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The Effect of Adhesive Quantity on Adhesion Quality and Mechanical Characteristics of Woven Kevlar Fabric-Reinforced Laminated Structures

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Abstract: This study investigated the adhesion and mechanical properties of woven fabric-reinforced laminates (FRLs) made with four distinct Kevlar fabrics of varying areal densities (36 g/m^2, 60 g/m^2, 140 g/m^2, and 170 g/m^2) under different fabric-to-adhesive weight ratios (1:0.5, 1:1, and 1:1.5) in both the warp and weft directions. A novel aspect of this research lies in our systematic study of the effect of adhesive quantity on FRLs, a topic that has received limited attention despite its critical role in laminate performance. Additionally, the application of a newly developed yarn pullout test alongside the standard T-peel test provides unique insights into the interfacial behavior of laminates. The results show that in lower areal density fabrics (36 g/m^2 and 60 g/m^2), adhesive quantity minimally affects the pullout and T-peel forces or tear strength, indicating that structural integrity can be maintained with reduced adhesive application. In contrast, higher areal density fabrics (140 g/m^2 and 170 g/m^2) benefit from an increased adhesive ratio, with a transition from 1:0.5 to 1:1 significantly enhancing the pullout resistance, while further increases to 1:1.5 yielded diminishing returns. Tensile strength remained consistent across all samples, highlighting that it is largely dictated by the inherent properties of the fibers and fabric structure rather than the adhesive. This study concludes that a 1:1 fiber-to-adhesive ratio offers an optimal balance of adhesion quality and mechanical performance for FRLs. By addressing the understudied impact of adhesive quantity on FRLs and introducing the yarn pullout test, this research provides novel and practical guidelines for optimizing FRLs in applications demanding high structural integrity and adaptability under challenging conditions.

Keywords: fabric-reinforced laminates (FRLs); yarn pullout in laminate test; high performance fibers (HPFs); composite materials; Kevlar; fiber-to-adhesive ratio

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1. Introduction

Composite materials are characterized by the amalgamation of two or more chemically distinct substances that are combined to exhibit enhanced properties compared to those of the individual materials. Within the composite, the constituent elements maintain their distinct identities, coexisting without complete dissolution or merging, synergizing in their collective impact [1–6]. Noteworthy advantages of composites include their lightweight nature, boasting superior strength-to-weight and stiffness-to-weight ratios surpassing those of traditional materials like steel or aluminum [7–9]. Most composites consist of a primary phase (matrix) that provides the structural integrity and a secondary phase (reinforcing agent) that determines the mechanical properties. The design of composites involves optimizing factors such as the concentration, size, and distribution of components, underscoring the complexity of creating materials tailored for specific applications [1,4,5].

Laminates made from fibers, typically high-performance fibers, are a subset of composites where the reinforcement form is primarily continuous or discontinuous fibers, fabrics, layers of other materials, and dispersed particles [4]. In this study, we focused on fabric-reinforced laminates (FRLs). FRLs are thin, flexible sheets that can be applied in a variety of applications, from the hull material of airships to other types of inflatables such as antennas and space-related items [10,11]. This flexibility and thinness distinguish FRLs from other composites or laminates, which may not be as adaptable and are often thicker. These characteristics make FRLs particularly suitable for applications where both structural integrity and flexibility are critical. Unlike more rigid composites, the flexibility of FRLs allows them to be used in applications that require bending, folding, or inflation [7]. For example, traditional composite materials used in the automotive or aerospace industries are typically designed for rigidity and high load-bearing capacity, making them less suitable for applications where flexibility is a necessity [12]. This difference in application requirements necessitates a detailed study of how varying the adhesive quantity affects the adhesion quality and mechanical properties of FRLs.

The adhesive quantity in fabric-reinforced laminates (FRLs) plays a critical role in determining the interface characteristics, bonding strength, and overall mechanical properties [13]. Optimizing the adhesive quantity is essential for achieving high-performance laminates as it directly affects stress transfer at the fiber–adhesive interface and the structural integrity of the composite. Insufficient adhesive can lead to poor bonding and reduced durability, while excessive adhesive can result in undesirable effects such as brittleness, increased weight, and higher material costs. Despite its significance, the effect of adhesive quantity has been extensively studied in composites like fiber-metal laminates (FMLs) and particle-reinforced composites but remains underexplored in FRLs [13–21]. This gap is particularly important to address, given that FRLs are increasingly being used in applications requiring both flexibility and mechanical robustness such as in airships, inflatable antennas, and other advanced engineering structures [10,11].

Previous studies on composites have shown that the adhesive quantity influences critical properties like the lap shear strength, interlaminar bonding, and fatigue resistance [16,22]. However, the unique structural requirements of FRLs including their thinness and flexibility necessitate a more tailored investigation. Understanding the optimal adhesive quantity for FRLs is crucial to balance the adhesion quality and mechanical performance, ensuring durability without compromising the material's adaptability. By systematically studying the relationship between the adhesive quantity and FRL properties, this research aims to fill a critical knowledge gap, providing actionable insights for designing laminates with enhanced performance in demanding environments.

Wu et al. [22] investigated the effects of surface pre-treatment and adhesive quantity in fiber-metal laminates (FMLs) like GLARE, ARALL, and CARALL, demonstrating that increasing the adhesive layers enhanced the lap shear strength, particularly on anodized surfaces. Their findings underscore the importance of optimizing the adhesive quantity to balance the bonding strength and structural integrity. Excessive adhesive can compromise durability, highlighting the need for precision in achieving the optimal performance without overuse. Li and Hu's research on novel FMLs (NFMLs) based on aluminum-lithium alloys further emphasized the importance of adhesive optimization. They observed that adhesive quantities between 0 g/m^2 and 60 g/m^2 significantly influenced the interlaminar, tensile, flexural, and fatigue properties, with a tensile strength peaking at 40 g/m^2 before declining due to delamination [16]. These results underline the necessity of tailoring the adhesive quantities to enhance bonding without compromising the mechanical integrity, particularly in fatigue critical applications.

Studies on other composite systems have revealed additional complexities. Jaafar and Chum [23] found that lower resin-to-fiber ratios improved the flexural strength in glass fiber-reinforced plastics, in contrast with Li and Hu's findings in NFMLs. Similarly, Guo and Zhang [24] highlighted that increasing the adhesive thickness in carbon fiber-reinforced plastic (CFRP) and aluminum hybrid joints negatively impacted the peak load and energy absorption, emphasizing the importance of controlling the adhesive thickness to maintain joint reliability. These studies illustrate how the optimal adhesive application varies across composite systems, requiring tailored approaches. Wang [25] and Davies [26] focused on the interplay between adhesive properties and thickness in hybrid and epoxy adhesive joints, respectively. Both studies found that bond thickness significantly affected the mechanical performance, with thicker adhesives altering failure modes and reducing strength. Kostin [27] addressed discrepancies between the theoretical and experimental findings in composite aircraft structures, revealing that optimal strength was achieved when the adhesive layer thickness matched the size of the pre-fracture zone. Together, these findings highlight the nuanced relationship between adhesive characteristics and composite performance, providing a foundation for precision design in advanced applications.

In conclusion, the quantity of adhesive in composite structures is a crucial determinant of their mechanical performance and durability. Systematic analysis and the optimization of adhesive quantity are essential for enhancing the bonding strength and ensuring the material's reliability in various industrial applications. The findings of the studies reviewed above collectively highlight the complex interplay between the adhesive quantity, interface characteristics, and mechanical properties, providing a comprehensive understanding that can guide future research and industrial practices. By synthesizing these insights and understanding the distinctions in how the adhesive amounts affect different types of composites and laminates, we can develop more effective strategies for material design and application. This comprehensive approach allows us to better design and optimize composite materials for specific uses, ensuring their reliability and efficiency in real-world applications. This research fills a critical gap in understanding the relationship between the adhesive quantity and mechanical properties of fabric-reinforced laminates (FRLs) across various fabric areal densities. By systematically exploring these effects, the study provides valuable insights for optimizing FRL design, which has been underexplored in the context of achieving the best balance between adhesion quality and mechanical performance.

2. Experimental Procedure

2.1. Materials

The selected laminate design followed the traditional structural and material principles used in laminate materials for inflatable structures like airships, aerostats, inflatable antennas, and similar applications. This design is also effective for evaluating the adhesion strength between the fiber and film layers. The laminate's structure is depicted in Figure 1.

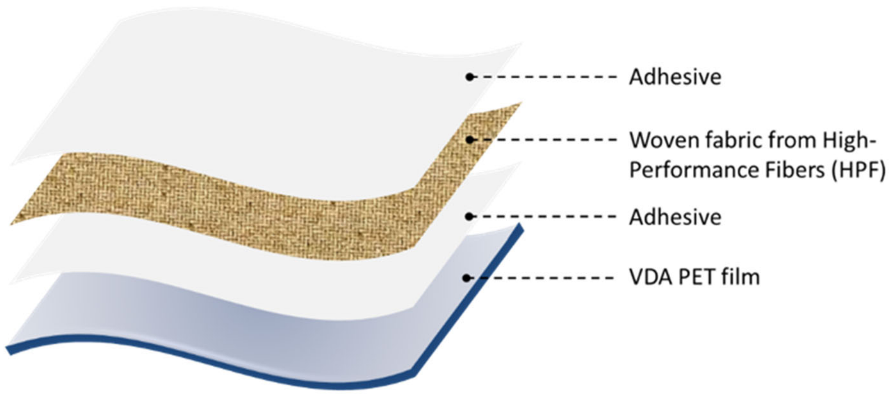


Figure 1. Laminate structure.

The laminate consists of a polyethylene terephthalate (PET) film with a vacuum-deposited aluminum (VDA) coating, known as Mylar (CS Hyde, Lake Villa, IL, USA), along with two adhesive layers that enclose the load-bearing layer. Mylar is a popular choice for producing FRLs due to its VDA coating, which significantly enhances the material's barrier properties, offering excellent protection against moisture, penetrating gases, and light transmission. For this study, woven fabrics made from Kevlar (CST, Tehachapi, CA, USA) (ACP Composites, Livermore, CA, USA) fibers were selected as the core strength-bearing and fiber-reinforcement elements. Kevlar fabrics were chosen for their high strength-to-weight ratio, which is critical in structural applications like FRLs. However, its chemical inertness and high crystallinity can pose challenges in processing and bonding. This study employed four plain woven Kevlar fabrics, each with distinct structural characteristics including variations in areal density, yarn linear density, and weave pattern. All fabrics had a square structure, so the fabric count was consistent in both the warp and weft directions. However, the other structural nuances significantly influenced the mechanical properties and adhesion behavior of the laminates, as summarized in Table 1, and are critical for interpreting the performance trends observed in the study.

Table 1. Overview of the specifications for the Kevlar plain woven fabrics.

No.	Fabric Areal Density (g/m^2)	Woven Fabric ID	Yarn Linear Density (tex, g/km)	Fabric Count (Ends/cm × Picks/cm)
1	36	KP36	21.5	8 × 8
2	60	KP60	21.5	13.5 × 13.5
3	140	KP140	150	5.3 × 5.3
4	170	KP170	127	6.5 × 6.5

In this study, thermoplastic polyurethane (TPU) was chosen as the adhesive because it is widely used in industry and works well with high-performance fibers like Kevlar. TPU's flexibility and ability to create strong bonds make it a good choice for fabric-reinforced laminates (FRLs), which need both strength and adaptability [8]. TPU contains urethane groups (-NHCOO-) that can form strong hydrogen bonds. These bonds interact with the amide groups (-CONH-) in Kevlar, which are highly polar and known for their strong bonding potential [8]. This interaction improves the adhesion at the fiber–adhesive interface, helping transfer stress effectively between the adhesive and Kevlar. The chemical compatibility between TPU and Kevlar supports the mechanical stability and durability of the laminate, especially under dynamic conditions.

To create three levels of adhesive quantity for each fabric, thermoplastic polyurethane (TPU) with three different thicknesses (0.015 mm, 0.025 mm, and 0.03 mm) was procured from KETAEBO, Suzhou, Jiangsu, China. These thicknesses were selected to represent the fiber-to-adhesive weight ratios of 1:0.5, 1:1, and 1:1.5, which span a practical range for evaluating the impact of adhesive quantity on laminate performance. These ratios were chosen to balance practical considerations in laminate manufacturing with the need to capture a range of bonding behaviors, from minimal adhesive application to higher-than-optimal usage.

The lamination process was carried out using a Pratix OK-12L Seamless Teflon Belt Drum Laminator. All components of the laminates were processed through a heated roller in a double pass, with a feeding speed of 0.32 m/min and a pressure of 413.685 kPa (60 psi). The temperature was maintained at 160 °C, following the TPU manufacturer's recommendations. A vacuum-deposited aluminum (VDA)-coated PET film was used as the polymeric layer, selected for its lightweight nature and excellent gas retention properties. The fiber-to-adhesive ratio was calculated based on the areal densities of the fiber and adhesive layers. For example, a laminate with a 1:0.5 ratio, such as 60_1:0.5, consisted of a fabric areal density of 60 g/m^2 and an adhesive areal density of 30 g/m^2, evenly distributed between the two adhesive layers at 15 g/m^2 each. These carefully selected ratios provide a framework for systematically studying how varying adhesive quantities influence the structural and mechanical properties of laminates.

To create the laminates with different fiber-to-adhesive ratios, we first converted the desired ratios into the corresponding adhesive thickness required by using the density provided by the manufacturer. We then selected from the three different thicknesses purchased, each with varying thicknesses. By layering combinations of these adhesives on top of one another, we were able to achieve the adhesive thickness close to what was needed for each ratio, since we only had those three thickness options. A summary of the calculations and the resulting adhesive thicknesses for each fiber-to-adhesive ratio can be seen in Table 2. There were twelve possible combinations of the four woven fabrics and the three fiber-to-adhesive ratios. However, due to the low and unavailable adhesive thickness of the 1:0.5 fiber-to-adhesive ratios for the 36 g/m^2 fabric, this sample was not able to be manufactured and tested. The laminate ID represents the fabric areal density followed by the fiber-to-adhesive weight ratios.

Table 2. Overview of the specifications for the plain-woven fabrics, adhesives, and corresponding Laminate IDs.

No.	Fiber-to-Adhesive Weight Ratio	Fabric Areal Density (g/m^2)	Adhesive Areal Density (g/m^2) *	Calculated Adhesive Thickness (mm)	Actual Adhesive Thickness (mm)	Laminate ID
-	1:0.5	36	9	0.008	-	-
1	1:1		18	0.015	0.015	36_1:1
2	1:1.5		27	0.023	0.025	36_1:1.5
3	1:0.5	60	15	0.013	0.015	60_1:0.5
4	1:1		30	0.025	0.025	60_1:1
5	1:1.5		45	0.038	0.040 (0.015 + 0.025)	60_1:1.5
6	1:0.5	140	35	0.029	0.030	140_1:0.5
7	1:1		70	0.058	0.060 (0.030 + 0.030)	140_1:1
8	1:1.5		105	0.088	0.090 (0.030 + 0.030 + 0.030)	140_1:1.5
9	1:0.5	170	42.5	0.035	0.040 (0.015 + 0.025)	170_1:0.5
10	1:1		85	0.071	0.070 (0.015 + 0.025 + 0.030)	170_1:1
11	1:1.5		127.5	0.106	0.105 (0.025 + 0.025 + 0.025 + 0.30)	170_1:1.5

* The fiber-to-adhesive ratio was calculated based on both adhesive layers in the laminate. The adhesive thickness values represent the thickness of each individual layer rather than the total combined thickness of both adhesive layers.

2.2. Testing Methods

T-peel test: The T-peel test was conducted to evaluate the interfacial adhesion properties of the fabric-reinforced laminates (FRLs). This test measures the force required to peel apart two bonded layers, providing insights into the adhesive strength of the laminates. The testing was performed in both the weft and warp fabric directions, with 10 replicates for each direction, following the ASTM D1867 standard [28]. The samples were prepared by separating the fabric and film layers, leaving each end free to facilitate the peeling process. During the test, the free ends were clamped in the grips of the testing machine, and a tensile force was applied to separate the bonded layers. The force–displacement data were recorded, and the average peel strength was calculated for each sample. This method helps assess the quality of adhesion at the interface between the adhesive and the reinforcement and potential weak points in the laminate structure.

Yarn pullout in laminate test: The newly developed yarn pullout [8] test assessed the adhesion strength, shear forces, and frictional forces within the fabric-reinforced laminate (FRL) by isolating and extracting a single yarn from the laminate under controlled conditions. To prepare for the test, the film backing was separated from the laminate by at least 50 mm. Ten strips, each 15 mm wide and aligned parallel to the yarn, were cut from the material. One yarn positioned near the center of these strips was selected, and the surrounding yarns in the same direction were removed. A small slit was made in the FRL to facilitate consistent detachment of the selected yarn. The slit was carefully positioned to enclose the selected yarn along with at least one adjacent yarn on either side, with precision ensured using a magnifying glass. Tabs were then attached to the ends of the sample using an adhesive that did not cover the slit, ensuring that the sample was securely gripped by the testing machine's jaws without obstruction. The test was conducted at a speed of 0.212 mm/s (0.5 inch/min) and performed in both the weft and warp fabric directions, with 10 replicates for each direction. This setup allowed for a thorough evaluation of the fiber–matrix bond and the yarn pullout behavior of various adhesive polymers.

Tear test: The tear test evaluated the material's resistance to tearing or the propagation of pre-existing flaws or defects. This test provided indirect information about adhesion, especially when the tear propagates along an interface influenced by adhesive properties. The tightness theory suggests that tighter textiles have a lower tear strength due to individual yarn breakage, while looser fabrics exhibit a higher tear strength as multiple yarns break simultaneously. This theory extends to laminates, where high adhesion causes individual yarn breakage, while weak adhesion leads to delamination and collective yarn failure. The central cut-slit tear testing method, as described in MIL-C-21189 [29], was employed to evaluate the tear resistance, with each sample tested five times in each fabric direction on an MTS Landmark servo hydraulic 250 kN testing machine.

Tensile test: Tensile strength is a critical property for FRLs, influencing their ability to withstand various loads. The tensile strength of the laminate samples was measured according to ASTM standard D5035 [30], with a focus on understanding the effects of weave design on the mechanical characteristics. This test can reveal failure modes such as maximum load, delamination, or adhesive failure, offering insights into potential areas for reinforcement. Each combination of fabric and adhesive was tested five times in the warp direction and eight times in the weft direction according to the standard on an MTS Landmark servo hydraulic 250 kN testing machine. Statistical analyses were performed using JMP Pro 17 software (v17.2, JMP Statistical Discovery LLC, Cary, NC, USA). Analysis of variance (ANOVA) was employed to determine the significance of the effects of fiber-to-adhesive ratios on the T-peel, yarn pullout in laminate, tear, and tensile tests.

3. Results and Discussions

3.1. T-Peel Test

The T-peel test, designed to measure the interfacial adhesion properties of the fabric-reinforced laminates (FRLs), unfortunately did not yield any results due to technical difficulties encountered during testing. During the testing process, it was observed that the film backing of the FRLs repeatedly tore rather than peeling cleanly from the laminate, as shown in Figure 2. This tearing issue was significant in most of the samples, which was enough to compromise the integrity of the test and prevented a reliable assessment of the adhesive properties.

As a result of these difficulties, no meaningful data on peel strength could be obtained using the T-peel test. The T-peel test, which traditionally measures the force required to peel two bonded layers apart, can be particularly challenging when dealing with laminates that involve complex fiber-reinforced structures. In these cases, issues such as uneven adhesive distribution, fiber distortion, or weak bonding interfaces can lead to inconsistent results. Additionally, the variability in fiber orientation and adhesive thickness within the laminate can introduce further complications, making it difficult to generate reliable and repeatable data from T-peel tests [8]. Given these complications, the yarn pullout in laminate test emerged as a potentially more effective alternative, especially in scenarios like those described. The yarn pullout test focuses on the behavior of individual yarns as they are pulled from the laminate. This method not only reduces the variability associated with the entire bonded area, as seen in the T-peel tests, but also isolates the interaction between the yarn and the adhesive matrix. By evaluating the pullout force required to remove individual yarns, the test offers a more direct measure of the adhesive's performance at a microstructural level.

Figure 2. Film layer tearing during the T-peel test, affecting the adhesive strength measurement [7].

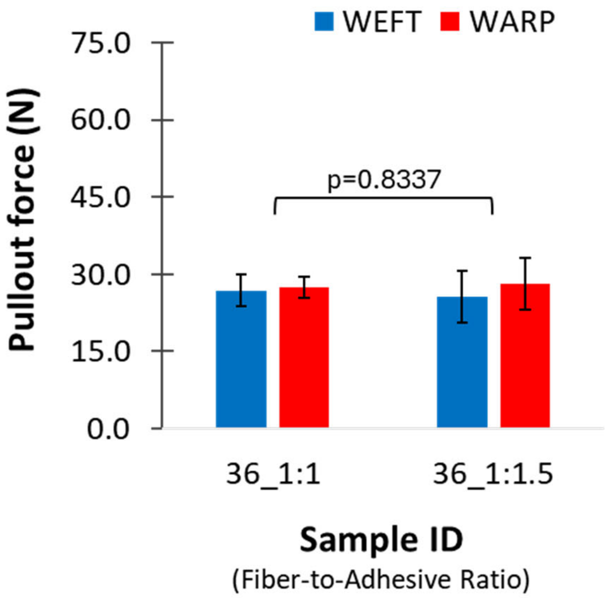
Moreover, our previous research has shown a strong correlation between the T-peel and yarn pullout forces, meaning that the pullout test can serve as a good proxy for evaluating peel strength [8]. The pullout test's ability to capture localized adhesive failures and yarn–adhesive interactions provides insights into the overall bonding performance of the laminate. In essence, while the T-peel test measures the adhesive performance on a macro level, the yarn pullout test provides detailed information on the adhesive effectiveness in smaller regions, often leading to more consistent and meaningful data in challenging laminate structures. Thus, in situations where the T-peel test fails to deliver reliable data, the yarn pullout test offers a robust and informative alternative.

The ANOVA results indicate that there was no statistically significant difference in the properties (yarn pullout force, tear strength, and tensile strength) between the warp and weft directions across all of the fabric samples tested. This consistency is most likely due to the structural characteristics of the Kevlar fabrics used in the study, which were square fabrics with equal yarn density in both the warp and weft directions, minimizing any directional variability in the results.

3.2. Yarn Pullout in Laminate Test

The yarn pullout test results provided valuable insights into the performance of various fabric areal densities (36 g/m^2, 60 g/m^2, 140 g/m^2, and 170 g/m^2) under different fiber-to-adhesive weight ratios (1:0.5, 1:1, and 1:1.5) in both the weft and warp directions. These findings help us understand the adhesive qualities and performance characteristics of these materials. The data for the yarn pullout test across all 11 samples are depicted in Figure 3a–d. For the fabrics with lower areal densities (36 g/m^2 and 60 g/m^2), there was no significant difference in pullout resistance with increasing adhesive amounts. This suggests that a 1:0.5 adhesive ratio provides sufficient bonding, and that additional adhesive does not enhance the yarn pullout resistance. It is important to note that after a certain adhesive quantity, there is no increase in adhesion quality—rather, only the cohesive layer within the adhesive itself increases. If this cohesive layer is weaker than the adhesive forces at the fiber interface, it can actually lower the overall adhesion quality. This highlights the delicate balance between adhesion and cohesion, where excess adhesive does not necessarily enhance the bond strength and may even introduce weaknesses.

(**a**)



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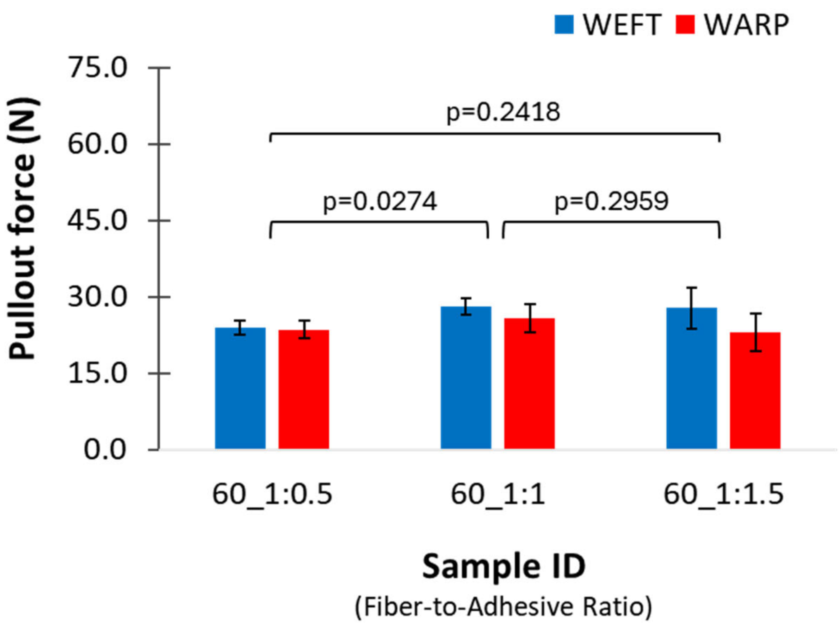

Figure 3. *Cont.*

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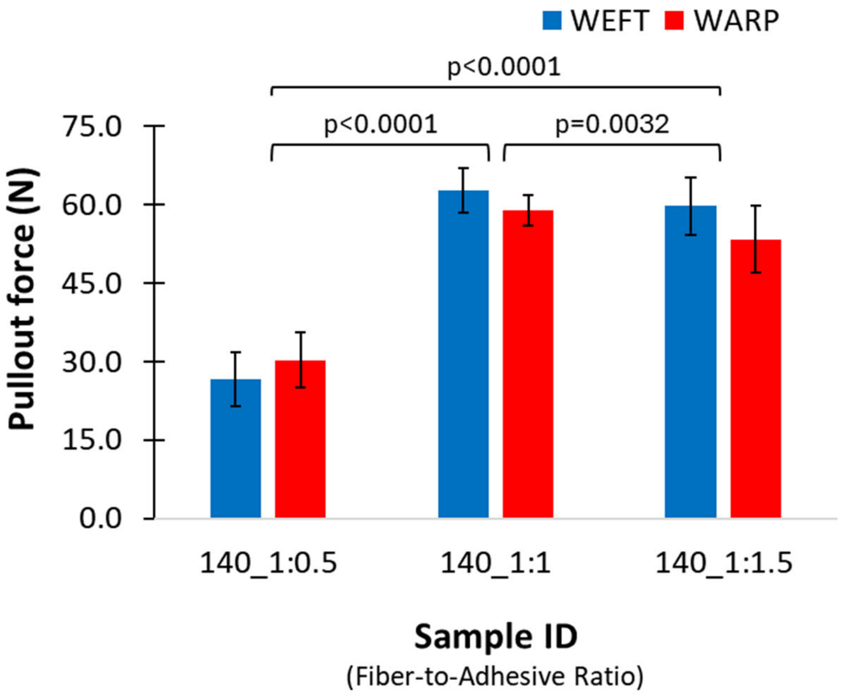

(d)

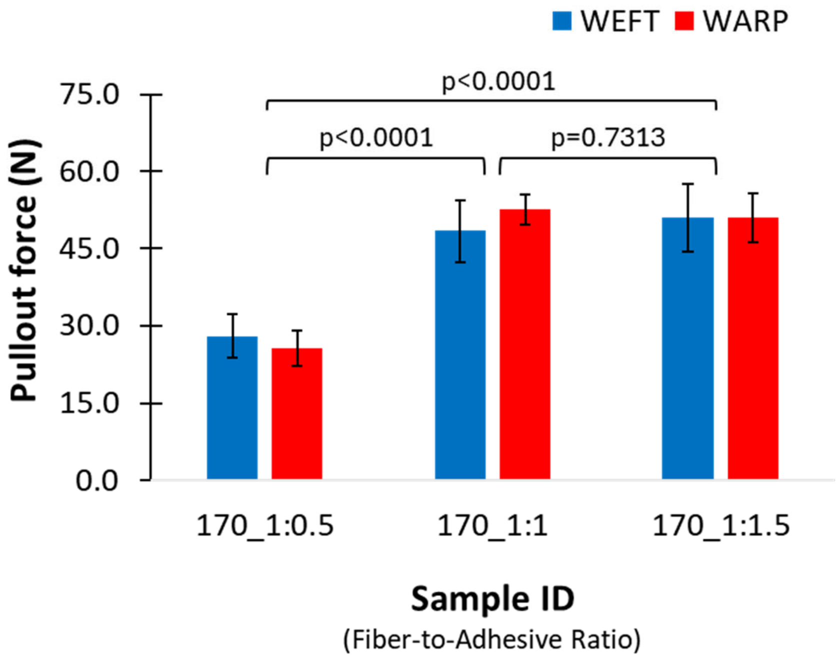

Figure 3. Yarn pullout in laminate test results in warp and weft directions for various fabric areal densities: (**a**) 36 g/m^2 (**b**) 60 g/m^2 (**c**) 140 g/m^2, and (**d**) 170 g/m^2.

Conversely, the fabrics with higher areal densities (140 g/m^2 and 170 g/m^2) showed a notable increase in pullout resistance as the adhesive amount increased from 1:0.5 to 1:1. This improvement indicates that these denser fabrics benefit from a higher adhesive quantity, which contributed to better interfacial bonding. However, further increasing the adhesive ratio to 1:1.5 did not improve the adhesion quality; in fact, it slightly reduced the yarn pullout resistance for the 140 g/m^2 samples. This decline may be due to excessive adhesive causing structural compromises with the increased cohesive layer, demonstrating that an optimal adhesive quantity exists beyond which performance may deteriorate.

Overall, the weft direction tended to exhibit slightly higher pullout forces compared to the warp direction, although this difference was not statistically significant. These results underline the complex interplay between adhesive quantity and material performance, highlighting the importance of optimizing adhesive application to achieve the best adhesion quality assessed by the yarn pullout resistance. Based on our observations, a 1:1 adhesive ratio is recommended for the samples that were tested in this study, as it performed adequately across all fabric samples.

Microscopic analysis of the laminated samples confirmed that after a certain threshold of adhesive application, the excess adhesive primarily contributed to increasing the layer of cohesion rather than enhancing the adhesion within the system. As illustrated in Figure 4a–f, showcasing the varying adhesive thicknesses, an optimal adhesive thickness is crucial for effective bonding between the laminate layers. Beyond this optimal amount, additional adhesive does not further improve interfacial adhesion; instead, it forms a thicker cohesive layer that may even hinder effective adhesion. This phenomenon highlights the importance of achieving a balanced adhesive application, where excess adhesive can lead to diminishing returns in adhesion performance.

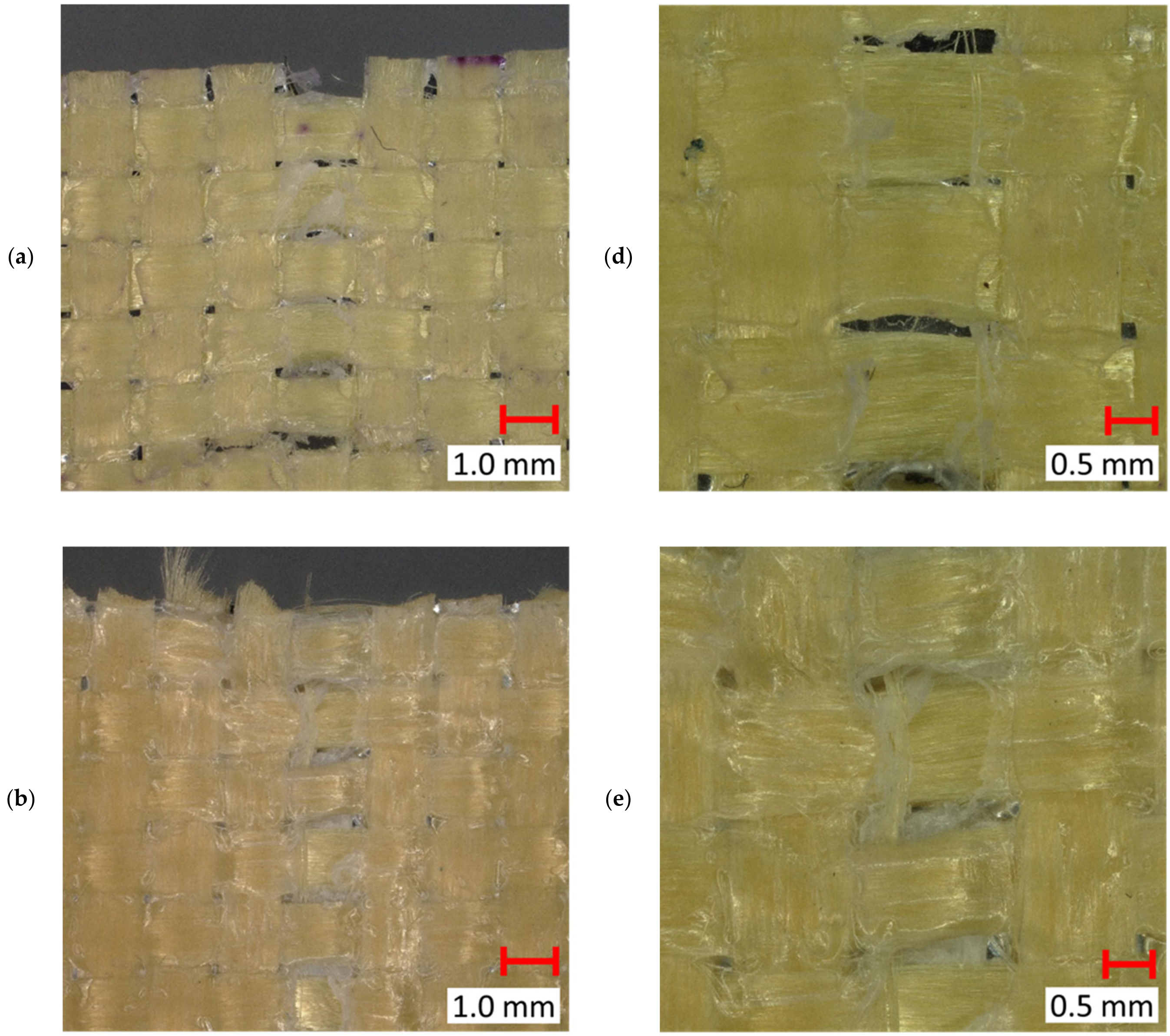

Figure 4. *Cont.*

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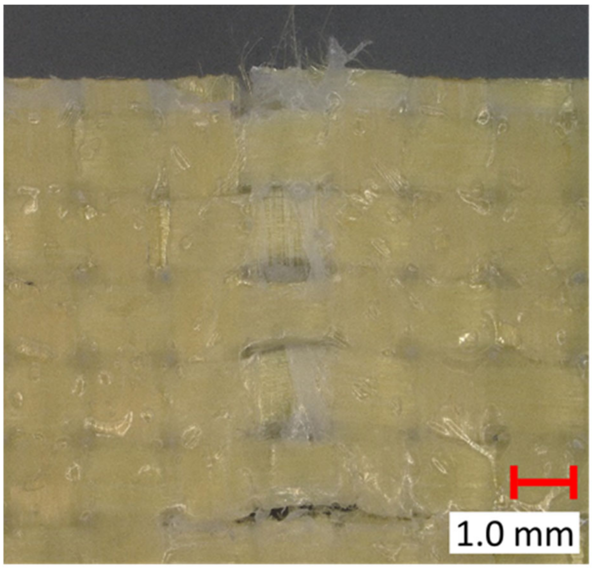

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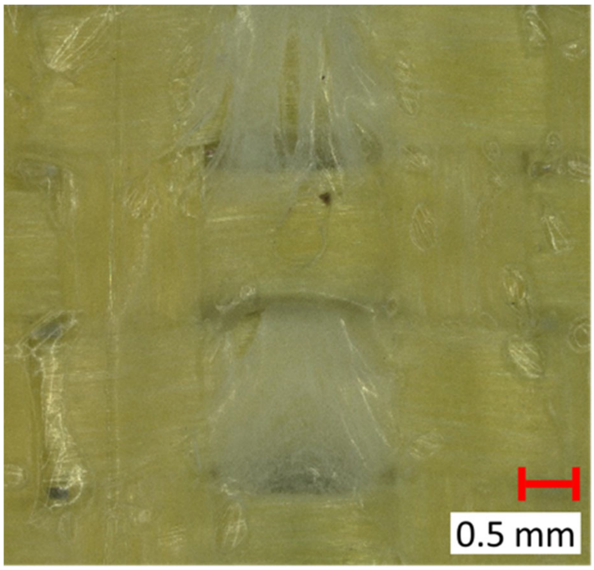


Figure 4. Microscopic images of 170 g/m^2 FRLs post yarn pullout test in (×20): (**a**) 1:0.5, (**b**) 1:1, (**c**) 1:1.5 and in (×40): (**d**) 1:0.5, (**e**) 1:1, and (**f**) 1:1.5.

3.3. Tear Test

The tear test results offer a comprehensive examination of how varying adhesive amounts influence the mechanical properties of flexible laminates. This evaluation spans different fabric areal densities and examines performance in both the weft and warp directions. The results reaffirm the complex interplay between adhesive quantity and the structural integrity of the laminates, with significant implications for their practical applications. In the lower areal density fabrics, such as those with 36 g/m^2 and 60 g/m^2, the amount of adhesive did not significantly alter the tear force, as shown in Figure 5a–d. Specifically, laminates with fiber-to-adhesive ratios of 1:0.5, 1:1, and 1:1.5 exhibited comparable tear strengths. This suggests that in these lower density fabrics, the adhesive amount in the 1:0.5 ratio is sufficient to maintain structural integrity, with additional adhesive not contributing meaningfully to enhancing the tear resistance.

Conversely, in higher areal density fabrics (140 g/m^2 and 170 g/m^2), the effect of adhesive quantity was more pronounced. For these fabrics, as the adhesive ratio increased from 1:0.5 to 1:1, there was a noticeable decrease in the tear forces. This trend became more apparent when the adhesive ratio was further increased to 1:1.5. At this higher adhesive amount, the tear force continued to decline, albeit slightly. This decline suggests that excessive adhesive may negatively impact the tear strength, potentially due to increased brittleness or other structural factors that prevent the laminate from effectively distributing stress during tearing. The differences between the 1:0.5, 1:1, and 1:1.5 adhesive ratios in higher density fabrics highlight the delicate balance required to optimize the adhesive quantities. While a higher amount of adhesive can improve adhesion quality, it can simultaneously reduce the laminate's overall tear resistance. This is because the additional adhesive can cause the fibers to be held more rigidly in place, leading to yarns breaking individually rather than collectively, which in turn reduces the tear force. Moreover, comparing the tear strength in the weft and warp directions across all fabric densities and adhesive ratios revealed a general trend: the weft direction tended to exhibit slightly higher tear forces compared to the warp direction. However, these differences were not significant enough to necessitate different adhesive quantities for each direction. This finding suggests a relatively uniform response of the laminate to tearing forces, regardless of the direction, under the tested conditions.

(**a**)

(**b**)

(**c**)

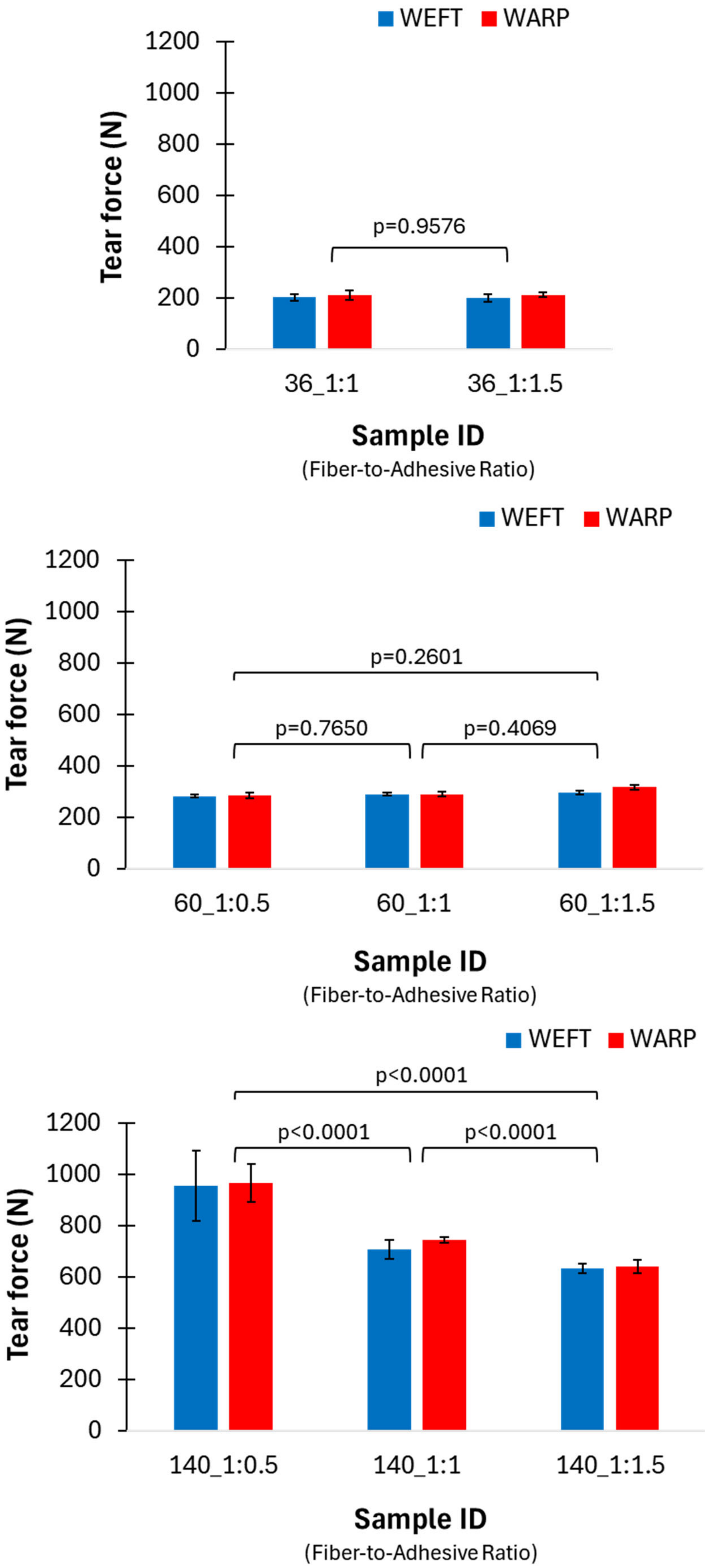


Figure 5. *Cont.*

(**d**)

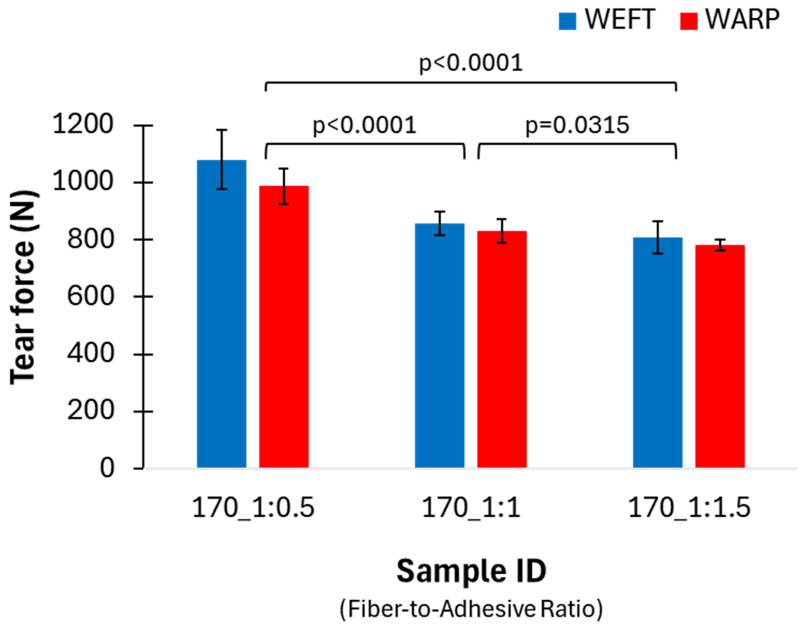


Figure 5. Tear test results in the warp and weft directions for various fabric areal densities: (**a**) 36 g/m^2 (**b**) 60 g/m^2 (**c**) 140 g/m^2, and (**d**) 170 g/m^2.

Overall, the tear test results emphasize the necessity of carefully balancing the adhesive quantities in the design of flexible FRLs. The observed trend—that increasing the adhesive amounts beyond a certain point leads to diminished tear resistance—suggests that an optimal adhesive quantity exists for each fabric type and density. For the materials tested, a 1:1 fiber-to-adhesive ratio appeared to provide the best compromise between maintaining adequate adhesion and preserving tear strength. This ratio effectively balances the need for sufficient adhesion to prevent delamination and the flexibility required to distribute stress without compromising structural integrity.

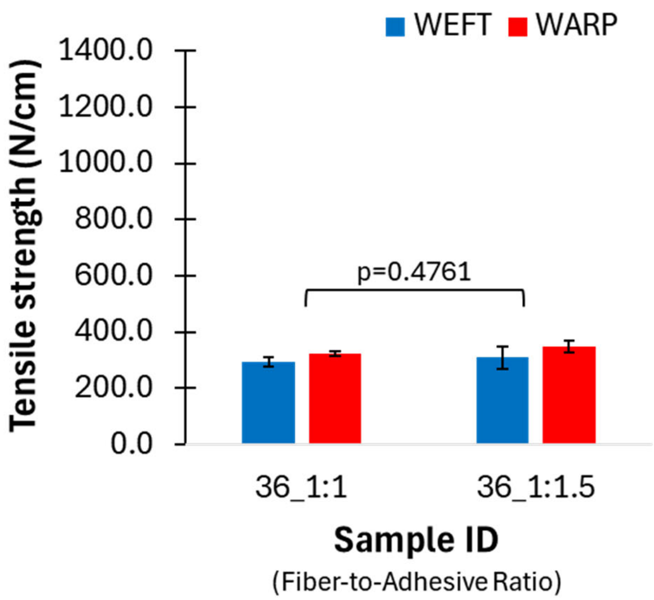
3.4. Tensile Test

In this study, the variation in adhesive quantity did not significantly influence the tensile strength of the fabric-reinforced laminates (FRLs), as illustrated in Figure 6a–d. This finding suggests that the tensile properties of the laminates are primarily governed by the inherent mechanical characteristics of the Kevlar fibers rather than the adhesive layer. Kevlar's high strength and stiffness, even under high loads, likely dominate the overall tensile performance, with the adhesive playing a supporting role by maintaining interlayer bonding. This hypothesis aligns with previous studies such as those by Singh et al. [2], which emphasized the dominant role of fiber properties in determining the tensile strength of composites. Additionally, the literature on the load distribution mechanisms in Kevlar-reinforced composites indicates that stress is primarily borne by the fibers, with the adhesive mainly functioning to transfer loads between layers and prevent delamination.

The consistent tensile strength across varying adhesive quantities for all tested fabric areal densities further supports this hypothesis. For higher areal density fabrics, the robust structural integrity provided by the densely packed Kevlar fibers likely overshadows any potential variations in adhesive quantity. This phenomenon indicates that, beyond a certain threshold, the tensile properties of the fabric dominate, rendering the adhesive's influence on tensile performance negligible. In contrast, studies on other polymer-based composites have reported significant adhesive effects on tensile properties, highlighting the unique characteristics of Kevlar-reinforced laminates where fiber properties overshadow adhesive contributions.

While this study provides valuable insights into the effects of adhesive quantity on mechanical performance, it does not include detailed structural or morphological analysis of the samples. Advanced characterization techniques such as SEM or TEM could provide direct evidence of adhesive distribution, fiber–adhesive interactions, and potential defects, which would further elucidate the observed trends. Such analyses could also reveal the stress distribution patterns between the adhesive and fibers during tensile testing, offering a deeper understanding of the load transfer mechanisms. Future research incorporating these methods will be crucial to validate and expand upon the findings presented here.

(a)



(b)

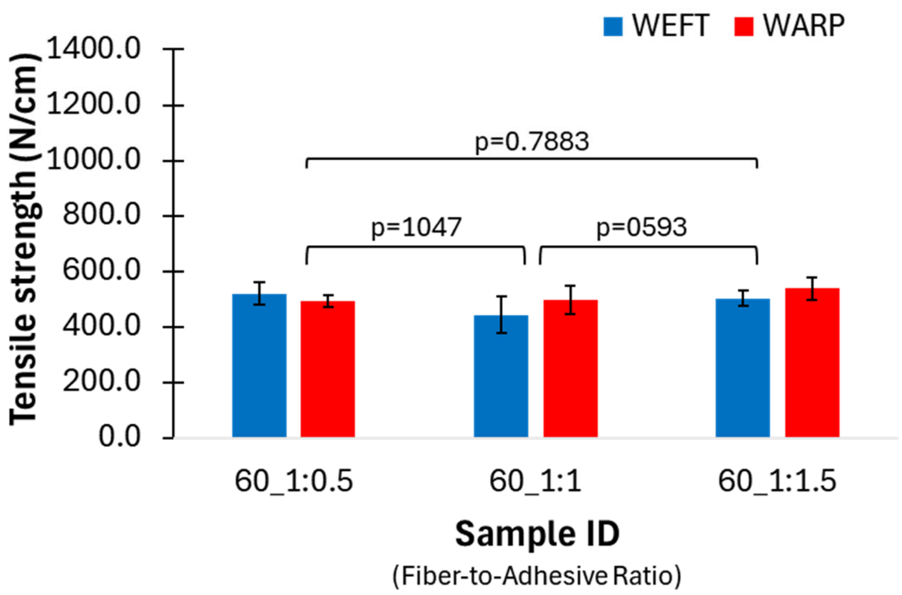
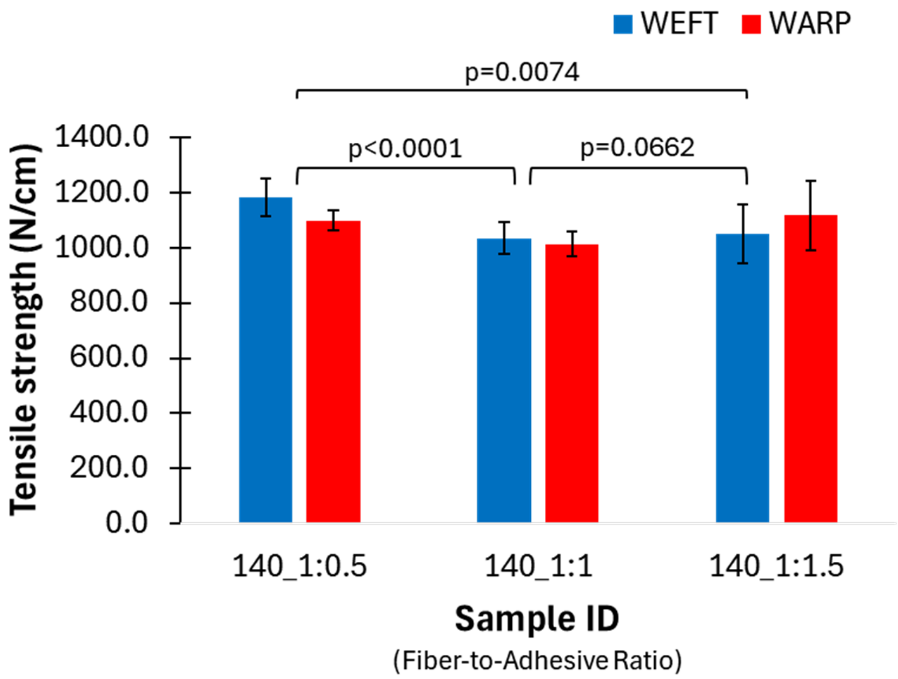


Figure 6. *Cont.*

(**c**)



(**d**)

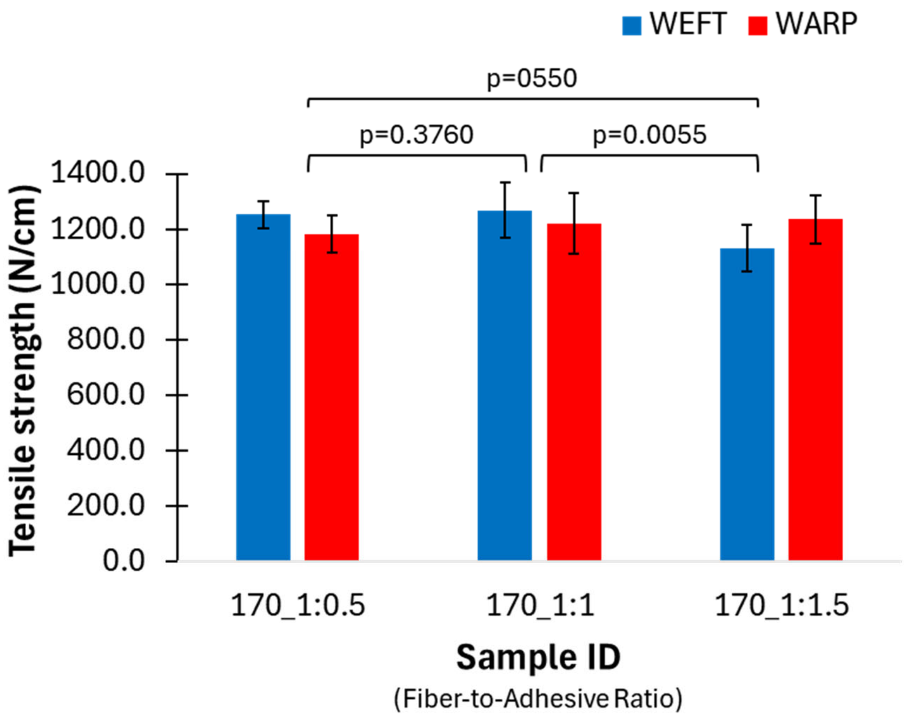


Figure 6. Tensile test results in the warp and weft directions for various fabric areal densities: (**a**) 36 g/m^2, (**b**) 60 g/m^2, (**c**) 140 g/m^2, and (**d**) 140 g/m^2.

4. Conclusions

This study comprehensively examined the effects of adhesive quantity on the mechanical properties of fabric-reinforced laminates (FRLs) with varying fabric areal densities through the yarn pullout, tear, and tensile strength tests. The findings revealed that the adhesive quantity plays a nuanced role in the mechanical behavior of FRLs, with its impact varying based on fabric areal density. For lower areal density fabrics (36 g/m^2 and 60 g/m^2), adhesive quantity had a minimal influence on pullout and tear strength, indicating that even the minimal adhesive application (1:0.5 ratio) could maintain adhesion quality and mechanical integrity. In contrast, higher areal density fabrics (140 g/m^2 and 170 g/m^2)

showed a more pronounced response to adhesive variations. Specifically, increasing the adhesive ratio from 1:0.5 to 1:1 improved the pullout resistance, while further increasing it to 1:1.5 yielded diminishing returns, and in some cases, slightly reduced the adhesive effectiveness. These results underscore the importance of balancing the adhesive quantity to optimize performance while avoiding drawbacks such as increased brittleness.

Under the conditions tested in this study, a 1:1 fiber-to-adhesive ratio emerged as the optimal ratio for achieving balanced mechanical performance across all fabric areal densities. For lower areal density fabrics (36 g/m^2 and 60 g/m^2), 1:1 provided sufficient adhesion without unnecessary adhesive application, ensuring effective interlayer bonding without compromising flexibility. For higher-density fabrics (140 g/m^2 and 170 g/m^2), the 1:1 ratio delivered the optimal pullout resistance and tear strength while avoiding issues such as the adhesive brittleness seen at higher ratios like 1:1.5. However, "optimal" in this context refers specifically to achieving a satisfactory compromise between adhesion quality, structural integrity, and material efficiency, based on the adhesive (TPU) and experimental parameters used in this study.

Tensile strength, however, was largely unaffected by variations in the adhesive quantity across all fabric types, suggesting that it is primarily governed by the intrinsic characteristics of the Kevlar fibers and fabric structure rather than the adhesive layer. This observation aligns with the existing literature on Kevlar composites, where fibers dominate the tensile properties under high loads, and the adhesive primarily supports interlayer bonding. These results emphasize the importance of tailoring adhesive applications to the specific mechanical demands of FRLs, with the adhesive quantity being more critical for adhesion-related properties than for tensile strength.

These findings provide guidance for the design and fabrication of FRLs in applications requiring both environmental sustainability and mechanical robustness such as aerospace, protective materials, and advanced inflatable structures. Future research should explore different adhesive chemistries as well as focus on advanced characterization techniques, such as SEM and TEM, to provide quantitative insights into the adhesive distribution and fiber–adhesive interactions at the microstructural level. Additionally, evaluating the performance of FRLs under impact loads, fatigue cycles, and long-term environmental exposure will further refine the understanding of adhesive–fiber dynamics and enhance the applicability of these materials in demanding operational conditions.

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