ARTICLE

Evaluation of High Performance Textiles: Modulus Reporting, Low-Strain Characteristics, and Maximum Tensile Capacity

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Abstract

Determination of the tensile characteristics of high-performance woven and knitted textiles, including geotextiles and geogrids, commonly utilizes roller grip-type clamping systems. These grips are engineered to enable tensile loading without imposing excessive compressive or crimping forces on the sample, thereby preventing premature failure. Roller grips, also referred to as capstan grips, offer the additional benefit of allowing the specimen to align itself with the applied load, ensuring uniform force distribution across the width. However, as the specimen tightens around the grip during testing, crosshead travel cannot be reliably used to measure strain, complicating the assessment of low strain characteristics and the selection of modulus values. Two critical challenges in measuring low strain properties are determining how to accurately measure strain and establishing a consistent and repeatable starting point for the test. This study investigates alternative gripping systems, strain measurement techniques, and data analysis approaches aimed at accurately capturing and reporting low strain properties of high-performance woven and knitted textiles.

Keywords: low-strain characteristics, tensile characteristics, knitted textiles, geotextiles, geogrids

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1 Introduction

The evaluation of high-performance composite materials, such as those used in advanced engineering applications like aerospace, automotive, and civil infrastructure, requires meticulous testing to understand their mechanical behavior [1, 2]. Composite materials, by nature, are complex systems made up of two or more constituent materials with different physical or chemical properties. When combined, these materials create a composite with superior mechanical performance, but they also introduce new challenges for testing, particularly in tensile strength, stress response, load-bearing capacity, and low-strain behavior [3]. Proper testing of these materials is essential for ensuring their suitability in high-stress environments where performance and safety are critical [4].

One of the primary challenges in testing high-performance composite materials is accurately capturing their response to applied loads, particularly in the initial phase where low-stress or low-strain properties are critical for long-term durability assessments [5]. The mechanical response of composites is largely influenced by their internal structure, including the orientation of fibers, matrix composition, and bonding quality between layers [6]. These factors complicate the testing process, as even slight variations in the material's architecture can lead to significant differences in performance, especially under complex loading conditions [7]. To accurately assess these materials' performance, it is crucial to use appropriate testing protocols that account for their

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unique mechanical characteristics [8].

Historically, tensile testing methods for high-strength fabrics, such as geotextiles, have served as a foundation for evaluating composite materials [9]. These tests are designed to measure the fabric's ability to resist forces that attempt to pull it apart, providing insight into its ultimate tensile strength, elasticity, and failure points. However, while these methods work well for certain textile applications, they often fall short when applied to composite materials due to the inherent differences in structure and load-bearing mechanisms [10]. For example, geotextiles exhibit relatively uniform tensile properties across their surface, whereas composites display anisotropic behavior, meaning their mechanical properties differ based on the direction of applied loads [11]. This anisotropy complicates the interpretation of test results, as the measured response may not represent the material's behavior in real-world applications [12].

In addition to anisotropy, the testing of composite materials is further complicated by the presence of matrix-dominated behavior [13]. Unlike traditional textile materials where individual fibers primarily bear the load, composite materials rely on both fibers and the matrix (the material that binds the fibers together) to distribute stress. The interaction between the fibers and the matrix plays a crucial role in determining the overall strength and stiffness of the composite [14]. Therefore, testing methods must account for this interaction to ensure that the results accurately reflect the material's true load-bearing capacity. Failure to do so can lead to an underestimation of the material's performance, potentially compromising the safety and reliability of the final product [15].

One critical aspect of testing composite materials is the accurate measurement of low-stress properties. These properties are essential for understanding the material's behavior under operational loads, where small deformations over time can lead to cumulative damage, such as creep or fatigue. Low-stress properties are particularly important in aerospace and automotive applications, where materials are subjected to repeated cyclic loading over extended periods. Failure to accurately assess these properties can result in unexpected material failure, leading to catastrophic consequences in critical systems. Traditional tensile testing methods often struggle to capture these low-strain behaviors due to the limitations of the clamping systems used and the difficulty in eliminating slack from the sample [17].

In typical tensile testing, the specimen is clamped at both ends and subjected to a controlled pulling force. However, if the clamping system is not properly aligned or if the specimen contains slack (i.e., is not taut), the test results may be skewed. Slack in the specimen can be mistaken for material elongation, artificially inflating the strain values and complicating the interpretation of the material's low-stress response. To mitigate this issue, preloads are often applied to the specimen before the test begins. A preload is a small force applied to the sample to remove any slack, ensuring that the test starts with the specimen in a tensioned state. While this approach helps ensure reproducibility, it also masks the material's initial deformation behavior, making it difficult to accurately measure low-strain properties [18].

Another common issue with traditional tensile testing is the choice of clamping systems. Roller grip-type clamping systems, which are frequently used for geotextile testing, are designed to hold the specimen securely while allowing it to align itself with the applied force. This self-alignment ensures that the load is distributed uniformly across the specimen's width, preventing premature failure due to localized stress concentrations. However, as the specimen tightens around the rollers during testing, the total crosshead movement (the distance the grips move during the test) includes both the specimen's elongation and the tightening around the grips. This combined movement makes it difficult to accurately measure the true strain in the specimen, particularly at low-stress levels where the material's behavior is most critical [19].

In the context of composite materials, these limitations are even more pronounced. Composite materials exhibit a wide range of mechanical behaviors depending on their composition, fiber orientation, and matrix properties. For example, in fiber-reinforced polymer composites, the fibers typically carry the majority of the applied load, while the matrix provides support and distributes stress between the fibers. At low-stress levels, the matrix plays a more significant role in determining the material's response, particularly in the early stages of deformation. Accurate measurement of this response is crucial for understanding how the composite will behave under long-term loading conditions, where matrix-dominated behavior can lead to issues such as creep, micro-cracking, and delamination [20].

Given these challenges, alternative testing methods are needed to accurately assess the low-stress properties and load-bearing capacity of high-performance composite materials. One promising approach is the use of wedge grips in combination with advanced strain measurement techniques, such as laser extensometry. Wedge grips provide a more rigid clamping mechanism, ensuring that the specimen is securely held without introducing slack or additional tension during the test. This rigid clamping allows for more accurate strain measurements, particularly at low levels of deformation where traditional clamping systems may introduce errors. Furthermore, the use of laser extensometry allows for non-contact strain measurement, eliminating the need for physical markers that can alter the specimen's behavior during testing.

Laser extensometers track the movement of reflective markers placed on the surface of the specimen, providing precise measurements of the material's elongation without the need for physical contact. This method is particularly advantageous for testing composite materials, as it allows for continuous monitoring of strain across different regions of the specimen. By using wedge grips and laser extensometry in tandem, it is possible to obtain accurate and repeatable measurements of low-strain properties, providing valuable insights into the material's long-term durability and performance under real-world conditions.

2 Materials

The choice of materials plays a critical role in determining the mechanical behavior and performance of high-performance composites, particularly under tensile testing conditions. Composite materials are highly engineered structures, typically consisting of two primary components: a reinforcing material, often in the form of fibers, and a matrix that binds these fibers together. The interaction between these components, along with their specific arrangement, dictates the material's overall strength, stiffness, and durability. For the purpose of this study, various composite configurations were selected to evaluate how different material compositions and structures respond to tensile stress, low-strain conditions, and shear forces.

In this study, we evaluated two broad categories of composite materials: fiber-reinforced polymers (FRPs) and woven composite laminates. Each of these categories represents a class of materials widely used in industries such as aerospace, automotive, and civil engineering due to their high strength-to-weight ratios, exceptional stiffness, and tailored performance characteristics. The specific materials selected for this study included unidirectional carbon fiber composites, woven glass fiber composites, and hybrid laminates composed of both carbon and glass fibers. These materials were chosen for their ability to demonstrate diverse mechanical behaviors under varying stress conditions, allowing for a comprehensive analysis of both low-strain properties and ultimate load-bearing capacities.

2.1 Fiber-Reinforced Polymers (FRPs)

Fiber-reinforced polymers (FRPs) are composite materials in which the load-bearing component is a fiber reinforcement embedded within a polymer matrix. The polymer matrix binds the fibers together, providing structural support and enabling load transfer between fibers. FRPs are known for their high tensile strength, stiffness, and resistance to environmental degradation, making them ideal for high-performance applications. In this study, carbon fiber-reinforced polymers (CFRPs) were selected as a representative material due to their widespread use in demanding engineering applications, particularly in aerospace structures where minimizing weight while maximizing strength is essential.

CFRPs consist of high-strength carbon fibers embedded within an epoxy resin matrix. The fibers provide the primary reinforcement, while the epoxy matrix distributes stress and protects the fibers from damage. One of the key advantages of CFRPs is their anisotropic nature, which allows for the tailoring of mechanical properties based on fiber orientation. In unidirectional CFRPs, fibers are aligned in a single direction, offering high tensile strength and stiffness along the fiber axis but relatively lower properties in the transverse direction. This makes them ideal for applications where loading occurs predominantly in one direction, such as aircraft wings or high-performance racing components.

For this study, unidirectional CFRP samples were prepared with fiber orientations of 0°, ±45°, and 90° to assess how fiber alignment influences tensile properties and low-strain behavior. These samples were subjected to tensile testing to determine their load-bearing capacity and strain response, particularly at low stress levels where the matrix-dominated behavior is most apparent.

2.2 Woven Fiber Composites

In addition to unidirectional composites, woven fiber-reinforced composites were also included in the study to evaluate the effect of fiber architecture on mechanical performance. Woven composites differ from unidirectional composites in that the fibers are interlaced in a fabric-like pattern, creating a more isotropic material with similar properties in multiple directions. This woven architecture provides enhanced resistance to impact and delamination, making woven composites ideal for applications requiring durability and damage tolerance, such as automotive body panels and protective structures.

For this study, glass fiber-reinforced polymers (GFRPs) were selected as a representative woven composite material. GFRPs are commonly used in industrial and commercial applications due to their lower cost compared to CFRPs, while still offering good mechanical properties and resistance to corrosion. The glass fibers provide strength and stiffness, while the polymer matrix, typically an epoxy or polyester resin, distributes loads and provides environmental protection. Woven GFRP samples were prepared with a balanced weave pattern to assess how the interlaced fiber architecture influences tensile strength, low-strain properties, and load distribution.

Woven composites are particularly interesting in tensile testing because their mechanical behavior is influenced by both the fiber-matrix interaction and the crimping of fibers as they pass over and under each other in the weave. This crimping introduces additional complexities in the material's response to tensile loads, as the fibers must straighten before they fully bear the load. This behavior is most evident at low-strain levels, where the matrix dominates the material's response, and the fibers are not yet fully engaged. Understanding how woven composites perform under these conditions is critical for predicting long-term behavior, especially in applications where cyclic loading or creep may occur.

2.3 Hybrid Laminates

To further explore the effects of combining different fiber types, hybrid laminates composed of alternating layers of carbon and glass fibers were included in the study. Hybrid composites offer the potential to combine the desirable properties of different fibers, such as the high stiffness and strength of carbon fibers with the impact resistance and toughness of glass fibers. By alternating layers of these materials, hybrid laminates can achieve a balance of performance characteristics that may be difficult to achieve with a single material system.

For this study, hybrid laminates with a [0°/90°] fiber orientation were fabricated, with alternating layers of carbon and glass fibers. These laminates were designed to assess how the combination of high-strength carbon fibers and more ductile glass fibers affects tensile properties, particularly at low-strain levels where matrix behavior and fiber interaction dominate. The hybrid samples were tested to determine how the interaction between different fiber types influences the material's overall load-bearing capacity, failure mechanisms, and ability to withstand cyclic loading.

2.4 Testing Parameters and Preparation

For each material type, samples were prepared in accordance with standardized testing procedures to ensure consistency across all tests. Specimens were cut to standardized dimensions with a gauge length of 500 mm and a width of 50 mm. The thickness of each sample was measured to ensure uniformity, as variations in thickness can significantly affect tensile properties. In addition, the samples were conditioned at room temperature to ensure that environmental factors, such as humidity and temperature, did not influence the test results.

All tests were conducted using both roller and wedge grip systems to compare how different clamping mechanisms influence the accuracy of tensile measurements, particularly at low-strain levels. The samples were loaded at a constant strain rate of 10 mm/min, and strain measurements were recorded using both mechanical extensometers and laser-based optical extensometers. These strain measurement systems provided high-precision data on the material's deformation, allowing for a detailed analysis of low-strain behavior, matrix-dominated response, and ultimate tensile strength.

By evaluating the tensile properties of these diverse composite material systems, this study aims to provide insights into how material structure, fiber orientation, and fiber-matrix interactions influence mechanical performance, particularly under low-strain conditions where accurate data is critical for predicting long-term behavior and material durability.

3 Sample Preparation and Testing Parameters

The proper preparation of samples and the careful selection of testing parameters are essential for obtaining accurate and repeatable results when evaluating the mechanical properties of high-performance composite materials. In this study, standardized sample preparation methods were employed to ensure uniformity across all tests, while testing parameters were carefully chosen to capture the materials' behavior under tensile stress, particularly at low-strain levels where matrix-dominated behavior and fiber-matrix interactions are critical.

3.1 Sample Dimensions and Geometry

All composite materials were cut into standardized specimens to ensure consistency throughout the testing process. The geometry of each sample was designed according to the ASTM D3039/D3039M standard for tensile testing of polymer matrix composite materials. This standard ensures that the specimen dimensions are appropriate for capturing the full mechanical behavior of the material without introducing unwanted variability from the sample's size or shape.

Each sample had a gauge length of 500 mm (approximately 20 inches) and a width of 50 mm (2 inches). These dimensions were chosen to provide sufficient surface area for accurate strain measurements while minimizing the likelihood of premature failure at the grips. The thickness of each specimen varied depending on the composite material type, but all samples were measured and recorded before testing to ensure uniformity. Thickness is a crucial factor in tensile testing, as even slight variations can affect the load distribution and strain response of the material. By maintaining consistent dimensions across all samples, the potential for variability in test results due to geometric factors was minimized.

3.2 Preparation of Fiber-Reinforced Polymer (FRP) Samples

For the fiber-reinforced polymer (FRP) samples, including unidirectional carbon fiber composites and woven glass fiber composites, special attention was given to the alignment of the fibers during specimen preparation. In unidirectional composites, fibers are aligned in a single direction, which maximizes strength and stiffness along that axis. To ensure that the mechanical behavior observed during testing accurately reflects the material's properties, the cutting of these samples was carefully controlled to maintain the desired fiber orientation (0°, ±45°, and 90°).

In woven composites, the fibers are interlaced in a specific pattern, creating a fabric-like structure. The preparation of woven composite samples requires precision to ensure that the weave pattern is not disrupted during cutting or mounting. For this study, woven glass fiber-reinforced polymer (GFRP) samples were prepared with a balanced weave pattern, where the warp and weft fibers were oriented at 0° and 90°, respectively. This configuration allowed for a more uniform distribution of load across the specimen during testing.

3.3 Hybrid Laminate Sample Preparation

Hybrid laminates, which consist of alternating layers of different fiber types (such as carbon and glass), present additional challenges in sample preparation due to the need to maintain consistent layer thickness and alignment. For this study, hybrid laminate samples were prepared by stacking alternating layers of carbon and glass fibers in a [0°/90°] orientation. This configuration ensured that the different fiber types would interact in a predictable manner during testing, allowing for the evaluation of how the combination of high-strength carbon fibers and more ductile glass fibers affects the material's tensile properties.

To prepare the hybrid laminate samples, the composite sheets were carefully cut using precision cutting tools to avoid damaging the fibers or disrupting the bond between the layers. Each layer was checked for uniformity in thickness, and the edges of the samples were inspected to ensure that no delamination occurred during the cutting process. Delamination, or the separation of layers within a composite material, can significantly affect the material's performance during tensile testing, leading to inaccurate results. By carefully controlling the preparation process, the risk of delamination was minimized.

Proper mounting and clamping of the samples are critical to ensure that the applied loads are uniformly distributed across the specimen during testing. In this study, two different clamping systems were used: roller grips and wedge grips. Each system has distinct advantages and disadvantages, and both were employed to compare their effectiveness in accurately measuring the tensile properties of composite materials, particularly at low strain levels.

3.4 Roller Grips

Roller grips are designed to hold the specimen by wrapping it around a rotating drum, allowing the sample to align itself with the applied force. This system is advantageous because it minimizes stress concentrations at the grip points, reducing the likelihood of premature failure at the ends of the sample. However, as the sample tightens around the roller during testing, some of the total crosshead movement (the movement of the machine's grips) is absorbed by the tightening of the specimen rather than the material's elongation. This makes roller grips less accurate for measuring strain, particularly at low stress levels where the initial deformation of the material is most critical.

For this study, roller grips were primarily used for testing ultimate tensile strength, as they excel at measuring high-stress properties. The specimens were mounted with a 1.8-meter (72-inch) separation between the grips, providing ample room for the material to elongate without interfering with the testing machine. The sample ends were wrapped around the rollers, and minimal preload was applied to remove slack without introducing significant tension. This ensured that the test would begin with the specimen in a near-relaxed state, allowing for more accurate measurement of early-stage deformation.

3.5 Wedge Grips

In contrast to roller grips, wedge grips provide a more rigid clamping mechanism, holding the specimen securely between two flat-faced plates. This system is ideal for measuring low-strain properties, as it minimizes the amount of slack or tightening that can occur during testing. Wedge grips are particularly useful for testing high-strength composite materials, where even small amounts of slack can lead to inaccurate strain measurements.

For the wedge grip system, the specimens were mounted with a 500 mm (20-inch) separation between the grips. To prevent slippage or damage to the specimen during testing, protective metal tabs were placed between the specimen and the grip plates. These metal tabs were made of soft, flexible steel and were designed to distribute the clamping force evenly across the specimen's width, reducing the risk of jaw breaks (premature failure at the grip point due to excessive clamping force).

To further enhance the gripping efficiency, epoxy adhesive was used to attach the metal tabs to the specimen in some tests. Epoxy provided a strong bond that helped prevent slippage without damaging the material, particularly in high-strength fabrics like unidirectional carbon fiber composites. In other tests, double-sided adhesive tape was used as a quicker, easier alternative to epoxy, though epoxy was generally found to offer superior results in terms of preventing slippage and ensuring repeatable testing conditions.

3.6 Strain Measurement Techniques

Accurate strain measurement is critical for capturing the material's deformation behavior, particularly at low strain levels where early-stage deformation can reveal important insights into the material's performance over time. Two strain measurement techniques were employed in this study: mechanical extensometers and laser-based optical extensometers.

Mechanical extensometers, which attach directly to the specimen and measure the elongation of the material as it is pulled, were used in some tests. However, these devices can introduce additional stress into the sample and are less effective at capturing fine-scale deformations at low strain levels. For more accurate measurements, laser-based optical extensometers were employed. These devices track the movement of reflective markers placed on the surface of the specimen without making physical contact, allowing for high-precision strain measurements without affecting the material's behavior during testing.

The laser extensometers provided strain data from multiple locations along the specimen's length, allowing for a detailed analysis of how strain was distributed across the material. This was particularly useful for evaluating the behavior of woven composites and hybrid laminates, where variations in fiber architecture can lead to localized differences in strain distribution.

3.7 Testing Conditions and Data Collection

All tests were conducted at room temperature under controlled conditions to minimize the influence of environmental factors such as humidity and temperature. The crosshead speed was set at 10 mm/min, resulting in a strain rate of 1% per minute. This strain rate was chosen to ensure that the material's response to loading was captured accurately without introducing dynamic effects that could skew the results.

Data on load, extension, and strain were recorded continuously throughout each test, allowing for detailed analysis of the material's behavior from the initial application of stress through to failure. By carefully controlling the sample preparation, mounting, and testing parameters, the study aimed to provide accurate and repeatable measurements of

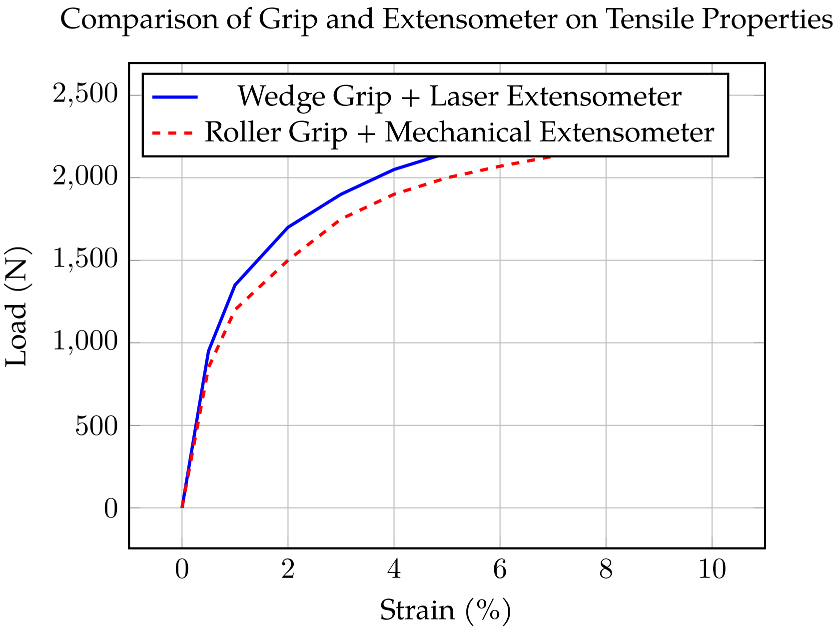

Figure 1. Comparison of Grip and Extensometer on Tensile Properties

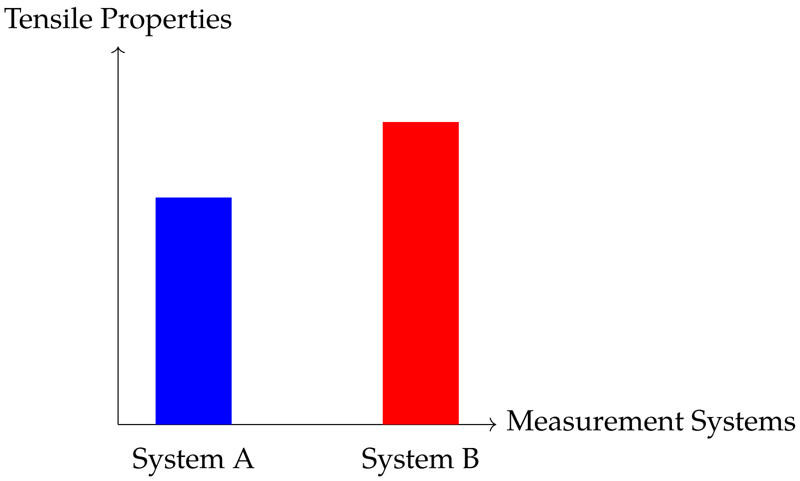

Figure 2. Comparison of the resultant tensile properties recorded using these two strain measurement systems demonstrates the relatively small amount of slippage that occurs with this system

the tensile properties of high-performance composite materials, particularly in the low-strain region where matrix-dominated behavior and fiber-matrix interactions play a critical role.

4 Comparison of Clamping and Measurement Techniques

The choice of clamping and strain measurement techniques is crucial for accurately assessing the mechanical properties of high-performance composite materials, particularly at low-strain levels where subtle material behaviors provide valuable insight into long-term performance and durability. In this study, two primary clamping systems—roller grips and wedge grips—were evaluated alongside different strain measurement techniques, including mechanical extensometers and laser-based optical extensometers. Each combination of clamping and measurement techniques offered unique advantages and challenges, depending on the material being tested and the specific mechanical property being measured.

4.1 Roller Grips

Roller grips are widely used in tensile testing because they allow specimens to align themselves with the applied force, ensuring uniform stress distribution across the width of the sample. This self-alignment reduces the likelihood of premature failure at the grip points, which can otherwise skew the test results. In roller grip systems, the specimen is wrapped around a drum at each end, which minimizes stress concentrations and ensures that the material experiences a more uniform load during testing.

One of the key advantages of roller grips is their ability to handle high-strength materials, such as unidirectional carbon fiber composites, without causing slippage or failure at the grip points. The rollers allow the specimen to tighten around the drums as the load is applied, effectively distributing the force across the entire width of the specimen. This makes roller grips particularly suitable for testing ultimate tensile strength, as they ensure that the specimen can be loaded to its breaking point without localized failures at the grips.

However, roller grips also have significant drawbacks, particularly when testing for low-strain properties. As the specimen tightens around the rollers during testing, some of the total crosshead movement is absorbed by the tightening rather than by the elongation of the material itself. This results in an overestimation of strain, particularly in the early stages of testing, where small deformations are critical for understanding the material's behavior. For low-strain measurements, this tightening effect complicates the interpretation of the data and makes it difficult to accurately capture the material's true response to stress. As a result, roller grips are less effective for tests that focus on low-strain properties or early-stage deformation behavior.

4.2 Wedge Grips

In contrast to roller grips, wedge grips provide a rigid clamping mechanism that holds the specimen securely between two flat, textured plates. This system eliminates the slack that can occur with roller grips, making wedge grips more suitable for low-strain testing. The rigidity of wedge grips ensures that the specimen is held firmly in place, preventing any movement or tightening during the test, which is essential for capturing accurate strain data, particularly in the early stages of loading.

Wedge grips are especially advantageous for testing materials where low-strain properties are critical, such as woven composites or hybrid laminates. In these materials, the early stages of deformation are often dominated by matrix behavior and fiber-matrix interactions, which are key indicators of the material's long-term durability and performance under cyclic loading. By providing a stable and secure clamping system, wedge grips allow for more accurate strain measurements in these critical regions.

One challenge with wedge grips, however, is the potential for slippage or failure at the grip points, particularly when testing very high-strength materials like unidirectional carbon fiber composites. To mitigate this issue, protective metal tabs or epoxy coatings are often used between the specimen and the grip plates to distribute the clamping force more evenly and prevent damage to the sample. In this study, both metal tabs and epoxy coatings were used in conjunction with wedge grips to ensure that the specimen was securely held without causing localized failures.

Despite these challenges, wedge grips offer several advantages over roller grips when testing low-strain properties. By eliminating the slack and tightening issues associated with roller grips, wedge grips provide a more accurate measurement of the material's true strain, particularly in the early stages of loading. This makes them the preferred choice for evaluating low-strain properties, matrix-dominated behavior, and fiber-matrix interactions, all of which are critical for predicting long-term material performance.

4.3 Mechanical Extensometers

Mechanical extensometers are traditional strain measurement devices that attach directly to the specimen and track its elongation during testing. These devices typically consist of two contact points that grip the specimen at a fixed distance apart, measuring the change in distance between the points as the specimen elongates. While mechanical extensometers are widely used and provide accurate measurements of strain, they have several limitations, particularly when testing composite materials.

One of the primary drawbacks of mechanical extensometers is that their physical contact with the specimen can introduce additional stress into the sample, potentially affecting its behavior during testing. This is especially problematic when testing low-strain properties, where even small amounts of added stress can skew the results. In addition, mechanical extensometers can be difficult to attach to very thin or delicate specimens without damaging the material, making them less suitable for testing certain types of high-performance composites.

Despite these challenges, mechanical extensometers are effective for measuring strain in the mid- to high-strain regions, where the material is undergoing significant elongation and the effects of the extensometer's contact are less pronounced. However, for low-strain measurements, alternative techniques are often preferred.

4.4 Laser-Based Optical Extensometers

Laser-based optical extensometers offer a non-contact method of measuring strain, eliminating many of the challenges associated with mechanical extensometers. These devices work by tracking the movement of reflective markers placed on the surface of the specimen, using a laser to measure the distance between the markers as the specimen elongates. This non-contact approach has several advantages, particularly for testing high-performance composite materials.

One of the key benefits of laser extensometers is their ability to capture strain data without physically contacting the specimen, ensuring that the material's behavior is not influenced by the strain measurement device. This makes laser extensometers particularly useful for testing low-strain properties, where the material's early-stage deformation is critical for understanding its long-term performance. In this study, laser extensometers were used in conjunction with both roller and wedge grips to provide high-precision strain measurements throughout the test.

Laser extensometers also offer greater flexibility in terms of where the strain is measured. By placing reflective markers at different points along the length or width of the specimen, it is possible to capture localized strain data, allowing for a more detailed analysis of how strain is distributed across the material. This is particularly valuable when testing woven composites or hybrid laminates, where variations in fiber architecture can lead to non-uniform strain distribution.

5 Conclusion

In summary, the combination of wedge grips and laser-based optical extensometry provided the most accurate and reliable measurements of low-strain properties in this study. While roller grips were effective for measuring ultimate tensile strength, their limitations in capturing early-stage deformation make them less suitable for low-strain testing. Mechanical extensometers, while effective in some cases, introduced unwanted stress into the specimen, further highlighting the advantages of laser-based systems for high-precision strain measurement. Together, wedge grips and laser extensometers offer a powerful combination for evaluating the critical mechanical properties of high-performance composite materials.

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