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Tensile Strength of Adhesively Bonded Steel to Hybrid Sisal-Glass Reinforced HDPE Composite Joint for Automobile Side Body Panel Application

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Abstract. *The increasing demand for lightweight, high-performance, and environmentally sustainable materials in the automotive industry has accelerated the adoption of adhesive bonding as an alternative to conventional joining techniques such as welding and mechanical fastening. Reliable prediction of stress distribution and debonding behavior in adhesively bonded composite–metal joints is therefore essential to ensure structural integrity under service loading. This study presents a comprehensive computational and experimental investigation of the tensile stress behavior of adhesively bonded single-side strap joints (ABSSSJ) formed between steel and hybrid sisal–glass reinforced high-density polyethylene (HDPE) composites for automobile side body panel applications. The hybrid composite adherend was modeled as an orthotropic laminate with a ([0°/+45°/90°/–45°/0°]) stacking sequence, while the adhesive layer was characterized using different epoxy systems (Araldite 2020, Araldite 2015, and AV138) with thicknesses ranging from 0.12 to 1.0 mm and elastic moduli between 1.85 and 6 GPa. An analytical variational method was employed to evaluate shear and peel stress distributions, and the results were verified using a cohesive zone model (CZM)-based finite element approach to simulate crack initiation and progressive debonding. Experimental tensile and shear tests were conducted to validate the numerical predictions. The results indicate that an adhesive thickness of approximately 0.75 mm provides an optimal balance between load transfer efficiency and stress reduction at the overlap edges. The numerical and analytical predictions exhibited strong agreement with experimental measurements, with a maximum deviation below 6%. The validated results demonstrate that hybrid sisal–glass reinforced HDPE composites, when combined with appropriate adhesive and joint design, offer a promising, lightweight, and sustainable solution for automotive side body panel structures.*

Keywords: *Tensile Strength; Adhesive Bonding; Cohesive Zone Model (CZM); Hybrid sisal-glass reinforced HDPE; Environmental effects.*

Type of the Paper: Regular Article.

1. Introduction

Adhesive bonding has become a key joining technology in modern automotive structures, particularly in lightweight and multi-material assemblies, due to its ability to distribute stresses uniformly, reduce stress concentrations, and contribute to overall vehicle mass reduction [1,2]. These advantages directly support global efforts to improve fuel efficiency and reduce greenhouse gas emissions. In this context, hybrid polymer composites combining natural and synthetic fibers

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have attracted increasing attention. Sisal–glass fiber reinforced high-density polyethylene (HDPE) composites represent a sustainable material solution, integrating the renewability and low density of natural fibers with the mechanical robustness of glass fibers [3,4]. Such hybridization improves stiffness, strength, and durability while maintaining environmental benefits, making these materials attractive for semi-structural automotive body components. When hybrid composites are adhesively bonded to conventional automotive steels, the resulting dissimilar material joints introduce complex interfacial stress states and failure mechanisms [5,6]. Understanding tensile strength development and debonding behavior in such joints is therefore essential for ensuring structural reliability in service.

Previous investigations have examined the mechanical performance of adhesively bonded joints using different adhesive systems, surface treatments, and joint geometries [7,8]. Key parameters such as adhesive layer thickness, overlap length, and adherend stiffness have been shown to strongly influence load transfer and failure modes. However, most existing studies primarily address metal–metal or composite–composite joints, with comparatively limited emphasis on steel-to-hybrid polymer composite interfaces relevant to automotive body panel applications [9,10]. Advances in numerical modeling, particularly Cohesive Zone Model (CZM)-based finite element analysis (FEA), have provided powerful tools for simulating interfacial damage initiation and progressive debonding in adhesively bonded joints [11,12]. CZM approaches enable a more realistic representation of failure processes compared to traditional strength-based criteria. The present study focuses on the tensile performance and debonding characteristics of adhesively bonded single-side strap joints (ABSSSJs) formed between structural steel and hybrid sisal–glass reinforced HDPE composites. Both experimental testing and CZM-based numerical simulations are employed to evaluate joint behavior under tensile loading. The effects of adhesive thickness, fiber-to-matrix weight ratio, and selected environmental conditions are systematically examined. The outcomes of this work provide design-relevant insights into the feasibility of using hybrid natural–synthetic fiber composites in adhesively bonded automotive side body panel applications, contributing to the broader adoption of sustainable polymer composite solutions in the automotive sector [13,14].

General Background and Justification, as a Background Adhesively bonded joints are widely used in the automotive industry due to their ability to provide high strength-to-weight ratios, which is crucial for reducing vehicle weight and enhancing fuel efficiency [1]. The use of composite materials, such as hybrid sisal-glass reinforced HDPE, has become increasingly popular for automotive applications because of their environmental sustainability and superior mechanical properties [3,15]. These materials combine the advantages of natural fibers, such as sisal, with the durability of glass fibers, making them an ideal candidate for lightweight automotive body panels

[5]. Adhesive bonding, particularly in single-side strap joints (ABSSSJ), offers a viable solution for joining dissimilar materials like steel and composite materials, which is common in automobile manufacturing [7]. The mechanical properties of these joints, including tensile strength, shear strength, and debonding behavior, are influenced by several factors such as adhesive thickness, fiber-to-matrix weight ratio, and surface treatment [9,14]. While much research has been dedicated to improving the performance of adhesive bonding systems, challenges remain in optimizing these parameters for automotive applications.

The Justification of the study, the growing need for lightweight and sustainable materials in automotive manufacturing presents a strong justification for studying the mechanical performance of adhesively bonded joints using hybrid composite materials. The automotive industry faces strict regulatory requirements to reduce emissions, necessitating the development of advanced materials that can reduce vehicle weight without compromising safety or structural integrity [10]. Hybrid composites offer the potential to meet these requirements, but their successful application depends heavily on the performance of the adhesive bonding systems, which are often the weakest link in the joint [6]. Furthermore, the performance of these joints under various conditions, such as exposure to moisture, temperature fluctuations, and different surface finishes, remains insufficiently understood [13]. Addressing these gaps is critical for optimizing adhesive bonding techniques and ensuring that hybrid composite materials can be effectively used in automobile side body panels and other structural components. This study aims to fill these gaps by focusing on the tensile strength and debonding behavior of ABSSSJs under a range of environmental and material conditions, providing valuable insights into their practical application in automotive manufacturing.

Background Gap of the study, despite the extensive body of research on adhesively bonded joints, there are notable gaps in understanding the full mechanical performance of ABSSSJs, particularly when applied to hybrid composite materials like sisal-glass reinforced HDPE [11,15]. Existing studies have primarily focused on either steel-to-steel or composite-to-composite bonding, with limited exploration of the steel-to-hybrid composite interface [4]. Additionally, the role of key factors such as adhesive thickness, overlap length, and fiber-to-matrix weight ratio on the tensile strength and debonding behavior of these joints has not been comprehensively studied, particularly under the environmental conditions relevant to automotive applications [5]. There is also a lack of integration between experimental data and advanced numerical modeling techniques, such as Cohesive Zone Model (CZM)-based finite element analysis (FEA), to predict the full-range debonding behavior of these joints [11]. As a result, a more comprehensive understanding of the mechanical behavior of ABSSJs, including the effects of moisture exposure, temperature variations, and surface finish, is necessary to guide the design of effective adhesive bonding systems for hybrid composite.

Comprehensive review of the existing literature on the mechanical behavior and failure modes of adhesively bonded joints (ABSSSJ), with a particular focus on hybrid composite materials such as sisal-glass reinforced HDPE for automotive applications. It also discusses the role of environmental conditions, material properties, and numerical modeling techniques, particularly the Cohesive Zone Model (CZM), in predicting debonding behavior.

Literature review Research Gaps, despite significant advancements in adhesive bonding technology, several research gaps remain. These include: Lack of Comprehensive Studies on Hybrid Composites: While there is considerable research on the mechanical behavior of glass fiber composites, studies focusing on hybrid sisal-glass reinforced HDPE composites in the context of adhesive bonding are limited. Further exploration is needed to understand the unique bonding challenges posed by these materials. Environmental Effects on Hybrid Composites: Although environmental factors are known to influence adhesive performance, studies that specifically examine the effects of temperature, moisture, and other environmental conditions on hybrid composite joints are sparse. Advanced Numerical Models: While CZM-based FEA has been widely used in adhesive bonding studies, there is a need for more advanced models that account for the complex interactions between adhesives and hybrid composite materials, as well as environmental degradation effects. Experimental Validation of Numerical Models: A gap exists between numerical simulations and experimental validation, especially for hybrid composite materials. There is a need for more experimental data to validate and refine numerical models. This literature review has highlighted the key advancements and challenges in the field of adhesive bonding, particularly concerning hybrid sisal-glass reinforced HDPE composites and automotive applications. The gaps identified here will guide the focus of the current study, which aims to address some of these challenges and advance the understanding of the mechanical performance of adhesively bonded joints under varying conditions.

Statement of the Problems are the primary challenges faced in the application of adhesively bonded joints in automotive side body panels involve the lack of comprehensive understanding of the factors affecting the mechanical performance of these joints. Specifically: Insufficient Data on Hybrid Composite Joints: There is limited research on the mechanical performance of adhesively bonded joints between steel and hybrid sisal-glass reinforced HDPE composites, particularly concerning tensile strength and debonding behavior under real-world conditions [11]. Uncertainty in Influence of Key Parameters: The effects of adhesive thickness, overlap length, moisture exposure, temperature fluctuations, and surface finish on the tensile strength and failure mechanisms of these joints are not well understood [9,10]. Lack of Comprehensive Modeling

Approaches: While Cohesive Zone Model (CZM)-based finite element analysis (FEA) has shown promise in simulating debonding behavior, there is a gap in fully integrating experimental results with advanced numerical models to predict the performance of adhesively bonded joints in hybrid composite materials for automotive applications [2,11].

Environmental Effects: The influence of environmental conditions, such as temperature and moisture, on the performance of these joints in automotive applications has not been adequately explored [5].

The main objectives of this study are to: Evaluate, Investigate the tensile strength and debonding behavior of adhesively bonded single-side strap joints (ABSSSJ) between steel and hybrid sisal-glass reinforced HDPE composite for automobile side body panel applications. Specific Objectives: Assess the Influence of Key Parameters: Examine the effects of adhesive thickness, overlap length, fiber-to-matrix weight ratio, temperature, moisture exposure, and surface finish on the mechanical performance of the joints, Develop and Validate Numerical Models: Employ Cohesive Zone Model (CZM)-based finite element analysis (FEA) to simulate the debonding process and validate the results with experimental data, Investigate Environmental Effects: Study the influence of temperature and moisture exposure on the tensile strength and failure mechanisms of ABSSSJs, replicating real-world conditions that the joints might face in automotive applications, Provide Design Guidelines: Provide critical insights and design recommendations for optimizing adhesive bonding systems in hybrid composite materials for automotive side body panels, ensuring the reliability and durability of the joints.

2. Materials and methods

This section describes the experimental procedures and numerical modeling framework adopted to evaluate the mechanical performance and debonding behavior of adhesively bonded single-side strap joints (ABSSSJs) formed between mild steel and hybrid sisal–glass reinforced HDPE composite adherends. A combined experimental–numerical approach was employed to investigate tensile strength, force–displacement response, and progressive debonding under the influence of adhesive thickness, fiber-to-matrix ratio, overlap length, temperature, and moisture exposure, as summarized in Table 1.

2.1 Materials and Composite Preparation

The lower adherend of the joint was fabricated from a hybrid sisal–glass reinforced high-density polyethylene (HDPE) composite, while the upper adherend consisted of automotive-grade mild steel. Recycled HDPE (density: 0.96 g/cm³) was sourced locally, washed, dried, and pelletized prior to compounding. Hybrid fiber reinforcement was achieved using sisal and E-glass fibers with varying fiber-to-matrix weight ratios, namely S15G15H70, S5G25H70, S10G20H70, S25G5H70, and S20G10H70, corresponding to total fiber contents of 29.2%, 34.6%, 42.4%, 48.7%, and 79.6%, respectively. Two stacking configurations were investigated to examine hybridization effects: Glass–Sisal–Glass (G–S–G), and Sisal–Glass–Glass (S–G–G). Both configurations were arranged in a [0°/+45°/90°/−45°/0°] lay-up sequence to ensure laminate symmetry and in-plane balance. E-glass fibers (2400 tex unidirectional roving, tensile strength 3.45 GPa, modulus 72 GPa) were supplied by Owens Corning, while sisal fibers (25–30 mm length, tensile strength ≈530 MPa, modulus ≈14 GPa) were locally extracted. To enhance fiber–matrix adhesion, sisal fibers were alkali-treated in a 5 wt.% NaOH solution for 3 h, rinsed thoroughly, and oven-dried at 80°C for 24 h. Composite laminates were fabricated using compression molding in a Carver hydraulic press at 180°C under 6 MPa pressure, with a 10 min dwell time, followed by controlled cooling at 3°C/min. Fiber mats were stacked in a steel mold ($150 \times 25 \times 3$ mm³) to achieve uniform thickness and fiber distribution.

Table. 1 Physical, Mechanical Properties and parameters of ABSSSJ for VM, and CZM Based FEM.

Properties	Material -1	Material -2			Material -2		
	(upper)Adherend	Adhesive			(Lower)Adherend		
	frame Mild steel	Araldite 2015	Araldite 2020	Araldite AV 138	Body Hybrid Composite		
					Sisal	E-Glass	HDPE
Young Modulus (E)(Gpa)	200	1.85	2.57	3.5	16	70	1.35
Poission Ratio (γ)	0.29	0.33	0.38	0.35	0.35	0.22	0.3
Tensile yield Strength (σy) (Gpa)	0.27	0.021	0.031	0.069	0.5	3.5	0.032
Shear modulus along plane (Gxy) (Gpa)	35	0.56	1.18	1.56	1.817	3.5	3.3
Density (δ) g/cm3	7.85	1.1	1.2	1.25	1.5	2.5	0.96
Material Models	Linear-Elastic	Linear-Elastic	Linear-Elastic	Linear-Elastic	Non Linear-Inelastic-Bilinear		
Materials	Isotropic-Plane 182	Cohesive Element INTER 202			Orthotropic-Shell 181		
Length(mm)	25,half (12.5)	Bond length (half)=12.5,free edge length=22.5			70 ,half(35)		
Thickness(mm)	steel 2	Adhesive thickness 0.12,0.2,0.5,0.75 and 1			Hybrid composite 2		
debonding toughness	GIC = 0.25, 0.5, 0.75, and 1.0kJ/m2,GIIC = 1.5GIC						
Adhesive to Adherends thickness ratio (ho/h2) mm	0.1, 0.25, 0.375, and 0.5						

2.2 *Adhesive and Surface Preparation*

A two-part epoxy adhesive (Araldite 2015, Araldite 2020. And AV138, Huntsman Advanced Materials) was selected due to its proven performance in automotive structural bonding applications. The adhesive was mixed at a 100:50 resin-to-hardener weight ratio and cured at 80°C for 2 h under 0.1 MPa pressure, followed by post-curing at room temperature for 24 h. Adherend surfaces were mechanically abraded using silicon carbide sandpapers with grit sizes 40, 60, 80, 100, and 120 to investigate the influence of surface roughness. All surfaces were subsequently cleaned with acetone to remove contaminants and ensure consistent bonding conditions. The adhesive layer thickness (h_0) was controlled using calibrated spacers and varied as 0.12, 0.20, 0.50, 0.75, and 1.00 mm.

2.3 Experimental Testing

Mechanical testing was conducted to evaluate tensile, shear, and debonding behavior of the ABSSSJs. Tensile and lap shear tests were performed using a Universal Testing Machine (Instron 3369) equipped with a 50 kN load cell, under displacement-controlled loading at 1 mm/min. Testing procedures followed ASTM D3039 (tensile), ASTM D1002 (lap shear), and ASTM D3163 (peel) standards. Each joint configuration was tested at least three times (n = 3) to ensure reproducibility. Force–displacement curves and strain data were continuously recorded.

2.4 Environmental Conditioning

To simulate realistic automotive service conditions, specimens were subjected to controlled environmental exposure prior to testing: Temperature levels: 25, 30, 35, 40, and 45°C. Moisture exposure durations: 2, 6, 8, 9, and 12 h in distilled water. Following conditioning, specimens were immediately tested to minimize recovery effects. Failure modes were classified as adhesive, cohesive, or mixed, based on post-fracture visual inspection and microscopy.

2.5 Numerical Simulation Using CZM-Based FEM

Numerical simulations were performed using ANSYS to predict the full-range debonding behavior of ABSSSJs. The Cohesive Zone Model (CZM) was employed to capture crack initiation and propagation within the adhesive layer. The steel adherend was modeled as an isotropic elastic material, while the hybrid composite adherend was treated as an orthotropic nonlinear material with bilinear stress–strain behavior. The adhesive layer was represented using cohesive interface elements (INTER202). Composite adherend: SHELL181. Steel adherend: PLANE182. Adhesive layer: INTER202. A mesh convergence study was conducted, with local refinement applied in the overlap region to ensure numerical accuracy.

2.6 Boundary Conditions and Material Parameters

Boundary conditions replicated the experimental setup, with one end fixed and controlled displacement applied at the opposite end. Cohesive parameters were defined as: Adhesive modulus (E_a): 1.85, 2.5, and 6.0 GPa. Mode I fracture toughness (G_IC): 0.25–1.0 kJ/m². Temperature and moisture effects were incorporated through degradation factors, derived from experimental trends. Simulation outputs included peel stress (σ_γ), shear stress ($\tau_{x\gamma}$) distributions, force–displacement response, and crack propagation length.

2.7 Model Validation

The numerical predictions were validated by comparison with experimental results and Variational Method (VM) analytical solutions. Model accuracy was quantified using Root Mean

Square Error (RMSE) and percentage deviation, which remained within ±10%, confirming strong agreement and predictive reliability of the CZM-based FEM framework.

3. Results and Discussion

This section presents a detailed discussion of the experimental and numerical findings obtained for adhesively bonded single-side strap joints (ABSSSJs) joining hybrid sisal–glass reinforced HDPE composite (lower adherend) to steel (upper adherend). The joint performance is evaluated in terms of tensile and shear strength, force–displacement response, failure mechanisms, and debonding behavior, considering both laboratory testing and CZM-based numerical simulations under varying geometric, material, and environmental parameters.

3.1 Tensile Strength and Force-Displacement Behavior

Experimental tensile results demonstrate that joint strength is highly sensitive to adhesive thickness, overlap length, and fiber-to-matrix composition. An increase in adhesive thickness led to a progressive rise in tensile strength up to an optimal value of 0.5 mm, beyond which the strength plateaued or marginally declined (Fig. 1).

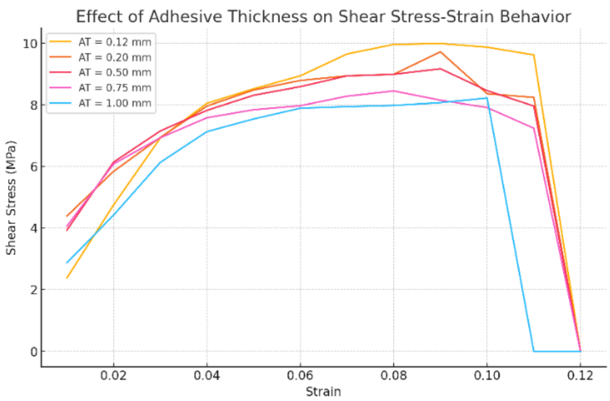


Fig. 1. Shears stress vs strain effect of adhesive thickness (AT) in ABSSSJ

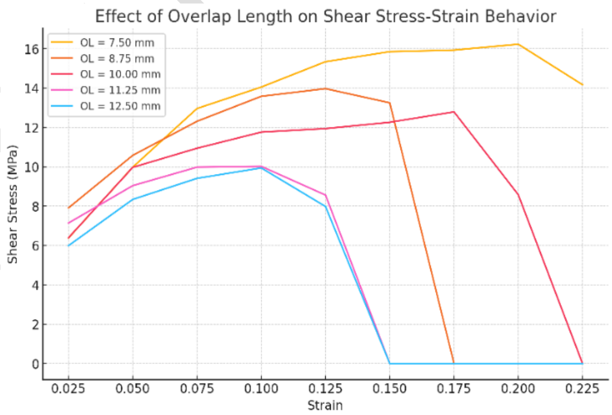


Fig. 2. Shear stress vs strain plot effect overlap length in ABSSSJ.

This trend indicates a balance between stress transfer efficiency and adhesive compliance, where excessively thick adhesive layers promote stress redistribution and premature interfacial deformation. The maximum tensile load was achieved for joints with an overlap length of 10 mm combined with a balanced hybrid composition (S10G20H70), as illustrated in Fig. 2 and Fig. 3. This confirms the critical role of joint geometry and hybrid fiber synergy in optimizing load-bearing capacity. Force–displacement curves exhibited an initial linear elastic response followed by a sudden load drop, corresponding to the onset of debonding and crack initiation within the adhesive layer. Stress–strain responses for different adhesive thicknesses (0.2–1.0 mm) revealed that thinner adhesive layers (0.2–0.5 mm) provided higher stiffness and improved load transfer, whereas thicker layers showed increased nonlinearity prior to failure (Fig. 6). These observations are consistent with previous findings reported for polymer-based hybrid composite joints [16,17].

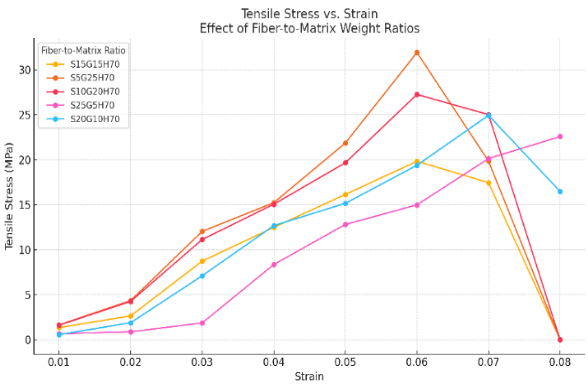


Fig. 3. Tensile stress vs strain effect of fiber to matrix weight ratios in ABSSSJ.

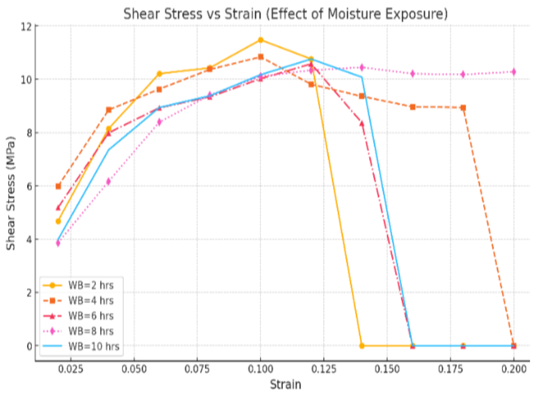


Fig. 4. Shear stress vs strain effect of moisture in ABSSSJ.

Environmental conditioning significantly reduced tensile performance, particularly under combined moisture and elevated temperature exposure. Specimens subjected to 12 h water immersion and 45 °C exhibited earlier debonding and reduced peak loads (Fig. 4 and Fig. 5). The degradation is attributed to adhesive plasticization, fiber–matrix interfacial weakening, and molecular relaxation within the polymer system, consistent with hydrothermal degradation mechanisms reported in hybrid natural–synthetic composites [18]. Joints with lower natural fiber content (e.g., S5G25H70) showed relatively better resistance to moisture-induced degradation.

3.2 Shear Test Results

Shear test results revealed a clear dependence of failure mode on adhesive thickness and overlap length. At lower adhesive thicknesses (0.12–0.5 mm), cohesive failure within the adhesive layer dominated, indicating effective stress distribution and energy dissipation. In contrast, thicker adhesive layers (≈1 mm) predominantly exhibited adhesive failure at the steel–composite interface, as shown in Fig. 6. Shear strength increased with overlap length up to approximately 10–12.5 mm, beyond which additional overlap provided marginal improvement (Fig. 7).

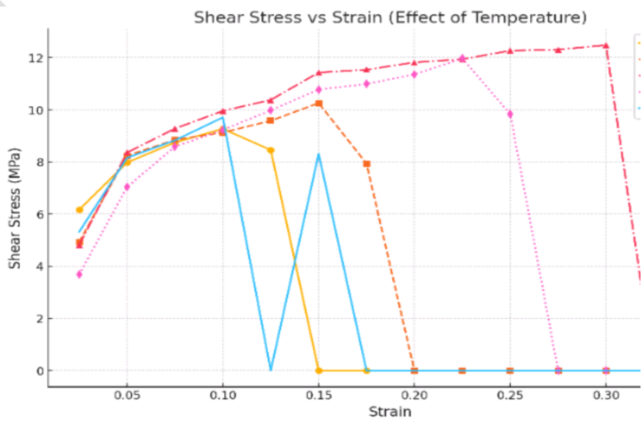


Fig. 5. Shear stress vs strain plot graph effect of temperature in ABSSSJ.

This saturation behavior suggests a limitation in effective stress transfer beyond a critical overlap length, a trend also observed in glass/epoxy bonded joints [19]. Shear stress–strain curves further indicated a reduction in shear modulus and yield stress with increasing temperature, confirming the temperature-sensitive viscoelastic behavior of the adhesive system. These findings align with reported thermal softening behavior in sisal–glass hybrid composites [20].

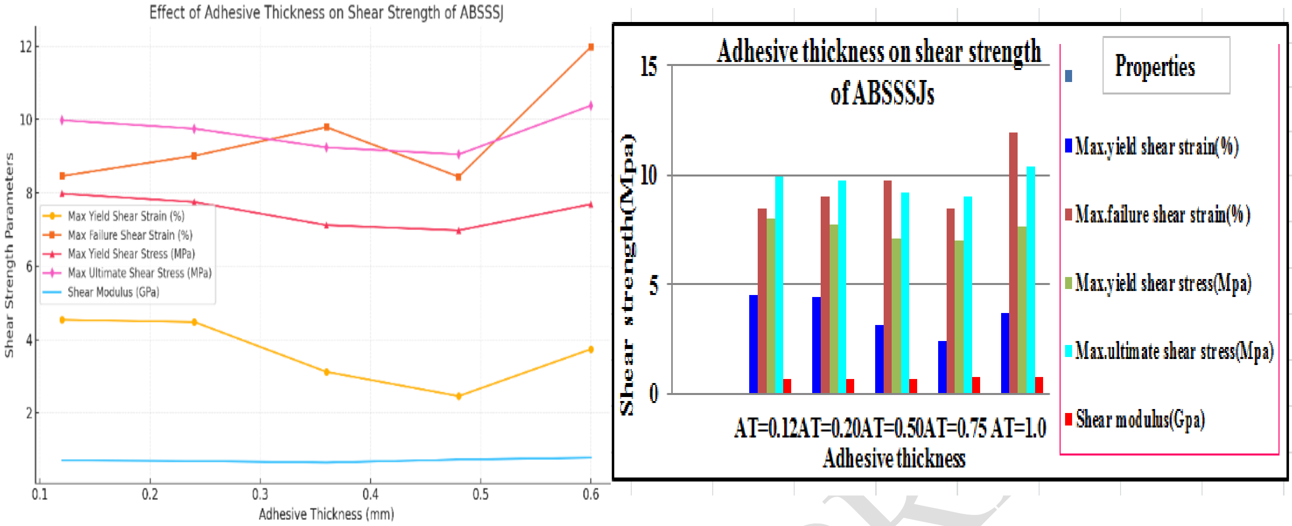


Fig. 6. Effects of adhesive thickness in failure mode of shear strength in ABSSSJ.

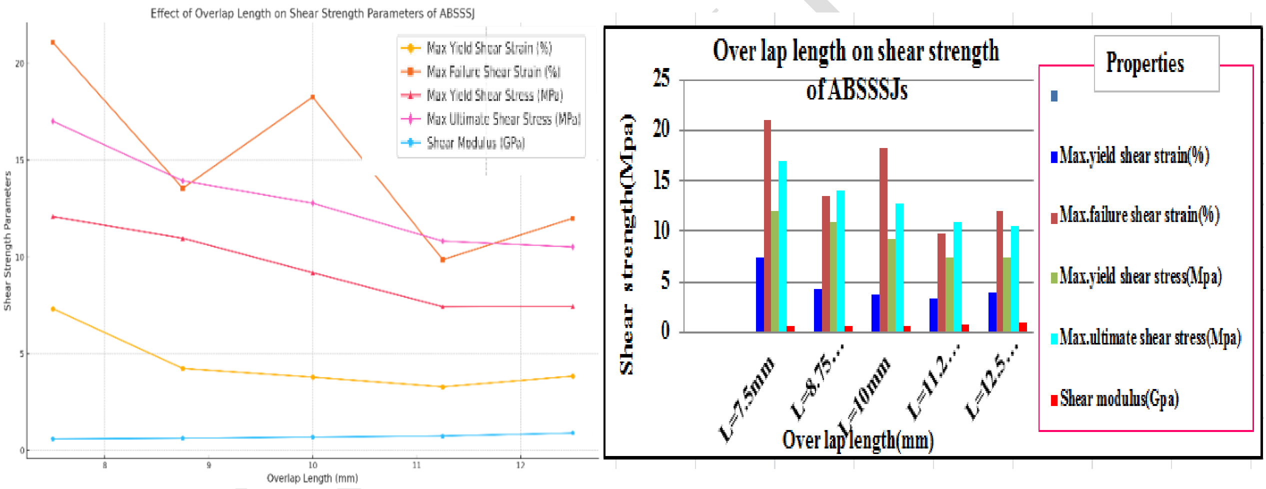


Fig. 7. Effects of overlap length in failure modes of shear strength in ABSSSJ.

3.3 *Numerical Simulation Results*

Cohesive Zone Model (CZM)-based finite element simulations were performed using ANSYS to replicate tensile and shear loading conditions. Boundary conditions were defined to accurately reproduce experimental constraints, with one end of the joint fixed and controlled displacement applied at the opposite end. The adhesive layer was discretized using INTER202 cohesive elements, with mesh refinement set to one-tenth of the adhesive thickness (1/10 h_0) to ensure numerical stability. Mesh convergence analysis (1/5, 1/10, and 1/20 h_0) confirmed that stress distributions and crack initiation locations were insensitive to further refinement, validating the numerical approach. Fig. 8 illustrates the CZM-based simulation under tensile loading, while Fig. 9 and Fig. 10 show von Mises stress contours before crack initiation and during crack propagation, respectively. The numerical force–displacement curves (Fig. 11) closely matched experimental responses, accurately capturing the elastic region, damage initiation, and progressive softening associated with adhesive debonding. The bilinear traction–separation law effectively modeled the nonlinear fracture behavior of the adhesive layer, in agreement with previous CZM studies [17,18].

3.4 Debonding Behavior and Crack Propagation

CZM simulations successfully predicted both the initiation and propagation of debonding within the adhesive layer. Crack initiation consistently occurred near the overlap edges, where stress concentrations were highest, followed by stable crack growth toward the joint center (Fig. 9 and Fig. 10). This behavior closely mirrored experimental fracture patterns, confirming the reliability of the numerical model in capturing full-range debonding behavior.

Overall Discussion: The combined experimental–numerical framework demonstrates that an adhesive thickness of approximately 0.5 mm, an overlap length of 10 mm, and a balanced hybrid fiber configuration (S10G20H70) provide optimal joint performance. Environmental exposure remains a critical degradation factor, emphasizing the need for moisture-resistant adhesive systems for automotive applications.

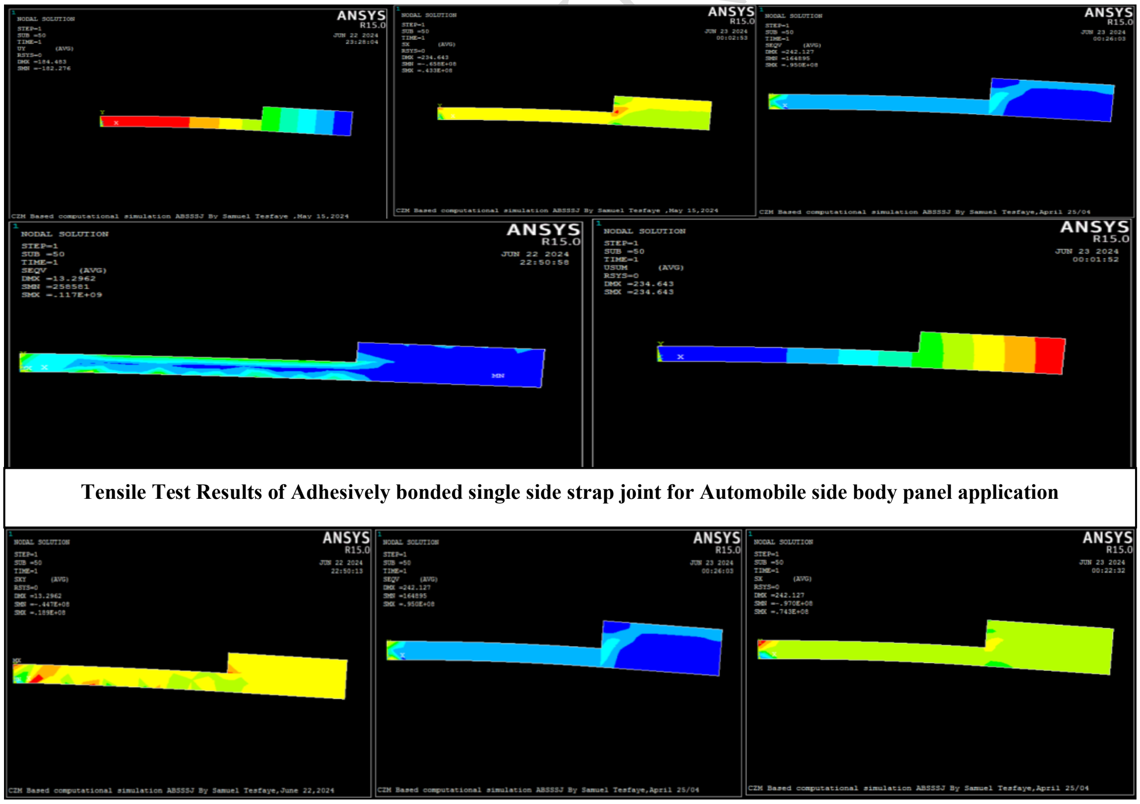


Fig. 8. CZM Based FEM Simulation under tensile load test of ABSSSJ.

The characteristic force-displacement diagrams during the entire debonding process of the joint are plotted at varying adhesive layer thickness and fixed adhesive elastic modulus and debonding toughness the figure as shown in Fig. 11. The detailed scaling analysis here provides the clear evidence of the impact of the adhesive layer thickness on the full-range force-displacement diagram and the failure of bonded joints. The computational scaling analysis indicates that ABJs with the lower adhesive layer thickness provides better debonding strength and mechanical properties.

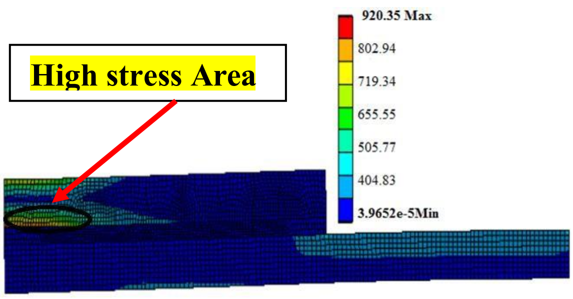


Fig. 9. ABSSSJ Stress contour before crack of a begin at end point of joints using ABAQUS.

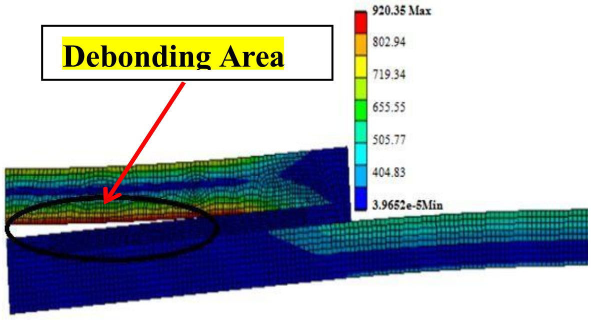
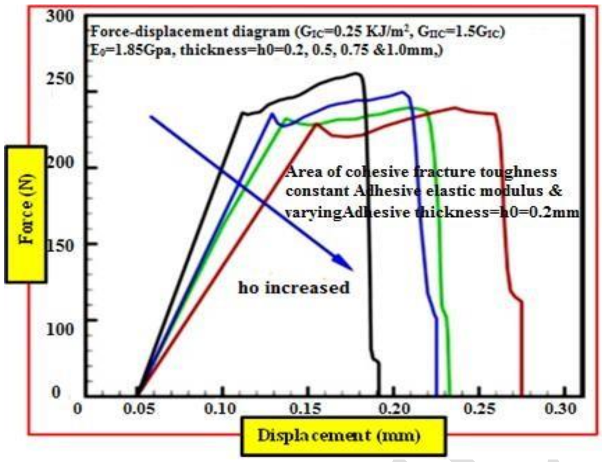
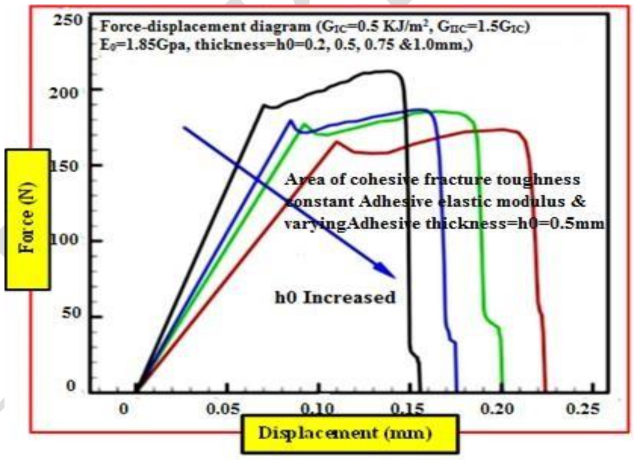


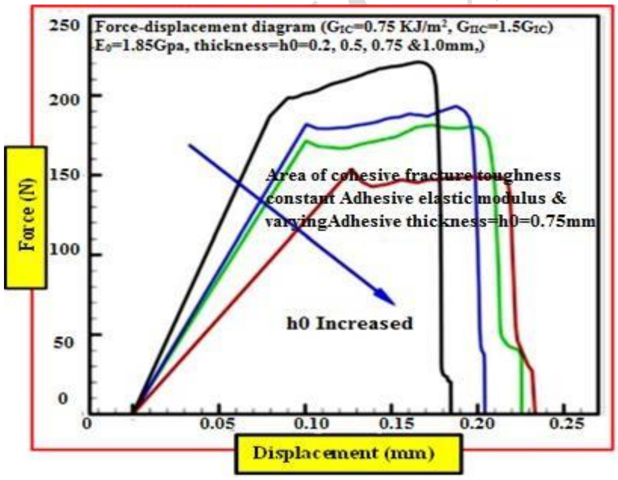
Fig. 10. ABSSSJ in higher stress contour debonding displacement using ABAQUS.



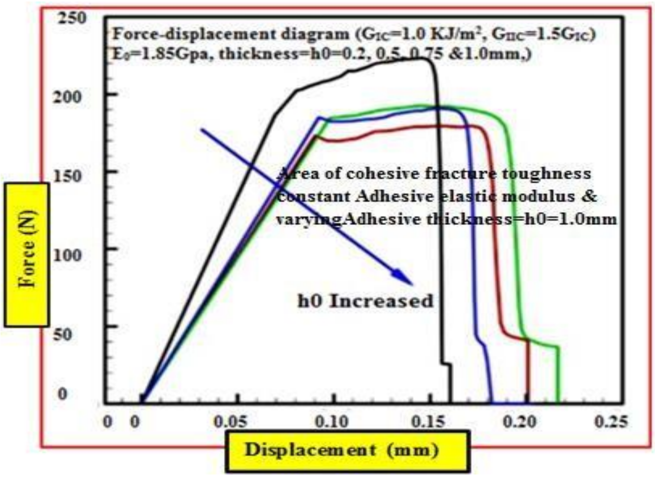
(a) Force-Disp.full rage at GIc=0.25 mm



(b) Force-Disp.full rage at GIc =0.5mm



(c) Force-Disp. full rage at GIc =0.75mm



(d) Force-Disp. full rage at GIc =1.0mm

Fig. 11. By varying adhesive thickness (*h0= 0.2, 0.5, 0.75and 1mm) of ABSSSJ to* Predicted force displacement diagrams.

The numerical results were consistent with experimental observations, validating the use of the Cohesive Zone Model for predicting debonding behavior in ABSSSJs.

Influence of Parameters: The sensitivity analysis showed that adhesive thickness and overlap length had the most significant effect on the tensile strength and debonding behavior. Fiber-to-matrix ratio and environmental conditions also influenced the mechanical properties but to a lesser extent compared to adhesive thickness and overlap length.

From CZM Based FEM Simulation results the minimum mesh size in the adhesive layer was controlled as one-tenth thickness(1/10 h_0 =0.2,0.5,0.75 and 1.0mm) of the adhesive layer, which shows very good numerical convergence and stability by comparison with results based on varying mesh sizes(1/5,1/10,1/20).The external tensile loads of the ABSSSJs were exerted via fixing the horizontal displacements of the left end of the hybrid composite adhered as a constant value and force residual tolerance < 1 and displacement increments limits < 0.01) ; the rest BCs((boundary conditions, control, displacement load(force),stress and strain)of the ABSSSJ follow the symmetric conditions and removal of rigid-body motion.

3.4 Comparison of Experimental and Numerical Results

Validation of the numerical framework: A strong correlation was obtained between the experimental measurements and the CZM-based finite element predictions, confirming the robustness of the adopted numerical framework. Both approaches revealed consistent trends in terms of global force–displacement response, peak tensile and shear stresses, crack initiation locations, and progressive debonding paths (Fig. 12). This agreement demonstrates that the cohesive zone formulation is capable of capturing the dominant interfacial failure mechanisms governing ABSSSJs.

Insights for Automotive Applications: The study provides valuable insights for optimizing the adhesive bonding design for hybrid sisal-glass reinforced HDPE composites used in automotive applications. The findings suggest that an optimal adhesive thickness, overlap length, and fiber-to-matrix ratio can significantly enhance the strength and durability of adhesively bonded joints under varying environmental conditions.

Minor discrepancies observed between experimental and numerical results are mainly attributed to unavoidable uncertainties in material characterization, adhesive layer thickness uniformity, and boundary condition idealization. In particular, experimentally induced imperfections and local stress concentrations are difficult to reproduce exactly within the numerical model. Nevertheless, these differences did not alter the overall failure trends or mechanical response characteristics.

Quantitative agreement and model accuracy: A quantitative assessment further confirmed the accuracy of the numerical predictions. The Root Mean Square Error (RMSE) between experimental and simulated force–displacement curves remained within 7.5%, while deviations in peak tensile and shear stresses were limited to 5–8%. These results indicate that the CZM-based FEM slightly underestimates the experimental strength, providing a conservative prediction that is advantageous for safety-critical automotive structural design.

The present findings are consistent with previously reported studies [18,19], reinforcing the reliability of the numerical approach and supporting the mechanistic interpretation of stress transfer, crack evolution, and debonding behavior in hybrid composite–steel adhesive joints.

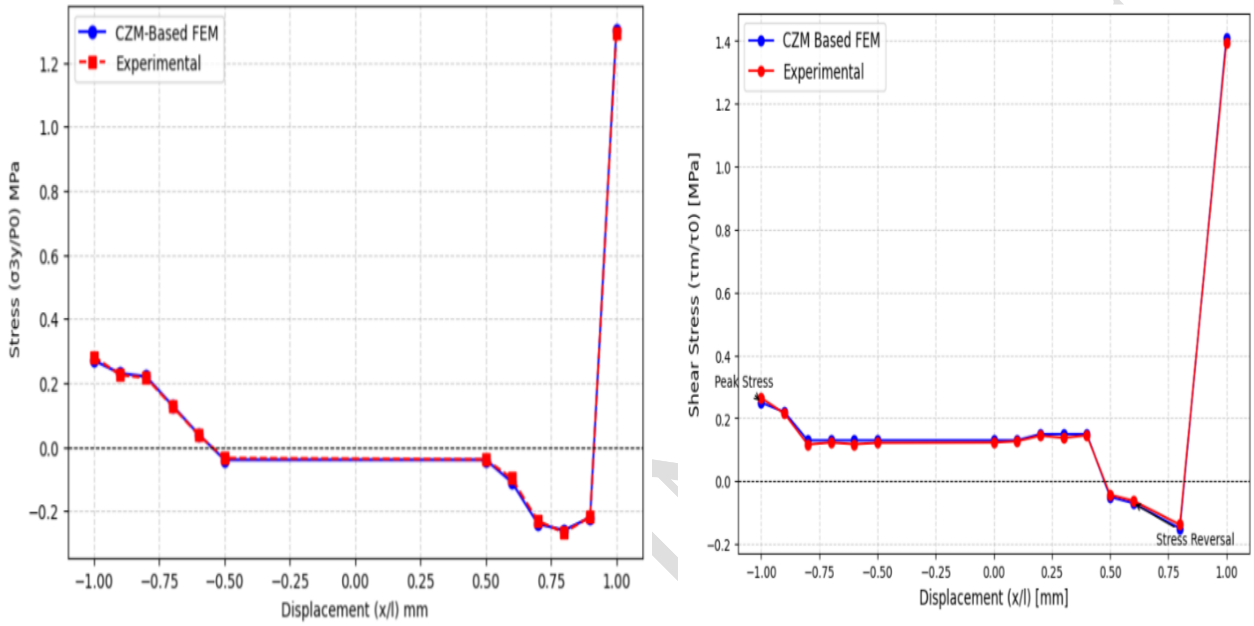


Fig. 12. Validation of CZM-based FEM predictions against experimental results for tensile and shear stress responses of ABSSSJs.

This section provides an in-depth analysis of the results, emphasizing the key findings from both the experimental tests and numerical simulations. The discussions aim to address the research questions and validate the hypotheses, while providing recommendations for improving the mechanical performance of ABSSSJs in real-world automotive applications.

3.5 Relevance to Automotive Applications

The hybrid sisal–glass reinforced HDPE–steel adhesively bonded single-strap joint (ABSSSJ) exhibited adequate load-bearing capacity, stable crack propagation, and predictable failure modes under quasi-static tensile and shear loading conditions. These characteristics are essential for structural components used in automotive side body panels, where controlled failure and damage tolerance are critical for passenger safety. The parametric and validation results indicate that careful optimization of adhesive layer thickness, overlap length, and hybrid fiber architecture can significantly improve joint strength and durability. In particular, thinner adhesive layers were found to enhance interfacial stiffness and debonding resistance, while the hybrid reinforcement strategy provided an effective balance between sustainability and mechanical reliability. Although the present study confirms the suitability of ABSSSJs for automotive side panel integration, further investigations are required to address long-term service conditions. Fatigue loading, impact resistance, and thermal cycling effects should be examined to ensure full structural validation. Nevertheless, the current work establishes a validated experimental–numerical baseline that can be extended to CZM-based fatigue modeling and environmental durability assessment in future research.

4. Conclusions

This research presents a systematic experimental and numerical investigation into the mechanical response and debonding characteristics of adhesively bonded single-side strap joints (ABSSSJs) formed between steel and hybrid sisal–glass reinforced HDPE composites for automobile side body panel applications. The combined use of laboratory testing and cohesive zone model (CZM)-based finite element analysis enabled a detailed understanding of the governing parameters affecting joint performance.

The results confirm that adhesive thickness, overlap length, fiber-to-matrix weight ratio, and environmental exposure (temperature and moisture) play decisive roles in determining joint strength and durability. Among these parameters, adhesive thickness and overlap length were identified as the most influential variables controlling tensile strength and debonding behavior.

An optimal joint configuration was achieved using a balanced fiber composition (S10G20H70), an adhesive thickness of 0.5 mm, and an overlap length of 10 mm, which collectively produced the highest tensile strength and stable force–displacement response. Deviations from these optimal values resulted in reduced stiffness, premature debonding, or stress redistribution within the adhesive layer.

Environmental conditioning revealed that moisture absorption and elevated temperature significantly reduced joint strength and accelerated damage initiation. This degradation was more pronounced in joints with thinner adhesive layers and lower fiber content, highlighting the sensitivity of hybrid composite–metal joints to hydrothermal effects.

Failure mode analysis demonstrated a clear transition with changing joint geometry. Cohesive failure within the adhesive layer dominated at lower adhesive thicknesses, indicating efficient stress transfer, whereas thicker adhesive layers promoted adhesive failure at the steel–composite interface due to increased compliance and peel stress concentration.

The CZM-based finite element simulations showed strong agreement with experimental observations, accurately predicting stress distribution, crack initiation, and full-range debonding behavior. Sensitivity analysis further validated the robustness of the numerical framework and confirmed its suitability for predictive joint design.

From an application perspective, the findings are directly relevant to automotive body panel manufacturing, where lightweight, high-strength, and reliable bonded joints are essential. The validated numerical model offers a practical tool for design optimization, enabling reductions in material usage, experimental trials, and development time. Moreover, the incorporation of natural fibers alongside glass fibers supports sustainable and eco-efficient manufacturing strategies aligned with modern automotive industry objectives.

In summary, this study provides a comprehensive and original contribution to the understanding of adhesively bonded hybrid composite–metal joints. The integrated experimental–numerical framework established herein offers reliable guidance for optimizing joint design under varying service conditions. Future investigations should extend this approach to fatigue, impact, and cyclic loading scenarios to fully assess long-term performance. In addition, advanced diagnostic techniques such as digital image correlation (DIC) and acoustic emission (AE) monitoring are recommended to capture real-time damage evolution and further refine failure prediction models.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Samuel Tesfaye Molla: Conceptualization, study design: Literature, write original draft, and final draft review. **Assefa Asmare Tsegaw**: analysis and supervision. **Teshome Mulatie Bogale**: supervision and validation. **Addisu Negash Ali** and **Asmamaw Tegegne Abebe**: review, validation, and supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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