



A REVIEW OF FLUID-STRUCTURE INTERACTION IN HULL LAMINATED WITH FIBRE REINFORCED POLYMER: EXPERIMENTAL AND COMPUTATIONAL APPROACHES

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Abstract:

Hull is an important part of marine structures; it offers buoyancy, stability and resistance to the surrounding environment. This literature review synthesizes current studies and research, highlights the advantages of using Fibre Reinforced Polymer (FRP) in marine applications, and identifies the research gaps in fluid-structure interaction (FSI) for FRP-laminated hulls. Mechanical properties like tensile strength, fatigue damage and crack initiation were evaluated by experimental methods. These results show that the layer sequence and orientation are also important factors affecting material performance. Computational methods including finite element analysis (FEA) and computational fluid dynamics (CFD), were used to model the FSI phenomena, with particular emphasis on wave slamming impacts on hull performance. Experimental results and FEA validation were discussed giving insight into the material responses under extreme conditions. The study revealed that FRP is very suitable for marine applications, because of its high strength-to-weight ratio, corrosion resistance and durability. However, several issues remain, including limited long-term study of the durability of FRP in marine environments, and improvements in modeling methods to predict material. This is a unique review on the fluid-structure interaction in FRP-laminated hulls that encompasses experimental and computational analyses. It provides novel insights into FRP-laminated hull performance and highlights the need for experimental verification and sophisticated modeling for the design of marine structures.

Keywords: Hull lamination, fluid-structure interaction, fibre reinforced polymer, finite element analysis, computational fluid dynamics

NOMENCLATURE

K	global stiffness matrix
$u,$	nodal displacement vector
F	applied load vector

Greek symbols

v	fluid velocity vector
ρ	fluid density
μ	dynamic viscosity

1. Introduction

Marine vessels, including boats and ships, are used significantly for both commercial and recreational water transport (Walker et al., 2019). A marine vessel's main component is its hull. It is composed of the bottom, sides and deck, giving buoyancy, stability and resistance to the harsh marine environment. These hulls will need to have a remarkable ability to withstand different dynamic loads arising from waves, slamming, and hydrodynamic forces (Kim et al., 2025). One of the promising solutions that could improve the mechanical properties of the hulls is the

use of Fibre Reinforced Polymer (FRP), a composite material that is very strong, light, and resistant to corrosion (Gudonis et al., 2014).

The significance of fluid-structure interaction (FSI) in marine applications is intrinsically linked to the performance specifications of hull materials such as FRP. FSI stands for the flow of fluids inside a solid boundary structure, which makes the loading conditions on the structure very complicated. Marine applications are very important for an FSI because the hull is affected by changing water pressures, wave impact, and slamming loads. These interactions have been known to cause fatigue damage and the start of cracks, which can shorten the life and performance of the ship (Ahmed et al., 2020). FRP which is exhibiting superior strength-to-weight ratio, high fatigue resistance, and durability, makes it a good choice for reducing these effects. FRP's inherent properties help reduce the negative effects of FSI, unlike traditional materials like steel and aluminium. This makes the structure more resilience and improved overall vessel performance under the tough conditions induced by FSI (Li et al., 2023).

The laminated FRP hulls are fabricated using different sequences and orientations of layers. These layers are very important in determining how the hulls respond to different loads. Mechanical properties of FRP laminate, which focuses on various stacking sequences and fibre orientations, have been studied through many experiments such as tensile, fatigue (Bagherpour, 2012; Sobri et al., 2020). In addition to experimental studies, the interaction between fluid and structure has been simulated using computer-based techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD) to predict the response of FRP to wave impact and hydrodynamic forces (Fitriadhy et al., 2021; Ramli et al., 2024). These simulations offer valuable insights into the hull's structural behaviour, and they also help optimize the design for enhanced performance.

While previous reviews have focused on either experimental characterization of FRP laminate behaviour or numerical fluid–structure interaction (FSI) modelling, this study aims to explicitly bring both of these together and offer a unified perspective on how laminate configuration impacts hull response under realistic marine loading conditions associated with wave slamming. It aims to highlight the advantages of FRP application in the marine sector, point out the research issues for existing FSI modeling techniques and emphasize the importance of the experimental validation of FRP-laminated hulls along with advanced computational simulations to enhance performance and durability. Therefore, it is hoped that this study can be useful in enhancing the efficiency and durability of marine vessels and be a step in the direction of sustainable solutions in engineering in the marine environment.

2. Hull Types and Fibre Reinforced Polymers (FRP) Materials

2.1 Hull types

The type of hull of a vessel is an important element when considering the interaction between the vessel and its operating environment in marine engineering (Cecchini et al., 2017). The hull is the primary structure responsible for buoyancy and stability, and for the hull's response to water under varying conditions. The hull forms can be classified as planing hulls, displacement hulls, and semi-displacement hulls, with each hull exhibiting distinct FSI characteristics. The main features of various hulls relating to FSI in marine applications are summarized in Table 1.

Table 1. Types of parent hulls (Ramli et al., 2023)

Hull Type	Key Features	Advantages	Disadvantages
Planing Hull (Faltinsen, 2006)	Shallow V or flat-bottom design 	High speed, reduced hydrodynamic drag.	Rough ride, instability in harsh conditions.
Displacement Hull (Alvarez & Martins, 2008)	Round-bottom, high buoyancy 	Smooth ride, efficient in rough waters.	Limited speed due to frictional resistance.
Semi-displacement Hull (Sun & Faltinsen, 2012)	Flatter at the aft, bulkier at the front 	Better stability than planing hulls.	Less efficient at low speeds, consumes more fuel.

The hulls for the planning are optimized for speed. The shape of the hull makes it easier for ships and boats to rise and glide over the water's surface at high speeds, which greatly reduces hydrodynamic resistance. Planning hulls have known features with a shallow V or flat bottom design that progressively flattens towards the stern (Tagliaferro et al., 2021; Volpi et al., 2017). Most planning hulls are superior in speed and more efficient because they can reduce drag in the water. However, they face difficulties due to slamming phenomena that put a lot of stress on the structure's integrity. Such events have been recorded to cause matrix cracking, interface debonding, and delamination (Grande & Xia, 2002; Judge, 2020; Lavroff et al., 2011).

The other type of hull, displacement hulls are rounded and designed to displace water when in motion. This helps with stability and makes the ride smoother. These hulls are suitable for cargo ships and other large ships that need to be very stable and operating at lower speed (Alvarez & Martins, 2008). Displacement hulls top speed is limited creating higher resistance of movement due to their dependency on buoyancy and water displacement. However, the design effectively reduces hydrodynamic stresses and improve fatigue performance in maritime environments (Van Oossanen et al., 2009).

The third type of hull, semi-displacement, combine the features of both planning and displacement hulls that can provide a balanced performance between speed and stability. Semi-displacement hulls are flatter at the stern and bulkier toward the bow, which allow the designs to relocate water at low speeds while creating some lift at higher cruising speeds (Sun & Faltinsen, 2012). Patrol boats, fast ferries, and offshore service vessels often use semi-displacement hulls because the need to balance between moderate cruising speed, fuel efficiency, and seakeeping performance, especially when working in coastal and semi-offshore conditions. However, semi-displacement hulls work less well at speeds below their designed speed (Shabani et al., 2019).

2.2 Fibre reinforced polymers (FRP) materials

Glass FRP is commonly used for maritime applications for boats and ships construction. FRP comes in three main types: E-glass, S-glass, and C-glass fibers. Each of these general forms serves for different performance needs. E-glass is the most common type of glass because it has a tensile strength of about 2200 MPa and is resistant to water and chemicals. It is deemed best for construction of hulls that consider factors of longevity and minimal maintenance, with reasonable cost. S-glass fibres have excellent strength-to-weight ratios that, under high mechanical stresses, provide outstanding performance at increased costs, limiting their applications to those where extremely high strength is needed. C-glass is not used as much as other types of glass, but it is known for its chemical resistance and has some benefits in places where corrosion is a big problem (Bagherpour, 2012; Bai & Jin, 2015; Ramli et al., 2023). Commonly, these FRP materials are applied with polymers like polyester, vinyl ester, or epoxy. Polyester resins are the most common type of resin because they are cheap and can be used for a lot of different things. Epoxy resins, however, possess superior mechanical properties and are employed in applications where high strength is required, as well as protection against environmental degradation (Perrot et al., 2021; Ruzuqi, 2021). As presented in Table 2, there are a number of advantages to FRP materials in marine applications, particularly against conventional materials such as steel and aluminium. These properties and advantages highlight the significance of FRP materials in marine structures, particularly in areas where durability, reduced maintenance, and weight efficiency are critical. FRP is characterized by its strength, corrosion resistance, low weight, and high fatigue resistance, making it an excellent material for enhancing the hull structure and performance in the challenging marine environment (Neşer et al., 2020).

Table 2. Benefits of FRP in marine applications (Neşer, 2017; Pascoe, 2021; Rajak et al., 2019)

Advantages of FRP in Marine Applications	Description
High Strength-to-Weight Ratio	Provides necessary structural strength without excessive weight, improving buoyancy and fuel efficiency.
Corrosion Resistance	Resistant to seawater corrosion, reducing maintenance needs and prolonging lifespan compared to metals like steel.
Fatigue and Impact Resistance	Withstands cyclic loading and wave slamming, essential for durability under harsh marine conditions.

Thermal and Acoustic Insulation	Natural insulation reduces noise and temperature changes, enhancing passenger comfort in leisure and passenger vessels.
Design Flexibility	Allows for complex shapes and streamlined hull designs, improving hydrodynamic performance, stability, and speed.
Reduced Maintenance and Lifecycle Costs	Longer service life and less maintenance due to durability and corrosion resistance lower the overall lifecycle costs.
Environmental Benefits	FRP composites emit fewer greenhouse gases in production and are lighter than metals, reducing energy requirements.

3. Experimental Approaches in FRP Hull Analysis

Experiments conducted on FRP hulls in marine applications include tensile strength, fatigue behaviour and crack initiation. In order to ensure uniformity among different studies, two well-known standards are the ASTM D3039 for testing tensile strength and ASTM D3479 for testing fatigue (ASTM, 2012, 2014; Wang et al., 2020; Zakaria et al., 2016). Some experimental methods, tools, and results for FRP hull laminate analysis are briefly discussed. In this section, a few experimental techniques, tools and findings in the field of FRP hull laminate analysis are summarized, which play a vital role in emphasizing the strength, durability and failure mechanisms of FRP laminate in marine applications. A summary of experimental approaches in FRP hull analysis is shown in Table 3.

Table 3. Summary of Experimental Methods in FRP Hull Analysis (Molent & Haddad, 2020; Pascoe, 2021; Ruzuqi, 2021; Wang et al., 2020).

Test	Common standards	Common techniques	Purpose
Tensile Strength	ASTM D3039/D3039M	Universal Testing Machine (UTM)	Evaluate tensile properties of FRP composites.
Fatigue Testing	ASTM D3479	Hydraulic fatigue testing machine	Assess fatigue resistance and crack initiation.
Crack Monitoring	ASTM E976; ASTM E1106 (guidelines)	Visual inspection, optical microscopy, acoustic emission	Track crack propagation in fatigue tests.

* Note: ASTM E976 and ASTM E1106 are recognized ASTM practices for acoustic emission monitoring of damage progression in composite and structural materials, widely used in fatigue-related studies.

3.1 Tensile strength testing

The tensile characteristics of FRP hull laminates are evaluated to define attributes like the ultimate tensile strength and modulus of elasticity. Most of the studies by Bajpai, (2018); Islam et al., (2019); Rahman & Putra, (2019); Wang et al., (2020), have subjected FRP specimens to controlled tensile loading by using UTM, following recommendations of the ASTM D3039 standard for specimen size, configuration of the test, and protocols for loading. The deformation can be captured by strain gauges, which are quite common in research and thereby enable comprehensive analysis in the stress-strain behaviour and tensile properties (Bhat et al., 2019; Ruzuqi, 2021). From these analysis techniques, some parameters of FRP laminates, such as fibre layer orientations, laminate stacking sequences, and resin types, significantly affect the tensile strength of the structure (Ramli et al., 2024; Rubino et al., 2020).

Typically, a +45° fibre layer orientation is known to improve shear and tensile strength, particularly under complex loads. This orientation increases the composite's ability to withstand off-axis loads and improves to higher fatigue resistance. According to Rubino et al., (2020), the +45° orientation improves flexibility and energy dissipation and improve the sturdiness to cyclic stresses. Additionally, the 90° orientation places fibres perpendicular to the applied load in tensile testing, which often results in lower tensile strength than the +45° orientation due to weaker interlaminar shear characteristics and a larger chance of matrix-dominated failure modes. Kootsookos & Mouritz, (2004), found that 90°-oriented laminates work well under under directed loads but are inefficient under multidirectional pressures. This is relevant in marine applications where the hulls are subjected to different wave impacts.

In some studies, it has been observed that by changing the order of stacking laminate and the direction of fibers, it can be made stronger as loads are distributed more uniformly in different directions, reducing the stress

concentration, such as $[0^\circ/90^\circ/+45^\circ/-45^\circ]$ (Ben Mlik et al., 2018; Das et al., 2019; Rajak et al., 2019). Patel et al. (2018) discovered that this even distribution is very important for maritime uses where hulls are put under fluctuating, multiaxial pressures. Symmetric stacking sequences are those in which the orientation of the fibers is the same on both sides of a central axis, which can help minimize warping and residual stresses, thus improving the structural integrity. This method led to enhancement of tensile strength and fatigue resistance in asymmetrical sequences, as shown by Barbero (2013) and Boisse (2007). Quasi-isotropic layups in a sequence of the type $[+45^\circ/-45^\circ/0^\circ/90^\circ]$ also result in near-isotropic properties of the laminate. Hosoi and Kawada (2018) found that these settings increase tensile properties, which indicates that they have a good impact on the distribution of stress and create a better durability by avoiding localized failure.

Resin in FRP composites plays a key role in their tensile strength, durability and environmental resistance, which all have a key importance in maritime applications. Though it has good bondability, is economical, and is widely used, polyester resin does not offer the same strength as epoxy in terms of tensile strength. According to Dholakiya (2012), polyester-based FRPs have relatively high tensile strength but have higher water absorption capacity, which may be harmful for the fibre-matrix bond in the future. However, epoxy resins are known for their strength and durability, making them suitable for projects with a longer lifespan. Rubino et al. (2020) state that epoxy FRPs are highly resistant to environmental attack, particularly if exposed to water on a continuous basis. This renders them ideal for the challenging sea conditions. Vinyl ester resins are a good middle ground between the strength of epoxy and the price of polyester. Vinyl ester resins which have high tensile strength are great for seawater exposure because of its water resistance and chemicals degradation ability where seawater exposure may impair material longevity (Islam et al., 2019; Perrot et al., 2021).

The preparation of the specimen, the application of the load, and the recording of the data are carried out according to ASTM D3039 that ensured a reliable assessment of the tensile properties of FRP materials. Hull structures aim to reduce weight while maintaining strength, and many studies have shown that FRP composites have a very high tensile strength-to-weight ratio. Selected studies showed that FRP laminates with specific fiber orientations and layer sequences subjected to tensile load deliver enhanced (Bagherpour, 2012; Ben Mlik et al., 2018; Ramli et al., 2023; Zakaria et al., 2016). Also, this information is very important for designing the hull to make sure it can carry optimal load-bearing capacity and durable.

3.2 Fatigue damage and crack initiation

Fatigue characteristics of the FRP Hull Laminates were investigated to understand the performance of the Hull Laminates under repeated loading in terms of long-term performance and structural integrity. Most of the studies used ASTM D3479 standard for tension-tension fatigue testing to simulate the cyclic stresses hulls must withstand while in operation (Cecchini et al., 2017; Finnegen et al., 2021; Han et al., 2017; Mu et al., 2022; Zakaria et al., 2016). These tests often involved cycling at certain percentages of the UTS and allowed the team to make observations on the fatigue lives and failure modes.

Based on the literature, some of the major factors that have been identified in influencing the fatigue resistance of FRP composites are highlighted. These are the material's composition, the orientation of the fibres, the order of the laminates, and the overall shape of the material (Molent & Haddad, 2020). Fibres with the correct orientation can help to reduce cyclic stresses and increase the durability of the material to fatigue cracks. This is particularly important in the low delamination case of the use of epoxy resins, which provide strength to the bond between fibers and the matrix and the latter provides resistance to the environmental stresses (Tanadrob & Suvanjumrat, 2017). Some stacking sequences, like quasi-isotropic layups, make it possible to distribute the applied stresses evenly through the laminate, which helps to reduce strain concentrations and consequently helps to resist fatigue (Hudisteanu et al., 2018). It is understood from these factors that strategic decisions on material orientation, composition and sequencing can greatly improve the fatigue life of FRP composites, and hence their effectiveness in highly stressed marine applications.

Crack initiation, one of the critical aspects in the analysis of fatigue, is mostly observed through visual inspection utilizing digital microscopy tools such as Dino-Lite. The regular inspection and microcracks imaging allow the researchers to generate their sizes and the rate of crack propagation. An example of images using scanning electron microscopy (SEM) shown in Fig. 1 clearly showed that fatigue-induced damage in FRP composites initiation as matrix microcracking and subsequently propagates along the fibre-matrix interface, leading to interlaminar

debonding and delamination under continued cyclic loading. The image can provide indication about the fatigue behaviour and the damage mechanism concerned (Hosoi & Kawada, 2018; Pupurs, 2012; Ramli et al., 2023).

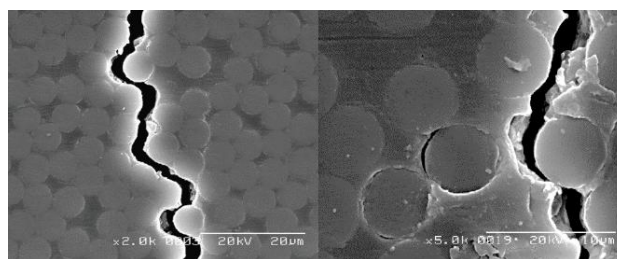


Fig. 1. Micro crack growth along the interface between a fiber and the matrix (Hosoi & Kawada, 2018)

Microscopy has frequently been utilized to examine diverse failure mechanisms in FRP composites, including initial damage and progression under cyclic loading. Results of studies have shown that matrix cracking is the most common first point of failure when fatigue loading occurs, and it spreads to the fibre-matrix interfaces (Lukáš, 2001; Rezaei Jafari et al., 2021; Rosenbloom & Laird, 1993). Cracks propagate and reduce the fibre-matrix bonding, leading to debonding and subsequent delamination. Pupurs (2012) suggested that repeated cyclic loading might be responsible for cracks to grow from the initial matrix fractures into the fiber interface, leading to failure of the structure. Scanning Electron Microscope (SEM) imaging and Dino-Lite imaging are the two most widely used imaging methods for researchers to closely examine the changes in microstructure to understand the fatigue mechanism. Delamination significantly decreases composite load-carrying capacity, since it disrupts the integrity of the laminate structure (Hosoi and Kawada, 2018). Based on the available microscopy studies from several sources, matrix cracking is typically the initial type of damage, with interfacial debonding and delamination typically occurring as the second type of damage that constitutes progressive fatigue failure in FRP hulls.

4. Computational Approaches to FSI Analysis

Researchers have investigated the dynamic performance of FRP-laminated hulls with various computational methods, including FEA and FSI modelling. These computational approaches enable researchers to simulate and analyze how hulls respond structurally under various simulated sea conditions, providing insights into the material behaviour under different load scenarios and fluid-structure interactions (Judge, 2020; Kim et al., 2025; Mohsin et al., 2013; Woo et al., 2014; Zhang et al., 2019).

4.1 Finite element analysis (FEA)

The use of FEA has grown in importance in hull structure analysis as it can depict complex stress distributions and behaviours within the material. FEA dissects the hull structure into sections, assigning each section separate material properties and boundary conditions, and simulating the real-world forces acting on the hull. In order to accurately represent the mechanical properties and response behaviours of the hull in maritime applications, the layers, orientations and stacking sequences need to be modelled (Barbero, 2013; Mitusch et al., 2021). In finite element analysis, FRP hull structures are controlled by the equilibrium equation (1).

$$Ku = F \quad (1)$$

in which K is the global stiffness matrix that comes from laminate constitutive relations, u is the nodal displacement vector and F is the applied load vector. The stress-strain behaviour of FRP laminates is described using classical lamination theory that correlates stresses and strains with anisotropic stiffness matrices that depend on the stacking sequence and fibre orientation (Barbero, 2013). Next, using meshing techniques, researchers determine the size and density of the components and balance between computational efficiency and required precision to capture stress and strain at critical areas within the structure (Sindi et al., 2024).

The selection of parameters in FEA is important because they directly affect the accuracy of the results from the simulations. The specific loading conditions found in the marine environment, such as wave forces and varying pressures (Sindi et al., 2024; Nasser et al., 2020), are considered in the specific configurations of the parameters: element type, mesh refinement, and material properties. One of the common methodologies adopted in literature

is to compare the Finite Element Analysis (FEA) results with experimental tests and a good agreement is always obtained, showing the reliability of the FEA. However, studies frequently show that discrepancies can be attributed to simplifications in the models or the assumption of material homogeneity, which can fail to accurately capture the complexities of FRP laminates (Dabit et al., 2020; Ramli et al., 2024).

4.2 Fluid-structure interaction (FSI) modeling

FSI modeling plays a vital part in improving the understanding of Hull-Interaction with its fluid environment, particularly for high-impact phenomena such as wave slamming. ANSYS is a widely used software for FSI simulations in marine applications, with specific modules designed to simulate hydrodynamic forces and the interactions of fluids with structural components.

The hydrodynamic behaviour in wave–structure interaction is governed by the incompressible Navier–Stokes equations, the conservation of mass and momentum in equation (2):

$$\begin{aligned} \nabla \cdot \mathbf{v} &= 0 \\ \rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) &= -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f} \end{aligned} \quad (2)$$

where $\mathbf{v}$ represents the fluid velocity vector, p the pressure, ρ the fluid density, and μ the dynamic viscosity. These equations are also used in FSI analysis, where they are coupled with the structural equilibrium equations using force continuity and displacement continuity at the fluid–structure interface, as is done in commercial software like ANSYS (Faltinsen, 2006; Volpi et al., 2017). FSI models are frequently highlighted in the research literature as playing an important role in predicting the impact of waves and slamming on FRP hulls and consequently could help in designing to avoid damage caused by repeated slamming.

When analysing wave slamming, modelling the transient effect of fluid forces on the hull surface is one of the challenges that researchers encounter (Judge et al., 2020; Temarel et al., 2016; Ma & Qian, 2018). Such consequences are intrinsically hard to simulate because the actual sea state involves random variations in wave height, velocity and pressure. Hydrodynamic interactions, which vary depending on hull velocity and direction, add to the complexity and affect structural response (Kim et al., 2014; Lavroff et al., 2011; Yang et al., 2024). These interactions are complex and require high-fidelity models and sophisticated computational resources to accurately model them, with the models often being validated with experimental results to enhance their validity (Butorova et al., 2023; Lv et al., 2023; Ramli et al., 2023; Yang et al., 2024).

While these computational approaches, like FEA and FSI modeling can provide valuable insights, the literature emphasizes the need for continued improvements in modelling methods to better represent real-world scenarios for FRP hulls (Dabit et al., 2020). Despite progress in modeling the dynamic interactions and transient loadings, challenges remain in accurately capturing these phenomena, underscoring the need for combining experimental validation with computational advancements to develop more robust and efficient hull structures for marine applications (Kim et al., 2025; Yang et al., 2024).

5. Computational Approaches to FSI Analysis

The impact and slamming of waves on marine hulls are of great interest in the design and survivability of marine hulls, particularly those that have to face high seas. Slamming occurs when a high-energy wave impacts the hull, causing high, localized pressures that can lead to structural damage, material fatigue, and long-term deterioration (Judge, 2020; Lavroff et al., 2017; Ma & Qian, 2018; Zhang et al., 2019). In this section, the characteristics of slamming, the hydrodynamic interaction during wave impact and the properties of FRP for reducing the slamming impacts are explored based on the data obtained from experimental and computational research.

5.1 Overview of slamming in marine structures

Wave slamming is a phenomenon involving a sudden high-pressure impact of the hull on the wave, where this impact may be very violent, especially during operations with high speed or in turbulent waters. The process generates heavy hydrodynamic pressure on the surface of the hull, especially at the bow and stern. Slamming is reported in the literature to result in rapid wear, matrix cracking, and delamination in FRP hulls (Fonseca et al.,

2023; Judge et al., 2020; Volpi et al., 2017; Yang et al., 2024). Hence, the design needs to be able to sustain multiple impacts. Comparing the results obtained from experimental and simulation studies (Judge et al., 2020; Lavroff et al., 2011; Ramli et al., 2024), it is noted that while simulations like FEA and FSI modeling predictions of slamming impacts are pretty accurate, experimental tests remain indispensable to validate these models due to the great differences between wave conditions and pressures in nature. shows the characteristics of wave slamming effects on FRP hulls.

Table 4. Characteristics of Wave Slamming Effects on FRP Hulls (Cecchini et al., 2017; Kim et al., 2025; Ramli et al., 2023; Tagliafierro et al., 2021).

Characteristic	Description
High-Pressure Impact	Localized, intense pressure on hull upon wave impact, affecting bow and stern.
Material Fatigue	Repeated slamming leads to fatigue, matrix cracking, and eventual delamination.
Variability in Conditions	Natural wave conditions vary, impacting pressure distribution and damage.

5.2 Hydrodynamic interaction and structural repair

The hydrodynamic interaction that occurs between the hull and water during slamming is intricate, with pressure distribution patterns significantly affecting the structural response. Research utilizing FSI modeling, especially with ANSYS, replicates how hydrodynamic pressures vary across the hull surface during slamming events. These simulations reveal that pressure distribution peaks at the point of impact and progressively diminishes along the hull's sides, a pattern validated by experimental studies that utilize sensors mounted on physical hull models to measure pressure (Julianto et al., 2020; Sun & Faltinsen, 2012; Tagliafierro et al., 2021).

The material properties play an important role in reducing slamming effects and FRP laminates have unique properties. High-strength, lightweight FRP composites are known to be excellent at distributing impact forces as compared to traditional materials such as steel, which makes catastrophic failure less likely (Sivasankar et al., 2020; Sobri et al., 2020). Additionally, stacking sequences and orientations in FRP laminates can enhance impact resistance due to stress dispersion throughout the layers (Rubino et al., 2020). Furthermore, FRPs made with epoxy resins have superior resistance to crack initiation and propagation, making them particularly suitable for marine applications where slamming and high-impact events occur frequently. The simulation of the hydrodynamic pressure distribution around the hull is depicted in Fig.2.

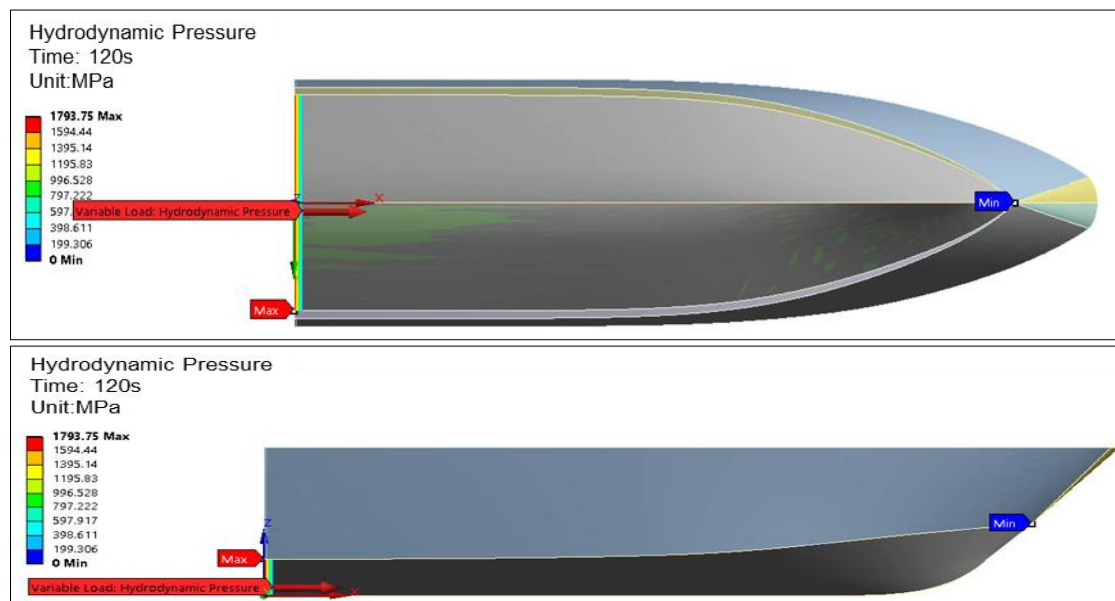


Fig. 2. Hydrodynamic pressure distribution on the bottom and side views of a hull during wave-slamming impact, obtained from numerical fluid–structure interaction (FSI) simulations. Adapted from Volpi et al. (2017)

Studies have demonstrated that the accuracy of pressure mapping and prediction of structural response models (SRM) is constantly improving thanks to innovations in simulation techniques (Alvarez & Martins, 2008; Ibrahim, 2015; Ma & Qian, 2018; Jiao 2021; Rodkina et al., 2022). However, there are still issues in fully capturing transient wave slamming effects. Combining experimental and modelling information is essential to create a hull that is not only strong but also optimised for operating in a marine environment with high impact levels.

6. Gaps Identified

With the advancement of research on FSI in FRP-laminated hulls, both experimental and computational methods have provided more insight into the interaction of FRP-laminated materials in marine applications. There are, however, important areas where current methods and analyses are lacking, suggesting further research and development areas.

6.1 Insights from experimental and computational methods

Experimental and computational techniques offer unique insights into FRP hulls behavior under FSI conditions. Experimental testing, particularly tensile and fatigue tests, provides valuable insights into mechanical performance, including tensile strength, fatigue life, and the mechanisms of crack initiation, offering a realistic understanding of FRP's behavior and durability under repeated loading conditions (Esmailzadeh et al., 2018). FEA and FSI modelling, have enabled a much better representation of more complex situations, including slamming events and wave strikes. These models enable the detailed mapping of pressure distribution and prediction of material interactions in various environmental situations (Sindi et al., 2024).

However, there are limitations to both methods. Creating realistic sea conditions in the laboratory is a challenging challenge, especially as there are many different wave heights, orientations and impact pressures. Although FSI models are very useful in computational aspects, these models are often based on assumptions and simplifications that reduce the accuracy of their forecasts (Karim and Ahmed, 2022; Ahmed et al., 2020; Harle, 2024; Wright et al., 2019). This leads to a discrepancy between the simulation results and real-world scenarios, particularly for high-impact and transient phenomena like wave slamming.

6.2 Challenges and limitations in current fsi analysis techniques

Existing FSI analysis methods are known to pose several issues, notably in modelling the transient and stochastic nature of maritime environments. Models are occasionally developed in idealized conditions and do not fully consider complicated real-world occurrences like multi-directional pressures and irregular wave patterns (Yang et al., 2024). One of the other major issues is the prediction of material failure in FRP-based composites. FEA/FSI models are often capable of capturing the stress concentrations, but are less successful in capturing progressive failure modes like delamination and fibre-matrix debonding under impact or cyclic loading (Pascoe, 2021).

In addition, experimental methods for fatigue and fracture propagation, although effective, are generally resource-consuming and time-intensive (Paik, 2019; 2024). However, the fatigue behavior of FRP composites depends on a large number of parameters, including the type of resin used, the layering sequence and the direction of the fibres, and hence in real life applications, the fatigue behavior can vary significantly, which requires the development of more flexible and efficient testing and analytical methods (Abdallah et al., 2018; Kim et al., 2025; Muda et al., 2022; Rajak et al., 2019; Rubino et al., 2020).

6.3 Gaps identifies in existing research

There are several gaps in current research that would benefit from further investigation to improve the accuracy and strength of FSI analysis techniques to be applied to FRP hulls:

- a) **Long-Term Durability Studies:** FRP hulls have not been thoroughly investigated for long-term performance under repeated cyclic and impact loading, especially for harsh marine environments (Rubino et al., 2020). Future long-term durability studies should include accelerated aging testing (such as long-term seawater immersion, wet-dry cycling and hygrothermal aging at controlled temperature) and periodic mechanical and microstructural evaluations to quantify changes in stiffness, strength and bonding between the interface.

- b) **Improvement of Simulation Fidelity:** The simulation realism of FSI is still of interest to better simulate the wave conditions and slamming occurrence in the real world (Yang et al., 2024). In the future, the focus should be on enhancements to computer models, especially for the simulation of progressive failure mechanisms and transient hydrodynamic interaction.
- c) **Environmental Impact Assessments:** Although FRP is appreciated for its durability, few studies have examined the environmental effect of FRP manufacture, use, and disposal in maritime environments (Dakhil & Khayyat, 2023). Future environmental impact studies should also consider emerging eco-friendly composite alternatives, such as bio-based fibre-reinforced polymers (e.g., flax or basalt fibre composites) and recyclable thermoplastic-matrix composites, which offer improved end-of-life recyclability compared to conventional thermoset FRPs. Recent developments in mechanical and thermal recycling techniques, including matrix dissolution and fibre recovery processes, further present viable pathways to reduce the environmental footprint of FRP materials in marine applications (Neşer, 2017; Rajak et al., 2019; Rubino et al., 2020).
- d) **Standardized Testing for Crack Initiation and Propagation:** While numerous microscopy techniques are used to monitor crack development, there is no consistent method for crack initiation testing in FRP composites (Lin et al., 2024). Establishing uniform fatigue and impact testing techniques across studies will improve the comparability and reliability of study findings.

7. Conclusion

Literature on FRP hulls and FSI highlights the immense potential of FRP materials for maritime use in terms of tensile strength, fatigue and impact durability. The results of tensile and fatigue testing, combined with computational methods like FEA and FSI modeling, have provided essential insights into the ability of FRP laminates to withstand the complex forces that a vessel is subjected to during maritime operations, including slamming and wave impacts. The main results indicate that the fibre orientation, laminate stacking sequence and resin type are critical parameters to improve the structural performance of FRP composites under cyclic and impact stresses. But some questions remain about durability, in-field FSI accuracy, and environmental impact, highlighting the need for additional research. Future studies should focus on the development of high-fidelity simulation models, on-going durability studies and standardization of test procedures. This review aims to provide researchers and designers a structured reference to the experimental and computational FSI modelling results of FRP-laminated hulls under realistic marine loading and also raises a need for high fidelity coupled simulations, standardized damage characterization, long-term durability and sustainability studies of numerically and experimentally testing FRP application in marine applications. Addressing these issues will be critical for progressing marine structure design and enhancing FRP materials for sustainability and robustness in harsh maritime settings.

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