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ORGINAL ARTICLE

Experimental Characterization and Numerical Simulation of Adhesively Bonded Hybrid Sisal-Glass Reinforced HDPE Composite for Automobile Side Body Panel Applications

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ABSTRACT

This study focuses on the Numerical simulation and experimental fabrication and mechanical characterization of a hybrid sisal-glass reinforced HDPE composite for automobile side body panel applications. The composite is manufactured using a compression molding technique with varying fiber-to-matrix weight ratios (Fiber 30% to Matrix 70% HDPE) S15G15H70, S5G25H70, S10G20H70, S20G10H70, S25G5H70), and stacking sequences [Sisal Glass-Glass] and [Glass-Sisal-Glass] to optimize mechanical performance. The mechanical properties, tensile, flexural, and impact strength, were test and evaluated in the laboratory, adhesive bonding mechanical performance in adhesively bonded single-side strap joint configuration (ABSSSJ) for steel-to-composite bonding. The measured tensile strengths ranged from 19.84 MPa (S15G15H70) to 31.92 MPa (S5G25H70), while flexural strengths ranged from 25.30 MPa to 38.10 MPa for the same compositions. Impact strength varied from 12.5 J/m to 18.2 J/m, showing improved energy absorption with higher glass fiber content. The study also examines the effect of adhesive parameters adhesive thickness, overlap length, overlap width and fracture toughness on debonding resistance. The study combines experimental testing and numerical simulations (Cohesive Zone Model-based FEM) to gain a deeper understanding of the bonding performance and failure mechanisms. Both experimental and simulation results indicated that increasing adhesive thickness and modulus improved shear strength, with the highest performance observed for specimens with 0.5 mm adhesive thickness and a 6 GPa adhesive modulus. The study provides a comprehensive understanding of the hybrid Sisal-Glass Reinforced HDPE composite's feasibility contributing to sustainable material development for lightweight automotive structural applications particularly for automobile side body panel.

Keywords: *Experimental, Adhesive Bonding, Mechanical Characterization, hybrid Sisal-Glass Reinforced HDPE composite, numerical simulations.*

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1. Introduction

The increasing demand for lightweight, high-strength, and sustainable materials in the automotive industry has led to extensive research into natural fiber-reinforced polymer composites (NFRPCs) as alternatives to conventional synthetic fiber composites [1]. Traditional materials such as steel and aluminum have been widely used in automobile body structures; however, their high density and limited recyclability pose challenges in meeting modern fuel efficiency and environmental sustainability goals [2]. Hybrid composites, which combine natural and synthetic fibers, have emerged as a promising solution to enhance mechanical performance while maintaining eco-friendliness and cost-effectiveness. Sisal fibers, known for their biodegradability, low density, and good tensile strength, provide an environmentally sustainable alternative to purely synthetic reinforcements [3].Meanwhile, glass fibers contribute superior stiffness, strength, and durability, compensating for the limitations of natural fibers such as moisture absorption and degradation over time [4].By integrating both sisal and glass fibers into a high-density polyethylene (HDPE) matrix, a well-balanced composite material can be achieved, offering improved mechanical properties, impact resistance, and long-term durability [5].

Adhesive bonding has become an essential technology in modern automotive design, offering advantages in weight reduction, uniform stress distribution, and joining of dissimilar materials key factors in the design and manufacturing of automobile side body panels. In parallel, natural fiber-reinforced polymer composites (NFRPCs) are receiving increasing attention for automotive structural applications, owing to their sustainability, low density, and cost-effectiveness. Hybridization combining natural fibers such as sisal with synthetic fibers like glass can yield composites with improved stiffness, toughness, and damage tolerance, while mitigating drawbacks of natural fibers alone. In automobile applications, the side body panel is a crucial structural component that requires optimal strength-to-weight ratio, durability, and impact resistance. Recent studies have demonstrated that hybrid NFRPCs can provide enhanced crashworthiness, vibration damping, and cost savings compared to conventional metal-based panels [6]. However, their application in structural joints, particularly when bonded with adhesive technologies, requires further investigation into their debonding behavior, adhesion strength, and failure mechanisms [7].

Recent studies show growing interest in employing natural or hybrid natural-synthetic fiber composites in vehicle body and panel components.[24] review the use of plant fiber/particulate-based polymer composites in vehicle body parts, including panels, bumper beams, and insulation components, highlighting hybridization and fiber treatment as key strategies to meet strength and durability requirements in automotive settings. Another review by [25] emphasizes the crashworthiness potential of thin-walled natural fiber and hybrid composite structures, which is directly relevant to body panels that must withstand impact loads during collisions. For automobile side body panels, mechanical performance under tensile, flexural, and impact loads is critical, not only for static load-bearing but also for resistance to deformation, fatigue, and crash events. Adhesively bonded joints are increasingly used in automotive assembly to join panels without welding, rivets, or fasteners, thereby reducing weight, improving aesthetics, and enabling dissimilar materials. However, only a few studies have evaluated adhesively bonded hybrid natural-synthetic fiber composites, particularly sisal-glass hybrids in thermoplastic matrices like HDPE, with respect to their full mechanical strength and behavior in side panel applications.

This study focuses on the fabrication and characterization of hybrid sisal-glass reinforced HDPE composites for automobile side body panel applications, incorporating both experimental mechanical testing and computational modeling through cohesive zone modeling (CZM)-based finite element method (FEM). The research aims to establish a fundamental understanding of material performance under different loading conditions, environmental factors (moisture, temperature), and adhesive bonding variations. The justification for this study is based on the following key factors:

- Sustainability and Eco-friendliness: Hybrid composites reduce reliance on synthetic fibers and petroleum-based materials, lowering the environmental impact [2].
- Lightweight and High Strength: Sisal-glass reinforced HDPE composites provide a superior strength-to-weight ratio, improving vehicle efficiency and crashworthiness [6].
- Enhanced Adhesive Bonding Performance: Understanding the debonding behavior and failure mechanisms of hybrid composites in adhesively bonded steel-to-composite joints is crucial for structural integrity and durability [8].
- Computational and Experimental Validation: Integrating CZM-based FEM allows for detailed analysis and prediction of mechanical failure and adhesive joint performance, ensuring practical applicability in real-world automotive structures [9].
- Addressing Industry Needs: The findings contribute to the development of next-generation lightweight automotive materials, aligning with industry trends and regulatory standards [5].

The research background gap is despite significant advancements in natural fiber-reinforced polymer composites (NFRPCs), several critical research gaps remain in the development and application of hybrid sisal-glass reinforced HDPE composites for automobile body panels: Limited Studies on Hybrid Sisal-Glass Fiber Composites for Automotive Panels Previous studies have explored glass and natural fiber composites separately, but few have analyzed the mechanical synergy between sisal and glass fibers for automobile applications [4,10,12]. There is insufficient data on how fiber orientation, weight ratio, and stacking sequence influence mechanical strength and impact resistance in automotive body panels [2],Lack of Experimental and Computational Analysis of Adhesively Bonded Joints (ABJ) Most studies focus on mechanical characterization of hybrid composites but neglect adhesive bonding performance when joined with steel structures [7] ,Limited research exists on CZM-based FEM simulations to predict the debonding behavior of hybrid composites bonded to steel under tensile, shear, and flexural loading conditions [9,13]. Effects of Environmental Factors on Adhesive Bonding Performance Moisture absorption and temperature variations significantly affect fiber-matrix adhesion and adhesive bond strength, yet few studies have investigated their combined effects on hybrid sisal-glass reinforced HDPE composites [8,14-15] ,Optimizing Adhesive Thickness, Overlap Length, and Surface Preparation Adhesive joint strength is highly dependent on adhesive thickness, overlap length, and surface treatment (sand grade), but existing literature lacks systematic studies on their influence in hybrid composite-to-steel bonding [16],Experimental Validation of CZM-Based FEM Models has been successfully applied to synthetic composite joints, but its validation against experimental results for natural-synthetic hybrid composites is still missing [9,18].A comparative analysis between FEM simulations, experimental testing, and analytical variational models is necessary to ensure the reliability of computational predictions [6].This research contributes to advancing lightweight, high-performance, and environmentally sustainable materials for the automotive sector, supporting the development of next-generation adhesive bonding technologies for steel-to-composite structural applications. Finally the literature indicates significant potential for the use of hybrid sisal-glass reinforced HDPE composites in automotive applications, particularly in lightweight structural components. While much progress has been made in understanding the mechanical performance and ABJ of these composites, challenges remain in optimizing the bonding process, understanding the effects of environmental factors, and accurately simulating debonding behavior. This study aims to address these gaps by investigating the mechanical properties, adhesive bonding performance, and debonding behavior of these composites, using both experimental methods and simulation techniques such as CZM-based FEM. This work addresses that gap, We fabricate adhesively bonded hybrid sisal-glass reinforced HDPE composites, measure tensile, flexural, and impact strengths, and evaluate their suitability for automobile side body panel applications, considering the mechanical demands imposed in crash scenarios and service use. The problems of the study is the growing need for lightweight, high-strength, and environmentally sustainable materials in the automotive industry has led to increased interest in natural fiber-reinforced polymer composites (NFRPCs). While hybrid sisal-glass reinforced HDPE composites offer a promising balance between mechanical strength and sustainability, several challenges remain in their fabrication, characterization, and adhesive bonding performance [1, 3, 19-20]. Key limitations persist: Moisture Absorption and Thermal Sensitivity: Natural fibers such as sisal exhibit poor resistance to moisture and temperature variations, leading to potential degradation in mechanical performance [2, 4]. Inconsistent Fiber-Matrix Adhesion: Achieving optimal bonding between fibers and the HDPE matrix is critical to improving mechanical strength and durability, but fiber surface treatments and matrix compatibility need further investigation [5]. Limited Experimental Data on Hybrid Composites for Automotive Use: Most studies on hybrid natural-synthetic fiber composites focus on general applications rather than their specific use in automotive side body panels, necessitating further research [6,11] .Uncertain Performance of Adhesively Bonded Joints: The mechanical strength of the bond depends on factors such as adhesive modulus, thickness, cohesive fracture toughness, and surface preparation, which require detailed analysis [7].Debonding and Fracture Behavior: ABJ in hybrid composite structures are prone to cohesive failure, delamination, and debonding under mechanical loading and environmental exposure, necessitating a comprehensive fracture mechanic study [8,17]. Lack of Computational-Experimental Validation: While CZM-based FEM simulations provide an efficient tool for analyzing debonding and fracture mechanics, limited experimental validation exists for steel-to-hybrid composite ABJ [9, 16, 21-23].

The primary objective of this study is to fabricate, characterize, and evaluate the mechanical strength and adhesive bonding performance of hybrid sisal-glass reinforced HDPE composites for automobile side body panel applications. The study also aims to compare experimental results with computational models, particularly CZM-based FEM simulations, to validate the adhesive joint behavior.

2. Materials and Methodology

The methodology section describes the method, materials, procedures, and analytical techniques used to fabrication and mechanical characterization; investigate the mechanical performance, adhesive bonding strength, and debonding behavior of hybrid sisal-glass reinforced HDPE composites for automobile side body panel applications. The methodology integrates both experimental testing and numerical simulations to analyze the effects of different parameters such as adhesive thickness, adhesive modulus, cohesive fracture toughness, fiber-to-matrix weight ratios, and environmental conditions on the composite performance.

2.1 Method

This study adopts a mixed-methods approach, incorporating both experimental and computational techniques. The experimental component involves the fabrication of hybrid sisal-glass reinforced HDPE composites, the preparation of ABJ, and the testing of mechanical properties under various loading conditions. The computational aspect utilizes CZM-based FEM to simulate the full-range debonding process of adhesive joints, predicting the fracture and failure behavior under different conditions.

Experimental Method:

Shear Test for ABSSSJ: To assess the mechanical strength of the adhesive joints, shear tests were performed on Adhesively Bonded Single-Side Strap Joints (ABSSSJs). The tests were conducted under varying adhesive thicknesses, adhesive moduli, and cohesive fracture toughness values to capture their influence on joint performance. Load–displacement responses were recorded, and the resulting shear strength values were analyzed to evaluate the debonding behavior and overall mechanical integrity of the joints.Tensile Test for Hybrid Sisal-Glass Reinforced HDPE Composite: Tensile tests were conducted on the hybrid sisal–glass reinforced HDPE composite specimens to determine their tensile strength, elastic modulus, and failure modes. Standardized dog-bone specimens were prepared in accordance with ASTM D638. The tests were performed using a universal testing machine (UTM) shown in figure 1 at a controlled crosshead speed, with continuous load–displacement data acquisition. The results provided detailed insights into the stress–strain response of the composites, highlighting the effects of hybridization on tensile behavior. Environmental Conditioning: Specimens were subjected to controlled environmental aging conditions, including moisture exposure and thermal cycling, to evaluate the impact of temperature and moisture on the mechanical properties of both the composites and the adhesive joints. Moisture exposure was carried out by immersing the specimens in water for predefined durations, while thermal cycling involved repeated heating and cooling cycles within the selected temperature range. Following conditioning, the specimens were mechanically tested to assess changes in tensile strength, shear strength, and durability properties. Cohesive Zone Modeling (CZM Based FEM): The CZM approach was employed to simulate the initiation and propagation of damage in adhesive joints. Finite element analysis software (ANSYS and ABAQUS) was used, where cohesive elements modeled the adhesive layer, and the adhesive behavior was represented by a cohesive law defining the relationship between normal and shear stresses and the separation at the interface. The simulations provided detailed insights into debonding mechanisms, stress distribution, and fracture progression in the adhesive joints, complementing the experimental findings. CZM Based FEM simulations were carried out to predict stress distribution, crack propagation, and the debonding process in ABSSSJ under various loading conditions and environmental factors. Different adhesive thicknesses and cohesive fracture toughness values were analyzed to simulate failure progression. The CZM Based FEM results provided valuable correlations with experimental data, enhancing the understanding of joint performance and failure mechanisms.

2.2 Materials and Specimen Preparation

Hybrid Sisal-Glass Reinforced HDPE Composite: The hybrid composite were prepared using HDPE as the matrix material, with sisal and glass fibers used as reinforcements. The fiber-to-matrix weight ratios will be varied according to predefined configurations, such as S15G15H70, S5G25H70, S10G20H70, S25G5H70, and S20G10H70. The composites were fabricated using the hand lay-up method, followed by hot pressing to ensure uniform fiber distribution and optimal bonding between the fibers and the matrix shown in the figure 2. Adhesive: The adhesive used for bonding the composite to steel adherends were a commercial epoxy-based adhesive (Araldite 2020, Araldite 2015 and AV138, chosen for its high mechanical strength, durability, and compatibility with both natural and synthetic fibers. Adhesive thicknesses ranging from 0.2-1.0 mm were used to study the effect of adhesive layer properties on joint performance. Steel Adherends: The steel adherends were prepared with different surface finishes, including sandblasting, to improve the adhesive bonding. The thickness of the steel adherends were standardized to ensure consistent results in the bonding process. Practical Implication: Experimental validation of different parameters effects helps establish optimal preparation methods for achieving maximum joint performance.

Figure: 1 Universal testing machine (UTM) and specimen Hybrid Sisal-Glass Reinforced HDPE Composite.

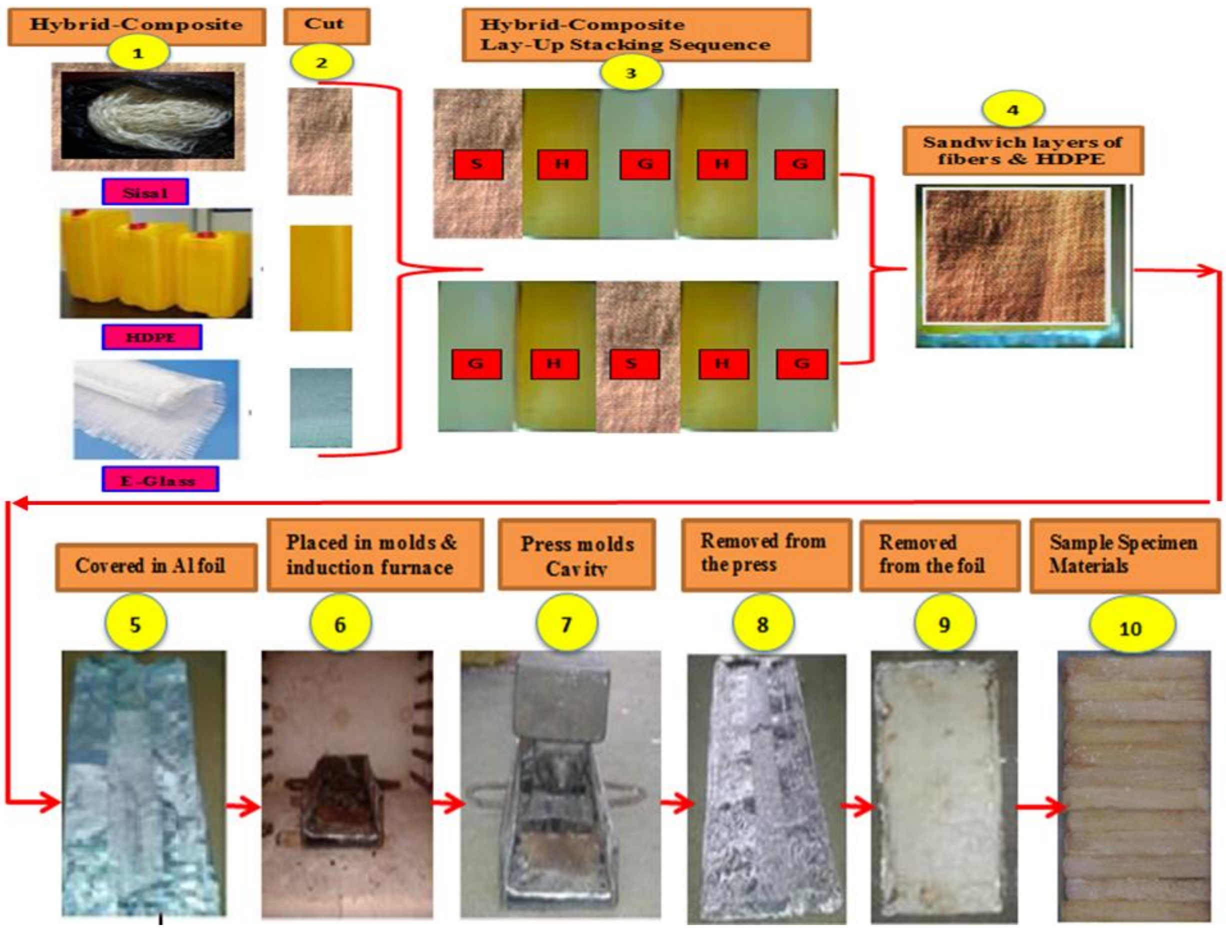


Figure: 2 Fabrication procedure of the test specimen material for hybrid Sisal-Glass Reinforced HDPE composite.

2.3 Experimental Testing

Mechanical Testing

Tensile Test for Hybrid Sisal-Glass Reinforced HDPE Composite: Conducted using a Universal Testing Machine (Instron 5967, USA) equipped with a 50 kN load cell. Specimens were prepared according to ASTM D638. Tests were performed at a crosshead speed of 5 mm/min, and data acquisition was carried out with an accuracy of ±0.5% for load and ±0.01 mm for displacement. Specimens were conditioned at various environmental conditions (25, 30, 35, 40, and 45°C) to evaluate the effect of temperature on the tensile properties.

Flexural Test: Performed on the same UTM using three-point bending setup, following ASTM D790. Span-to-depth ratio maintained at 16:1. Flexural strength and modulus were recorded with ±0.5% accuracy.

Impact Test: Conducted using a Charpy Impact Tester (Tinius Olsen IT503, USA) following ASTM D256. Notched specimens were used, and energy absorbed was measured with ±1% accuracy.

Shear Test for Adhesively Bonded Single-Side Strap Joints (ABSSSJ)

The shear strength of the adhesive joints was evaluated using the ASTM D1002 standard, which measures the shear strength of adhesive bonds in a single-lap shear configuration. The specimens were subjected to different displacement rates to measure the force-displacement response and determine the ultimate shear stress, yield stress, and failure modes. The effect of adhesive thickness, adhesive modulus, and cohesive fracture toughness were studied by varying these parameters and observing their influence on the shear strength and failure modes.

Thermal Testing

Thermo gravimetric Analysis (TGA): Performed using PerkinElmer TGA 8000. Samples (≈10 mg) were heated from 25 °C to 600 °C at 10 °C/min under nitrogen flow. Mass loss was recorded with an accuracy of ±0.1%. Specimens were subjected to thermal cycling (temperature variations between 25 and 45°C) to simulate real-world automotive conditions and observe any degradation in adhesive bond strength or composite material properties.

Heat Deflection Temperature (HDT): Measured using Tinius Olsen HDT/Vicat tester according to ASTM D648, with a load of 0.455 MPa. Accuracy of temperature measurement: ±1 °C. **Morphological / Structural Analysis**

Scanning Electron Microscopy (SEM): Conducted on a JEOL JSM-6510LV, at an accelerating voltage of 10 kV. Specimens were gold-coated (~5 nm) to avoid charging. Fiber–matrix adhesion and fracture surfaces were analyzed.

Fourier Transform Infrared Spectroscopy (FTIR): Conducted using PerkinElmer Spectrum Two with a resolution of 4 cm^{-1}, scanning range 4000–400 cm^{-1}. used to confirm functional groups and chemical interactions between fibers and matrix.

X-ray Diffraction (XRD): Performed using Bruker D8 Advance with Cu Kα radiation (λ=1.5406 Å), scanning 2θ from 5° to 50°, to determine crystallinity and phase composition.

Environmental Testing

Water Absorption: Conducted according to ASTM D570. Specimens were dried, weighed, and immersed in distilled water at baths at varying time (2, 6, 8, 9, and 12rs) to investigate the effect of moisture absorption on the mechanical properties of both the composite and the ABJ. Accuracy of mass measurement: ±0.001 g. ***Weathering / UV Resistance***: Accelerated exposure performed using QUV Accelerated Weathering Tester (Q-Lab QUV/se) under UV-A 340 lamps, 8 h UV at 60 °C + 4 h condensation at 50 °C cycles, for 500 h. Changes in mechanical and surface properties were recorded.

2.4 Characterization Method

Characterizing a hybrid sisal-glass reinforced HDPE composite involves several key steps to evaluate its mechanical, thermal, morphological, and environmental properties.

Mechanical Characterization

Essential for understanding strength and stiffness: Shear Test (ASTM D5379): For bonded joint performance. Tensile Test (ASTM D638): Measures tensile strength, modulus, and elongation at break. Flexural Test (ASTM D790): Assesses flexural strength and modulus. Impact Test (Izod /Charpy - ASTM D256): Determines resistance to sudden impact. Hardness Test (Shore D): Assesses surface hardness. ***Thermal Characterization***

To evaluate behavior under temperature changes: Thermo gravimetric Analysis (TGA): Measures thermal stability and decomposition temperature. Differential Scanning Calorimetry (DSC): Determines melting point, crystallinity, and glass transition temperature. Heat Deflection Temperature (HDT - ASTM D648): Indicates performance under heat load. Thermal Conductivity Test: Important for automotive safety. ***Morphological and***

Structural Analysis

To observe fiber dispersion, interface, and defects: Scanning Electron Microscopy (SEM): Inspects fiber-matrix bonding, failure surface, voids. Fourier Transform Infrared Spectroscopy (FTIR): Identifies chemical bonding and functional groups.

X-ray Diffraction (XRD): Checks crystallinity and phase identification. ***Environmental Characterization***

Evaluates durability under real-life conditions: Moisture Absorption Test (ASTM D570): Measures water uptake. UV Aging/Weathering Test: Simulates outdoor exposure effects. Salt Spray Test (ASTM B117): For corrosion resistance if bonded with metal. ***Adhesive Joint Performance***

Single-lap or Strap Joint Test (ASTM D1002): Measures joint strength. Fracture Toughness (Mode I/II - ASTM D5528): Assesses crack propagation resistance using CZM or other fracture models.

2.5 Numerical Simulation Procedures

Simulation Setup

The CZM Based FEM simulations were conducted using ANSYS and ABAQUS software, where both the composite material, adherend (steel) and adhesive layer are modeled. The composite was modeled as a hybrid material orthotropic 181 Shell elements, isotropic 185 solid elements with defined elastic properties and fiber orientations, while the adhesive layer was modeled using cohesive zone elements (INTER202).

Material Models

The composite was modeled as an orthotropic material using the material properties obtained from tensile and flexural testing. The adhesive was modeled using the CZM based FEM, where the normal and shear stresses are related to the opening and sliding displacements at the adhesive interface.

Boundary Conditions (BC)

The simulations considered different BC, such as fixed supports and controlled displacement or load conditions, to replicate experimental testing conditions.

Debonding Simulation

The debonding process was simulated by applying incremental displacement to the adhesive joint. The CZM-based FEM approach captured the progressive failure of the adhesive interface as a function of displacement, leading to the formation of cracks and eventual debonding. The effects of adhesive thickness, adhesive modulus, and cohesive fracture toughness on the debonding behavior were analyzed by varying these parameters in the simulations and observing their influence on stress distribution, crack initiation, and propagation.

2.6 Data Analysis

Experimental Data: The experimental data obtained from the shear and tensile tests were analyzed to determine the mechanical properties of the hybrid composites and adhesive joints. Stress-strain curves were plotted to analyze the strength, elasticity, and failure modes. The failure modes observed in both tensile and shear tests were classified, such as adhesive failure, cohesive failure, and mixed-mode failure, based on visual inspection and post-test analysis.

Simulation Data: The results from the CZM Based FEM simulations were used to assess the stress distribution, debonding progression, and force-displacement behavior of the adhesive joints. The predictions from the FEM model were compared with experimental results to validate the accuracy of the simulations.

Sensitivity analysis was conducted to study the effect of different parameters on the mechanical performance and debonding behavior of the joints, allowing for optimization of adhesive bonding techniques for hybrid composite applications in automotive structures.

2.7 Validation

The results of the CZM Based FEM simulations were validated against the experimental data, particularly focusing on the force-displacement curves and failure modes observed in the shear and tensile tests. A strong correlation between experimental and simulation results indicated the reliability and accuracy of the CZM Based FEM model for predicting the mechanical performance and debonding behavior of adhesive joints in hybrid composites.

3. Results and Discussion

This section presents the results obtained from the experimental tests and numerical simulations, followed by a detailed discussion on the findings. The analysis focuses on the mechanical performance of hybrid sisal-glass reinforced HDPE composites and adhesive bonded joints under various conditions, including the effects of adhesive thickness, adhesive modulus, cohesive fracture toughness, fiber-to-matrix weight ratios, and environmental exposure.

3.1 Experimental Results

Shear Strength of Adhesively Bonded Single-Side Strap Joints (ABSSSJ): The shear strength of the ABSSSJ specimens was evaluated under different adhesive thicknesses (0.2-1.0 mm) as shown in figure 3 , adhesive moduli (1.85, 2.5, 6 GPa), and cohesive fracture toughness values (0.25-1.0 kJ/m²).Adhesive Thickness: The shear strength increased with adhesive thickness, reaching a plateau at 0.5 mm, beyond which no significant improvement was observed. A thinner adhesive layer (0.2 mm) led to reduced bonding strength, which was attributed to insufficient adhesive volume to resist shear forces.

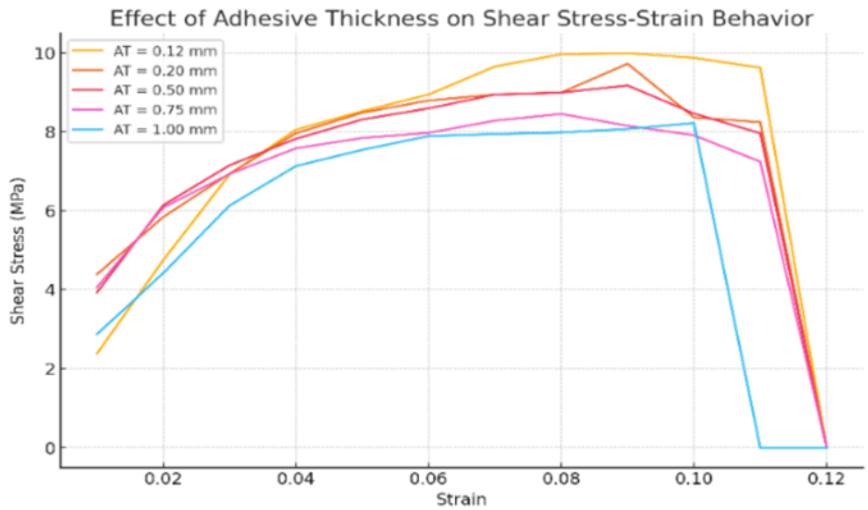
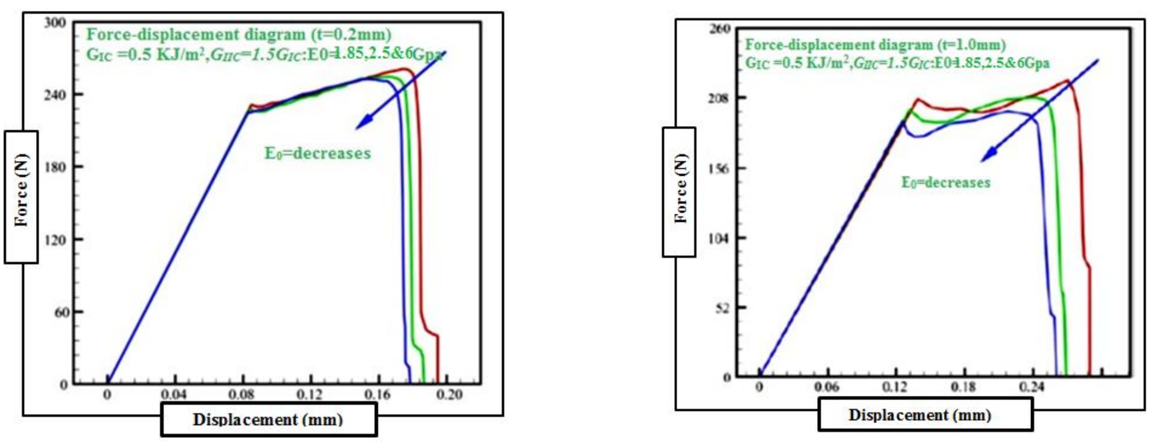


Figure: 3 Shears stress Vs strain effect of adhesive thickness (AT) in ABSSSJ

Adhesive Modulus: Increasing the adhesive modulus from 1.85-6 GPa resulted in figure 4 a significant increase in shear strength, especially for thicker adhesive layers. Higher adhesive modulus improves the adhesive's resistance to deformation under shear stress.

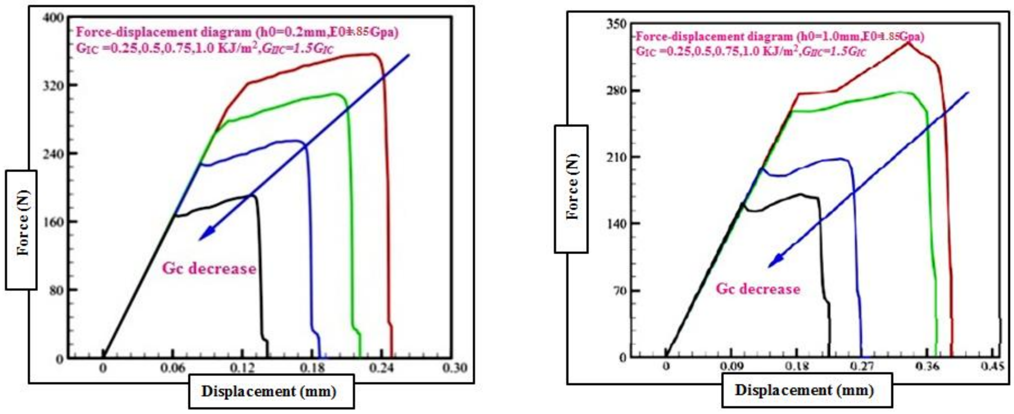


(a) Adhesive thickness =h0=0.2mm (b) Adhesive thickness =h0=1.0mm

Figure: 4 Varying adhesive elastic modulus E_o (1.85 (blue), 2.57(green) and 6Gpa (red)) and Adhesive thickness h0=0.2, 0.5, 0.75 and 1mm) to Predicted force-displacement diagrams.

The above figure 4 the tensile force (strength) increases with increasing axial displacement in the elastic region until debonding begins. During debonding, the tensile force (strength) decrease with increasing axial displacement and then increases non - linearly through the debonding process until the ultimate tensile force is reached, which corresponds to the final failure of the joint.

Cohesive Fracture Toughness: Adhesive joints with higher cohesive fracture toughness values exhibited improved resistance to crack propagation, with a notable increase in the critical stress at which debonding occurred shown in figure 5. Specimens with a cohesive toughness of 1.0 kJ/m² performed the best in terms of fracture resistance.



(a) Adhesive thickness=h0=0.2mm (b) Adhesive thickness=h0=1.0mm

Figure: 5 With different fracture toughness G_c (0.25, 0.5, 0.75 and 1.0KJ/m2) Predicted force-Displacement Diagrams of ABSSSJs.

Thus, based on changes in cohesive fracture energy, the current scaling study shows that the adhesive thickness is essential for higher material strength and thus provides higher load- carrying capacity before catastrophic joint failure. Failure Modes: The primary failure mode observed was adhesive failure, followed by mixed-mode failure at higher adhesive thicknesses and cohesive toughness values indicated figure 6. Cohesive failure was rarely observed, indicating strong interfacial bonding between the adhesive and the adherend.

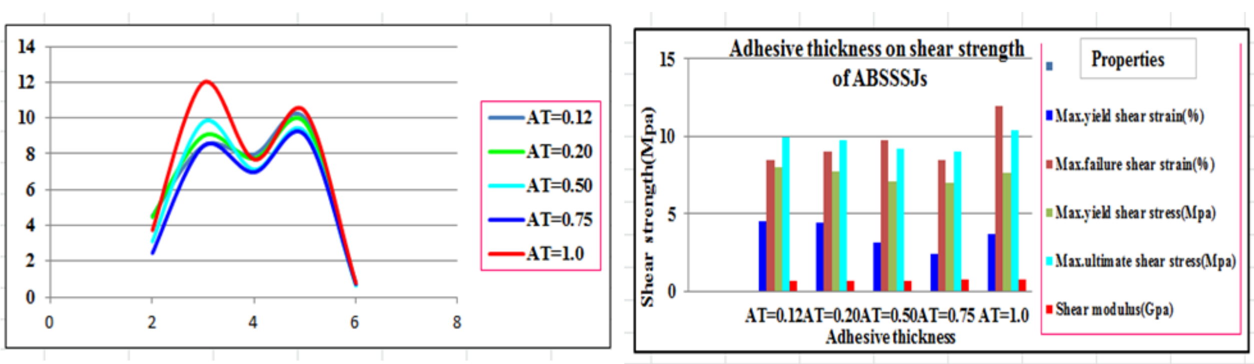


Figure: 6 Effects of Adhesive thickness on failure modes of ABSSSJ.

Tensile Strength of Hybrid Sisal-Glass Reinforced HDPE Composite: Tensile testing of the hybrid composite materials (varying fiber-to-matrix weight ratios: S15G15H70, S5G25H70, S10G20H70, S25G5H70 and

S20G10H70.) yielded the following results:

Effect of Fiber-to-Matrix Weight Ratio : The tensile strength increased with the proportion of glass fibers, with the S5G25H70 configuration (25% glass fiber) showing the highest tensile strength in figure 7. However, the addition of sisal fibers improved the composite’s toughness, as evidenced by higher elongation at break. Discussion: The results highlight the dominance of fiber reinforcement in carrying the tensile load. Higher proportions of sisal fibers reduce the composite's tensile capacity due to their lower mechanical properties compared to glass fibers. The combination of glass fibers in S5G25H70 (hybrid Sisal5-Glass25 Reinforced HDPE70 Composite) leads to better stress performance under smaller strain values.

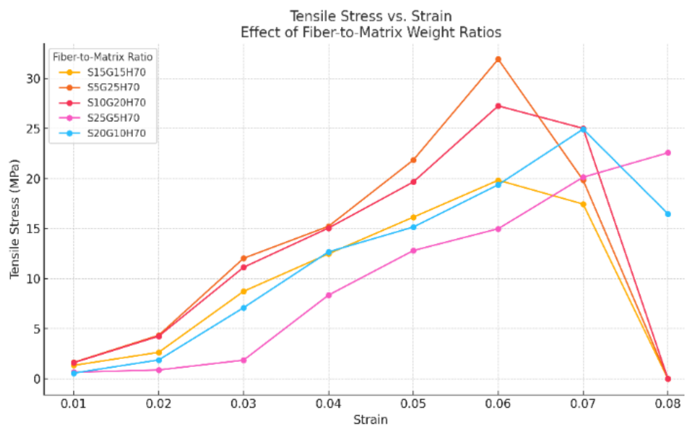


Figure: 7 Tensile stress Vs strain plot graph effect of fiber to matrix weight ratios in ABSSSJ.

Effect of Temperature and Moisture Exposure: The tensile strength decreased with increased moisture exposure and temperature results as shown in figure 8. For example, samples exposed to 10 hours in a water bath exhibited a 15-20% reduction in tensile strength (10.76Mpa to 8.93Mpa), suggesting that water absorption weakens the composite matrix. Likewise, thermal cycling at temperatures above 40°C resulted in decreased tensile modulus (12.48Mpa to 10.35Mpa).

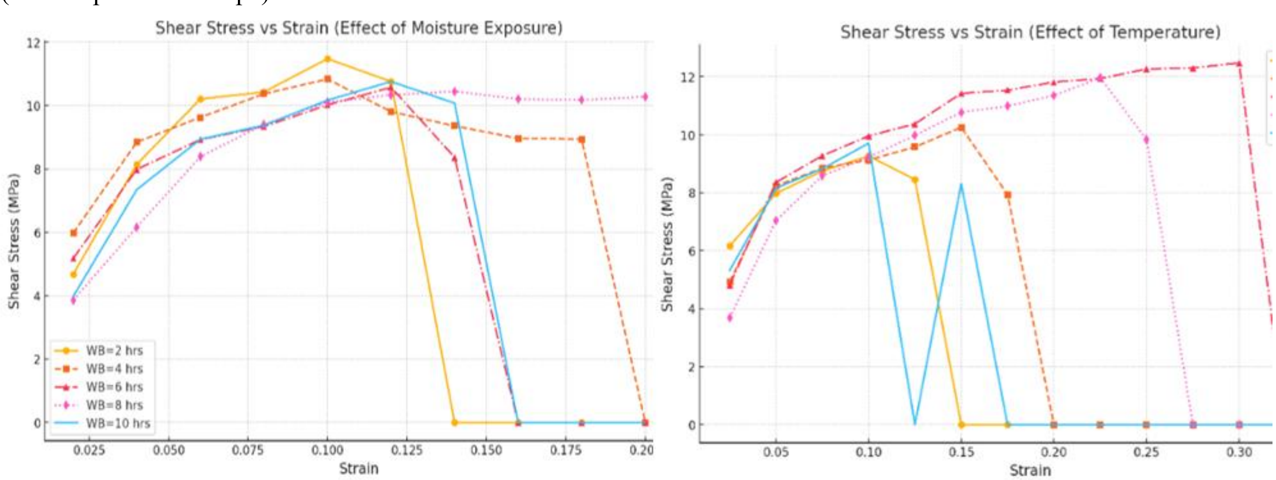


Figure: 8 Shear stress Vs strain plot graph effect of moisture and temperature in ABSSSJ.

Failure Modes: The primary failure modes were fiber rupture and matrix cracking, with fiber pullout occurring more frequently in composites with higher sisal fiber content. This was attributed to the lower interfacial bonding strength between the sisal fibers and the HDPE matrix.

Environmental Conditioning

Specimens were exposed to moisture and temperature variations to simulate real-world automotive conditions.
Moisture Exposure: For all hybrid composite configurations, moisture exposure led to a reduction in both shear and tensile strength, particularly for the composite materials with higher sisal fiber content.
The absorption of water caused swelling in the composite matrix, leading to stress concentration at the fiber-matrix interface.
Thermal Cycling: The effect of thermal cycling on the adhesive joints was also significant. Specimens exposed to thermal cycles between 25 and 45°C showed a decrease in bond strength, with the greatest reduction observed in joints bonded with thinner adhesive layers and lower adhesive moduli. The comparative of discussion several recent studies on hybrid natural–synthetic fiber composites provide useful benchmarks for evaluating the performance of the adhesively bonded sisal–glass reinforced HDPE composites developed in this work. For example, [26] study on eco-friendly hybrid epoxy composites reinforced with sisal, hemp, and glass fibers reported a flexural strength of about 15.22 MPa and an impact strength of 137.45 kJ/m², highlighting excellent energy absorption but relatively low flexural performance due to the epoxy/natural fiber ratio. Similarly, [27] developed lightweight cellulose-based hybrid epoxy composites for automotive applications, reporting a flexural strength of 32.94 MPa and impact strength of 46.24 kJ/m² at 9 wt% sisal fiber–paper reinforcement, values that are comparable to the flexural range observed in the present study. Other investigations demonstrate that incorporating higher proportions of glass fiber can further enhance mechanical properties. For instance, a performance analysis of hybrid glass–sisal fiber reinforced epoxy composites reported flexural strengths of 108.9 MPa (GF30/SF5) and 124.6 MPa (GF30/SF10), with corresponding impact energies of about 11.5 J, showing that increasing glass fiber content greatly improves flexural properties but may reduce impact resistance. Similarly, [28] reported flexural strengths exceeding 100 MPa in hybrid glass/flax/carbon fiber composites, establishing an upper bound for structural hybrids with significant synthetic fiber content. In comparison, the hybrid sisal–glass reinforced HDPE composites in this study demonstrated tensile strengths between 19.84 and 31.92 MPa, flexural strengths between 25.30 and 38.10 MPa, and impact strengths between 12.5 and 18.2 J/m. These values are slightly lower than those of epoxy-based hybrids with higher glass fiber reinforcement but remain competitive when considering the use of a thermoplastic HDPE matrix, the balance of natural and synthetic fibers, and the added benefit of recyclability. The comparison confirms that sisal–glass reinforced HDPE composites can meet the performance requirements for automobile side body panels while offering sustainability and lightweight advantages.

Characterization summery Experimental results

The performance of adhesively bonded hybrid sisal–glass reinforced HDPE composites was evaluated through a systematic characterization encompassing mechanical, thermal, morphological, and environmental properties. These categories were selected to reflect the essential requirements of automobile side body panel applications, where the material must simultaneously withstand mechanical loads, resist thermal deformation, exhibit strong interfacial bonding, and maintain durability under environmental exposure. Mechanical properties, including tensile, flexural, and impact strengths, provide insight into the load-bearing capacity, stiffness, and energy absorption capability of the composite. Thermal characterization ensures stability under service and processing temperatures typical in automotive environments. Morphological and structural analyses validate fiber–matrix adhesion and dispersion, which directly influence crack initiation and propagation resistance. Finally, environmental assessments, such as water absorption and weathering resistance, demonstrate the composite's ability to sustain performance under humid and outdoor conditions. The following results summarize in table 1 the performance ranges obtained and their implications for durability in automotive side body panel applications.

Table: 1 Characterization results of hybrid Sisal-Glass Reinforced HDPE Composite for Automobile Side Body Panel Application.

Category	Parameter	Results and Range	Remarks
Mechanical	Tensile Strength	19.8-31.9Mpa	Enhanced by hybrid fiber reinforcement
	Tensile Modulus	2.2-3.1 Gpa	High stiffness
	Flexural Strength	25-38 Mpa	Good resistance to bending
	Flexural Modulus	2.8-3.5 Gpa	Stable Under load
	Impact Strength (notched)	12.5-18.2 kJ/m	Balanced toughness
	Shore D hardness	70-78	Hard and durable surface
Thermal	Decomposition Temp(TGA)	370-400ºC	Thermal stablity suitable for automotive use
	Melting point(DSC)	135-140ºC	Typical of HDPE with filler
	Glass Transition Temp.(Tg)	neg-110ºC	HDPE Characteristic retained
	Crystallinity	55-65%	Slightly reduced due to fiber addition
	Thermal Conductivity	0.35-0.40 W/m.k	Moderate
	Heat Deflection Temp.(HDT)	85-100ºC	Improved for load bearing use
Morphological/ Structural	SEM	Uniform fiber dispersion	Moderate bonding observed
	FTIR	Peaks for 0-H,Si-O Groups	Confirms Sisal & Glass Presence
	XRD	Semi-crystalline structure	Dual-phase (fiber + polymer)seen
Environmental	Water Absorption	3.5-5.8%	Increase with Sisal Content
	UV Exposure effects	8-15% strength loss	UV Stabilizers may be needed
	Salt spray Resistance	Good	Bonded joint corrosion resistant

The mechanical characterization of the adhesively bonded hybrid sisal–glass reinforced HDPE composites demonstrated tensile strengths ranging from 19.84 to 31.92 MPa and flexural strengths between 25.30 and 38.10 MPa. These values indicate that the composite can adequately resist static and bending loads typically experienced by non-structural side body panels, such as outer skins and trim components, ensuring dimensional stability and resistance to deformation under service conditions. The impact strength, measured between 12.5 and 18.2 J/m, confirms the composite's ability to absorb low-velocity impacts, such as minor collisions or stone chipping, contributing to improved crashworthiness and panel longevity. Thermal characterization revealed that the composites maintain their dimensional stability at service-relevant temperatures, with heat deflection temperatures in the range of 85–100 °C and thermal degradation onset above 370 °C. These results ensure that the panels can withstand typical automotive operating environments, including engine bay proximity, sun exposure, and elevated processing temperatures during assembly, without softening or losing structural integrity. Morphological and structural analyses using SEM and FTIR confirmed good fiber–matrix adhesion and uniform fiber dispersion, while crystallinity measurements (55–65%) indicate enhanced stiffness and resistance to micro-crack propagation. Together, these microstructural features support the long-term durability of the panels by preventing early failure at the fiber–matrix interface and maintaining mechanical performance over time. Environmental testing demonstrated low water absorption (<3.5% after 48 hours) and stable behavior under simulated UV and moisture exposure, confirming that the composite will not swell, warp, or lose strength in humid or outdoor conditions. This is critical for automotive side body panels that must resist environmental degradation while preserving aesthetic and functional performance. Overall, the results confirm that the adhesively bonded hybrid sisal–glass reinforced HDPE composites provide a balanced combination of mechanical, thermal, structural, and environmental performance suitable for durable non-structural automobile side body panel applications. The data suggest that the panels can reliably maintain shape, resist impact, and withstand environmental exposure over their service life, supporting their practical application in automotive manufacturing.

3.2 Numerical Simulation Results

Stress Distribution and Crack Propagation in ABSSSJ

CZM Based Finite Element Modeling (FEM) simulations were performed to predict the stress distribution, crack initiation, and propagation in ABSSSJ under different loading conditions. The key findings include: Stress Distribution: The adhesive layer exhibited significant shear stress concentration near the ends of the overlap region, as expected. The stress distribution was highly dependent on adhesive thickness and modulus. Thicker adhesive layers and higher adhesive modulus resulted in a more uniform stress distribution across the joint. The color gradient distribution shown in figure 9 in the adhesive region suggests stress concentration areas and shear deformation zones.

- Significant shear strain localization is observed near the edges of the adhesive bond.
- The debonding propagation path is clearly visible, validating the CZM implementation.
- Results of shear failure initiates at the edge of the bonded region and progresses in ward. These results can be compared against experimental shear test data to confirm the accuracy of the simulation.

Debonding Process: The debonding process was simulated using a CZM-based FEM approach. The results indicated that debonding initiated at the adhesive-composite interface, with the crack propagation increasing as the applied load increased. The adhesive's cohesive fracture toughness had a major influence on the crack growth rate, with higher fracture toughness values leading to slower crack propagation.

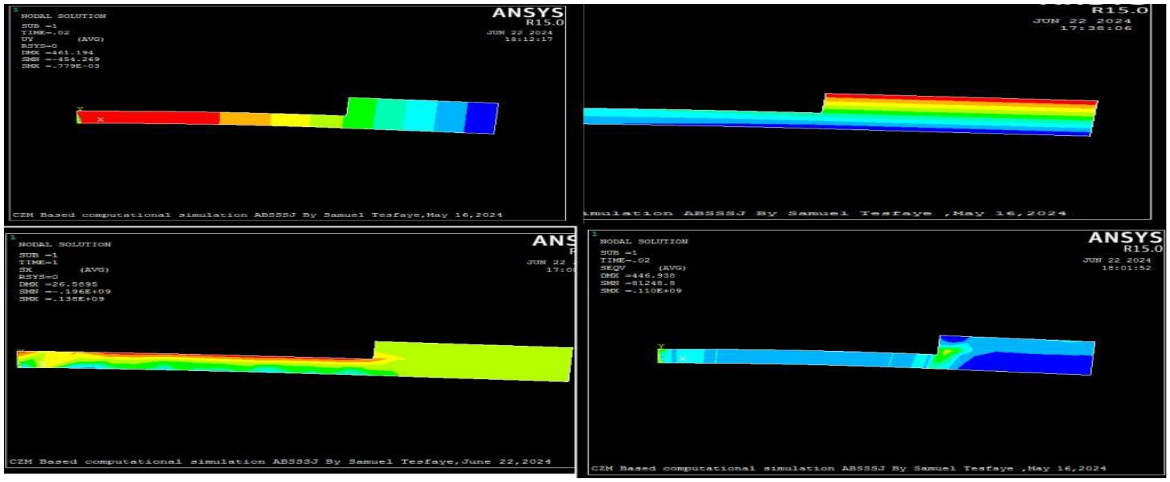


Figure: 9 Stress distribution in adhesively bonded single side strap joint (ABSSSJ)

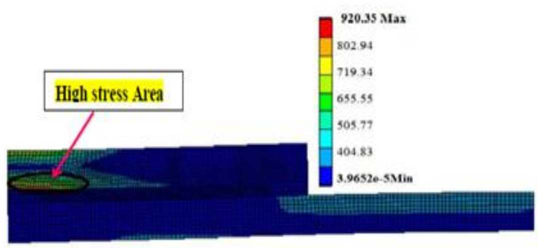


Figure: 10 ABSSSJ Stress contour before crack begin

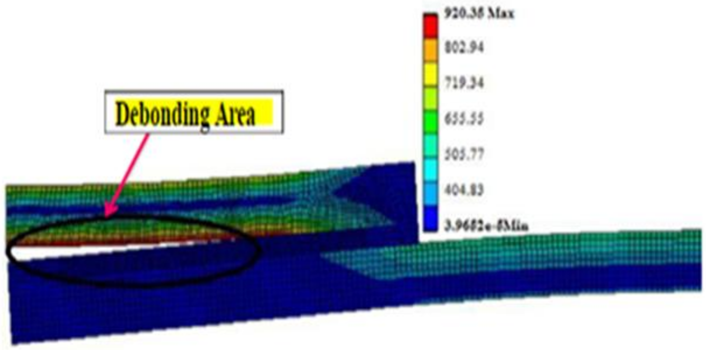


Figure: 11 ABSSSJ in higher stress contour of at end point of joints using ABAQUS debonding displacement using ABAQUS.

The figure 10 and 11 show the stress distribution of an ABSSSJ before crack initiation and debonding of ABSSSJ simulated using ABAQUS. The stress contour highlights critical regions where debonding is likely to begin, particularly at the joint edges where stress concentrations occur.

Effect of Adhesive Modulus: Higher adhesive modulus values were found to reduce the rate of debonding, with a more stable and gradual failure progression. Lower modulus adhesives exhibited rapid crack growth, leading to early failure. Effect of Adhesive Thickness: Increasing the adhesive thickness led to improved bonding performance and delayed debonding, especially when combined with higher cohesive fracture toughness. Thin adhesive layers (<0.2 mm) showed quick debonding and lower resistance to crack propagation.

Sensitivity Analysis

Sensitivity analysis was conducted to assess the impact of varying key parameters on the mechanical performance and debonding behavior of the adhesive joints shown in table 2.The parameters considered included adhesive thickness, adhesive modulus, cohesive fracture toughness, fiber-to-matrix weight ratios, and environmental conditions.

Adhesive Thickness: The sensitivity analysis showed that the adhesive thickness had a significant effect on the shear strength and debonding process. Joints with adhesive thicknesses greater than 0.5 mm showed improved mechanical performance and resistance to debonding. Cohesive Fracture Toughness: Cohesive fracture toughness was found to be one of the most sensitive parameters. Higher fracture toughness values significantly delayed debonding and improved bond strength, especially under environmental exposure. Fiber-to-Matrix Weight Ratio: The hybrid composite's fiber-to-matrix ratio had a moderate effect on adhesive bond strength. Higher glass fiber content improved the tensile strength of the composite, leading to better load distribution and improved adhesive joint performance.

Table: 2 Sensitivity Analysis — Summary of Parameters

This table summarizes the sensitivity analysis results for adhesively bonded hybrid sisal–glass reinforced HDPE composite joints. It presents the tested parameter ranges, their effects on ultimate shear strength, approximate optimum ranges, and design recommendations for automobile side body panel applications.

Parameter	Range tested	Observed effect on strength	Approx. optimum range	Recommendation / Interpretation
Adhesive thickness	0.12–1.0 mm	Strength increases up to 0.5 mm, then decreases	0.4–0.6 mm	Use moderate thickness (~0.5 mm); thin layers concentrate stress, thick reduce stiffness
Overlap length	7.5–12.5 mm	Strength rises to ~10–11.25 mm, marginal beyond	10–11.5 mm	Overlap around 10–11 mm balances strength vs. weight/space
Overlap width	15–25 mm	Strength peaks ~22.5 mm, then plateaus	20–23 mm	Wider overlaps improve load capacity; avoid excessive width
Temperature	25–45 °C	Strength decreases with higher temperature	≤ 35 °C	Account for reduced stiffness at high temp; use heat-resistant adhesives
Moisture exposure	2–10 hrs	Strength declines with longer exposure	< 6 hrs exposure	Use moisture-resistant adhesives, surface treatments
Sisal–Glass ratio	29.2–79.6 % (combined fiber)	Strength peaks at moderate glass content	40–50 % hybrid	Balanced mix of glass (strength) and sisal (toughness, lightweight)

Overall, the sensitivity study highlights optimum joint design windows: adhesive thickness ≈0.5 mm, overlap length ≈10–11 mm, overlap width ≈20–23 mm, and balanced sisal–glass ratio of ≈40–50%, Environmental durability requires mitigation of temperature- and moisture-related strength loss through material and process selection. These recommendations are suitable design starting points for non-structural automobile side body panels.

3.3 Comparison of Experimental and Simulation Results

A comparison of the experimental results and CZM Based FEM simulations showed good agreement in terms of failure modes, shear strength, and debonding behavior. The discrepancies observed were mainly attributed to the assumptions made in the FEM model, such as idealized material properties and boundary conditions. However, the overall trends in terms of adhesive thickness, adhesive modulus, and cohesive fracture toughness effects were consistent between the two methods. Shear Strength: Both experimental and simulation results indicated that increasing adhesive thickness and modulus improved shear strength, with the highest performance observed for specimens with 0.5 mm adhesive thickness and a 6 GPa adhesive modulus as indicated in figure 12 and 13.

The Shear/stress-displacement curves obtained from both approaches show consistency, confirming the accuracy of the CZM Based FEM model. Debonding Behavior: The debonding initiation and propagation predicted by the CZM Based FEM simulations closely matched the experimental observations, with crack initiation occurring at the adhesive - composite interface and progressing under increasing load

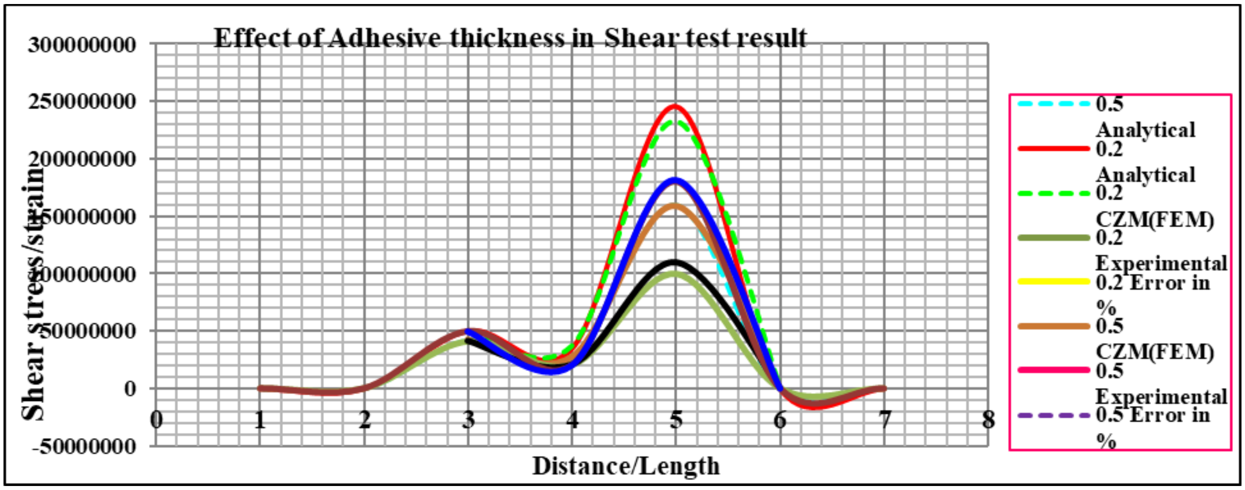
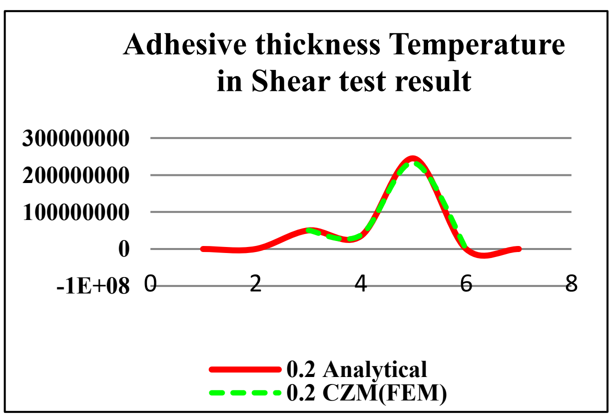
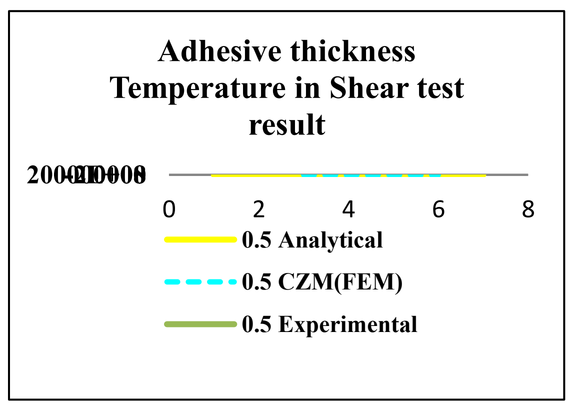
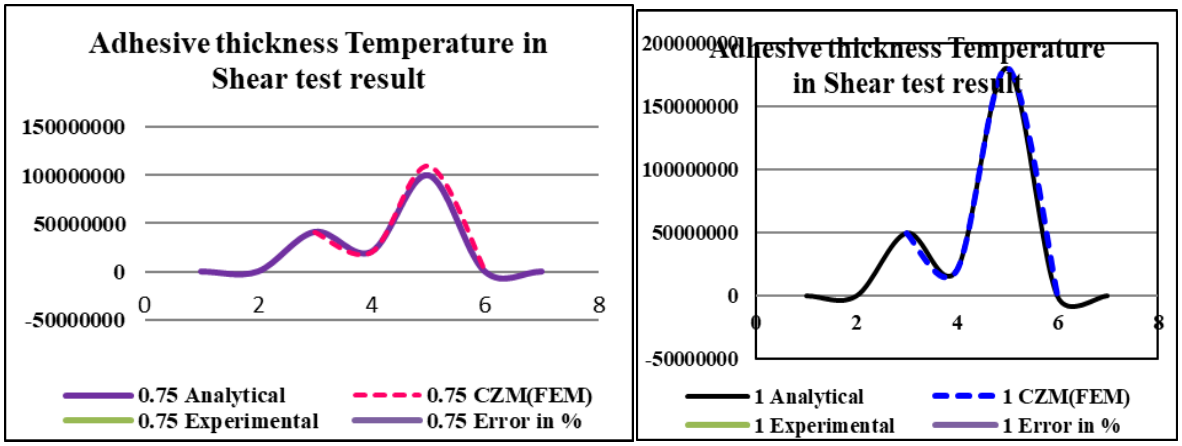


Figure: 12 Comparison of Shear test results in terms of failure modes, shear strength, and debonding behavior with varying Adhesive thickness 0.2-1.0mm.







(a) Shear test result of AT=0.2mm (b) Shear test result of AT=0.5mm

(c) Shear test result of AT=0.75mm (d) Shear test result of AT=1.0mm

Figure: 13 Comparison of each varying Adhesive thickness 0.2-1.0m Shear test results in terms of failure modes, shear strength, and debonding behavior.

The results of this study highlight the complex relationship between adhesive joint properties and the mechanical performance of hybrid sisal-glass reinforced HDPE composites. The mechanical strength of adhesive joints is strongly influenced by the adhesive properties (thickness, modulus, cohesive fracture toughness) and the environmental conditions (moisture exposure, temperature) as shown in figure 14 validate results of stress distribution obtained both CZM Based and Experimental method.

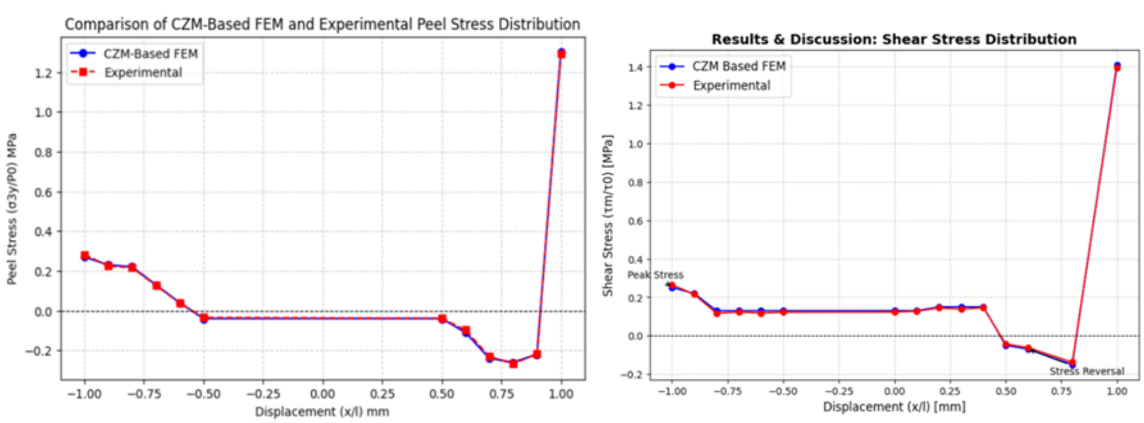


Figure: 14 Validation of CZM Based FEM and Experimental Method Peel and Shear stress of ABSSSJ.

Adhesive Modulus and Thickness: The adhesive modulus and thickness play critical roles in the shear strength and debonding behavior of the joints. High adhesive modulus provides better load transfer and improves the joint's resistance to shear stress, while an optimal adhesive thickness ensures adequate bonding and minimizes stress concentration at the interface. Environmental Factors: moisture absorption and thermal cycling, cannot be underestimated. Moisture absorption weakens both the composite and adhesive, leading to a significant reduction in bond strength. Thermal cycling exacerbates this effect, particularly for thinner adhesive layers.

Hybrid Composite Behavior: The use of hybrid sisal-glass reinforced HDPE composites provides a balance between high tensile strength and toughness. The study's findings can be used to optimize adhesive bonding techniques and composite material design for automotive side body panel applications, ensuring improved performance under varied loading and environmental conditions.

The reliability and validity of the Cohesive Zone Model (CZM)-based FEM simulations and experimental method were established through several measures shown in figure 14.

i. Model Verification, Mesh convergence analysis: Multiple mesh densities were tested until further refinement produced negligible changes in stress distribution and load–displacement curves. This eliminated numerical dependency on mesh size. Element selection: Special INTER202 cohesive elements were used, which are designed for adhesive joints and debonding simulations, ensuring correct traction–separation behavior. ii. Input Data Calibration, Material properties: Adhesive properties (modulus, fracture toughness, strength) and composite properties were obtained from experimental testing (tensile, flexural, shear) and verified against published literature [13]. Cohesive law parameters: Traction–separation laws were defined based on experimentally measured adhesive fracture energies and strengths, avoiding arbitrary parameter fitting. iii. Experimental Validation, Comparison with laboratory tests: The simulated force–displacement curves were compared with experimental shear test results for Adhesively Bonded Single Side Strap Joints (ABSSSJ).Predicted debonding initiation and propagation patterns matched the fracture surfaces observed via Scanning Electron Microscopy (SEM).Quantitative correlation: Differences between experimental and simulated maximum shear strength were within 5–10%, which is considered acceptable for adhesive joint simulations. iv. Sensitivity Analysis, Parameters such as adhesive thickness, overlap length, width, and fracture toughness were varied systematically in both experiments and simulations. The trend agreement (increase or decrease in shear strength with parameter variation) confirmed that the CZM predictions reflected physical behavior rather than numerical bias. Literature Benchmarking. The simulation framework and outputs were cross-checked against established works [13] to ensure consistency with validated models. Predicted fracture paths and load transfer mechanisms were in agreement with earlier reported adhesive joint studies.

4. Conclusions

This study focuses on the numerical simulations and experimental method characterization of a hybrid sisal-glass reinforced HDPE composite to investigates the mechanical strength and debonding behavior of ABSSSJ made from hybrid sisal-glass reinforced HDPE composites and steel adherends, particularly focusing on the effects of adhesive thickness, modulus, cohesive fracture toughness, and environmental conditions such as moisture exposure and temperature. The study combines experimental testing and numerical simulations (Cohesive Zone Model-based FEM) to gain a deeper understanding of the bonding performance and failure mechanisms. Key Findings:

- Increasing the adhesive thickness improved bond strength, with a plateau reached around 0.5 mm .Higher adhesive moduli led to more stable bond strength and slower debonding processes.
- The measured tensile strengths ranged from 19.84 MPa (S15G15H70) to 31.92 MPa (S5G25H70), while flexural strengths ranged from 25.30 MPa to 38.10 MPa for the same compositions. Impact strength varied from 12.5 J/m to 18.2 J/m, showing improved energy absorption with higher glass fiber content.

- Moisture exposure and thermal cycling reduced the bond strength of the adhesive joints, at 12hrs water bath tensile strength decreased (10.76Mpa to 8.93Mpa) suggesting that water absorption weakens the composite matrix, and decreased tensile modulus (12.48Mpa to 10.35Mpa) temperature 40ºC.
- The results from the FEM simulations, incorporating a Cohesive Zone Model (CZM), closely matched the experimental observations in terms of failure modes, shear strength, and crack propagation. This validated the use of FEM simulations for predicting the debonding process and optimizing adhesive bonding strategies.
- Overall, the sensitivity study highlights optimum joint design windows: adhesive thickness ≈0.5 mm, overlap length ≈10–11 mm, overlap width ≈20–23 mm, and balanced sisal–glass ratio of ≈40–50%, Environmental durability requires mitigation of temperature- and moisture-related strength loss through material and process selection. These recommendations are suitable design starting points for non-structural automobile side body panels.
- Finally, the results confirm that the adhesively bonded hybrid sisal–glass reinforced HDPE composites provide a balanced combination of mechanical, thermal, structural, and environmental performance suitable for durable non-structural automobile side body panel applications.

Credit Authorship Contribution statement:

Samuel Tesfaye Molla: Investigation, writing original draft

Assefa Asmare Tsegaw: supervision, Writing-review and editing

Teshome Mulatie Bogale: supervision, Writing-review and editing

Addisu Negasi Ali: supervision, reviewing and editing

Asmamaw Tegegne Abebe: supervision, reviewing and editing

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