

## Analysing Flexural Strength of Induction Welded Epoxy Resin Coated Carbon Fiber/Basalt Fiber/PET Hybrid Composites

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(Alınış / Received: 20.12.2025, Kabul / Accepted: 14.01.2026, Online Yayınlanma / Published Online: 31.01.2026)

### Keywords

Carbon Fiber,  
Basalt Fiber,  
Polyethylene Terephthalate,  
Induction Welding,  
Hybrid Composite

**Abstract:** The increasing demand for lightweight, high-performance, and cost-effective solutions has accelerated research on hybrid composite materials. In this study, epoxy resin-coated carbon fiber fabrics, basalt fiber fabrics, and polyethylene terephthalate (PET) films were bonded using induction welding to produce hybrid composite laminates in a short processing period. The manufactured specimens were characterized through three-point bending test and scanning electron microscopy (SEM) analyses to evaluate their mechanical behavior and interfacial properties. The results revealed that the specimens exhibited flexural strength values of the literature average, while SEM observations confirmed effective fiber-matrix interaction. This study demonstrates that the utilization of low-cost, fast produced and widely available PET films and BF can contribute to the development of sustainable hybrid composites and support their broader adoption in the market.

## İndüksiyonla Kaynaklanan Epoksi Reçine Kaplı Karbon Fiber/Bazalt Fiber/PET Hibrit Kompozitlerin Eğme Mukavemetinin Analizi

### Anahtar Kelimeler

Karbon Fiber,  
Bazalt Fiber,  
Polietilen Tereftalat,  
İndüksiyonla Kaynaklama,  
Hibrit Kompozit

**Öz:** Hafif, yüksek performanslı ve uygun maliyetli çözümlere yönelik artan talep, hibrit kompozit malzemeler üzerine yapılan araştırmaları hızlandırmıştır. Bu çalışmada, epoksi reçine kaplı karbon fiber kumaşlar, bazalt fiber kumaşlar ve polietilen tereftalat (PET) filmler, kısa bir işlem süresi içinde hibrit kompozit laminatlar üretmek için indüksiyon kaynağı kullanılarak birleştirilmiştir. Üretilen numuneler, mekanik davranışlarını ve arayüz özelliklerini değerlendirmek için üç nokta eğme testi ve taramalı elektron mikroskobu (SEM) analizleri ile karakterize edilmiştir. Sonuçlar, numunelerin literatür ortalamasına yakın eğilme dayanımı değerleri sergilediğini, SEM gözlemlerinin ise etkili fiber-matris etkileşimini doğruladığını ortaya koymuştur. Bu çalışma, düşük maliyetli, hızlı üretilen ve yaygın olarak bulunan PET filmlerin ve bazalt fiber kumaşların kullanımının, sürdürülebilir hibrit kompozitlerin geliştirilmesine katkıda bulunabileceğini ve bunların pazarda daha geniş çapta benimsenmesini destekleyebileceğini göstermektedir.

### 1. Introduction

The demand for high-performance, lightweight, and cost-effective materials in sectors such as automotive, aerospace, wind energy, and construction has necessitated intensive research on composite materials [1]. Among

these materials, thermoplastic matrix composites reinforced with carbon and basalt fibers (CF/BF) stand out due to their superior mechanical properties, environmental resistance, and potential for industrial-scale production.

Studies on the development of such thermoplastic (TP) matrix composites have also increased interest in systems using hybrid reinforcement elements. Hybrid composite materials offer optimized solutions in terms of mechanical strength, thermal resistance, and cost-effectiveness by combining the properties of different fiber and matrix systems in a single structure [2]. Structures combining reinforcement materials such as CF and BF, in particular, are widely evaluated in many engineering applications ranging from automotive to construction [3, 4].

CF fabrics are preferred due to their superior mechanical properties, such as high specific strength, stiffness, and fatigue resistance. However, limitations in terms of cost and sustainability necessitate the use of alternative reinforcement elements. In this context, BF fabrics offer environmental and economic advantages thanks to their natural origin, high temperature, and chemical resistance [5, 6].

Thermoset (TS) resins do not change shape after curing and have high thermal stability; however, their inability to be reprocessed leads to a loss of flexibility in some production processes. In contrast, TP films stand out as suitable interface materials for hybrid structures thanks to their reshapeability, low cycle times, and recyclability [7, 8].

While research mainly has focused on high-performance TP resins such as PEI, PEEK, and PPS, there is limited research on hybrid structures using more economical and accessible TP polymers such as PVC and PET [9, 10]. It is assessed that further research is needed on systems using CF and BF reinforced PET or PVC films [11, 12]. Therefore, the development of such TP film applications represents an important area of research, especially in line with sustainability and recycling goals.

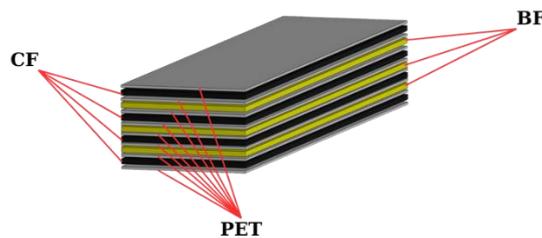
While hybridization studies using thermoplastic matrix carbon fiber (CFTP) fabrics are generally available in the literature, comprehensive research on the hybridization of thermoset coated carbon fiber (CFTS) fabrics with other fibers, such as basalt, using TP films is limited [13]. This demonstrates the need for further research in this area.

This study addresses the development and characterization of BF and epoxy resin-coated carbon fiber (CFTS) fabrics reinforced hybrid PET matrix composites produced using induction welding. The high elastic modulus and tensile strength of CF are critical for structural applications [14]. BF, on the other hand, offer advantages such as better interfacial bonding and lower cost compared to CF [14]. Studies have shown that bond strength, fiber-matrix interaction, and microstructural discontinuities at the interfaces play a decisive role in final composite behavior [15, 16].

In this study, a hybrid composite structure was developed in which CFTS fabrics were combined with BF using PET films, and the mechanical behavior and microstructural properties of this structure were investigated. This study aims to contribute to the development of sustainable composite solutions using low-cost, easily accessible, and recyclable materials [17, 18].

## 2. Material and Methods

The laminates were prepared by combining carbon fiber and basalt fiber fabrics as reinforcement materials and integrating these reinforcements with polyethylene terephthalate (PET) film, a TP matrix material. CFTS and BF fabrics were stacked in interply configuration. A total of seven reinforcement layers were stacked, consisting of four layers of CFTS fabric and three layers of BF fiber fabrics. Eight PET films were placed between each reinforcement layer to ensure bonding and integration between the layers. The stacking structure of the laminates is shown in Figure 1. The sequence of stacking CFTS and BF fabrics is arranged according to the induction heating mechanism that the heat generated on each layer of CFTS fabrics can be transferred to PET films simultaneously.



**Figure 1.** Stacking sequence of matrix and reinforcement materials

PET has good tensile and impact strength, as well as excellent chemical abrasion resistance. The melting temperature of PET is 250 °C. The PET films used in this study are transparent because of the low degree of semi-crystallinity (10-30%). The weight ratio of the PET films was 47% in the specimens, and the thickness of each film was 100 µm. The BF fabric bundles used in the study had a 1K filament density, and their weight fraction in the total mass of the specimens was 11%. The thickness of each BF fabric was 160 µm. BF fiber have high tensile strength, good thermal stability, and chemical resistance. Furthermore, BF interact better with polymer matrix materials than CF. In the hybrid use of CF and BF, both mechanical and bonding properties become more efficient [19].

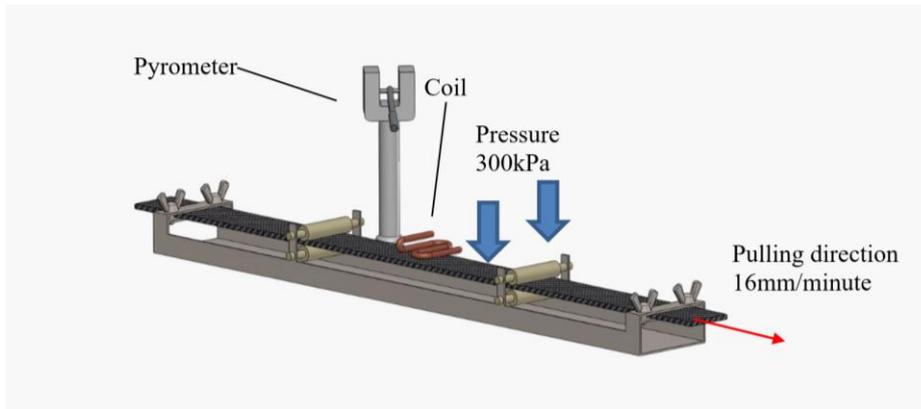
The CFTS fabrics were supplied by DowAksa Advanced Composite Materials Industry and Trade Co. Ltd. in a 5 harness satin weave with epoxy resin resin coating. The CFTS bundles had a 4K density, the weight fraction in the specimens was 42%, and the thickness of each CFTS fabric was 360 µm. CF fabrics are essential in induction heating mechanism due to their ability to provide simultaneous heating across the cross-sectional areas of composite specimens [20]. Furthermore, fatigue resistance, low coefficient of thermal expansion, and high resistance to environmental factors of CF make it an ideal reinforcement material for the hybrid composite structure.

The weight ratios of the materials in the specimens are given in Table 1.

**Table 1.** The weight ratios of the materials in specimens

Material	wt%
PET film	47
Carbon weave fabric with epoxy resin matrix	42
Basalt weave fabric	11

The laminates were produced in the form of strips in the set-up in Figure 2, by continuous induction heating production method at 320 °C, under 300 kPa pressure, by pulling them through the cylinders with an Arduino at a speed of 16 mm/min. Although the melting temperature of PET is approximately 250 °C, a higher processing temperature of 320 °C was selected to ensure sufficient melt flow and effective impregnation of the fiber bundles. At temperatures just above the melting point, the viscosity of PET remains relatively high, limiting its ability to fully wet the reinforcement fabrics. Increasing the processing temperature significantly reduces melt viscosity, thereby improving fiber–matrix interaction and interfacial bonding. Moreover, due to the localized and short-duration heating characteristic of the induction welding process, PET is not exposed to prolonged thermal degradation. The selected temperature is also well below the decomposition temperature of the epoxy resin coating on the CFTS fabrics (~400 °C), preventing interfacial defects such as void formation.



**Figure 2.** Continuous induction welding set-up

The bonding processes were carried out using continuous induction welding. While traditional methods, such as autoclave and hot press, require considerable time, applications using induction welding are completed in minutes. This method consists of two distinct processes: continuous and discontinuous. In continuous welding, the material or coil being processed is mobile. In discontinuous welding, the apparatus is stationary. The generator power of the induction system is 2.8 kW and operates at a frequency of 900 kHz was used for this method. The power of the induction system is automatically adjusted via an IR pyrometer to maintain a constant temperature. The thickness of the laminates produced was measured as 2.35 mm (±0.05). Then, the specimens were cut into 15x10mm dimensions for SEM analysis and 117.5x15x2.35mm dimensions for ISO 14125 three-point bending test as shown in Figure 3.



**Figure 3.** ISO 14125 test specimen dimensions

Scanning Electron Microscope (SEM) analysis was performed to examine the bonding cross-sectional areas and interface properties of the laminates. Five samples were tested under a three-point bending test prepared in accordance with the ISO 14125 test standard to reveal the flexural strength of the specimens.

### 3. Results

According to the results of the three-point bending test and SEM analysis, the bending strength and microstructural properties of the specimens are assessed.

#### 3.1. Bending Test Results

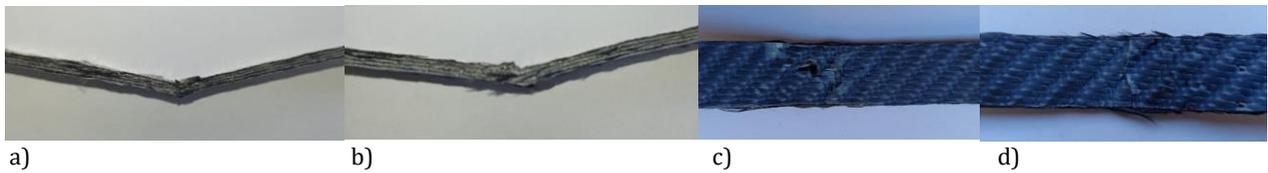
To determine the flexural behavior and strength of composite materials, the forces applied to the specimens and the resulting stress values were recorded as in Table 2.

**Table 2.** ISO 14125 three-point bending test results

Specimen	Flexural Strength (N/mm <sup>2</sup> )
1	100,385
2	118,832
3	107,515
4	101,856
5	119,069

The flexural strength values ranged from 100.39 to 119.07 MPa, with an average value of  $109.53 \pm 9.0$  MPa. The observed scatter is attributed to minor variations arising from manual stacking of the reinforcement layers and localized temperature gradients associated with the moving induction coil. Despite this variation, the results indicate acceptable repeatability for a laboratory-scale induction welding process.

Examining the fracture and surface areas of the specimens, it was observed that the PET matrix in the lowermost layer, where tensile stress occurred, fractured. There was no fracture in the compressive stress region and the corresponding interfaces. However, deformation and delamination were observed in the same areas. Figure 4 shows the tensile stress surfaces and deformation in the cross-sectional areas of specimens 2 and 3, which demonstrate this behavior. No delamination was observed in the regions of the specimens other than the compressive stress-applied region. It is understood that PET exhibits ductile behavior due to its low crystallization rate in its internal structure.



**Figure 4.** The surfaces and cross-sectional areas of specimens. a) The cross-sectional area of specimen 2, b) The cross-sectional area of specimen 3, c) The fracture surface of specimen 2, d) The fracture surface of specimen 3.

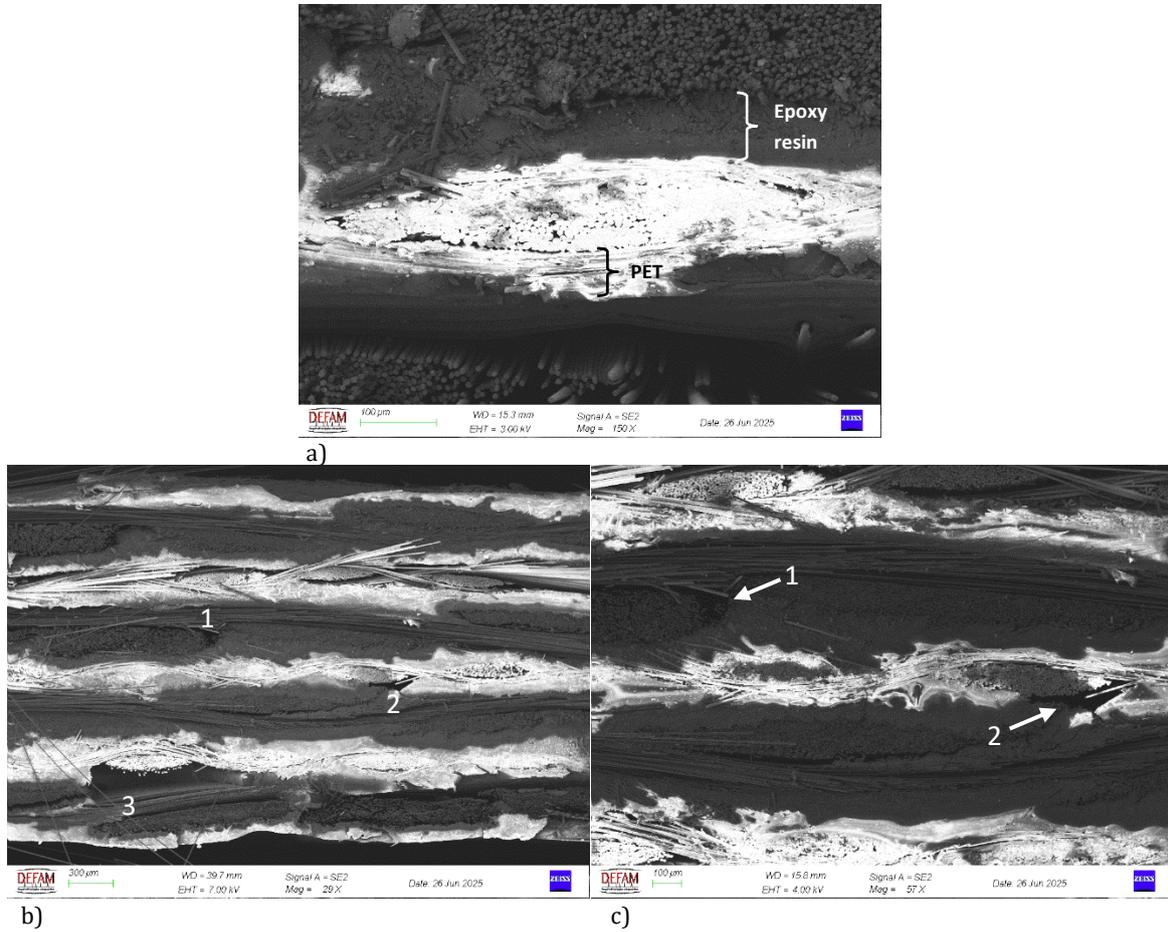
#### 3.2. SEM Results

SEM images obtained from the cross-sections of two different samples are shown in Figure 5. Figure 5a shows that the PET matrix penetrated both fiber groups to a depth of 40–50  $\mu\text{m}$ , forming a compact structure without voids at the interfaces. It is observed that the light-colored PET films interacted well with the epoxy resin matrix of the dark-colored CFTS fabrics. The application temperature of 320  $^{\circ}\text{C}$ , which is below the decomposition temperature of the epoxy resin coating of the CFTS fabric (400  $^{\circ}\text{C}$ ), prevented void formation at the interface. The voids labeled 1, 2, and 3 in Figures 5b and 5c are attributed to the inherent weaving structure of the fabrics.

A critical feature of the proposed hybrid composite system is the interface between the thermoplastic PET matrix and the epoxy resin-coated carbon fiber fabrics. As PET is a thermoplastic material and the epoxy coating is a fully cured thermoset, the interfacial bonding is governed primarily by mechanical interlocking and interfacial wetting rather than chemical crosslinking.

During the induction welding process, localized heating generated within the carbon fiber fabrics enables sufficient softening and flow of PET, allowing it to conform to the surface topography of the epoxy-coated fibers. This promotes intimate contact at the interface and enhances mechanical anchoring. In addition, the elevated temperature may allow limited molecular interpenetration at the polymer-resin interface, contributing to improved interfacial adhesion.

The SEM images presented in Figure 5 reveal a continuous and void-free interface without signs of interfacial debonding or microcracking, indicating good compatibility between the PET matrix and the epoxy resin coating. The absence of premature delamination and the observed deformation behavior under bending loads further suggest that the PET-epoxy interface is capable of effective load transfer. These results demonstrate that, despite the thermoplastic-thermoset nature of the system, sufficient interfacial compatibility can be achieved through appropriate processing conditions. In this case, the fiber bundles maintained their integrity without separation; therefore, internal stresses in the laminates did not result in additional defects.



**Figure 5.** SEM images of cross-sectional areas of specimens. a) PET and epoxy resin interaction, b) Void defects due to the weaving form of fabrics.

#### 4. Discussion and Conclusion

The average flexural strength obtained from the tests was 109.53 N/mm<sup>2</sup>. Comparable studies using thermoplastic matrices reported in the literature are summarized in Table 3 [21–26], where flexural strength values vary depending on the manufacturing method, material type, reinforcement stacking sequence and orientation, and three-point bending test conditions. The flexural strength achieved in this study is consistent with the reported literature values (111.95 MPa).

Kang et al. reported a flexural strength of 73.92 MPa using induction heating molding [23]. Using a similar process, the present study achieved a 48% higher flexural strength. Further improvements may be possible by increasing the PET crystallization rate through an additional induction annealing step.

SEM analysis indicates effective wetting of both BF and CFTS fabrics by the PET films. However, increasing PET film thickness, applying pressures higher than 300 kPa, and extending the induction welding duration are recommended to ensure complete impregnation of BF bundles and further enhance bending performance.

**Table 3.** Flexural strength values of fiber reinforced TP matrix composites in literature.

Flexural Test	Material	Method	Specimen Thickness (mm)	Flexural Strength (MPa)	Reference
ASTM D790	Short CF Filament Reinforced with CCF	3D Printing	3,2	134.58	[21]
ASTM D790	PA12/CF Filament	3D Printing	3,2	119.9	[22]
ASTM D2344	CF/PS	Induction-Heating Molding	3	73,92	[23]
ISO 178	Basalt-Carbon Fiber (BCF) /Bio-Based PET	Injection Moulding	4	126,3	[24]
ISO 178	BCF PP	Injection Moulding	4	~110	[25]
ASTM D790	BF/PLA	Extrusion	3,2	107	[26]

In this study, composite laminates were manufactured using commercially available CFTS and BF fabrics with low-cost thermoplastic PET films via continuous induction welding. PET films showed good welding and wetting behavior with both BF and CFTS fabrics. Increasing BF fabric and PET film thickness, as well as applying higher pressure and longer welding times, is expected to further improve flexural strength.

Future work should examine the effect of increasing the PET crystallization rate through induction annealing on fiber-matrix interaction, bending performance, and aging behavior. Enhancing the crystallinity of amorphous PET films may lead to improved mechanical properties.

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