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A review of composite materials for marine purposes: Historical perspective and current state

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Abstract

This study offers a concise review of the application of composite materials in marine environments, encompassing both historical perspectives and current conditions. Composite materials, which are both lightweight and robust, have been widely used in maritime structures, such as ships and offshore platforms, to enhance resistance to structural failure. The main focus of this study encompasses three aspects: the historical development of composites, failure theories of composite materials with an emphasis on damage caused by external loads, and recent advances in failure criteria for durability optimization. In this study, several failure theories, including the maximum stress-strain, Hashin, Tsai-Hill, Tsai-Wu, and Puck theories, are presented and reviewed, along with recent research results presented in tabular form. The expected results of this study can provide essential guidance for future research directions aimed at enhancing the reliability of composite materials in the maritime sector.

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Keywords: Composite Materials; Marine Purposes; Failure Criteria

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1. Introduction

Composite materials combine two or more materials to obtain unique mechanical and physical properties. This combination often enhances the desired qualities of each constituent, which can be organic, inorganic, or metallic or can also be in the form of fibers, rods, or particles. Typically, composites are composed of a matrix phase and a reinforcement. Composite materials are widely used in various industries, including shipbuilding, automotive, sports equipment, construction, and aerospace, Okuma et al. (2023), Tong et al. (2002). In the marine industry, fiber-reinforced polymer composites are widely used due to their high tensile strength, workability, corrosion resistance, thermal conductivity, and lightweight properties. These composites are used in masts, decks, curtains, and propellers. Scientific studies on various types of ships, including minesweepers, patrol boats, fishing vessels, and submarines, continue to support the increasing use of fiber-reinforced polymer composites in the marine sector, Sobey et al. (2003). In particular, most pipelines connecting offshore oil and gas platforms to onshore facilities are now made of fiberglass, Brkić and Praks (2021), and hybrid fiber composites have recently become popular in propeller manufacturing, Raheem and Subbaya (2021). Although composites have been increasingly used in the marine industry over the past few decades due to their high specific strength, several critical limitations still limit their applications. These limitations are often related to invisible defects and damage that can compromise the remaining strength of the composite structure.

In general, defects in composite materials are classified into two categories: manufacturing process-related defects and unintentional or service-related damage resulting from load. The first category includes problems such as porosity, delamination, matrix cracks, fiber breakage, curing stresses, and fiber misalignment. Designers can address these defects by incorporating safety factors based on the results of quality control. The second category encompasses defects resulting from in-service or unintentional loads. In particular, composite structures can sometimes return to their original shape after experiencing internal damage, leaving no visible indication of damage (a phenomenon known as Barely Visible Damage, or BVD), Calomfirescu and Hickethier (2010), Liu and Change (1994). Given this, structures must be designed for damage tolerance, ensuring that small, undetected defects do not compromise structural integrity. However, if these defects are not promptly identified and repaired, they can lead to catastrophic failure. Even when damage occurs at the material level (micro or meso), it can affect the overall structural performance. Therefore, challenges remain in using composite materials, including complex failure mechanisms for which insight is still limited, and developing a properly tractable failure model is difficult. Composite failure behavior is complex—even with unidirectional laminates—but is difficult to predict under different loading conditions, Talreya (2014). Engineers conduct extensive testing to address this and understand how composite laminates respond to different loads. For example, uniaxial and pure shear tests help establish the failure envelope of laminates, reducing design costs. Using lamination failure criteria, engineers can more accurately predict the onset and mode of failure in composites, particularly under combined stress conditions Sun et al. (1996). This paper summarizes the historical use of composites in maritime applications and reviews standard failure criteria commonly used in previous studies.

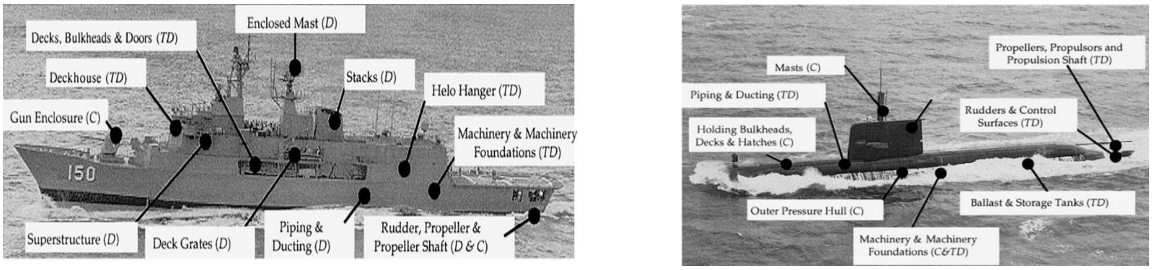
2. History of Composite for Marine Purpose

In the post-war era, when materials with lightweight, robust, and corrosion-resistant qualities were prioritized due to necessity, composite materials first appeared in nautical structures. Following World War II, composites were first employed in shipbuilding, particularly in the maritime sector, where they were used to construct small personnel ships for the US Navy. These ships proved to be rigid, robust, long-lasting, and easy to repair. The usage of composites in various ship types has rapidly expanded due to these material advantages (see Table 1). Composites were later utilized in the Vietnam War as well. Over 3000 ships were constructed from composite materials, and hundreds of personnel ships, river patrol boats, landing craft, and many reconnaissance vessels were in service. In addition, the US Navy employed composites in the masts of certain communications ships, the deckhouses of small ships, the piping of destroyers, and the fairwater sand casings of submarines (see Figure 1 for examples of composite components).

A more detailed history of composites in marine use, particularly in the United States and Europe, where manufacturers, development, and trading activities took place, is described in Figure 2. In the mid-1960s, the hand lay-up method was applied to produce mats and matting using fiberglass roving materials. In the 1970s, sandwich construction began in related industries. Alternative resins, such as vinyl esters and epoxies, began to be used with the development of the market in the late 1970s. The growing market required faster production, prompting the development of more advanced fabrication techniques. Since the early 1980s, alternative reinforcement materials, such as aramid, Kevlar, and carbon fiber, have begun to be used in the industry. The 1990s was the time to introduce vacuum-assisted and infusion methods for production, Marsh (2003). After that, its development was faster and more comprehensive, so that it was used in various functions such as fire resistance, vulnerability reduction, ballistic protection, shock resistance, etc., by paying attention to optimizing the function and quality of the materials used through variations in the composition and fabrication methods applied (see Figure 2.).

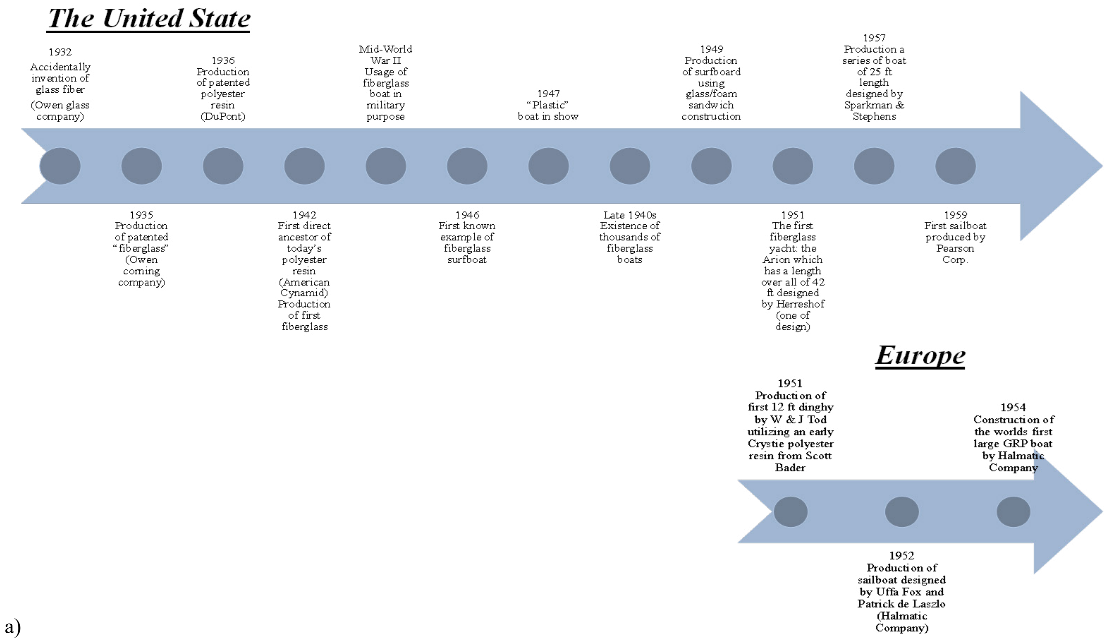
Table 1. Applications of composite materials in maritime structures.

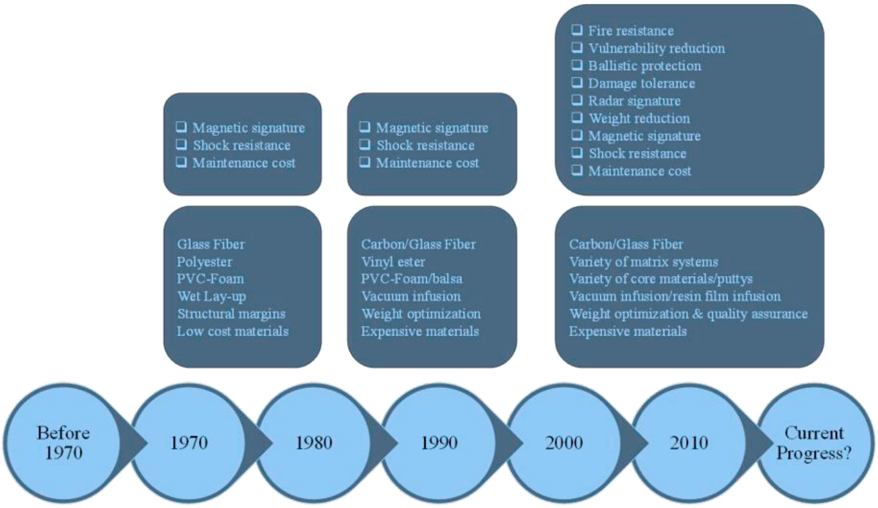
Applications		Year	Composite Type	Representation of Structure	Ref.
Structure	Sections				
Navy Ship	Piping & Minesweepers	1940s	FRP	Higgins Boat	Greene (1999)
	Patrol boat	Early 1960s	GFRP	KNM Skjold, Smyge MPC2000	Huand and Sun (2007)
Submarine	Sonar dome, rudder pole, ship's sleeve	1940s	FRP	Collin-class submarine	Graner (1969) McKenzie et al. (1954)
Civil and commercial crafts	Fishing boats, fast ferries	1950s	FRP and GFRP	-	Selvaraju et al. (2011) Kootsookos et al. (2004)



(a) (b)

Figure 1. Application of composite materials in maritime structures, Mouritz et a. (2001): (a.) Naval Ship and (b.) Submarine.





(b)

Figure 2. A detailed history of composite usage in the maritime space from the 1930s-2010 (redrawing from Marsh (2010) and Neşer (2017): (a) US and Europe, and (b) all summarized progress.

3. Theories of Failure in Composite:

Composite materials have non-homogeneous material properties. Therefore, the failure mechanism of composite materials is very different from other materials that generally have homogeneous properties. Generally, failure in composite structures is characterized by two phases: the elastic phase, where damage does not appear in the structure because it is still within the threshold of its elasticity, and the plastic phase, where a certain stress level causes damage, Shen and Zhou (2017), Tarpani et al. (2006). In addition, it can also be classified into intra-laminar failures, such as fiber breakage, the release of bonds between fibers and the matrix (Figure 3.a), and progressive damage to the matrix (Figure 3.b); inter-laminar failure such as delamination damage (Figure 3.c), which occurs at the interface between adjacent layers. These damages can occur separately or simultaneously.

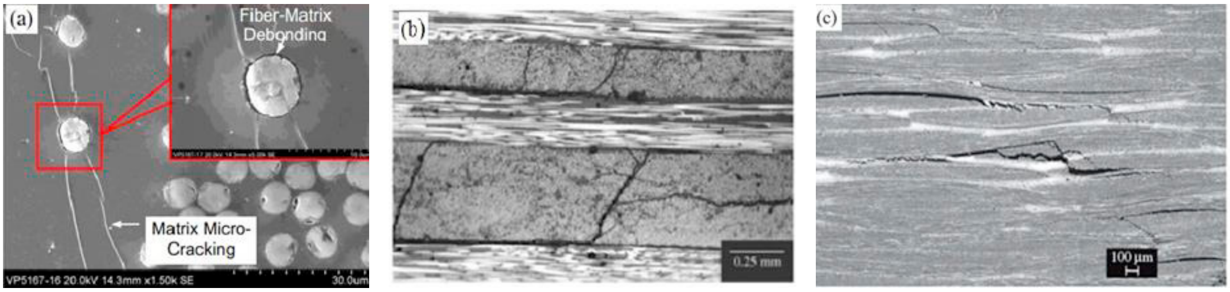


Figure 3. Damage in multi-layered composite, Shen and Zhou (2017), Tarpani et al (2006), Paiwa et al. (2005): a) matrix-fiber debonding; b) progressive damage in the matrix; c)delamination damages.

Several failure criteria and theories have been developed and refined to estimate the failure envelope for composite laminates, including the maximum strain/stress criterion, the quadratic failure theory (also known as the Tsai-Wu theory), the Tsai-Hill criterion, the Hashin criterion, and the Puck failure criterion, among others Nali and Carrera (2012), Velmurugan et al. (2020). Compared to experimental data, the Hashin and Puck failure criteria are the two hypotheses with negligible errors, Chowdhury (2016). Three categories comprise these failure criteria, Koh and Masedn (2017), Daniel (2016), Daniel et al. (2018): restricted or inactive theories, such as maximal stress and strain. Second, theories based on failure modes or partial interaction, such as the UN-Daniel Tao, Hashin-Rotem, and Puck theories. Third, completely interactive theories, such as the Tsai-Wu and Tsai-Hill theories. The following is a brief description of some of the hypotheses.

- Maximum strain/stress failure theory

Following the maximum stress failure theory, composite materials fail when their stress exceeds their ultimate/yield strength. Limited or noninteractive theories include both maximum stress and strain failure theories.

(i) Maximum stress criterion

The maximum stress criterion is stated as [29]:

$$\begin{gathered}(\sigma_1 - X_T)(\sigma_1 + X_C)(\sigma_2 - Y_T)(\sigma_2 + Y_C)(\sigma_3 - Z_C) \\ (\sigma_4 - R)(\sigma_4 + R)(\sigma_5 - S)(\sigma_5 + S)(\sigma_6 - T)(\sigma_6 - T) \ge 1\end{gathered} \tag{1}$$

where the maximal material strength in the fiber, matrix, and in-plane directions is denoted by X, Y, and S, respectively. Tensile and compressive are denoted by the subscripts T and C, respectively.

(ii) Maximum strain criterion

The maximum strain criterion is expressed as, Chen et al. (2019):

$$\begin{gathered}(\varepsilon_1 - X_{\varepsilon T})(\varepsilon_1 + X_{\varepsilon C})(\varepsilon_2 - Y_{\varepsilon T})(\varepsilon_2 + Y_{\varepsilon C})(\varepsilon_3 - Z_{\varepsilon C}) \\ (\varepsilon_4 - R_\varepsilon)(\varepsilon_4 + R_\varepsilon)(\varepsilon_5 - S_\varepsilon)(\varepsilon_5 + S_\varepsilon)(\varepsilon_6 - T_\varepsilon)(\varepsilon_6 - T_\varepsilon) \ge 1\end{gathered} \tag{2}$$

A two-dimensional strain-based theory predicts the ultimate failure of fiber-reinforced composite laminates under multiaxial stress. The maximum strain failure theory examines stiffness degradation in multidirectional laminates. Then, the three-dimensional micromechanical model was suggested for investigating CFRP composite laminates under tension. Maximum strain failure criteria describe fiber and matrix failure, assuming isotropic and elastic-plastic matrix and transversely isotropic fiber.

- Hashin failure criteria

Hashin failure criteria is a partial interactive or failure-based theory used to obtain the fiber failure, matrix failure, and fiber-matrix failure in tension, compression, and shear out plies condition, Deng et al. (2019).

- Tsai-Hill failure criteria

It is called energy-based interaction theory, and the polynomial equation of Tsai-Hill failure criteria is expressed as:

$$\begin{gathered}\left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\sigma_3}{Z}\right)^2 - \left(\frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2}\right)\sigma_1\sigma_2 - \left(\frac{1}{Y^2} + \frac{1}{Z^2} - \frac{1}{X^2}\right)\sigma_2\sigma_3 - \\ -\left(\frac{1}{Z^2} + \frac{1}{X^2} - \frac{1}{Y^2}\right)\sigma_1\sigma_3 + \left(\frac{\sigma_4}{R}\right)^2 + \left(\frac{\sigma_5}{S}\right)^2 + \left(\frac{\sigma_6}{T}\right)^2 \ge 1\end{gathered} \tag{3}$$

- Tsai-Wu failure criteria

It is called Interaction tensor polynomial criteria, and Tsai and Wu proposed the modified tensor polynomial failure criteria for composite laminates and expressed as follows, Mejlej et al. (2017):

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j \ge 1 \tag{4}$$

where F_i and F_j denotes strength coefficient tensor for second and fourth-order, respectively. $j = 1, 2, \ldots, 6$.

$$\begin{gathered}F_1\sigma_1 + F_2\sigma_2 + F_3\sigma_3 + 2F_{12}\sigma_1\sigma_2 + 2F_{23}\sigma_2\sigma_3 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + \\ +F_{33}\sigma_3^2 + F_{44}\sigma_4^2 + F_{55}\sigma_5^2 + F_{66}\sigma_6^2 \ge 1\end{gathered} \tag{5}$$

where:

$F_1 = \frac{1}{X_T} - \frac{1}{X_C}; F_2 = \frac{1}{Y_T} - \frac{1}{Y_C}; F_3 = \frac{1}{Z_T} - \frac{1}{Z_C};$

$F_{11} = \frac{1}{X_T X_C}; F_{22} = \frac{1}{Y_T Y_C}; F_{33} = \frac{1}{Z_T Z_C};$

$F_{44} = \frac{1}{R^2}; F_{55} = \frac{1}{S^2}; F_{66} = \frac{1}{T^2};$

$F_{12} = -\frac{1}{2}\frac{1}{\sqrt{X_T X_C Y_T Y_C}}; F_{13} = -\frac{1}{2}\frac{1}{\sqrt{X_T X_C Z_T Z_C}}; F_{23} = -\frac{1}{2}\frac{1}{\sqrt{Y_T Y_C Z_T Z_C}}$

- Hoffman's criteria

The polynomial equation of Hoffman's failure criteria is expressed as:

$$\frac{1}{2}\left(\frac{1}{Y_T Y_C}+\frac{1}{Z_T Z_C}-\frac{1}{X_T X_C}\right)(\sigma_2-\sigma_3)^2+\left(\frac{1}{Z_T Z_C}+\frac{1}{X_T X_C}-\frac{1}{Y_T Y_C}\right)(\sigma_3-\sigma_1)^2+\left(\frac{1}{X_T X_C}+\frac{1}{Y_T Y_C}-\frac{1}{Z_T Z_C}\right)(\sigma_1-\sigma_2)^2+ \\ +\left(\frac{1}{X_T}-\frac{1}{X_C}\right)\sigma_1+\left(\frac{1}{Y_T}-\frac{1}{Y_C}\right)\sigma_2+\left(\frac{1}{Z_T}-\frac{1}{Z_C}\right)\sigma_3+\left(\frac{\sigma_4}{R}\right)^2+\left(\frac{\sigma_5}{S}\right)^2+\left(\frac{\sigma_6}{T}\right)^2 \geq 1 \tag{6}$$

- Puck failure criteria

Puck failure criteria is a failure-based theory that determines different failure modes, including fiber failure, inter-fiber failure, in-plane shearing, and significant transverse compression. A new fatigue theory for multidirectional fiber-reinforced laminates was developed using Puck's failure theory and the non-linear residual stiffness and strength model. The finite element method was used to evaluate the ultimate failure analysis of composite laminate plates, assessing first-ply-failure and last-ply-failure stress envelopes under biaxial loading conditions. The initial and progressive failure of carbon/fiber-reinforcement composite laminates was also proposed.

4. Recent efforts have focused on failure criteria for the failure mechanism

Numerous researchers have developed failure criteria for different composite material failure mechanisms to forecast initial failure, propagation, and final failure under circumstances like tension, compression, and shear. This failure analysis can help find certain failures in multi-layer composite laminates, as shown in Table 2, Yao et al. (2018), Lee and Yoh (2015), Orifici et al. (2008), Gan et al. (2018), Liu and Zhang (2010), Sabik (2019), Soden et al. (1998), Sunardi et al. (2023), Fekaouni et al. (2023), Naufal et al. (2023), Lazuardy and Fakhruddin (2024), Krausz et al. (2023), Akbar et al. (2020), Utami et al. (2023), Fajri et al. (2024), Thakur et al. (2019), Islami et al. (2024), Wiranto et al. (2024), Naufal et al. (2024).

Table 2. Summary of failure criteria for fiber and matrix failures.

Name of Failure Criteria	Failure Type	Load Type	Main Equation	Year	Ref.
Max-strain	Fiber failure	Multi-axial loading	$\frac{\varepsilon_1^2}{\varepsilon_{1T}\varepsilon_{1C}}+\left(\frac{1}{\varepsilon_{1T}}-\frac{1}{\varepsilon_{1C}}\right)\varepsilon_1\ or-(\varepsilon_{1C}<\varepsilon_1<\varepsilon_{1T})$	2015	Yao et al. (2018)
	Matrix failure		$\frac{\varepsilon_2^2}{\varepsilon_{2T}\varepsilon_{2C}}+\left(\frac{1}{\varepsilon_{2T}}-\frac{1}{\varepsilon_{2C}}\right)\varepsilon_2\ or-(\varepsilon_{2C}<\varepsilon_2<\varepsilon_{2T})$		
Max-stress		Tensile	$\varepsilon_1 \geq \varepsilon_{1T}\ for\ \sigma_{11} > 0$	2008	Lee and Yoh (2015)

	Fiber failure	Compressive	$\varepsilon_1 \geq \varepsilon_{1C}\ for\ \sigma_{11} < 0$		
	Matrix failure	Tensile	$\varepsilon_2 \geq \varepsilon_{2T}\ for\ \sigma_{22} > 0$		
		Compressive	$\varepsilon_2 \geq \varepsilon_{2C}\ for\ \sigma_{22} < 0$		
Hashin 2D	Fiber failure	Tensile	$\frac{\sigma_{11}}{X_T} \geq 1\ for\ \sigma_{11} > 0$	2017, 2018	Orifici et al. (2008)
		Compressive	$-\frac{\sigma_{11}}{X_T} \geq 1\ for\ \sigma_{11} < 0$		
	Matrix failure	Tensile	$\left(\frac{\sigma_{22}}{Y_T}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 \geq 1\ for\ \sigma_{22} > 0$		
		Compressive	$\left(\frac{\sigma_{22}}{Y_C}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 \geq 1\ for\ \sigma_{22} > 0$		
Tsai-Wu	Fiber & Matrix failures	Tensile, Compressive, and Shear	$F_i\sigma_i + F_{ij}\sigma_i\sigma_j + F_{ijk}\sigma_i\sigma_j\sigma_k \geq 1$	2010, 2018	Gan et al. (2018) Liu and Zhang (2010)
Puck	Fiber failure	Tensile	$\frac{1}{\varepsilon_{1T}}\left(\varepsilon_1 \frac{\upsilon_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) = 1\ for\left(\varepsilon_1 \frac{\upsilon_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) \geq 0$	1998, 2018	Sabik (2019) Soden et al. (1998)
		Compressive	$\frac{1}{\varepsilon_{1C}}\left\|\left(\varepsilon_1 \frac{\upsilon_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right)\right\| + \left(10\gamma_{12}\right)^2 = 1$ $for\left(\varepsilon_1 \frac{\upsilon_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) < 0\ and\ \sigma_1 < 0$		

5. Conclusions

This study highlights the role of composite materials as a superior solution for improving structural resilience in marine applications. Composite materials, especially those based on polymer fibers, have significantly benefited the maritime industry, including warships, patrol boats, submarines, and other infrastructure, due to their lightweight, corrosion-resistant, and robust properties. However, using composites in harsh marine environments still presents challenges, particularly in terms of invisible damage and limitations in predicting failure modes. In addition, this study has also highlighted several failure methods and analytical criteria to understand the behavior of composite materials under various loading conditions. The approaches used, including failure criteria such as Hashin, Tsai-Wu, and Puck, showed varying effectiveness in predicting initial damage and damage progression to final failure. The analysis also indicated that more interactive criteria, such as Tsai-Wu and Puck, provide results closer to natural conditions.

However, they still need further refinement to match the complexity of layered composite materials. Future challenges include improving composite manufacturing techniques and developing reliable predictive models for long-term failure under extreme marine conditions. In addition, this study recommends developing more accurate non-destructive inspection methods for the early detection of internal damage, which is crucial for preventing undetected structural failures. With research focused on optimizing the durability and performance of composite materials, it is expected to yield more durable and reliable material innovations that meet the needs of the maritime industry in the future.

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