-related technical practices might save these expenditures by around one third (Bowman et al. 2016).

Due to this huge capital cost related to corrosion, most of the ship owners had been reluctant for repair and maintenance of ships and which had resulted in the marine disasters even in the recent decades. Each incident resulted in severe pollution that had long-lasting, devastating effects on marine biological systems, endangered flora and fauna, but also resulted in several human deaths. Corrosion of the ship's hull had a significant impact on strength reduction, even if most of the incidents themselves were caused by human error (Tscheliesnig 2004). There is a considerable danger of oil tanker accidents, as seen by previous disasters, and maritime transportation is especially crucial for Europe, where 90% of oil is coming by sea and 3 thousand ships deliver oil and oil-related products to and from European seaports. Some of the worst accidents over the previous several decades were Liberty ships (Zhang 2016), SS Rotterdam (Zunkel et al. 2014), Braer, Erika, Prestige (Albaigés et al. 2006), Swanland (Tscheliesnig 2004). Fig 1 (a) presents the collapse of M/T Erika (WRECKSITE 1999) and Fig 1 (b) presents the sinking of M/T Prestige. Later studies revealed that corrosion considerably damaged the structures of these ships, which along with the overloading of the hulls, led directly to the catastrophic accidents that occurred (Goulielmos et al. 2012).

Figure 1. (a) Broken tanker ship 'Prestige' (Albaigés et al. 2006) *(b) Sinking tanker ship 'Erika'* (WRECKSITE 1999).

Due to the corrosion, mechanical performance and serviceability of marine structures are thereby reduced, by phenomena like yielding, widespread fatigue cracking and notable buckling. There are two ways to tackle this problem; 1) Replace any parts that score below specified allowable limits during scheduled maintenance, 2) Use contemporary coatings to prevent corrosion. This review is focusing on the development of structural coatings to avoid different failure modes associated with corrosion. Previously, multiple types of contemporary coatings have been being used in shipbuilding industry since they are cheap, but they have certain limitations which will be discussed in the following chapters of this review.

Except corrosion prevention and structure reinforcement, another phenomenon associated with the coating is drag, or hull resistance which plays major role in a ship's efficiency and fuel consumption. 95% of worldwide general cargo is transported by the marine industry, and ships can use up to 85% of their available energy to combat hydrodynamic forces (Tarafder 2007). By reducing drag, a ship can operate more efficiently and use less fuel, resulting in cost savings and reduced environmental impact. A coating on the hull of a ship can help reduce hull resistance by creating a smoother surface that is less likely to create drag as the ship moves through the water. In addition to reducing drag, a coating can also improve a ship's manoeuvrability. By creating a smooth, even surface on the hull, the structural coating can help reduce turbulence and improve the flow of water around the ship. This can make it easier for the ship to manoeuvre through the water, especially at high speeds or in rough seas. By keeping the hull smooth and free of build-up, composite coatings can help maintain a ship's performance and reduce the need for costly repairs and maintenance. Therefore, several methods for reducing drag on maritime vehicles have been developed based on the concept of structural coating. Hutchins et al. (2023) used a power-mean averaging approach proposed for heterogeneous roughness to find an equivalent roughness length scale that can capture the combined effect of permeability and roughness. Abu Rowin et al. (2021) created a new drag-reducing polymer coating with a polydopamine (PDA) layer that may adhere to any metallic surfaces. Woo Yang et al. (2014) also investigated a drag-reducing polymer coating that combined a self-polishing Anti-Fouling (AF) paint and PolyEthyleneOxide (PEO). Although drag-reduction is important feature of marine coatings, this work is mainly focused on the possible use of structural coatings which are mainly aimed for corrosion prevention and giving extra strength to the structures.

Several review works have been written by different authors for the coatings in the marine industry, as shown in Table 1. But those review articles were about antifouling coatings (Wang et al. 2020; Pistone et al. 2021; Nwuzor et al. 2021; Pourhashem et al. 2022; Sousa-Cardoso et al. 2022; Li et al. 2023), use of nano materials for corrosion prevent (Radhamani et al. 2020; Mirzaee et al. 2021; Sharma and Sharma 2023). Still, none of the authors addressed the topic of structural coatings for marine industry even though they are of crucial importance because of their multi-purpose (anti-corrosion, load-bearing, extra strength, hull smoothness) applications.

Table 1. A brief summary of existing review articles on marine coatings.

References	**Type of existing reviews on marine industry**	**Comments**
Li et al. (2023)	Antifouling coatings	Bioinspired antifouling mechanisms, and design strategies.
Qu et al. (2021)	Concrete and reinforced concrete	Deterioration of concrete under marine environment.
Sousa-Cardoso et al. (2022)	Antifouling Performance of Carbon-Based Coatings for Marine Applications	Application of CNTs and graphene for the development of antibiofilm for marine surfaces.
Radhamani et al. (2020)	Nanocomposite coatings on steel for enhancing the corrosion resistance	Use of nanomaterials (alumina, titania, silica) to prevent the corrosion of steel.
Wanchoo et al. (2021)	Investigations on air and underwater blast mitigation in polymeric composite structures	Use of polymer-based sandwich composites in the marine industry for encountering high-intensity underwater or in air explosive loading.
Mirzaee et al. (2021)	Corrosion properties of organic polymer coating reinforced two-dimensional nitride nanostructures	Use of nitride nanoparticles to prevent the corrosion of materials.
Nwuzor et al. (2021)	Self-polishing anti-fouling coatings	Anti-fouling coatings for hindering the biological fouling of marine architectures.
Pistone et al. (2021)	Mechanical Properties of Protective Coatings against Marine Fouling	Development of hydrophobic protective coatings based on siloxane for anti-fouling.
Faccini et al. (2021)	Anticorrosive Polymeric Coatings	Bio-based, water-borne epoxy, polyurethane, graphene-based fillers for anticorrosive polymeric coatings.
Sharma and Sharma	Graphene-based polymer	Graphene and its composite as an

(2023)	coatings for preventing marine corrosion	anticorrosive coating for marine applications.
Wang et al. (2020)	Anti-protein fouling coatings materials	Development of anti-protein adsorption foul coatings.
Verma et al. (2019)	Protective polymeric coatings for marine applications	Polymer-based surface coatings to protect against marine biofouling.

In recent years some of the structural coatings based on fibres (carbon fibre, glass fibre, aramid fibre, and blast fibre) and resins (epoxy, polyester, and vinyl ester, phenolic, and polyurethane) have been discovered. These FRP based coatings have potential to be used as structural coatings in the field of civil engineering, aeronautical engineering and in ocean engineering.

Already a lot of research has been carried out in the field of civil engineering on the behaviour and performance of these types of structural coatings for different failure modes like fatigue, debonding, and tensile properties before and after corrosion, mostly concerning beam-type structures, and these coatings have been proven very useful for preventing corrosion and structure reinforcement which shows the maturity of research in civil engineering. Although these results are valuable, but the thin-walled structural components (such as plates) are the primary type that should be considered in terms of ship structures (Khalili et al. 2005). On the other hand, ocean engineering is still suffering from corrosion and its impact, this is because the performance of these structural coatings has not been fully explored which makes their usage very limited in the marine industry (Aljabar et al. 2016; Li et al. 2019). So, there is a need to understand the behaviour of different failure (tensile strength, fatigue resistance, bond strength and ductility) modes related to the plates structures when they are reinforced with structural coatings before and after corrosion (Momber 2011). Therefore, this article is mainly focusing on its possible applications in ship and offshore structures and will also help us give a deep critical insight into the performance of existing structural coatings which will guide the future work directions. Therefore, the article seeks to review the literature that helps answer the following research questions:

- What is lacking in the contemporary knowledge on existing structural coatings for widespread use for ships and offshore structures?
- How do the structural coatings affect the tensile properties of steel plates?
- How is fatigue life of steel plates influenced when reinforced with structural coatings?
- What is the buckling behaviour of steel plates, when reinforced with structural coatings?
- What is the role of adhesive bonding in structural coatings when a steel plate is reinforced?
- What are the shear properties of the reinforced steel plates?

The presented article is organised as shown in Fig 2. Section 2 provides the brief introduction into effects of corrosion and fatigue on possible failure of structural components. Section 3 presents the ordinary means of corrosion mitigation and their limitations. Section 4 gives the concept of structural coatings. Section 5 elaborates the performance of structural coatings considering different failure modes. Section 6 highlights the contemporary applications and limitations associated with existing structural coatings. Section 7 identifies the knowledge gap and Section 7 concludes the conducted literature review, leading to possible future works identified in Section 9.

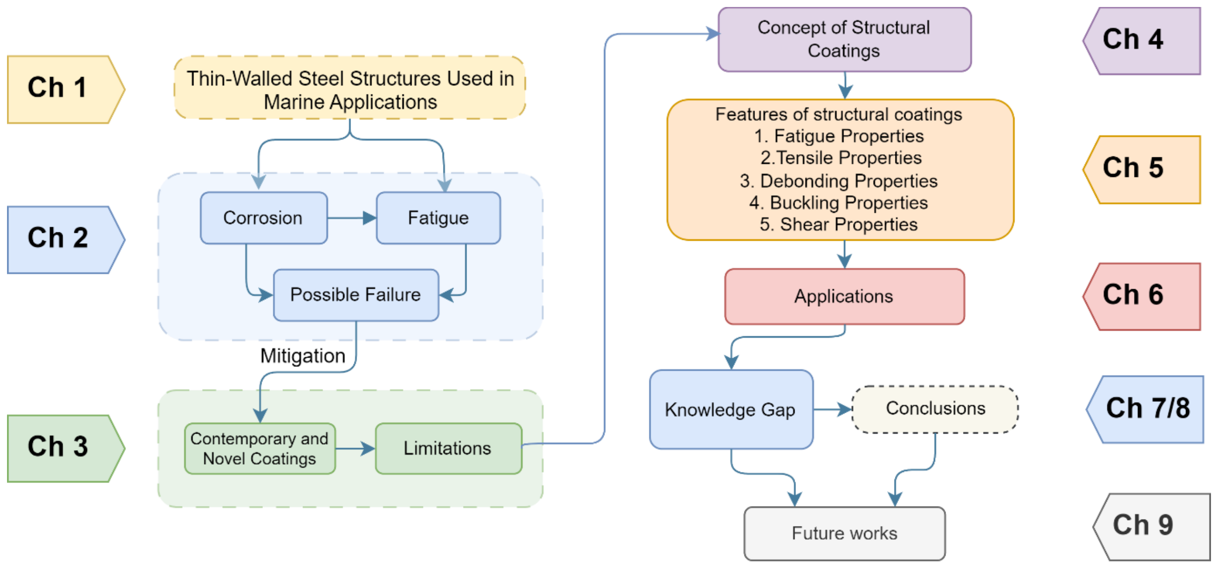

Figure 2. Flowchart showing the organisation of the presented article.

2. Impact of Corrosion and its Prevention

The mechanical performances of corroded steel samples have been tested in terms of the general corrosion and the local corrosion in different scales by laboratory tests or numerical simulations (Woloszyk et al. 2021). Research on reliability-based maintenance of ship hulls shows that when the thickness of a damaged plate decreases to 75% of its design thickness, it should be replaced (Katsoudas et al. 2023). Details of different damage types in ships and offshore structures are given in Table 2 (Dehghani and Aslani 2019).

Table 2. Different types of damage associated with steel offshore structures (Dehghani and Aslani 2019).

Mechanical damage	**Corrosion with mechanical stresses**	**Corrosion without mechanical stresses**
Dents	Stress-corrosion cracking (SCC)	Uniform or general
Deflection	Corrosion fatigue	Pitting
Gouge	Corrosion-erosion	Crevice
Separated Members	Fretting	Intergranular
Buckling	Dealloying	-
	Galvanic	-

The different types of local and general corrosions which are very common in ships and offshore structures include **general corrosion** which causes a more or less uniform penetration throughout the entire exposed metal region. **Pitting** is essentially a highly localised form of corrosion that appears as sharp holes of varying sizes (Momber 2011). Another important corrosion types are: crevice corrosion, intergranular corrosion, dealloying, galvanic corrosion and stress-corrosion cracking. In marine structures, general, pitting, and fatigue corrosion is very common, therefore, in this article, we would be mainly focusing on them (International Association of Classification Societies 2017).

It is widely known that coating is the best method for protecting a material from deterioration due to environmental exposure (Sørensen et al. 2009). Coatings are inevitable for every structure regardless of its material type either concrete, or metal to protect them from harsh and critical environment because if they are not protected against them, those structures will deteriorate over time, and it will reduce their expected life. It is now essential to safeguard the material from further degradation as its purity declines. For high-stakes structures operating in hostile locations, such as ships and offshore structures, ignoring this severe impact might lead to economic and environmental fatalities as we discussed earlier.

Corrosion-prevention coatings should be able to provide a strong physical barrier, blocking the path of hostile species toward the metal surface. Several types of anti-corrosive coatings are grouped together based on the strategy they use to prevent corrosion. The main anti-corrosion protections include barriers protection, cathodic protection, anodic passivation, electrolytic inhibition, and active corrosion inhibition (Hughes et al. 2010). The most commonly used anti-corrosion coatings will be briefly introduced in the next Section.

3. Contemporary Means of Prevention

In order to better understand anti-corrosion coatings, we may divide them into three major categories: (i) organic coatings, (ii) inorganic coatings, and (iii) metallic coatings (Radhamani et al. 2020). A marine coating must meet a number of requirements, including excellent adhesion to the substrate, the necessary mechanical and functional properties, such as scratch and wear resistance, hydrophobicity and hydrophilicity, antibacterial, antifouling, antistatic, chemical resistance, etc., while also considering the temperature at which the marine structures will operate (Verma et al. 2019).

Many coatings were made of different plastic materials even though, not all of them were resistant to corrosion as coatings, even if they were all chemically robust to the conditions experienced in marine environment. Especially, at the points where two or more structural components join each other, paint coatings deteriorate quickly, because moisture and dust may accumulate around the contact point and speed up the degradation (Kim et al. 2021). As simple paint-based coatings only act as barriers and any pinholes or other flaws in the coatings would lead to rusting of the steel substrate and resultant failure of the coating, conventional paints are not regarded to offer adequate protection in maritime conditions, since they do not endure for the entire life span of structures and it is not easy for the marine structures to be painted again and again due to their complicated design and the economic expense connected with it. Except that, the marine structures are also subjected to the fatigue because of cyclic load, sea waves and high wind pressure which causes this paint-based coating to wear off, and eventually fully erode from the surface, leaving the steel components to the direct exposure of the harsh critical environment which leads to corrosion, and hence cross-sectional area will reduce. These simple paint-based coatings are not enough to protect both new and particularly corroded marine structures from corrosion and also cannot increase the strength of marine structures, so it would be beneficial to prepare such reinforcements which can protect marine structure from corrosion and can increase its strength.

In addition to those traditional contemporary coatings, some of the researchers (Boomadevi Janaki and Xavier 2020; Liu et al. 2020; Cheng et al. 2021; Qiu et al. 2021; Bahremand et al. 2021; Fitriya et al. 2021; Zeng et al. 2022; Lin et al. 2022; Kalangi and Bolleddu 2022) worked on different novel materials including nanocomposite to improve hardness (>40 GPa), corrosion resistance (>800°C), and thermal stability up to 1200°C, since these nanocomposite materials are super hard (Pogrebnjak et al. 2018). But such coatings are quite expensive and their current applications in shipbuilding and offshore structures will be not so straightforward. It has been discovered that reinforcements of these nanocomposites may increase heat resistance, corrosion resistance, and mechanical properties of a metal matrix due to their own specific features (Radhamani et al. 2020). Because of the high specific stiffness, high specific strength, and strong resistance to corrosion and fatigue, fibre reinforced polymer (FRP) composites coatings have been attractive for structural and anti-corrosion applications in the civil engineering and maritime communities (Hollaway 2010). Thus, the concept of structural coating has been introduced in the next Section.

4. Concept of Structural Coatings

When FRP composites are applied on the surface of ships and offshore structures which are usually made of steel plates with the help of epoxy they are called structural coatings as shown below in Fig 3. FRP composites consist of a matrix (vinyl ester, polyester, epoxy, polyurethane, phenolic etc.) and fibres (aramid, carbon, glass, and basalt) are the good example of structural coatings (Sasy Chan and Zhou 2014). The structural coating contains the reinforcement which is called structural, and there are two main purposes of the reinforcement: 1) strengthening the entire structure covered by the coating, for instance ship hull, and plates of offshore rig jackets etc.; 2) strengthening the coating layer itself in order to prevent cracking, blistering, and other failures of the coating for the sake of ensuring its long-lasting contribution to the structure performance. In addition to the above-mentioned advantages of structural coatings they could also help to extend the expected serviceability life of a ships (Li, Xu, et al. 2022).

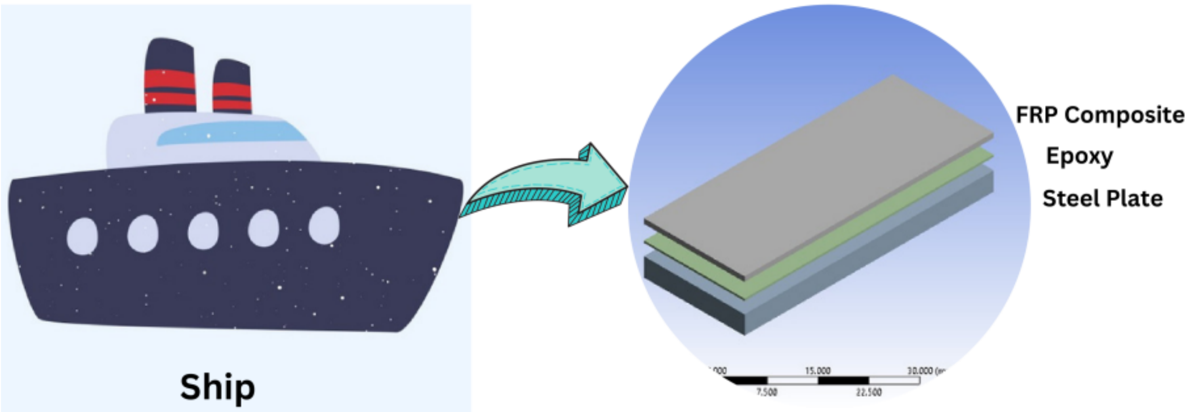

Figure 3. How structural coatings are applied on ship hulls.

4.1. Resins for Matrices

Resins are essential to create reinforcements with desirable thermal and mechanical properties. The ideal resins for use with reinforcements would be those that could be laminated, cured at room temperature, and be compatible with the materials being used. The resins such as vinyl ester, polyester, epoxy, polyurethane, and phenolic are frequently used as the adhesives. The vinyl esters have mechanical properties and costs between polyesters and epoxies (Marsh 2007). The vinyl esters have fewer reactive sites and resist chemical corrosion and hydrolytic degradation (Marsh 2007). The vinyl esters are harder and more flexible than polyesters. As a matrix in the FRP laminates, they resist fatigue-induced hull and deck failure (Hoge and Leach 2016). The vinyl esters operate at 200°C. Due to its durability, the vinyl ester is used to build bigger ships, particularly military ships. In order to get excellent fibre-resin adhesion with vinyl esters, one must first carefully prepare the surface and treat the material under certain environmental conditions, unlike with polyesters where either of these actions is sufficient. To comply with stricter industrial emissions regulations, the resins must have a minimum concentration of styrene (Hoge and Leach 2016).

The polyester and vinyl ester resins laminate well, cure quickly, and resist water, but both shrink 7-10% and emit styrene, requiring specific solutions to reduce worker exposure (Hoge and Leach 2016). Epoxy is ideal for injection operations without steam curing, because of its low viscosity and low curing temperature. The epoxies outperform PE and VE in elongation, tensile strength, and modulus (Hoge and Leach 2016). The FRP matrices are typically polyester or epoxy resins. The phenolic resins are fire-resistant at 200°C and emit little smoke or harmful fumes, but polyesters have 10-20% better mechanical properties then phenolics (Rubino et al. 2020). Table 3 presents the most prominent mechanical properties of the most widely used thermosetting polymer resins used for reinforcements (Teng et al. 2012). The epoxy and vinyl ester resins are popular matrices. In cyclic loading, the epoxy outperforms other resins, whereas the vinyl ester is cheaper and water-resistant (Rubino et al. 2020). Vizentin and Vukelic 2022) proved that epoxy/glass composites outperform polyester/glass in tensile strength and demonstrated the role of biofouling in the deterioration of composite materials' mechanical properties in marine environment.

Table 3. Typical mechanical properties of thermosetting polymer resins (Teng et al. 2012).

Resin	Density (g/cm^3)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Max. Elongation (%)
Polyester	1.2	4.0	65	2.5
Epoxy	1.2	3.0	90	8.0
Vinyl ester	1.12	3.5	82	6.0
Phenolic	1.24	2.5	40	1.8
Polyurethane	varies	2.9	71	5.9

4.2. Fibres

Fibres including carbon, glass, aramid, and basalt are often used in the FRP composites for reinforcements. Large composite structures often use glass fibres since they are up to 10 times less expensive than carbon fibres, though this excludes several aerospace applications. The mechanical and physical properties of commercially available varieties of glass fibres are listed in Table 4. E-glass fibre has remained the most popular reinforcing material for maritime applications due to its high maximum tensile strength of around 2200 MPa, low ultimate tensile strain of about 2.5%, and excellent resistance to moisture and chemical aggression. Due to its chemical composition, the E-glass provides superior electrical insulation. S-glass, R-glass, and T-glass are the common names in the US, Europe, and Japan for glass fibres made of high-strength glass. The S-glass typically contains between 40 and 70 percent more SiO_2, Al_2O_3, and MgO than the E-glass. Although both E-glass and S-glass maintain a good resistance, their tensile strengths decrease by as much as 50 percent when heated from room temperature to approximately 540°C (Gargano et al. 2017). In addition, all glass fibres are harmful to aquatic life and are not biodegradable. To avoid these risks, researchers have come up with a different way to make glass fibre, which is "fishnet", which is made of nylon fibres. The fishnets may replace glass fibres because of their same flexural strength, modulus of rigidity, and impact strength, but lower tensile strength (Rohith et al. 2019).

Table 4. Approximate mechanical properties of commercially available different fibre grades are shown in (Bank 2006).

Fibre grade	Density [g/cm3]	Fibre Diameter (μm)	Tensile Modulus [GPa]	Tensile Strength [MPa]	Max. Elongation (%)

Glass fibre E	2.57	10	72.5	2200-3400	2.5
Glass fibre A	2.46	-	73	2760	2.5
Glass fibre C	2.46	-	74	2350	2.5
Glass fibre S	2.60	10	88-90	4600	3.0
Carbon Standard	1.7	7-10	250	3700	1.2
Carbon High Strength	1.8	-	250	4800	1.4
Carbon High Modulus	1.9	-	400-500	2000-3000	0.5
Carbon UHM	2.1	7-10	800	2400	0.2
Aramid 49	1.45	12	130	2760-3600	2.40
Aramid 29	-	12	-	2750	4.00
Boron	2.6	130	400	3400	-
Polyethylene	0.97	12	117	2.6	-
Basalt fibre fabric	-	-	91	2350	2.6

The carbon fibre is a semicrystalline organic material composed of two-dimensional arrays of carbon atoms, making it a solid at the molecular level. In comparison to glass, carbon fibres excel in both strength and stiffness. The carbon fibres have a maximum tensile strength of about 4800 MPa, with a break elongation of 0.9% to 2% as shown in Table 4 (Grabovac 2003; Hassan et al. 2022). The price of carbon fibres is significantly higher than that of glass fibres; as a result, reinforcing structures with carbon fibre is not a feasible option in most cases, and hybrid laminates composed of carbon and glass fibres are proving to be very attractive to ship designers.

Aromatic polyamide molecular chains constitute aramid fibres. Early FRP prestressing tendons were made using aramid fibres (Kevlar). In the 1980s they were being used in Europe and Japan for wrapping of columns with aramid fabrics (Bank 2006). Table 4 lists the important mechanical properties of commercially available aramid fibres, whereas Table 5 gives the most prominent mechanical properties of different prominent fibres when they are blended with epoxy.

Table 5. Displays typical parameters of different FRP composites made using the pultrusion method, with a fibre and epoxy matrix ratio by weight of 60% (Hollaway and Teng 2008).

Composite Material	Specific Weight	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (Gpa)
E-glass/epoxy	1.90	750-1050	40.00	1450	40.00
S-2 glass/epoxy	1.80	1650	55.00	-	-
Aramid 49/epoxy	1.45	1150-1400	70-110	-	-
Carbon (PAN) /epoxy	1.60	2670-1950	150-220	1600	-

Carbon (pitch) /epoxy	1.80	1400-1500	280-350	Failure strain 0.40 > 330	-

4.3. Hybrid Fibre Composites

When compared to standard GFRP composites, hybrid composites made of glass and carbon fibre are both stronger and lighter (Ahamed et al. 2016). As a bonus, the hybrid composites reduce the need for high-priced reinforcements such as carbon fibre, Kevlar, or nanofillers in polymer composites, all without compromising strength or durability. The hybrid composites will play a critical role in propelling the development and widespread adoption of composites because of their reduced production costs (Nayak and Ray 2018). Jesthi and Nayak (Jesthi and Nayak 2019) developed five distinct carbon/glass fibre combinations and found that the tensile strength, flexural strength, and modulus of seawater-aged [GCG2C] type hybrid composite were increased by 14%, 43%, and 64%, respectively, when compared to plain GFRP composite. However, its impact strength was reduced by 44.5%. Epoxy/E-Glass panels show 25% greater fatigue resistance than vinyl ester/E-Glass panels for in-plane fatigue loads on dry samples, according to a comparison of fatigue resistance between epoxy and vinyl-ester resin laminates with E-glass reinforcements made of a blend of glass and carbon fibres (Narasimha Murthy et al. 2010).

4.4. Limitations of the FRP

The FRP have limited practical uses to build entire ship hulls because of some primary drawbacks. Most notably, the FRPs have the following problems: (1) low elastic modulus, particularly for GFRP, AFRP, and BFRP, which implies that the stiffness of the FRP reinforced structures is relatively low and may have a detrimental impact on the performance of structures during the service stage; (2) poor shear capacity and ductility; (3) low rate of strength utilization in structural applications; (4) high initial cost especially carbon fibres; (5) inability to satisfy criteria for low cost structural material; (6) and poor ductility are all problems with the FRP-reinforced structures as a sole material (G. Wu et al. 2012).

5. Features of Structural Coatings

In addition to disadvantages mentioned in previous chapter, the FRPs have emerged as a viable alternative to traditional repair and reinforcement methods like welding, bolting, and riveting, because these techniques often lead to flaws, including the structure's own self-weight, the fatigue sensitivity of weld flaws, and the inconvenient nature of the process in the field of steel structure reinforcement. Strengthening system with the FRP bonded to steel substrate has been shown to be more effective, with minimally increased permanent load, eliminated stress concentration, and increased durability (Wang et al. 2021). The crack development rate and fatigue life in corroded steel plates were greatly reduced by increasing the FRP strengthening stiffness or by using prestressed FRP plates (Li, Xu, et al. 2022). As a result of its superior fatigue, corrosion resistance, and performance properties, the FRPs are the promising option for the reinforcement and retrofitting of steel structures (Guo et al. 2018). Furthermore, the epoxy-bonded FRPs have gained increased interest, but there is still a dearth of literature on the topic of steel plates in comparison to that of the FRP-strengthened beam-type structures. Researchers have shown that the changing mechanical properties of a FRP composite depends on the fibre strength and stiffness, volume fraction, and orientation of the kind of fibre used, as well as the type of adhesive (Hollaway and Teng 2008). When these reinforcements (CFRP, GFRP, BFRP etc.) are used to strengthen marine structures, a number of mechanical properties are significant, such as fatigue, debonding and buckling, etc. Thus, in each subsection of the presented chapter reviews the works dealing with failure mode.

5.1. Fatigue Properties

The stiffness of the FRP strengthening, the amount of prestressing, the patch configuration, the adhesive thickness, the degree of steel surface preparation, and initial degree of damage to the steel plate are the elements that determine the efficiency of fatigue strengthening of defective steel plates reinforced with the FRP materials. In the case of cracks in steel plates, external patching using the FRP materials reduced the average stress amplitude, prevented crack opening through the "bridging effect", slowed the stress intensity factor, fracture development rate, and decreased the crack propagation (Li, Xu, et al. 2022). Numerous studies have investigated how the FRP materials improve fatigue performance of damaged steel plates. From the perspective of the original defect types, the defective steel plates reinforced using the FRP materials described in the current literature may be categorised into the following groups: a central hole in a CFRP-strengthened steel plate (Wang et al. 2017), a central hole in a CFRP-strengthened steel plate with two symmetric fractures at either side of the hole (Jones and Civjan 2003), a steel plate with a central hole and a unilateral vertical fracture made of CFRP (Lepretre et al. 2018), two V-shaped edge notches on a CFRP-strengthened steel plate (Jones and Civjan 2003), two U-shaped edge cuts and two vertical fractures in a CFRP-strengthened steel plate (Lepretre et al. 2018), a single edge fracture in a CFRP-strengthened steel plate (Colombi et al. 2015), a steel plate reinforced by CFRP and has a central hole with two inclined fractures (Aljabar et al. 2017), etc. In an experiment, C. Wu, X.L. Zhao, et al. (2012) discovered that if the steel plates were bonded using ultra-high modulus CFRP, the fatigue life of broken steel plates may be extended by 3.26 to 7.47 times of reference plate.

By using the double-sided repair approach, Liu et al. (2009) demonstrated that the fatigue life of CFRP sheets with a normal modulus was increased by a factor of 2.2–2.7 over un-patched steel plates, and by a factor of 4.7–7.9 over un-patched steel plates with a high modulus. Hence CFRP sheets with a higher modulus were much more effective, they also used GFRP sheets between CFRP sheet and steel plates which can act as buffer to avoid thermal stresses between two materials and can also prevent galvanic corrosion. Täljsten et al. (2009) demonstrated that the fatigue life of non-prestressed laminates could be increased by approximately four times compared to a reference sample, and that prestressing laminates totally prevented crack formation. At fracture angles (b<45°) UHM-CFRP laminates are at their most effective, extending fatigue lifetimes by a factor of 1.6 compared to a factor of 2.2 for completely repaired samples (Aljabar et al. 2016). Wang et al. (2018) studied how steel plates with a central hole behaved when they were submerged in saltwater. Crack propagation of steel plates slowed down by using CFRP, and also increased their bearing capacity and ductility.

Corroded steel plates' fatigue behaviour was greatly improved by applying an external CFRP patch, and their fatigue life was restored or even exceeded that of uncorroded steel plates (Li, Xu, et al. 2022). The patched sample had a fatigue life that was more than 85.3 times (nearly twice as long) as that of the corroded steel plate that was left unpatched. The fatigue performance of corroded steel structures might be enhanced by using CFRP materials that are externally bonded (Li, Xu, et al. 2022). Xu and Qiu (2013) tested 8 sets of corroded and uncorroded Q235 steel plates in a neutral salt spray corrosion environment and found that the fatigue life of corroded steel plates decreased rapidly with the increase of rust pit depth (Li, Xu, et al. 2022). It was found that increasing the rate of corrosion in a steel plate, the size of the initial crack, or the adhesive thickness, they all contribute to a shortening of the fatigue life, while increasing the stiffness or prestress level of CFRP plate has the opposite effect, increasing the fatigue life. When a CFRP plate of 2.0mm thickness was used, no damage was found even after 17 million fatigue cycles, hence the thickness of reinforcement has great influence on fatigue life (Li, Xu, et al. 2022). Karatzas et al. (2015) studied and tested the different steel plates that had been reinforced with CFRP. The results demonstrated that samples whose surface was grit-blasted prior to bonding were more effective in retarding the crack propagation rate, hence extending the fatigue life of the fractured samples by 1.7 to 5.6 times. Table 6 helps us understand the effect of different parameters on the fatigue life when different types of the FRPs are used for reinforcement. When the FRP is prestressed and double-sided configuration is used for reinforcement they are most effective and increase the fatigue life.

Table 6. Fatigue life comparison at different parameters.

FRP Specification	Corrosion /Month	Strengthening Configuration	CFRP Prestress Level	CFRP Thickness [Mm]	Increase of Fatigue Life Ratio [-]	Angle	Ref.
CFP-520	15	Double-sided	4.5%	2.0	85.3	-	Li, Wang, et al. (2022)
CFP-514	15	Double-sided	4.5%	1.4	15.0	-	
CFRP-UHM	-	Single partial sided	-	1.46	1.7	45°	Aljabar et al. (2016)
CFRP-UHM	-	Single full sided	-	1.46	2.2	45°	Aljabar et al. (2016)
CFRP-NM	-	Double-sided	-	-	2.0	-	Liu et al. (2009)
CFRP-HM	-	Double-sided	-	-	7.9	-	Liu et al. (2009)
CFRP-UHM	-	Double-sided	00	-	3.74	-	Täljsten et al. (2009)
CFRP-UHM	-	Double-sided	15kN	-	10.5	-	Täljsten et al. (2009)

CFP – carbon fibre plate; UHM – ultra-high modulus; NM – normal modulus; HM – high modulus

5.2. Tensile Properties

The modulus of elasticity, elastic limit, elongation, proportional limit, decrease in cross-sectional area, ultimate tensile strength and yield strength are all pieces of information that may be gleaned from a material's tensile qualities. The yield strength, ultimate tensile strength and the Young's modulus are the tensile qualities that are most often addressed (Rahman and Putra 2018).

Woloszyk et al. (2022) investigated the mechanical properties of normal strength steel that had been exposed to corrosion degradation level below 25% due to immersion in marine environment. It was discovered that when the deterioration level reached 25%, the yield stress dropped by around 10%. Zhang et al. (2021) have studied the effectiveness of uniformly corroded steel plates in great detail, resulting in the discovery of degradation rules of their mechanical properties. According to the data, uniform corrosion reduces steel's nominal strength and deformation capacity, leading to a less prominent yield point, early necking, and a shorter yield plateau. Huang et al. (2022) studied the tensile behaviour of uniform and localised corroded tensile steel and found that corroded samples' load-displacement curves were found to be quite different from those of uncorroded ones. Because of the stress concentration, the total yield stress of the localised corroded samples was visibly lower than that of the uncorroded samples. From this point of view, the structural coatings have potential to increase the deteriorated mechanical properties of corroded steel.

Li et al. (2014) examined the tensile behaviour of steel plates connected with BFRP. Both the post yield modulus and ultimate bearing capacity of basalt steel composite rose approximately linearly with the number of outside BFRP layers from zero to eight. In contrast, Tavakkolizadeh and Saadatmanesh (2003) discovered that the average failure stress of CFRP declined from 75% of the ultimate tensile strength to 42% as the number of CFRP layers increased from one to five, resulting in a reduction in the strengthening effectiveness of the beams. Shenghu Cao et al. (2009) examined CFRP and hybrid FRP tensile qualities at extreme temperatures. They observed that the FRP materials weakened at high temperatures due to the resin matrix melting, which lost its ability to transfer load between wavy fibres. Wang et al. (2018) studied how steel plates with a central hole behaved under tension when they were submerged in saltwater. After being subjected to 180 wetting and drying cycles, the mechanical deterioration degree was above 20%, and the drop in strengthening effect was significantly worse. Ashori et al. (2016) shown that tensile strength may be improved by including short carbon fibres (SCFs) in a polypropylene matrix. The fibrous fracture was seen in experiments on CFRP composites conducted at temperatures over 200^0C, as reported by Cree et al. (2015). The fibrous fracture, which revealed a disorganised dispersion of fibres rather than discrete pieces, was taken as evidence of the epoxy resin's enhanced ductility. Lu et al. (2015) examined the tensile strength of steel plates reinforced with CFRP sheets. He discovered that adding more CFRP layers reduced their effectiveness in hardening and stiffening the material. The failure modes were shown to be considerably influenced by temperature changes, but were unaffected by the inclusion of more CFRP layers or a variation in strengthening methods. The yield load and elastic stiffness hardly responded to an increase in CFRP layer count. The mechanical properties of the double-sided strengthened samples were superior to those of the single-sided strengthened ones. The yield load and the elastic stiffness both dropped with increasing temperature. Table 7 helps us understand the effect of different parameters (temperature, strengthening configuration, number of the FRP layers) on the tensile properties when different types of the FRPs are used for reinforcement.

Table 7. Tensile properties comparison of different FRPs at different parameters.

Specification Sample	FRP Layers	Strengthening Configuration	Yield Loads [kN]/ Yield Stress [Mpa]	Temp. °C	Elastic Stiffness [kN/mm]/ Young's Modulus [GPa]	Ref.
CFRP	1	Single-sided	17.3 kN	25	95.9 kN/mm	Lu et al. (2015)
CFRP	4	Single-sided	20.2 kN	25	94.9 kN/mm	Lu et al. (2015)
CFRP	4	Single-sided	20.2 kN	25	94.9 kN/mm	Lu et al. (2015)
CFRP	4	Double-sided	20.6 kN	25	120.3 kN/mm	Lu et al. (2015)

CFRP	1	Single-sided	17.3 kN	30	93.4 kN/mm	Lu et al. (2015)
CFRP	1	Single-sided	16.1 kN	120	90.2 kN/mm	Lu et al. (2015)
BFRP	2	Double-sided	455 MPa	-	134 GPa	Li et al. (2014)
BFRP	8	Double-sided	551 MPa	-	117 GPa	Li et al. (2014)

5.3. Debonding Properties

For restoring steel structures, the FRP is bonded to the steel surface using epoxy adhesives. The epoxy adhesives are used to transmit the load to the FRP material (Hollaway 2010). The interfacial bonding has a crucial role in how well the FRP strengthened steel structures operate. Several studies carried out at room temperature have shown that the adhesive layer is the composite system's weak link, with debonding of CFRP from the steel substrate being one of the most often seen failure types (C. Wu, X. Zhao, et al. 2012). The bond properties between externally bonded CFRP materials and steel plate are influenced by inherent and extrinsic variables. The intrinsic elements generally include CFRP material forms and modulus (e.g., CFRP plate with normal modulus and ultra-high modulus (Yu et al. 2012)), adhesive kinds (e.g., a variety of adhesives, both liner and non-liner (Al-Mosawe et al. 2015)), and methods for preparing the surface (e.g., grit blasting, sandpaper gridding, and solvent cleaning, etc. (Fernando et al. 2013)). The extrinsic elements include loading types (quasi-static, impact, and fatigue loading (Al-Mosawe et al. 2016)), ambient conditions (temperature, humidity, and water ingress (Borrie et al. 2015)), and the combined effect of severe environment exposure and long-term loading (e.g., fatigue loading combined with an ocean environment, etc. (Borrie et al. 2015)). Problems associated with the adhesive's long-term exposure to the atmosphere, an alkaline atmosphere, heat, creep and relaxation, UV light, and fatigue should be studied (Wu et al. 2013).

Several CFRP materials externally bonded to steel substrates bond stress-slip models have been developed (Wang and Wu 2018). Al-Zubaidy et al. (2012) studied double strap joints subjected to static and dynamic tensile loads, examining how the number of CFRP layers, bond lengths, and loading rates affected the joints. The corrosion damage causes section loss and harsh surface topography, which changes surface roughness, contact area, free energy, and stress concentration, which changes CFRP-steel substrate bond properties. The influence of surface preparation on adhesion qualities has been investigated, and it has been shown that changes in steel surface physical and chemical properties may even modify CFRP-steel plate bond strength and failure modes (Fernando et al. 2013). Li et al. (2019) examined CFRP-corroded steel bonding with double-lap joints, six corrosion durations and four adhesive thicknesses were examined. The failure modes of the samples were found to be more dependent on the thickness of the adhesive coating than the duration of the corrosion process, except when the adhesive layer reached a critical thickness. The effective bond length of the corroded samples was found to be greater than that of uncorroded samples, leading to an increase in the ultimate load for samples with the same failure mechanism of steel/adhesive interfacial failure, whereas increasing the adhesive thickness from 0.5 to 1.0, 1.5, and 2.0mm improved the effective bond length. Wang et al. (2021) used a single lap shear test to investigate the influence of bonding thickness and adhesive toughness on the performance of CFRP-steel bonds. When the bonding thickness is increased from 0.5 mm to 1.5 mm, the fracture energy of the strong adhesive increases, and the interface stiffness decreases. In contrast, the brittle adhesive shows almost little variation in performance as a function of bonding thickness.

Li et al. (2016) analysed the bond between CFRP and steel plate at temperatures ranging from 27 °C to 120 °C. A significant decrease in load bearing capacity was recorded at temperatures above the adhesive's glass transition temperature. Nguyen et al. (2011) evaluated steel/CFRP adhesively bonded double strap joints at increased temperatures around the adhesive's glass transition temperature (Tg, 42 °C). At 20-60 °C, joints with varying bond lengths were tested until failure. When temperature reached Tg, joint failure switched from adherend failure to debonding failure. The effective bond length increased, and the ultimate load and joint stiffness decreased at temperatures around and above Tg. The effects of three different epoxy resins on high modulus CFRP-steel bonded joints were investigated (Al-Shawaf et al. 2009) at temperatures ranging from 20 °C to 60 °C. Specifically, the ultimate joint load was found to be significantly reduced, and the strain level over the CFRP surface decreased to nearly nothing, all because of the adhesive softening and degrading in characteristics at temperatures near and above transition temperature. Nevertheless, there is a dearth of research on the bond behaviour of CFRP and steel at elevated temperatures, and further study is needed to completely comprehend the performance of the CFRP-steel interface under such circumstances.

LIU et al. (2010) conducted a series of fatigue experiments on double strap joints manufactured from both standard and high modulus CFRP sheets. Before and after fatigue loading, interfacial debonding was shown to be the primary cause of failure for the samples made of normal modulus CFRP sheets. When the fatigue load ratio was more than 0.3, the sample reportedly broke under the stress of fatigue loading. In contrast, high modulus CFRP ruptured only even when the load ratio reached 0.55 and the sample was exposed to 10 million fatigue cycles with little or no bond strength. B. Hu et al. (2020) investigates hybrid carbon and glass fibre reinforced polymer to steel single-lap joints using both experimental and numerical bond behaviour analysis. The experimental results show that the failure mechanisms of the hybrid FRP-to-steel joints are similar to those of the three-layered CFRP-to-steel joints. The bond strength of hybrid FRP-to-steel joints is stronger than that of single-layered CFRP-to-steel joints and about the same as that of triple-layered CFRP-to-steel joints. The bond length of hybrid FRP-to-steel joints is about the same as that of three-layered CFRP-to-steel joints. In order to increase the adhesion between an aluminium substrate and a CFRP, Han et al. (2022) suggested a simple method using resin pre-coating (RPC) with carbon nanotubes (CNTs). The shear bond strength between the aluminium substrate and the CFRP was increased by 30–100% as a result of CNTs crossing over the interface between the adhesive joint and the aluminium substrate and RPC sealing micro–/nano–cavities. Table 8 helps us understand the effect of different parameters on the bond strength when different types of FRPs are used for reinforcement. The increasing temperature has negative effect on the FRP, whereas increasing the layers of the FRP and increasing the bond length have positive effect on the bond strength.

Table 8. Bond strength comparison of different FRPs at different parameters.

FRP	Bond Length (mm)	Layers of FRP	Temperature (°C)	Ultimate Load (kN)	Failure Mode	Ref.
CFRP	-	-	27	10.614	I	Li et al. (2016)
CFRP	-	-	50	8.95	II	Li et al. (2016)

CFRP	-	-	120	0.316	II	Li et al. (2016)
CFRP	20	1	-	2.62	I	B. Hu et al. (2020)
CFRP	80	1	-	2.42	II	B. Hu et al. (2020)
CFRP	20	3	-	3.44	I	B. Hu et al. (2020)
CFRP	80	3	-	4.88	II	B. Hu et al. (2020)
CFRP/GFRP	20	-	-	2.86	I	B. Hu et al. (2020)
CFRP/GFRP	80	-	-	4.37	II	B. Hu et al. (2020)

Mode I failure is steel substrate-adhesive debonding. Mode II failure is adhesive-CFRP sheet debonding.

5.4. Buckling Properties

When a structure is exposed to excessive compressive stresses, a phenomenon known as buckling occurs. When a structure is subjected to severe shear forces, shear buckling occurs. When the steel has been corroded away or the load is too severe, the deck or bottom of the ship may buckle all the way across possibly leading to hull girder failure (Raju and Premanandh 2018). Elastic instability is often the root cause of buckling failure. Plate and shell constructions are more vulnerable to bend under compressive pressures because of their thin-walled characteristics. Several buckling modes have been established for comparable thin-walled structures by extensive buckling research (Falkowicz et al. 2019; Debski et al. 2021). Several publications (Falkowicz et al. 2019; Debski et al. 2019; Debski et al. 2021) provide a range of case studies illustrating the use of computational and experimental failure analysis to thin-walled composite columns. Multiple researchers (Zhao et al. 2006; Shaat and Fam 2007; Silvestre et al. 2008; Gao et al. 2013; Yoresta et al. 2020) studied the buckling behaviour of columns.

According to a review of the relevant literature (Rozylo et al. 2020), intralaminar failure, also known as matrix cracking and compression or rupture of the tension fibre, and interlaminar damage or delamination are the most often reasons for failure in composite structures. Due to greater elastic modulus, CFRP is better for reinforcing steel structures than GFRP. High or ultra-high modulus CFRP is desirable for buckling resistance increase (Teng et al. 2012).

The buckling stress of hybrid composite plates (carbon, glass, and aramid) were investigated by Yeter et al. (2014), who conducted research on the impact of changing the angle at which the fibres were oriented in symmetrical and asymmetrical layer configurations. Swapping out the fibre types had a major impact on the buckling behaviour. Using fibres with greater stiffness (carbon fibres) in the outer layers enhanced the buckling stresses. It was determined that hybrid plates that were manufactured using stacking sequences of [(0/90)3]s had a greater buckling strength than other types of stacking sequences. Madenci et al. (2023) researched at how CNTs modify the buckling behaviour of the FRP composites. The results show that, adding 0.3% CNTs to the composite made it more resistive to buckle. Finally, compared to the simple-simple boundary condition, the average load-carrying capacity for the clamped-clamped condition was 268% higher in the CNT samples and 282% higher in the standard CNT samples. Yang et al. (2013) predicted the ultimate strength of different plates made of laminated composite material under a compressive load. Several models are made, and each one is based on the theory of first-order shear deformation and the assumption regarding small deflections. The methods provide approximations for the thicker plates that are appropriate but slightly cautious. The findings are highly conservative for the thinner plates since the behaviour after buckling is not taken into consideration in the analysis. Some of the models will have to use a large deflection plate theory to reach their full potential. Table 9 helps us understand the effect of different parameters on the buckling behaviour when different types of FRPs are used for reinforcement. Increasing the layers of the FRP and changing the fibre directions have positive effect on the buckling.

Table 9. Comparison of buckling behaviour of different FRPs at different parameters.

FRP & Metal	Layers of FRP	Ply Orientations	Pmax (kN)	% Gain in Strength	Ref.
CFRP Steel	2	-	374.06	26	Gao et al. (2013)
CFRP Steel	8	-	544.88	84	Gao et al. (2013)
CAG	3	[(0/90)3]s	2.242	-	Yeter et al. (2014)
CGA30	3	[(30/-60)3]s	9.68	-	Yeter et al. (2014)
CGA 45	3	[(45/-45)3]s	9.81	-	Yeter et al. (2014)
CGA *	3	[(0/90)3]us	1.636	-	Yeter et al. (2014)
CFRP with 0.3% CNT	-	-	17.812	-	Madenci et al. (2023)
CFRP with 0% CNT	-	-	15.506	14.80	Madenci et al. (2023)

Pmax – max load; G – glass fibre; C – carbon fibre; A – aramid fibre; 30- [(30/-60)3]s ; 45- [(45/-45)3]s

5.5. Shear Properties

The shear strength of a material or part is its capacity to withstand shear forces without breaking. In shipbuilding, it is important to know the shear strength of plates and elements of primary supporting members (e.g., floors in double bottom), where high shear stresses could occur. Thus, such other structural parts can be designed or specified in the most cost-effective way possible while still being able to withstand shear forces (Paik et al. 2004). The shear testing was performed on thin steel plates reinforced with bonded CFRP laminates by Khazaei Poul et al. (2016). The yield strength, ultimate strength, secant stiffness, and energy absorption were all found to be greatly enhanced when the strengthening was applied.

In the civil engineering, the characteristics of steel shear walls reinforced with bonded CFRP were investigated by Hatami et al. (2012) using experimental test and numerical modelling. The increases in stiffness, energy absorption, over-strength, and capacity were achieved at the expense of ductility, as was the case with walls with greater fibre contents. The cyclic behaviour of perforated steel shear walls enhanced with bonded CFRP was investigated by Sahebjam and Showkati (2016). The elastic stiffness and maximum base shear were both improved using CFRP, and the yielding of the steel walls was delayed. Dong et al. (2022) investigated the novel hybrid seawater sea-sand concrete beam type known as SWSSC and reinforced it with the BFRP. The findings shown that the shear resistance of the suggested hybrid SWSSC beams may be increased by the existence of the BFRP.

5.6. Summary

This chapter studied different structural coatings based on fibre types (carbon, glass, basalt, and aramid). A comparative study of different types of structural coatings is given in Table 10 below. According to this study, we can estimate that more than 85 percent of the previous research work has been done on carbon-based FRP, followed by glass, basalt, and aramid composites. Thus, glass, basalt, and aramid fibres can be potential research topics in the future. Similarly, almost 85 percent of the previous studies have been conducted on uncorroded steel and only 15 percent have focused on corroded steel. Corroded steel has more potential and should be explored more in the future. 33 percent of the work has been conducted on fatigue; 25 percent of the work has been conducted on tensile properties; 25 percent of the work has been conducted on debonding; and only 17 percent of the work has been conducted on buckling. Therefore, technically, the buckling failure mode has significant research potential. These are the reasons for the current limitations of structural coating usage in the shipbuilding and offshore industries.

Table 10. Summary of publications related to different failure modes with steel which are covered in this review article.

FRP Type	Tensile		Fatigue		Debonding		Buckling	
	Corroded	Un-corroded	Corroded	Un-corroded	Corroded	Un-corroded	Corroded	Un-corroded
Carbon FRP	3	10	3	15	2	12	0	9
Glass FRP	0	0	0	2	0	1	0	1
Basalt FRP	0	2	0	0	0	0	0	0
Aaramid FRP	0	0	0	0	0	0	0	1

Note: Not enough research related to the shear properties of plates was found that’s why its column has not been made.

It is noted, that vast research was focused on the investigation of steel specimens reinforced with Carbon FRP. The main strength of these solution is the relatively high mechanical properties (i.e. it represents the modulus of elasticity similar to or even higher than steel). However, one major weakness needs to be considered. The steel and CFRP composite form a galvanic couple, resulting in galvanic corrosion, which was already reported in early works (Tavakkolizadeh and Saadatmanesh 2001). Thus, even though good retrofitting effectiveness could be achieved with the application of CFRP, its effectiveness for long-term exploitation could be jeopardized.

In the case of Glass FRP, the obtained mechanical properties are lower than in Carbon FRP. However, compared to the latter, it is much cheaper, and we will not face problems of galvanic corrosion. In the case of Basalt and Aramid fibres, the corrosion problems should not be problematic but will require a higher cost.

6. Applications

From the literature review we can see that the FRP composites can be used in two ways: 1) as reinforcement of other material; or 2) can be used itself for manufacturing of different components, often relatively small, to full-scale structures. One way mentioned later, in which the FRP composites are used, is extremely extensive and applies to highways (Van et al. 2003), bridges (W. Hu et al. 2020), automobile (Arifurrahman et al. 2018), infrastructure (GangaRao 2011), air force (BIELAWSKI 2017), marine sector (Caramatescu and Mocanu 2019), and oil and gas exploration and exploitation (Pérez-Collazo et al. 2015). Similarly, the FRPs composites are already being used in marine as a sole material without steel (Lowde et al. 2022). During the Second World War, the US Navy then put out 8.50-meter-long river patrol boats, counting on the material's ability to cut costs for maintenance and production (Caramatescu and Mocanu 2019), while nowadays many yachts are manufactured with purely composite hulls.

The first FRP-based structural coatings as reinforcement were researched as an alternative of aviation maintenance technology, with Baker et al. (2009) among the first to evaluate the efficacy of this repair technique in both laboratory and field applications. One of the most important works in this field is work by Roach (1998), where tests showed a life extension of about 20 times for reinforced defective samples and four times for standard samples without defects. Different researchers (Wang and Pidaparti 2002; Chung and Won H. Yang 2003; Chung and Won Ho Yang 2003; Okafor et al. 2005) have also done experiments that showed how well the reinforcement repair works.

Similarly, a lot of research based on application of structural reinforcement in the field of civil engineering on the FRP composites, concreate and steel applications (Van et al. 2003; Hollaway and Teng 2008; Hollaway 2010), has been conducted. For instance, composite reinforcements are widely used in the United States, Canada, Europe, China and Japan for the seismic retrofitting of columns, as well as the rehabilitation of bridges and structures.

The composites based anti-corrosion reinforcement are very important for marine structures which have stringent serviceability requirements and high maintenance costs (Yan et al. 2022). As seen in literature, the contemporary coatings have limitations to protect crucial marine structures, but the polymeric coatings are capable to reinforce the structure while also protecting them from the elements, i.e.: ultraviolet light, marine biofouling, and corrosion.

The aluminium superstructure on an Adelaide Class frigate of Royal Australian Navy (RAN) was reinforced using an CFRP. After the reinforcement of the superstructure, there has been no more cracking in the problematic region during the preceding seven years. In spite of being subjected to the harsh conditions of the marine environment, the bonded composite reinforcements have not suffered any significant damage (Grabovac 2003). Another ship of RAN was reinforced using a CFRP to prevent the recurrence of super structural fatigue cracking. After 15 years of service on an operational RAN ship, the CFRP reinforcement showed no signs of failure. There was no evidence of deck cracking beneath or around the patches (Grabovac and Whittaker 2009). Lam et al. (2011) conducted a finite element study of a FRP patch repaired steel pipe. The composite-based structural coating enhanced the pipe's fatigue life by 22 times. The EU-founded project Co-Patch was also carried out to see the potential of retrofitting corroded marine structures with FRP. The tensile tests of corroded steel samples with reinforcement of CFRP were presented in Karatzas et al. (2013), showing the potential of such retrofitting method. The numerical studies regarding the applicability of such joints in larger marine structures were presented in Burlović et al. (2016). In principle, the authors presented a high potential of such a method, suggesting at the same time that much more experimental work, regarding e.g. temperature effect, is needed.

Still, the performance and durability of these structural coatings as reinforcement in service have not been meticulously documented in shipbuilding and offshore structures, and this is lacking in the marine industry. This is valid, especially when compared to other fields like aerospace and civil engineering. As was shown at the beginning of this Section, the FRP composites as the reinforcement of metallic structures were already successfully applied in those fields. The discussed research works, especially in the field of civil engineering, presented the application of structural coatings in the retrofitting of existing infrastructure, indicating the potential for marine structures too.

And it is equally important to preserve existing ships by increasing their life span due to the huge cost associated with the construction of new ships and sustainable development and protection of the environment. The research that has been conducted in civil engineering is very promising and inspiring, as it opens up new doors for research ideas in the marine industry. But the only difference is that, thin-walled steel plates are used instead of thick bars for the construction of ships, and the mechanical properties of plates are different than those of bars. When they are exposed to the harsh sea environment, they face corrosion, fatigue, and buckling, and their tensile properties also change over time. It is necessary to conduct a thorough analysis of the mechanical properties of structures that are exposed to the marine environment in order to prevent failures due to corrosion. The tensile strength of exposed steel has been shown to significantly decrease after being exposed to corrosive environments. Over time, corrosion pits enlarge in diameter and link together, and the form of the pits changes due to the influence of sea tide, becoming more rounded and smoother (Vukelic et al. 2022). When they are reinforced with FRPs, the adhesive bonding is also very important.

The final issue that needs to be discussed regarding possible applicability is cost-effectiveness. The typical maintenance strategy, especially in ship structures, requires replacing excessively corroded structural elements. In the case of FRP, the replacement will not be needed, but strength loss will be compensated by structural coating, which will also provide a further solid barrier from corrosion degradation. Due to the lack of solid data, it is hard to judge which method will result in lower financial effort. As for now, since feasibility studies of such retrofitting methods are lacking, the studies on cost-effectiveness are lacking, too. Nevertheless, this aspect need also be taken into account in future studies.

7. Knowledge Gap

When marine structures are washed by or immersed in seawater, their mechanical strength decreases significantly due to the impacts of the actual aquatic environment. Still, FRPs are not fully capable of replacing steel and aluminium on large cargo or naval ships (Saravanan and Kumar 2021). However, FRPs are expected to become an increasingly significant supplement to retrofitting existing ships and offshore structures. Despite the growing use of FRPs as reinforcement in marine and offshore structures, there is a knowledge gap in understanding the long-term durability and reliability of the FRP-reinforced structures in harsh marine environments. Specifically, there is a need for further research to assess the effects of prolonged exposure to saltwater, high humidity, UV radiation, and extreme temperature fluctuations on the mechanical properties and structural integrity of the FRP-reinforced marine and offshore structures over extended periods of time(Radhamani et al. 2020; Mirzaee et al. 2021; Qu et al. 2021; Nwuzor et al. 2021; Sharma and Sharma 2023; Li et al. 2023). More research is needed to determine the optimal design, fabrication, and maintenance practices for the FRP-reinforced marine and offshore structures to ensure their long-term performance and safety. Additionally, there is a need for standardisation of testing protocols and guidelines for the design and installation of FRCs in marine and offshore structures to ensure their safe and effective use.

8. Conclusion

The literature shows that many researchers are working on novel coatings to protect ship and offshore structures from corrosion, biofouling, etc. but only a very few researchers are working on structural reinforcement. As we know contemporary coatings cannot withstand loads and cannot reinforce structures, our primary objective in this article was to provide a detailed review of structural coatings designed to protect ships from corrosion, strengthening their structures and also coating itself. So, we looked at the evolution of different FRP materials, their current applications, and which structural coatings are being used to retrofit marine structures. After analysing the literature published to date on marine reinforcements, finally we are able to address the research questions of this article which we assumed at the beginning. So, the aim of this study has been achieved as it has given us the future research directions. Below are the observations made by this study:

1) Carbon-based FRP coatings were investigated for different failure modes like tensile, fatigue, debonding, and buckling on uncorroded steel; however, they have not been studied on corroded steel.
2) Fatigue properties of carbon-based FRP coatings have been thoroughly investigated depending on strengthening configuration, CFRP prestress level, thickness, corrosion, and angle. However, in this case, the use of other resin matrices needs careful attention.
3) The tensile properties of carbon-based FRP coatings have been well investigated depending on the number of FRP layers, strengthening configuration, and temperature, but the effect of corrosion needs careful attention, whereas the tensile properties of other FRP-based structural coatings (glass, aramid, and basalt) and their hybrids are yet to be explored.
4) The corrosion effect, strengthening configuration, and CFRP prestress levels need attention when evaluating carbon-based FRP coating buckling properties. Whereas the study of other FRP coatings (glass, aramid, and basalt) and their hybrids are lacking.
5) Adhesive bonding of carbon-based FRP coatings has been investigated for variation in bond length, FRP layers, and temperature. However, the use of other resin matrices and corrosion needs careful attention. And the bonding properties of other structural coatings based on FRPs (glass, aramid, and basalt) and their hybrids are yet to be explored.
6) Shear properties of the reinforced steel are almost fully unknown for all types of structural coating.

9. Recommendations for future works

There are several areas where future research and development can focus to improve the use of fibre reinforced polymers (FRPs) for reinforcing marine and offshore structures:

Further research is needed to better understand the long-term durability of the FRP composites in marine environments, especially in harsher conditions such as high salinity, high temperatures, and high UV exposure. Aging and degradation mechanisms should also be studied to help predict the long-term behaviour and performance of FRPs. Numerous studies on the fatigue, tensile, buckling, and debonding properties of carbon fibre-based structural coatings have been conducted; however, it has been found that several truly significant factors, such as resin matrices other than epoxy, corroded steel, strengthening configurations, and prestress levels, remain untapped. Like this, research on the buckling, debonding, fatigue, tensile, and shear properties for both corroded and uncorroded steel is still insufficiently focused on structural coatings containing glass, basalt, aramid, and their hybrid fibres when it comes to factors like prestress level, temperature, strengthening configuration, type of resins, ply orientation, and FRP layers, among others. Consequently, glass fibre, aramid fibre, basalt fibre, and their hybrid structural coatings for defending marine structures need further research for performance assessment, adhesion, and mechanical strength testing under complicated marine circumstances.

It has been proposed that, after filling the gaps revealed by reviewing the existing literature, structural coatings can be effectively used to repair damaged ship plates. This will protect them from corrosion, increase their lifespan, and bring significant economic benefits.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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