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An experimental investigation to predict the durability of polyester-glass fiber composite subjected to tensile loading

Uma investigação experimental para prever a durabilidade do composto de poliéster e fibra de vidro submetido a cargas de tração

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ABSTRACT
Glass Fiber and resin composites represent a significant advance in the industry thanks to their lightness, strength, and versatility. Their mechanical strength, highlighting a number of critical aspects in the development of high-performance materials, opens up new prospects in sectors as diverse as aerospace, automotive, and construction, among others. These advances stimulate ongoing research and development in the field of composite materials, underlining the importance of these efforts in meeting future needs in terms of materials performance and durability. This study examines the capacity to predict the durability of polyester-glass fiber composites when subjected to tensile loading. The experimental approach involves exploring the mechanical properties of the composite material and changes in glass fiber content, fiber length, and plate thickness. The process includes performing tensile tests on composite specimens to assess characteristics like Young's modulus and fracture stress. The study uses analytical prediction tools, precisely the Monte Carlo approach, to evaluate the damage distribution within the composite material. The study emphasizes the substantial influence of glass fiber content with a maximum content of 60% mass resin and length with the optimum size of 60 mm on the mechanical properties where Young's modulus attains a value of 4 GPa and longevity of the composite. The study highlights the significance of plate thickness in improving structural performance and fracture toughness, where Young's modulus shows consistency across varying thicknesses. In contrast, stress shows an increasing trend with thickness, culminating in a value of 3.4 MPa. The results enhance comprehension of polyester-glass fiber composites' mechanical characteristics and prediction ability under tensile stress.

Keywords: polyester-glass fiber composite, tensile loading, durability prediction, mechanical properties, Monte Carlo method.

RESUMO
Os compostos de fibra de vidro e resina representam um avanço significativo no setor graças à sua leveza, resistência e versatilidade. Sua resistência mecânica, destacando uma série de aspectos críticos no desenvolvimento de materiais de alto desempenho, abre novas perspectivas em setores tão diversos quanto o aeroespacial, o automotivo e o de construção, entre outros. Esses avanços estimulam a pesquisa e o desenvolvimento contínuos no campo dos materiais compostos, ressaltando a importância desses esforços para atender às necessidades futuras em termos de desempenho e durabilidade dos materiais. Este estudo examina a capacidade de prever a durabilidade de compósitos de poliéster e fibra de vidro quando submetidos a cargas de tração. A abordagem experimental envolve a exploração das propriedades mecânicas do material composto e as alterações no conteúdo de fibra de vidro, no comprimento da fibra e na espessura da placa. O processo inclui a realização de testes de tração em amostras compostas para avaliar características como o módulo de Young e a tensão de fratura. O estudo usa ferramentas de previsão analítica, precisamente a abordagem de Monte Carlo, para avaliar a distribuição de danos no material composto. O estudo enfatiza a influência substancial do teor de fibra de vidro com teor máximo de 60% da massa de resina e comprimento com o tamanho ideal de 60 mm nas propriedades mecânicas, em que o módulo de Young atinge um valor de 4 GPa e a longevidade do composto. O estudo destaca a importância da

espessura da placa para melhorar o desempenho estrutural e a resistência à fratura, em que o módulo de Young mostra consistência em espessuras variadas. Em contrapartida, a tensão mostra uma tendência de aumento com a espessura, culminando em um valor de 3,4 MPa. Os resultados aprimoram a compreensão das características mecânicas e da capacidade de previsão dos compostos de fibra de vidro de poliéster sob tensão de tração.

Palavras-chave: compósito de fibra de vidro-poliéster, carga de tração, previsão de durabilidade, propriedades mecânicas, método Monte Carlo.

1 INTRODUCTION

Polyester-glass fiber composites are widely used in different industries because of their favorable mechanical characteristics, such as high strength-to-weight ratio and resistance to corrosion (Hussein; Rasheed, 2023; Rajabi; Kadkhodayan; Ghanei, 2018; Wulandari *et al*., 2023; Zimmermann *et al*., 2023). It is essential to comprehend the resilience of these composites beneath various loading conditions to guarantee their reliability in practical applications (Mohammad Shohel; Hossain Riyad; All Noman, 2023; Pan; Yan, 2021; Venkatesan *et al*., 2020).

Tensile loading is one of the most common mechanical stresses experienced by composite materials (Muslim *et al*., 2023; Muthalagu *et al*., 2021; Shanti; Vemula; Satyadevi, 2023). In this regard, predicting the behavior of polyester-glass fiber composites under tensile loading becomes paramount for designing durable structures. Factors such as the content and length of glass fibers and the composite plates' thickness significantly influence their mechanical performance (Akpinar; Akpinar, 2023; Chavan *et al*., 2023; Gokulkumar *et al*., 2022; Moustapha Sarr; Kosaka, 2023).

This experimental investigation focuses on the prediction of durability for polyester-glass fiber composites under tensile loading. This study aims to analyze and test various combinations of glass fiber content, fiber length, and plate thickness to determine how these variables affect the mechanical properties of the composite. The distribution function of damage inside the composite is also evaluated using analytical prediction methods, precisely the Monte Carlo method (Liu *et al*., 2023; Ma *et al*., 2023; Mechab *et al*., 2014, 2016).

The outcomes of this investigation are anticipated to enrich the fundamental comprehension of the mechanical attributes exhibited by polyester-glass fiber composites. Furthermore, these findings are poised to facilitate the formulation of predictive frameworks crucial for evaluating the durability of such composites under the rigors of tensile loading. Ultimately, these insights hold significant promise for refining the design methodologies and enhancing the performance of composite structures across diverse engineering domains.

The main objective of this study is to assess the strength and durability of a composite subjected to tensile loading by analyzing its response and resistance to tensile forces over time. In addition, it seeks to predict the behavior of the composite under natural conditions by anticipating its reactions in various practical situations. The analysis also aims to identify the factors influencing the durability of the composite, such as its composition as a function of the level of glass fiber added, the length of the fibers, and the thickness of the composite plate studied, as well as its manufacturing quality.

2 MATERIALS AND METHODS

2.1 MATERIALS

Unsaturated polyester resin: SYNOLITE 593-62-0050. Table 1 presents the essential properties of used polyester.

Table 1 – Unsaturated polyester proprieties

Proprieties	**Values**	
Density (20°C) kg/m³	1200	
Flexural strength (DIM 53452) N/mm²	142	
Tensile strength (DIN 63455) N/mm²	87	
Modulus of elasticity (tensile) N/mm²	3600	
Elongation at break %	4.2	
Heat distortion temperature (ASTM D 642-56) (ISO 75 A) °C	96	
Curing characteristics (SPI test)	Gel time	8 min
	Exothermic peak	195 °C
	The time interval between 66°C and the exothermic peak	9 min 30 s

Source: Authors.

E-type glass fiber coil (ROVING): is a torsion-free assembly of parallel base wires with a standard linear mass of around 2400 TEX (2400 g/Km). Table 2 shows the essential properties of glass fiber (ROVING).

Table 2 – Glass fiber (ROVING) proprieties

Proprieties	Values		
tensile resistance	4.5 cm	18.6 cm	87 cm
	286 kg/mm²	233 kg/mm²	171 kg/mm²
Moisture content	0.6 % according to ISO 1887 standard.		
Sizing rate	0.925 % according to ISO 1887 standard.		
Linear mass	2127 g/k TEX according to ISO 1889 standard.		

Source: Authors.

The tube production unit at ENPC Chlef in Algeria provided both materials.

2.2 SYNTHESIS

The contact molding process is the simplest method of manufacturing reinforced polyester. After applying the release agent to the mold surface, the laminate is created by placing the reinforcement in the mold cavity and impregnating it with catalyzed resin. Trapped air is removed with a roller or brush. Several layers of reinforced material are superimposed to achieve the desired thickness. Our specific requirement was to work with Roving (individual threads; Figure 1).

Once applied, the resin hardens to create a solid part that takes on the shape of the original surface or form (Figure 2). This process is commonly used in industry to produce lightweight and durable components.

Figure 1 – Roving (individual threads)

Source: Authors.

Figure 2 – Samples of glass fibers- polyester composite

Source: Authors.

2.3 TENSILE PROPERTIES

Tensile strength, a pivotal mechanical characteristic, denotes the utmost force a material can endure before experiencing deformation or fracture under uniaxial tensile stress. An experimental evaluation of tensile strength was executed using an INSTRON 1195 machine, as illustrated in Figure 3.

Figure 3 – Tensile loading test

Source: Authors.

Mechanical characterization was predicated upon tests conducted on pristine specimens of straightforward geometrical configuration subjected to tension. The outcomes of these assessments serve as the basis for appraising elastic moduli and stress at the point of fracture, as depicted in Figure 4.

Figure 4 – Sample after tensile test

Source: Authors.

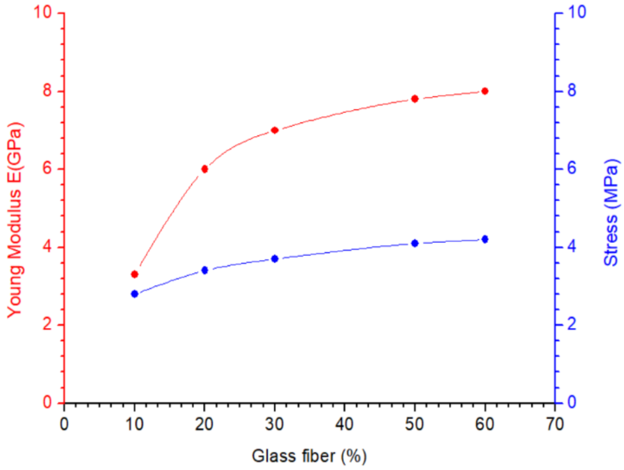
3 RESULTS AND DISCUSSIONS

This investigation endeavors to scrutinize and elucidate the outcomes of various tests performed on polyester/glass fiber composite specimens. The study aims to dissect and assess the individual impacts of three key variables, namely, the glass fiber content, the length of the glass fiber, and the plate thickness, on the mechanical attributes governing the behavior of the composite material. Furthermore, an examination is warranted to discern the composite's response to chemical aggression and other pertinent properties.

3.1 EFFECT OF GLASS FIBER PERCENTAGE

Figure 5, delineating the progression of Young's modulus and fracture stress as a function of fiber content, unveils discernible patterns. A systematic augmentation is observed in both mechanical tensile properties with escalating fiber content. Notably, when the glass fiber content reaches 60%, Young's modulus attains a pinnacle value of 7.2 GPa, concomitantly with the peak tensile strength of the analyzed plate, which registers at 3.5 MPa.

Figure 5 – Evolution of modulus of elasticity and fracture stress as a function of fiber content



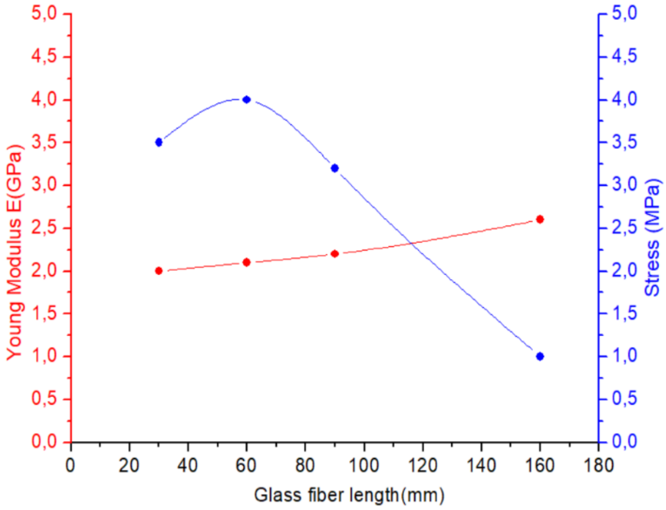
Source: Authors.

Elevating the glass fiber content enhances the tensile strength of the scrutinized structure. Nonetheless, it is imperative to recognize that this trajectory towards augmented fiber content is finite; a threshold level of reinforcement exists beyond which the integrity of the fiber-matrix interface cannot be assured.

3.2 EFFECT OF FIBER LENGTH

The progression of mechanical properties under tensile loading needs explicit theoretical elucidation. Deciphering such outcomes entails a complex interpretation, necessitating a series of reproducible experiments to elucidate the impact of varying fiber lengths (rovings) on the mechanical behavior of our composite material under tension.

Figure 6 – Evolution of modulus of elasticity and fracture stress as a function of fiber length



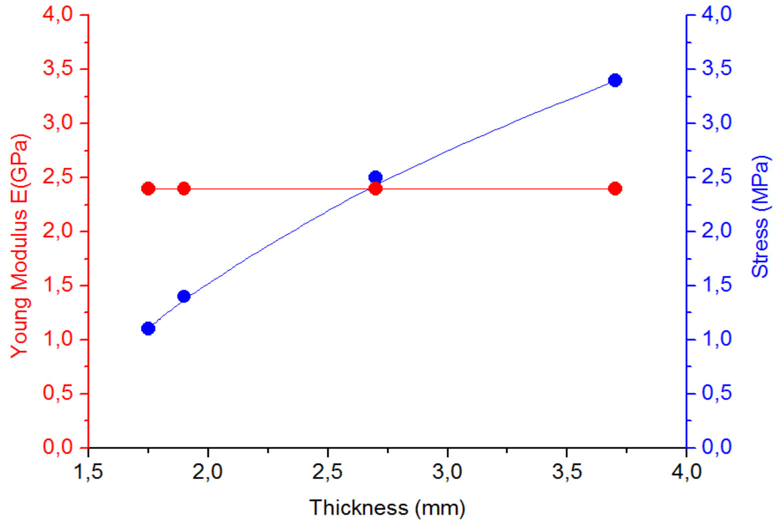
Source: Authors.

Figure 6 depicts the evolution of Young's modulus and tensile stress as a function of glass fiber length. It becomes evident that these two mechanical properties under tension exhibit a proportional relationship, steadily increasing up to a length of 60 mm. Young's modulus attains a value of 4 GPa at this juncture, concurrent with a plate fracture stress of 3.5 MPa. However, with a continued augmentation in fiber length, the fracture strength of the plate diminishes, reaching a stress of 1 MPa at a height of L=160 mm. Consequently, the elongation of fibers results in a decrement in the fracture strength of the structure. This observation aligns with the theoretical premise that longer fibers foster a stronger bond with the matrix, implying that milled fibers with a length of 1 cm provide lesser particle reinforcement than longer fibers.

3.3 EFFECT OF PLATE THICKNESS

Figure 8 depicts the progression of Young's modulus and fracture stress concerning plate thickness. Notably, Young's modulus exhibits constancy across varying thicknesses, while stress displays an increasing trend with thickness, culminating in a value of 3.4 MPa.

Figure 7 – Evolution of modulus of elasticity and fracture stress as a function of plate thickness



Source: Authors.

This observation suggests that increasing thickness helps to improve the fracture toughness of the structure under examination, thereby extending its service life. By enhancing the understanding of these mechanical properties, these results highlight the importance of plate thickness in the context of structural performance and fracture toughness.

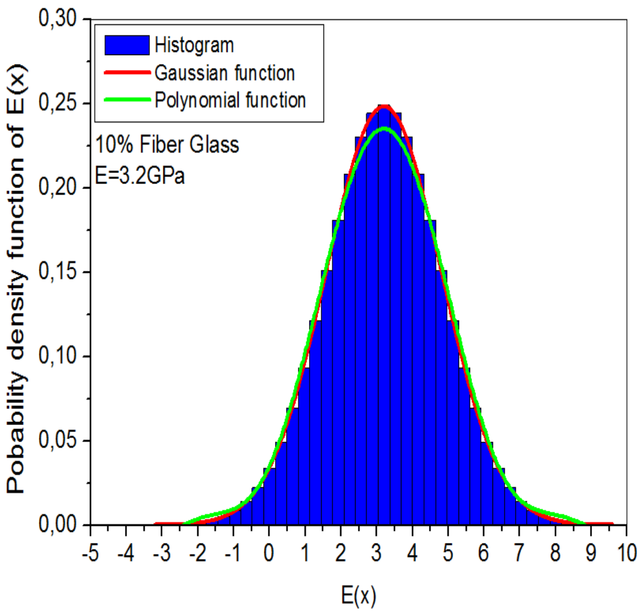
3.4 ANALYTICAL PREDICTION

3.4.1 Random Parameters

By creating samples for the input parameters and computing responses for each sample, the Monte Carlo method is used to evaluate the density function (IBRAHIM; SERIER; MECHAB, 2018; SERIER *et al*., 2016). The results of 105 simulations were used to construct this computational approach in the FORTRAN computer language.

Some examples of random elements are E, υ, α n, and σ, the applied stress. The likelihood density function obtained by using models to match the histogram is shown in Figure 8. We looked at two distribution laws: the polynomial law and the Gaussian law. By comparing, we find that the Gaussian rule gives an average forecast that is close to the E(x) probability density function.

Figure 8 – Graphical representation and mathematical function of the expected value of x

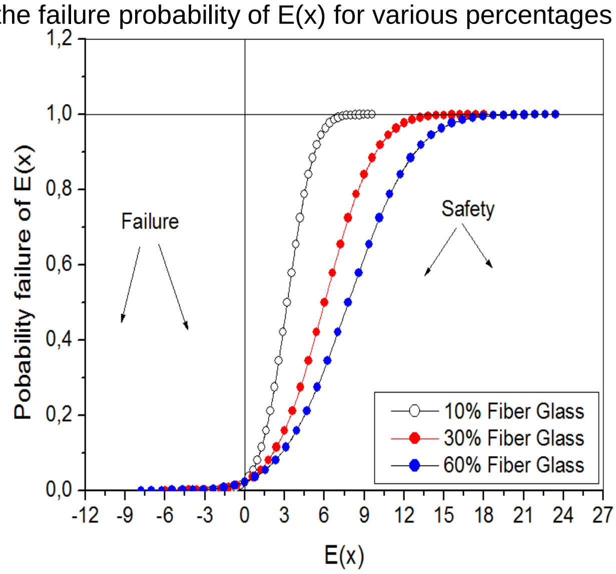


Source: Authors.

Figure 9 delineates the probability of failure of E(x) for varying glass fiber percentages. Notably, a substantial likelihood of failure is observed when the glass fiber percentage is low. The margin significantly increases with uncertainties associated with the glass fiber percentage, underscoring its pivotal role in influencing the likelihood of failure.

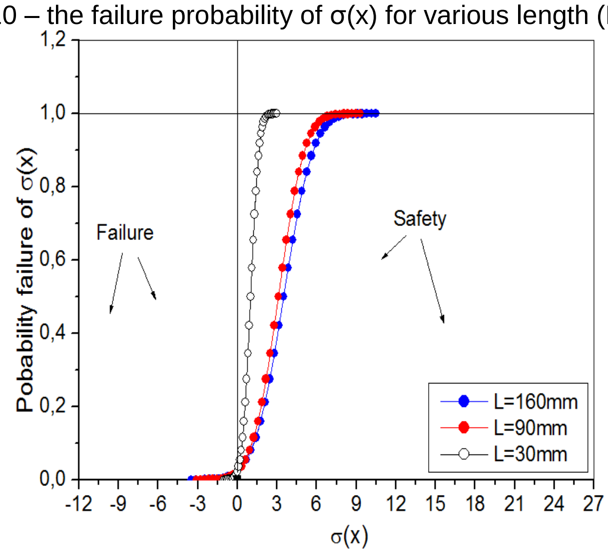
Figure 10 portrays the failure probability of σ(x) across different glass fiber lengths. It is discernible that smaller glass fiber lengths correspond to a lower likelihood of failure of σ(x). However, as the glass fiber length increases, uncertainties associated with this parameter lead to a notable expansion in the margin. The uncertainty surrounding the glass fiber length significantly impacts the probability of failure, particularly for considerable lengths. Ultimately, the likelihood of failure is contingent upon the length of the glass fiber.

Figure 9 – the failure probability of E(x) for various percentages of fiberglass



Source: Authors.

Figure 10 – the failure probability of σ(x) for various length (L) values



Source: Authors.

4 CONCLUSION

This study proposes to optimize the design and manufacture of the composite by improving these aspects to maximize its durability and performance in various applications. On the other hand, the main aim is to provide relevant information for industry and future research by guiding future research into resin-glass fiber composites while offering practical advice to industries using these materials.

As a whole, the results of this research on the mechanical properties and predicted longevity of composites made of polyester and glass fibers under tensile stress are encouraging. The influence of critical parameters such as glass fiber content, fiber length, and plate thickness on mechanical properties has been elucidated through systematic experimentation and analysis.

The findings reveal that increasing the glass fiber content enhances the tensile strength of the composite structure up to a certain threshold, beyond which the integrity of the fiber-matrix interface may be compromised. Additionally, the study highlights the importance of considering fiber length, with longer fibers generally contributing to increased strength up to a point, after which diminishing returns are observed due to potential fiber-matrix detachment.

Moreover, plate thickness influenced fracture stress, with a consistent trend observed across different thicknesses while maintaining Young's modulus. These observations underscore the significance of optimizing material composition and structural design parameters for enhancing the performance and durability of composite structures.

Furthermore, analytical prediction methods, including the Monte Carlo method, were employed to assess the distribution function of damage within the composite. The results underscored the critical role of glass fiber percentage and length in determining the probability of failure, emphasizing the need for meticulous consideration of these factors in composite design and analysis.

Overall, the findings of this study contribute to advancing the understanding of polyester-glass fiber composites and provide valuable insights for optimizing their mechanical performance and durability in practical applications across various engineering domains. Further research could explore additional factors influencing composite behavior and refine predictive models for enhanced accuracy and reliability.

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