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Low-velocity impact analysis of metal-composite joints with grain-refined A356 and reinforced epoxy adhesive using six node pentahedron cohesive elements

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ABSTRACT

This study evaluates the strength of double lap joints composed of metal composite adherends and epoxy adhesive subjected to low impact energies (20 J, 40 J). The study was carried out through experimental and numerical methods to understand the strength of lap joints comprehensively. In the production of double lap joints, A356 aluminum and grain-refined aluminum adherends were used as the metal components. To refine the grain structure, titanium (Ti) and boron (B) were added to the liquid metal at a rate of 0.01% of the total metal weight (A356-TiB). The composite laminates consisted of glass/epoxy and aramid/epoxy, made with unidirectionally oriented fibers. Araldite 2015 epoxy adhesive, available in both unreinforced and copolyester-reinforced forms, was utilized to bond the metal and composite materials. In the numerical analysis of double-lap joints, the metal and composite adherends are modeled using 8-node solid elements, while the adhesive is represented by 6-node pentahedron cohesive elements. Furthermore, a surface-to-surface, two-way treatment of contact was created between the impactor and the metal adherend. Consequently, the maximum impact loads obtained from the numerical analysis are in good agreement with the experimental results for both impact energies.

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A356 grain-refined aluminum adherends; Double lap joint; six-node pentahedron cohesive elements

1. Introduction

Today, metal and composite materials are commonly used across various sectors. Composite materials are chosen for their lightweight, strength, and ease of formability.^[1] In contrast, metal materials are favored for their high strength and long service life.^[2] With advancing technology, the use of metal-composite joints – where metal and composite materials are combined – has become increasingly prevalent in many applications.^[3–5] Although the mechanical behavior of metal-composite joints under different loadings is widely available in the open literature, their behavior at low-

impact velocities is still not sufficient.^[6,7] Karimi^[8] conducted tests on single-lap metal composite joints made from glass/polymer composite laminates and aluminum sheets at low-impact velocities of 22.5, 27.5, and 32.4 J. After conducting the impact tests, it was noted that there was delamination in the composite layers of the metal-composite joint. The findings also indicated that the use of Z-pins in metal composite connections positively contributes to the impact resistance of the joint. M. Yilmaz and M. Ekrem^[9] studied the behavior of aluminum composite joints under various impact energies and temperatures. They enhanced the adhesive used in the metal-composite joint by incorporating nanofibers at weights of 1%, 3%, and 5%. Their findings indicated that temperature influenced the impact and that separations in the adhesive became more prominent as the impact speed increased. In their study,^[10] the researchers examined the strength of a new-generation composite material created by hybridizing basalt and flax fibers under low-impact tests. They utilized metal composite joints in three configurations: asymmetric, symmetric, and sandwich. Their findings indicated that the asymmetric configuration of the metal composite connection exhibited the best impact resistance when subjected to identical boundary conditions and impact loads. The researchers examined the failure strength of single-layer and double-layer thin-layer composite bolted joints. They compared the experimental results with those obtained from an established numerical model. To simulate the delamination that occurs during failure, they employed an interface cohesive zone model based on the Benzeggagh-Kenane (B-K) law. They concluded that the findings from the numerical analysis showed good agreement with the experimental results.^[11] The experimental and numerical investigation of the failure behavior of metal composite joints under impact loads can be followed regarding studies.^[12–15]

Although studies have been conducted on the numerical model of adhesively lap joints, the literature still lacks numerical analysis of metal composite joints over double-lap joints. Yibo Li et al.^[16] conducted a study on adhesively bonded lap joints, examining their performance under varying impact energies and temperatures through both experimental and numerical methods. They tested four different impact energies (4, 8, 12, and 16 J) and four ambient temperatures (−30 °C, RT, 50 °C, and 80 °C). In their numerical modeling of the adhesive, they employed a bilinear cohesive zone model. Their findings revealed that, except for the 80 °C condition, different temperatures did not significantly impact the extent of impact damage. Additionally, they reported that the results from their numerical models aligned well with the experimental findings. They conducted both experimental and numerical studies on a double-lap joint model of aluminum and carbon fiber-reinforced polymer (CFRP) metal composite joints. The experimental studies were performed under both static and fatigue loads. Additionally, they verified the potential

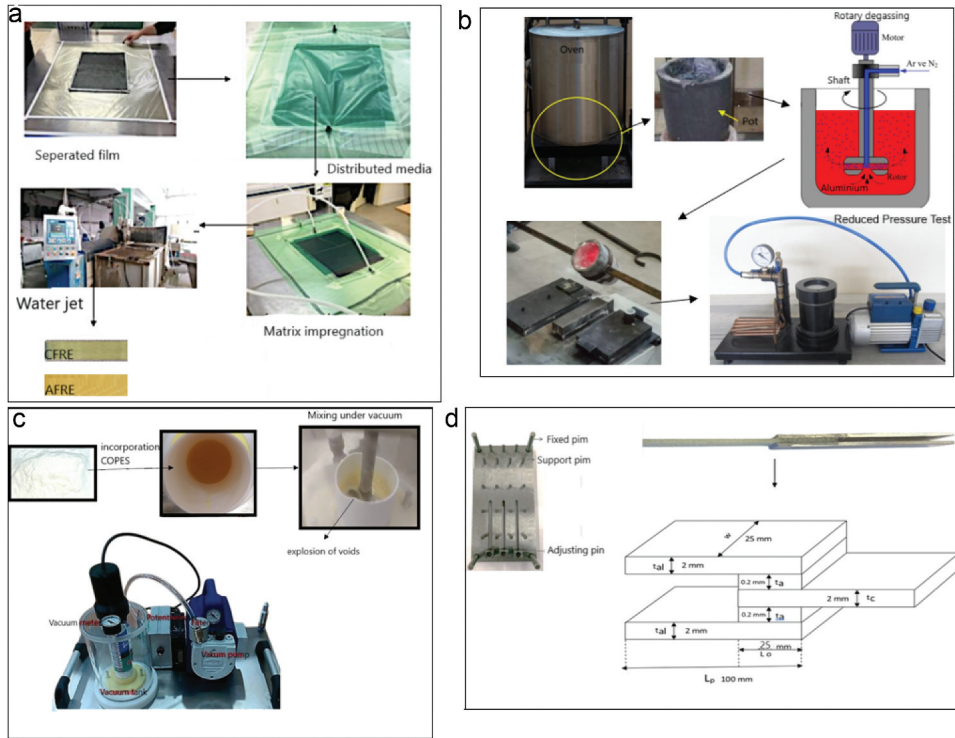
damage resulting from the experimental loadings using the model they developed in their numerical analysis.^[17] Research on the numerical modeling of lap joints can be found in the relevant literature.^[18,19]

This study aims to make significant contributions to the existing literature by exploring the effects of incorporating a grain refiner into metal adherends within metal-composite double-lap joints. The primary focus will be on how this addition influences the impact resistance of the joint. A three-dimensional 8-node cohesive element will be utilized for cohesive modeling; however, it is known to degenerate into mesh elements under loading conditions that induce substantial rotations, such as those encountered during impact. To mitigate this issue, we propose the implementation of six-node pentahedron elements. Furthermore, this study will also assess the impact of copolyester-reinforced adhesives on the overall impact resistance of the lap joint.

2. 2. materials and preparation

This study examined a metal composite double lap joint, which consisted of A356 aluminum and grain reinforced aluminum A356 adherends. The composite materials used were glass fiber-reinforced epoxy matrix woven composite laminate (GFRE) and aramid fiber-reinforced epoxy matrix woven composite laminate (AFRE). The specific fiber and resin materials used in the production of composite materials were supplied by Dost Chemical Company.^[20] Two types of adhesives were employed for the lap joints: an unreinforced epoxy adhesive and a twenty percent copolyester-reinforced (Copes) epoxy adhesive. The production stages of the double lap joint are explained in detail below.

The VARTM (Vacuum-Assisted Resin Transfer Molding) technique was used to fabricate the composite laminates for this study. During the production stages of the VARTM process, sealing tapes were applied, and a release film was positioned on the tool plate. Then, the dried materials were layered one on top of the other on the release film. A distribution medium was established to ensure that the hardener and epoxy resin spread simultaneously. Both ends of the resin and vacuum pumps were connected to spiral hoses. The air within the vacuum bag was evacuated using the hose connected to the vacuum pump, while the curing agent and adhesive were drawn in through the spiral hose attached to the resin. This process was repeated until the liquid resin, consisting of epoxy and hardener, was fully impregnated into the materials. Finally, the assembled materials were placed on a heated plate at 100 °C for one hour to complete the curing process. Composite materials are manufactured in eight layers, arranged with warp and weft yarn sequences. Composite laminates were cut to the desired dimensions for use in lap joints using a water jet. It should be stated that the high pressure of the water allows



liters per minute and 300 revolutions per minute, respectively, during the liquid metal cleaning processes. To evaluate the cleanliness of the liquid metal after the degassing process, a Reduced Pressure Test (RPT) device was used. This vacuum solidification device exploits the possibility of impurities and gases being trapped in the liquid. These impurities are then subjected to inflation, allowing for proper analysis. Finally, the aluminum adherends were removed from the mold, and the machining processes were performed to achieve the necessary dimensions for use in the lap joint (see [Figure 1\(b\)](#)).

Araldite 2015 epoxy adhesive produced by Huntsman Corporation. was mixed with a high-hardness, heat-resistant co-polyester thermoplastic (Copes) produced by the Schaetti® company using a vacuum mixing mechanism. The mechanical and physical properties of both thermoplastic and adhesive are detailed in [Tables 1 and 2](#). During the mixing of the adhesive with various hardeners and additives, air bubbles can form, which are known to negatively impact bonding strength. To mitigate this issue, the mixing process was conducted under vacuum conditions. It was observed that the air bubbles present in the adhesive were effectively removed during this process. The vacuum mixing system comprises a vacuum tank, a plastic container for mixing the adhesive, a DC motor, a mixing paddle, a potentiometer, a vacuum gauge, a filter, a valve, and a vacuum pump. The vacuum pump operates at a capacity of 850 mbar. Additionally, a valve between the vacuum tank and the pump allows for the maintenance of a constant vacuum level at the desired pressure. The mixing process was carried out at a controlled speed within the vacuum environment, regulated by the potentiometer in the mixing unit (see [Figure 1\(c\)](#)).

Double-lap joints were produced using a specialized mold. In the mold, support pins were utilized to prevent lateral shifting during the curing of the lap joint, and adjustment pins were included to accommodate lap joints of various sizes. The adhesive thickness of the lap joint placed in the mold was

Table 1. The properties of Araldite 2015 epoxy adhesive^[21,22].

Elasticity modulus	MPa	1850
Poisson's ratio		0.33
Tensile strength	MPa	21.63
Tensile yield strength	MPa	12.63
Tensile failure strain	%	4.77

Table 2. The properties of thermoplastic materials (Copes)^[23].

Melting point	°C	109–119
Hardness	Shore	D70
Density	g/cm ³	21.63
Particle size	µm	80

achieved using 0.2 mm thick mylar tape. A mold separator was employed to facilitate the separation of the lap joint from the mold. The geometric dimensions of the lap joint were determined according to the literature.^[24] All the steps involved in obtaining a double lap joint are depicted in Figure 1 (see Figure 1(d)).

The double-lap joint, illustrated in Figure 1, has been developed in eight different configurations. Each model varies based on the materials used and the type of adhesive applied. The first model features A356 aluminum for the bottom and top adherends, with a glass-epoxy composite laminate in the middle plate. It uses Araldite 2015 epoxy adhesive without any additives (*A356-GFRE-A356-Unreinforced*). The second model also uses A356 aluminum for the bottom and top adherends, a glass-epoxy composite laminate for the middle plate, and Araldite 2015 epoxy adhesive reinforced with 20% copolyester (*A356-GFRE-A356-Reinforced*). The third model employs A356 aluminum for the bottom and top adherends, with an aramid-epoxy composite laminate in the middle. It uses Araldite 2015 epoxy adhesive without any additives (*A356-AFRE-A356-Unreinforced*). The fourth model features A356 aluminum for the bottom and top adherends, an aramid-epoxy composite laminate for the middle plate, and Araldite 2015 epoxy adhesive with 20% copolyester added (*A356-AFRE-A356-Reinforced*). The fifth model incorporates A356-TiB aluminum for both the bottom and top adherends, a glass-epoxy composite laminate for the middle plate, and Araldite 2015 epoxy adhesive without any additives (*A356TiB-GFRE-A356TiB-Unreinforced*). The sixth model uses A356-TiB aluminum for the bottom and top adherends, a glass-epoxy composite laminate for the middle plate, and Araldite 2015 epoxy adhesive with 20% copolyester (*A356TiB-GFRE-A356 TiB-Reinforced*). The seventh model consists of A356-TiB aluminum for the top and bottom adherends, with an aramid-epoxy composite laminate in the middle and Araldite 2015 epoxy adhesive without any additives (*A356TiB-AFRE-A356TiB-Unreinforced*). The eighth model features A356-TiB aluminum for both the top and bottom adherends, an aramid-epoxy composite laminate for the middle plate, and Araldite 2015 epoxy adhesive reinforced with 20% copolyester (*A356TiB-AFRE-A356TiB-Reinforced*).

3. Experiments

In this study, the mechanical properties of A356 and A356-TiB materials were evaluated through tensile testing. These tests were conducted using a universal testing machine at a consistent loading rate of 1 mm/min. Each test involved three samples, and the average results were calculated utilizing the Moving Average method as implemented in MATLAB. Tensile test samples were prepared in accordance with the ASTM-E8 standard. The stress-strain curves of A356 and A356-TiB materials are shown in Figure 2.

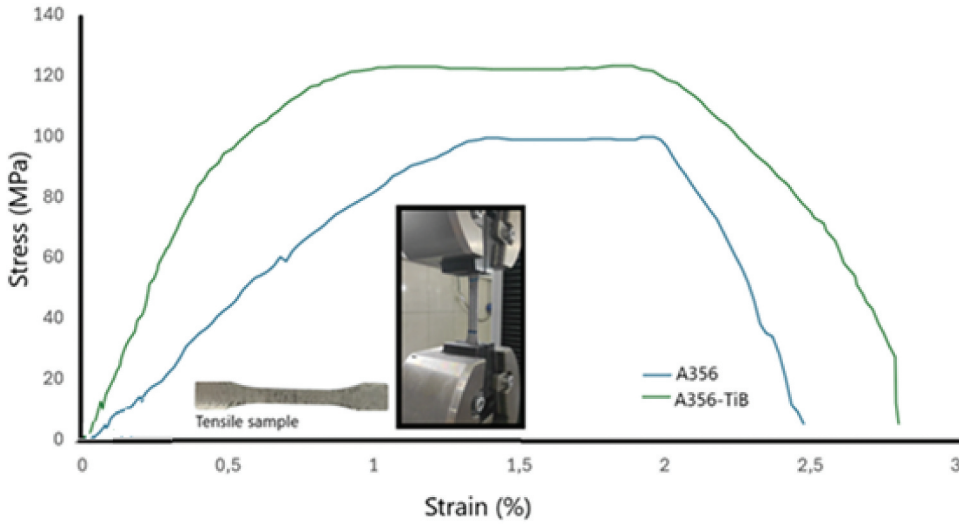


Figure 2. The stress-strain curves of A356 and A356-TiB.

Table 3. The mechanical properties of the aluminum materials.

Properties	A356 aluminium	A356-TiB aluminium
Elasticity Modulus (MPa)	69.85 ± 2.15	71.35 ± 1.75
Yield Strength (MPa)	82.75 ± 3.75	88.50 ± 4.25
Ultimate Tensile Strength (MPa)	100.5 ± 4.6	118.2 ± 3.15
Failure Strain (%)	2.5 ± 0.25	2.75 ± 0.35

The maximum stress, maximum strain, and toughness values of A356-TiB aluminum are higher than those of A356 aluminum, as shown in Figure 2. Additionally, the mechanical properties of the aluminum materials are summarized in Table 3.

The copolyester thermoplastic material (Copes) was incorporated into the Araldite 2015 epoxy adhesive. It is important to note that copolyester was added to the adhesive in various percentages, with the most significant change in mechanical behavior observed at 20%. Tensile samples were prepared following BS 2782 standards and subjected to a tensile load at a rate of 1 mm/min in a universal testing machine. During the experiments, three samples were tested for each adhesive condition. The stress-strain curves of the adhesive reinforced with copolyester are illustrated in Figure 3.

As shown in Figure 3, adding copolyester to the adhesive increased the maximum strain of Araldite 2015 epoxy adhesive, while the maximum tensile strength decreased. This indicates that the adhesive became more ductile with the incorporation of the thermoplastic material. Additionally, the mechanical properties of both reinforced and unreinforced adhesives are presented in Table 4

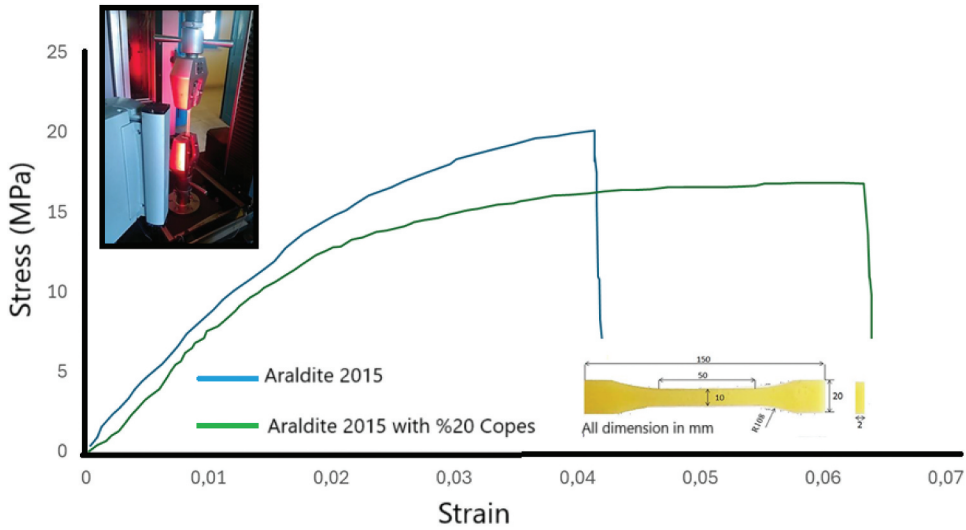


Figure 3. The stress-strain curves of reinforced/unreinforced adhesive.

Table 4. The mechanical properties of the reinforced/unreinforced adhesive.

Properties	Unreinforced adhesive	Reinforced Adhesive
Elasticity Modulus (MPa)	1750 ± 35.75	991 ± 44.35
Ultimate Tensile Strength (MPa)	20.3 ± 2.25	15.1 ± 2.55
Failure Strain (%)	4.18 ± 0.25	6.45 ± 0.37

Table 5. The mechanical properties of the composite materials^[25].

Properties	GFRE	AFRE
Elasticity Modulus (GPa)	35 ± 1.25	67 ± 2.65
Ultimate Tensile Strength (MPa)	590 ± 30	1420 ± 85
Poisson ratio	0.3 ± 0.03	0.34 ± 0.025
Failure Strain (%)	2.29 ± 0.18	1.8 ± 0.15

The mechanical properties of GFRE and AFRE composite laminates were presented at [Table 5](#).

The INSTRON CEAST 9350 impact test apparatus was utilized to conduct low-velocity impact tests on double-lap joints. These tests were performed in accordance with ASTM D7136/D7136M standards. A 5 kg impactor with a diameter of 16 mm was employed for the impact tests. The velocity of the impactor was set according to the impact energy. The low-velocity impact tests were conducted at two different impact energy levels (20 J and 40 J). The experimental setup of the low-velocity impact on the double lap joint is presented in [Figure 4](#).

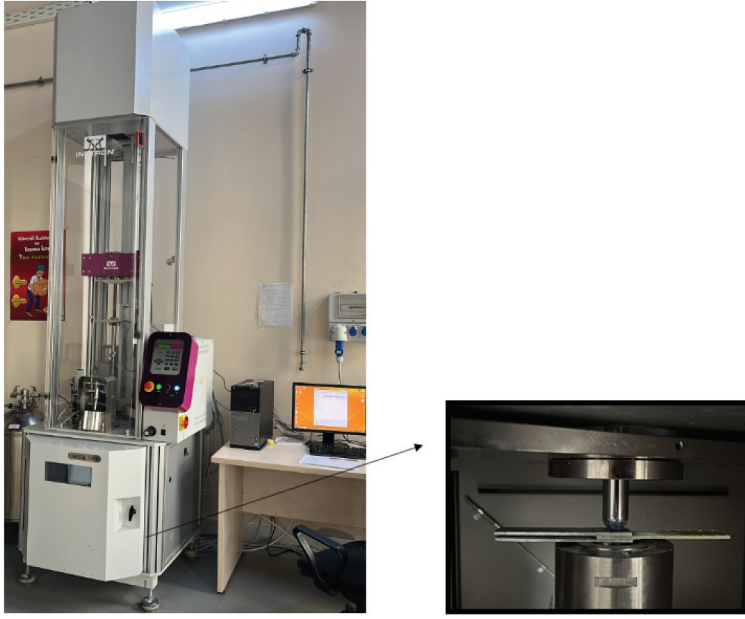


Figure 4. The experimental setup of the low-velocity impact on the double lap joint.

4. Numerical model

4.1. A mixed-mode traction cohesive zone model

A traction-separation rule characterizes the fracture behavior within the cohesive zone model, where the fracture process zone is depicted as a singular cohesive layer. This framework defines the fracture energies as the maximum dissipation energy required for the initiation and propagation of cracks, as dictated by the cohesive law. Furthermore, the method incorporates both traction and displacement values across the normal and shear directions to describe the cohesive region. The cohesive zone effectively encompasses the adhesive and adherend materials, along with the corresponding interface energies. In the mixed-mode cohesive zone model, traction is defined as follows^[26]

$$T = \sqrt{\beta^{-2} T_t^2 + T_n^2} \quad (1)$$

where, T_n normal traction and T_t is the tangential traction. The displacements corresponding to the tractions can be written as^[27]

$$\Delta = \sqrt{\Delta_n^2 + \Delta_t^2} \quad (2)$$

where, Δ_n , Δ_t are the normal and tangential displacements respectively. β represents the mix mode, and the initial separation distances in tangential and normal directions are utilized to define its value^[27]

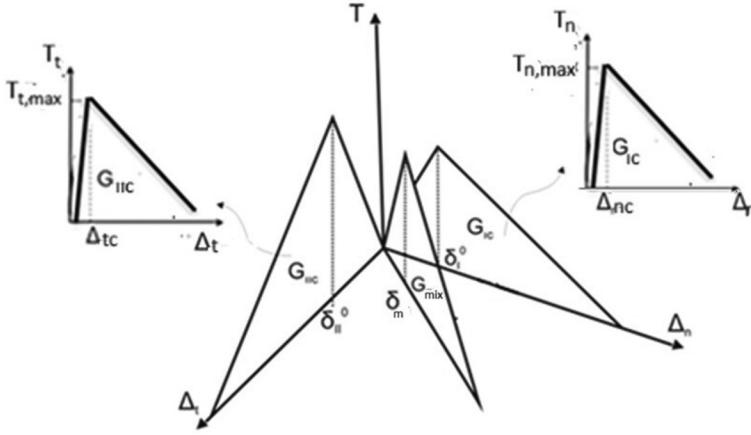


Figure 5. The mixed-mode traction cohesive zone model.

$$\delta_m^0 = \delta_I^0 \delta_{II}^0 \sqrt{\frac{1 + \beta^2}{(\delta_{II}^0)^2 + (\beta \delta_I^0)^2}} \quad (3)$$

where, δ_m^0 is initial mixed mode displacement, $\delta_I^0, \delta_{II}^0$ are the initial normal (Mode I) and tangential (Mode II) displacement. Cohesive failure is defined as the point at which cohesive stress reaches (T_{n-max}, T_{t-max}) its maximum at the critical separation distance $(\Delta_{nc}, \Delta_{tc})$. This principle holds true for both modes of failure. As a result, the strain energy release rates for each mode are determined based on these values.

$$G_{IC} = \frac{T_{n-max} \Delta_{nc}}{2} \quad G_{IIc} = \frac{T_{t-max} \Delta_{tc}}{2} \quad (4)$$

The mixed-mode traction cohesive zone model, including all displacement and traction values, is illustrated in [Figure 5](#).

4.2. Implementation of the mixed-mode traction cohesive zone model

In the finite element analysis of double-lap joints, the metal and composite plates are modeled using 8-node solid elements, while the adhesive is represented by 6-node pentahedron cohesive elements. Each node of the 8-node element has a total of six degrees of freedom, which include both axial and rotational movements. It is important to note that the rotations are unconstrained in all cartesian coordinates. This is based on impact tests that have demonstrated bending damage in both metal and composite plates. Shape functions define the damage displacement in the adherends when subjected to an impact load. The shape functions for the 8-point solid element are defined as follows^[28],

$$\Delta_x = \sum_{i=1}^{k=8} N_i(\xi, \eta) \Delta_y = \sum_{i=1}^{k=8} N_i(\xi, \eta) y_i$$

$$N_1(\xi, \eta) = -\frac{1}{4}(1 - \xi)(1 - \eta)(1 + \xi + \eta)$$

$$N_2(\xi, \eta) = -\frac{1}{4}(1 - \xi)(1 - \eta)(1 - \xi + \eta)$$

$$N_3(\xi, \eta) = -\frac{1}{4}(1 + \xi)(1 - \eta)(1 - \xi + \eta)$$

$$N_4(\xi, \eta) = -\frac{1}{4}(1 - \xi)(1 + \eta)(1 + \xi - \eta)$$

$$N_5(\xi, \eta) = \frac{1}{2}(1 - \xi^2)(1 - \eta)$$

$$N_6(\xi, \eta) = \frac{1}{2}(1 + \xi)(1 - \eta^2)$$

$$N_7(\xi, \eta) = \frac{1}{2}(1 - \xi^2)(1 + \eta)$$

$$N_8(\xi, \eta) = \frac{1}{2}(1 - \xi)(1 - \eta^2)$$

where N is shape function, ξ and η is the local coordinate for the shape function.

In this study, we utilized a 6-node pentahedron cohesive element, which is believed to provide a novelty for modeling adhesive in finite element analysis. The cohesive element used in the adhesive allows for 6 degrees of freedom at each node. The proposed finite element model of the adhesive, middle node points are defined unlike the 8-node solid element, and rotations are specified for these node points (see [Figure 6](#), cohesive element). Therefore, new vectors are required to define the cohesive element ($\omega_1, \omega_2, \omega_3$). With these added middle node points, the node displacements within the cohesive element are calculated by interpolating with these new node points. The displacements at the node points of the relevant cohesive element will be defined using shape functions.^[29]

$$\Delta = \sum_{i=1}^{k=3} N_i(q_i - q_{i+k})$$

$$N_1 = 1 - \xi - \eta$$

$$N_2 = \xi$$

$$N_3 = \eta$$

$$N_4 = 1 - \xi - \eta$$

$$N_5 = \xi$$

$$N_6 = \eta$$
(6)

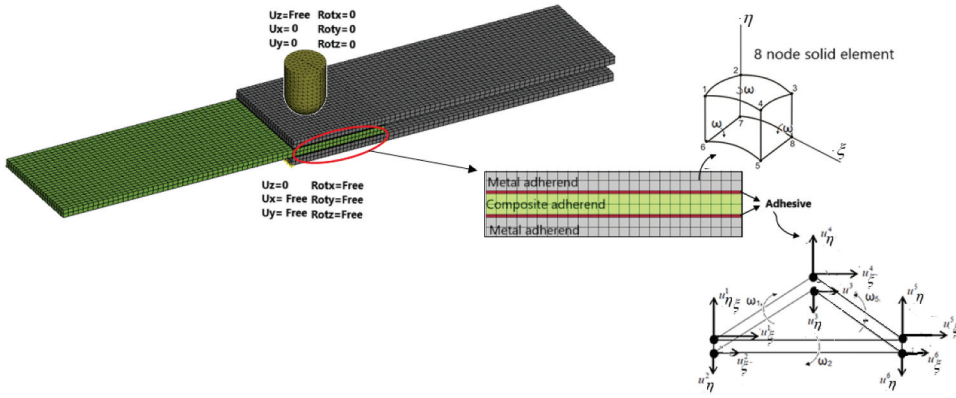


Figure 6. The finite element representation of the double lap joint.

where q is nodal displacement and Δ is the final displacement. In addition, it should be stated here that the large rotations will occur in the cohesive element with the impact load. Large rotations can cause degenerated distortions in 3D 8-node cohesive elements. In this work, the 6-node pentahedron element is proposed as a solution to this problem due to its effectiveness in transition regions between different mesh types.^[27]

The explicit finite element program LSDYNA was used to create the numerical model. First, the geometry used in the experimental method was designed. Using an orthotropic material model for composite materials and an isotropic elasto-plastic material model was utilized for the metal adherends. The plastic behavior was accurately represented by integrating the stress-strain data derived from experimental methods into the program. The adherends utilized in the double-lap joint were represented as solid elements. A mixed-mode cohesive material model (MAT 138) existed in LS DYNA software was used in the finite element modeling of the adhesive. The energy-based fracture criterion was used for crack initiation and propagation in the relevant material model.^[27] The cohesive parameters for the cohesive element, as outlined in equations 1-4, were sourced from existing literature relevant to the adhesive and assigned into the program.^[30] The material properties are defined by the values listed in [Tables 3 and 4](#). The boundary conditions for the double-lap joint under impact load were established based on the experimental conditions. The edges of the lap joint that contacted the bottom part of the impact device were restricted translational motion in the z direction. Meanwhile, the impact load was applied from the center point directly above the lap joint. A surface-to-surface, two-way treatment of contact was created between the impactor, which imparts the impact load, and the metal adherend. In this setup, the impactor surface was designated as the contact surface, while the metal adherend surface served as the target surface. Due to the significant deformations occurring in the impact models, it is challenging to accurately

predict the damage orientations of the contacting parts. The two-way treatment of contact is most appropriate for handling such scenarios.^[27] Considering the mesh sensitivity of the double lap joint, the cohesive elements were divided into 2028 nodes and 1250 elements, while the adherends were divided into finite elements using 5616 nodes and 3550 elements. The finite element representation of the double lap joint is illustrated in Figure 6.

5. Results and discussion

This section explores the impact loads of double-lap joints prepared in eight different configurations, as detailed in the material and preparation section.

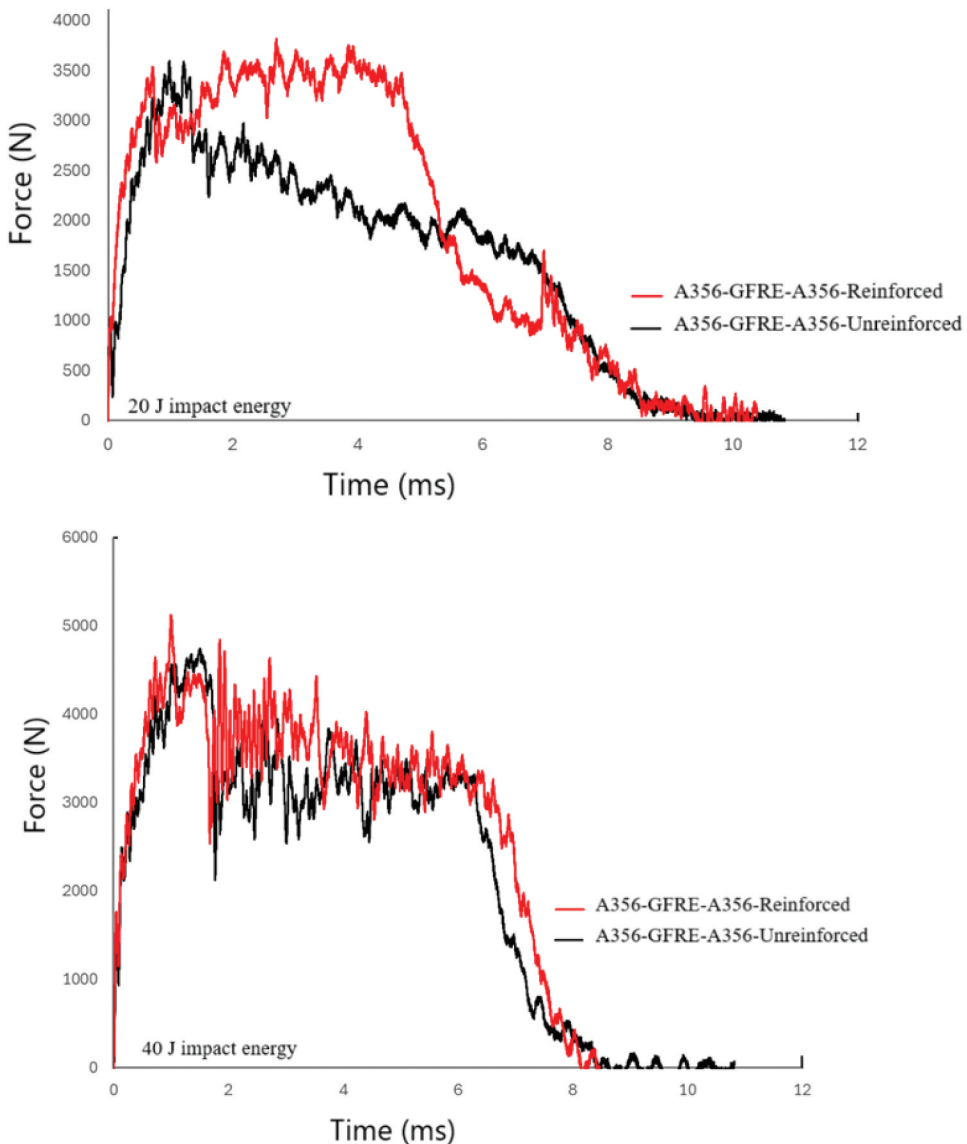


Figure 7. The impact load-time curves for the A356-GFRE-A356 configuration.

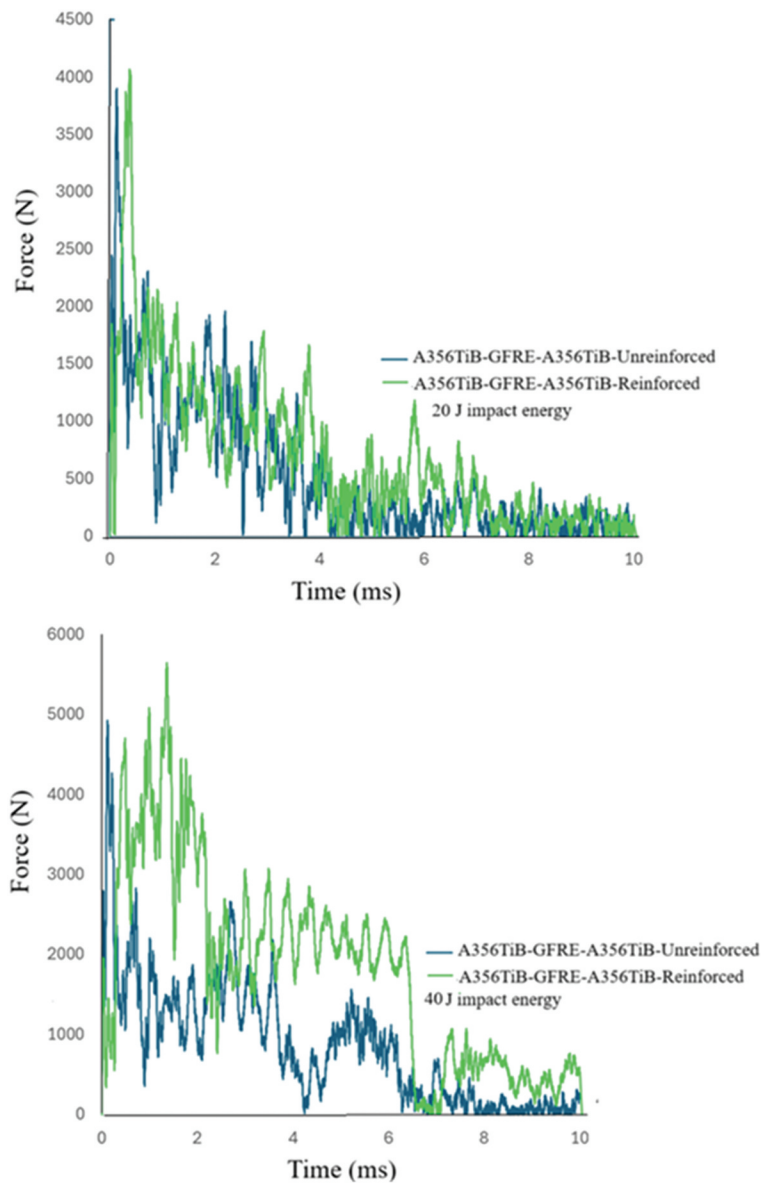


Figure 8. The impact load-time curves for the A356 TiB-GFRE-A356 TiB configuration.

The investigation was conducted both experimentally and through a finite element analysis approach, considering impact energies of 20 J and 40 J. The load-time graphs corresponding to these impact energies for the eight distinct double-lap joint configurations are illustrated in [Figures 7–10](#). Furthermore, the individual presentation of the graphs for each impact energy value provides clear reading of the impact load values, thereby reducing the likelihood of any confusion.

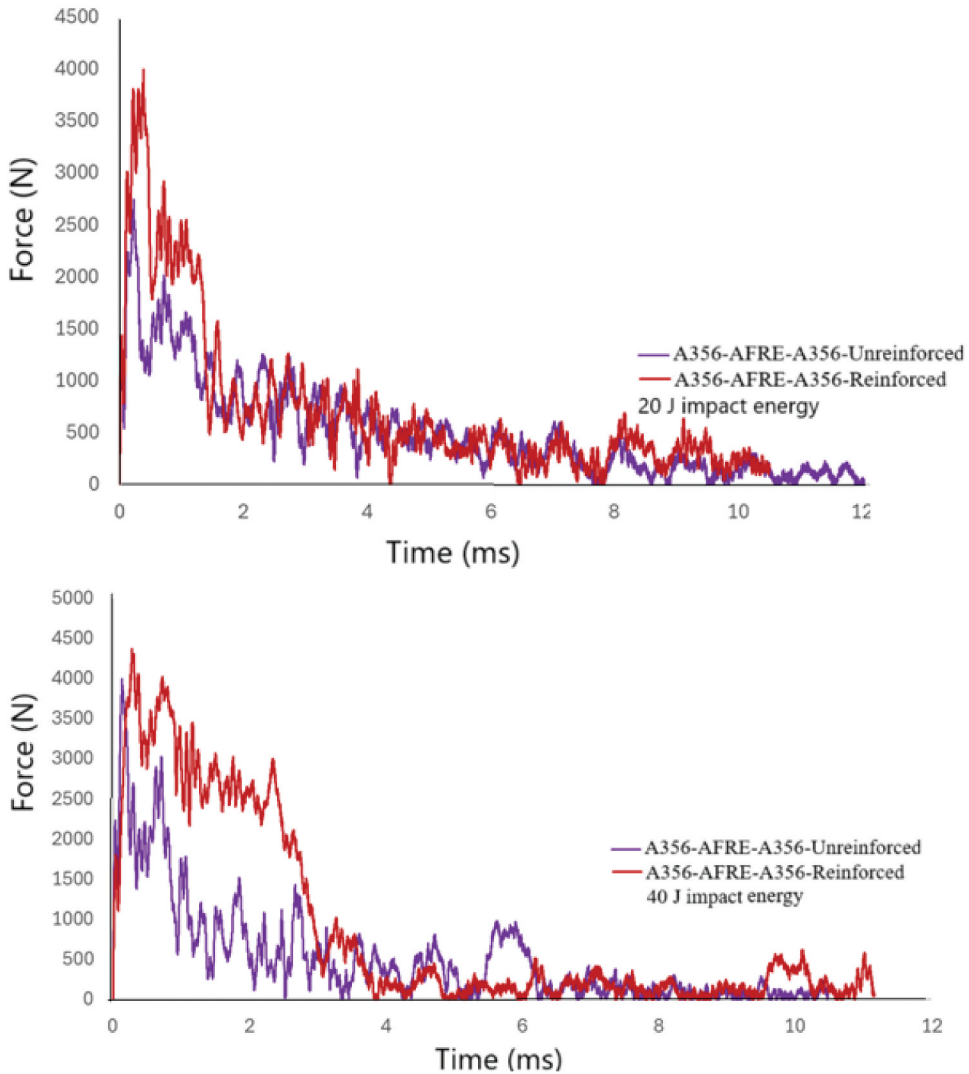


Figure 9. The impact load-time curves for the A356-AFRE-A356 configuration.

Figures 7–10 show that all impact load-time graphs exhibit an oscillatory pattern. These oscillatory behaviors commence upon the initial contact between the impactor and the surface of the upper adherend and continue until a state of failure is observed. Such oscillations result from the impactor's loading and unloading dynamics. Additionally, the characteristics of these oscillatory movements imply that damage occurs progressively and persists throughout the impact process. The highest impact load was achieved with the A356TiB-GFRE-A356TiB double lap joint under an impact energy of 40 J. Conversely, the lowest impact load was observed from the A356-AFRE-A356 double lap joint under 20 J impact energy. Notably, the incorporation of

the thermoplastic material (Copes) into the adhesive formulation enhanced the impact load across all connection configurations tested at both 20 J and 40 J impact energies, indicating a positive influence on the impact resistance of the metal composite double lap joint. Furthermore, it was noted that double lap joints fabricated with fine grain reinforced aluminum adherends exhibited increased impact resistance at both energy levels. The fine grain reinforced aluminum adherends contributed significantly to the overall performance of the double lap joint. Lastly, the GFRE composite laminate demonstrated superior impact load-carrying capacity in comparison to the AFRE composite

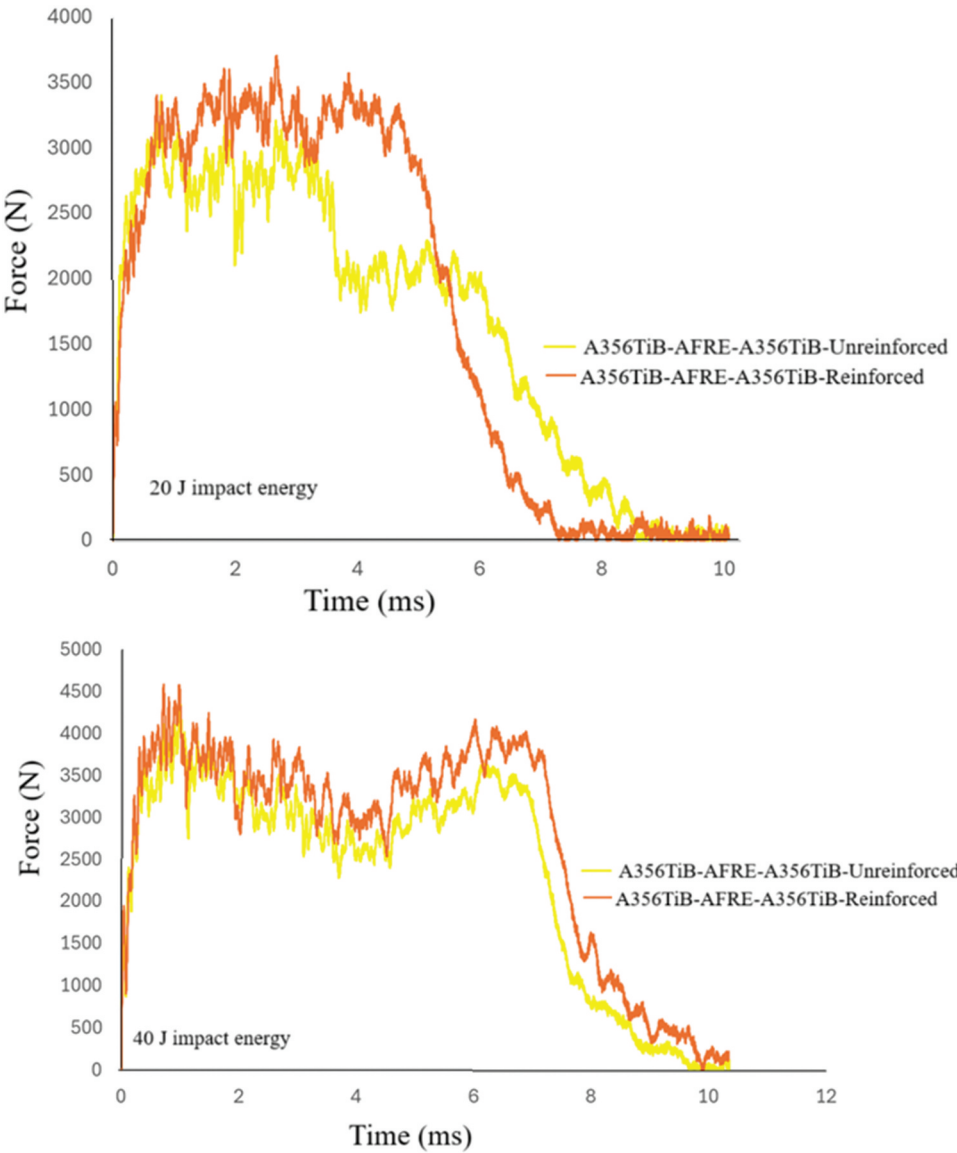
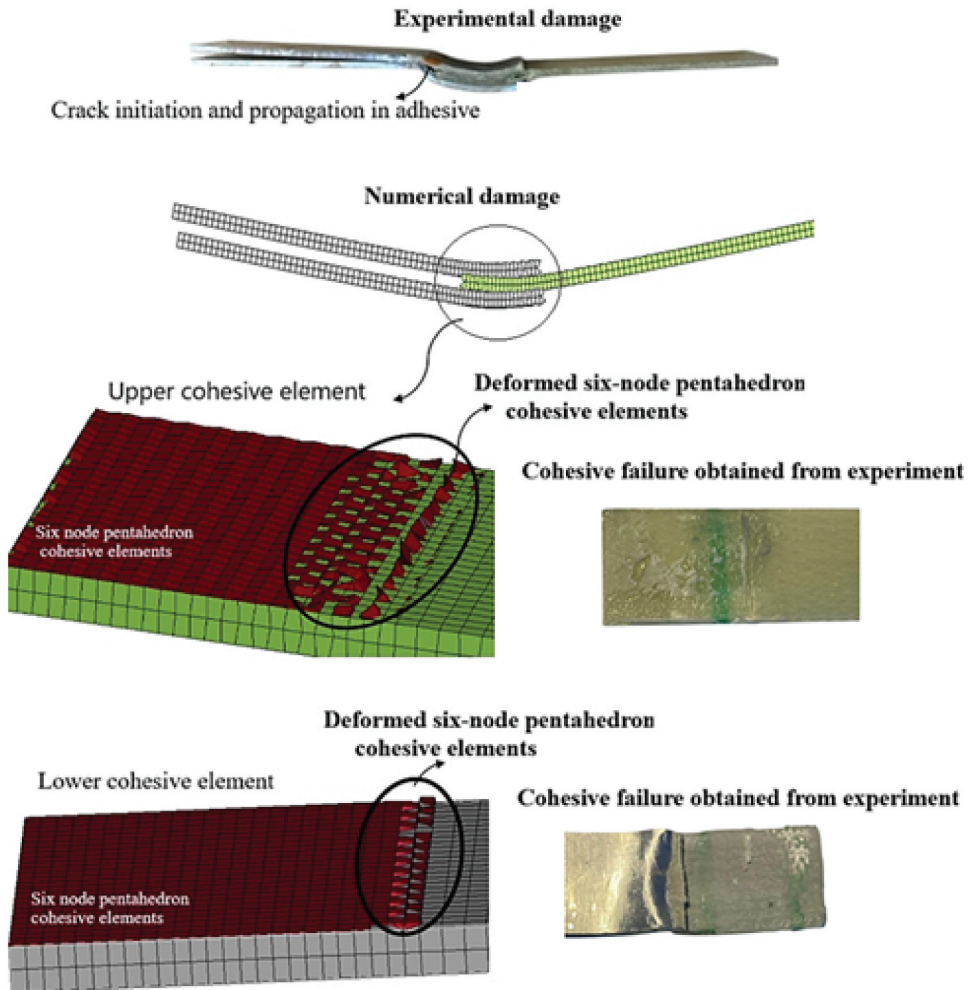


Figure 10. The impact load-time curves for the A356 TiB-AFRE-A356 TiB configuration.

Table 6. The maximum impact loads for double lap joints configurations.

Double lap joint configuration	Impact energy at 20J	Impact energy at 40J
A356-GFRE-A356-Unreinforced	3550 ± 40.5 N	4675 ± 57.6 N
A356-GFRE-A356-Reinforced	3750 ± 47.6 N	5075 ± 28.75 N
A356TiB-GFRE-A356TiB-Unreinforced	3800 ± 39.4 N	4900 ± 38.25 N
A356TiB-GFRE-A356TiB-Reinforced	4050 ± 37.6 N	5550 ± 37.13 N
A356-AFRE-A356-Unreinforced	2750 ± 41.5 N	3975 ± 42.65 N
A356-AFRE-A356-Reinforced	3975 ± 50.05 N	4400 ± 29.6 N
A356TiB-AFRE-A356TiB-Unreinforced	3300 ± 28.37 N	4250 ± 33.2 N
A356TiB-AFRE-A356TiB-Reinforced	3650 ± 44.2 N	4500 ± 45.5 N

**Figure 11.** The impact damage comparison for experimental and numerical approaches under 20 J impact.

laminate across all tested configurations. The maximum impact loads, along with their standard deviations, are detailed in [Table 6](#).

In the evaluation of the numerical analysis results, first, the damage in the double lap joint obtained in the experimental approach was compared with those obtained as a result of the numerical analysis. Subsequently, we verified the findings by comparing the load-time data derived from the numerical model with the experimental results. Figures 11–12 compares the impact damage in the double lap joint using both experimental and numerical approaches.

As illustrated in Figures 11 and 12, the damage observed in the double lap joint under 20 J and 40 J impact loads closely resembles the damage identified in the numerical model. Furthermore, the damage zones

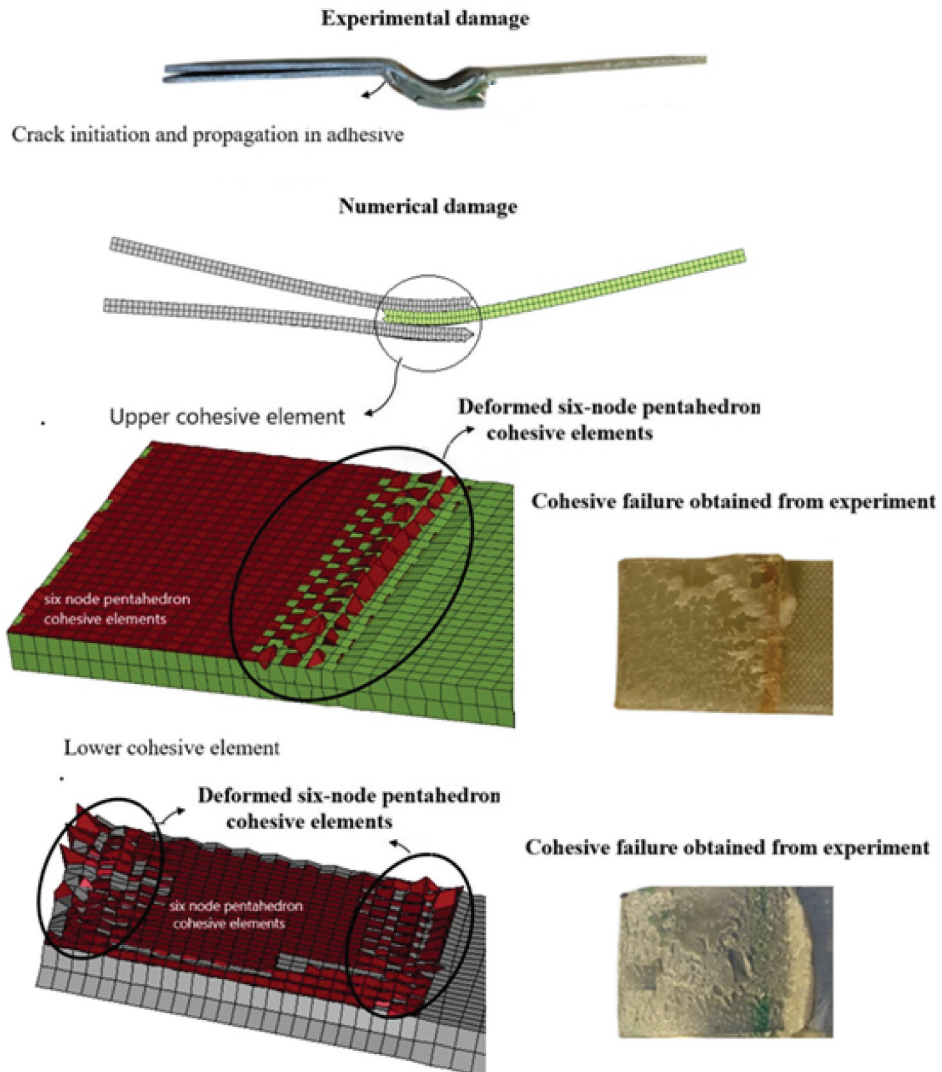


Figure 12. The impact damage comparison for experimental and numerical approaches under 40 J impact.

identified in the six-node pentahedron element are consistent with the results obtained from the experimental approach for both impact loads. This situation suggests that the cohesive element employed is well-suited for the boundary conditions associated with impact loading. The experimental and numerical results illustrated in Figures 11 and 12 are associated with the A356-GFRE-A356-Reinforced configuration. While images of similar damage were observed in other configurations, they are not included in this report for the sake of brevity.

The load-time curves derived from the experimental approach have been compared with those obtained through numerical analysis, as illustrated in Figures 13–16. In numerical analysis, load values were calculated based on the

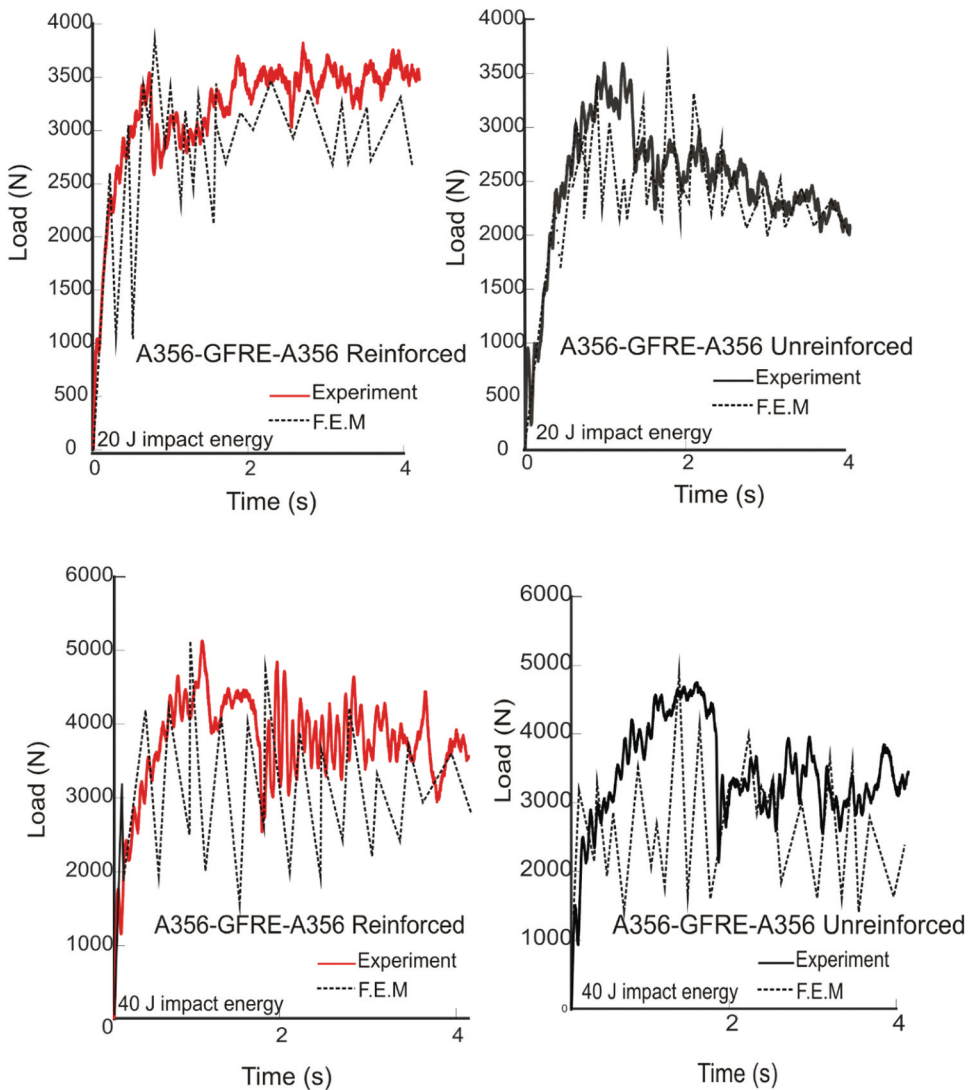


Figure 13. The load-time curves comparison for A356-GFRE-A356.

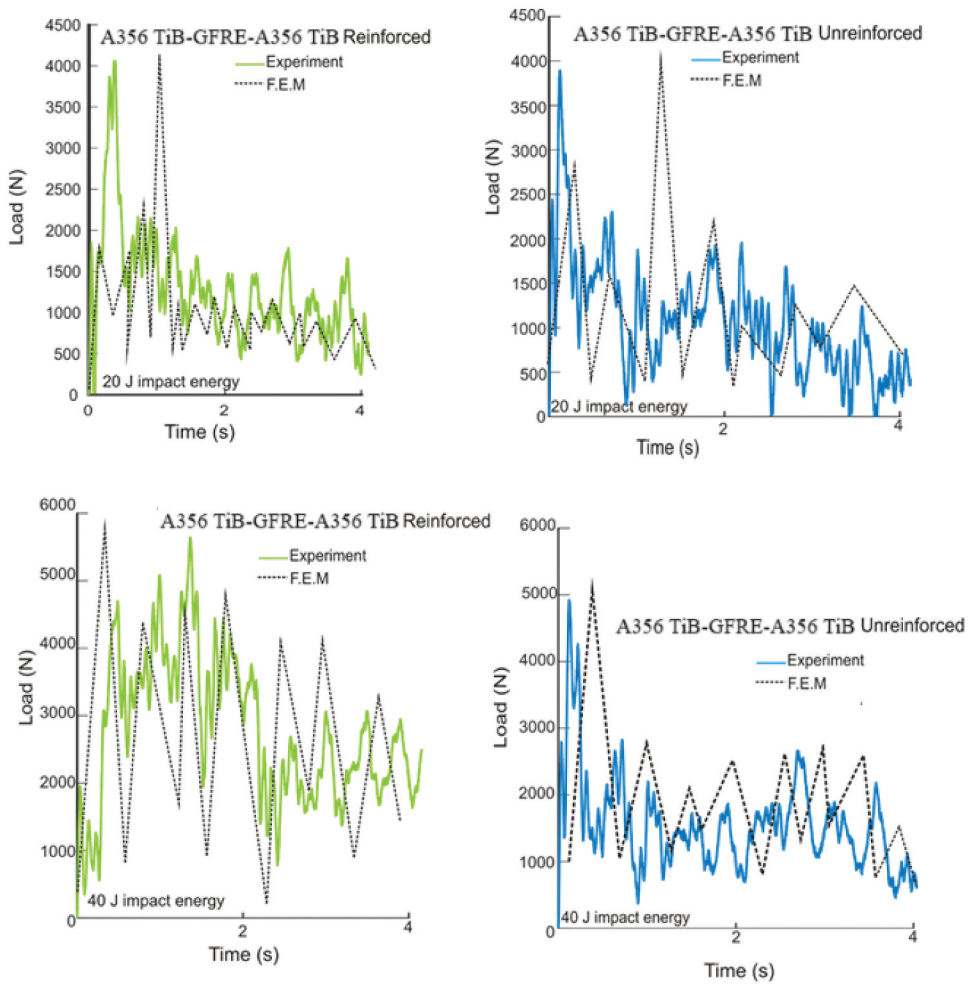


Figure 14. The load-time curves comparison for A356 TiB-GFRE-A356 TiB.

displacement of the contact element nodes. The numerical analysis was conducted utilizing time intervals that matched those of the experimental conditions. To facilitate a clear comparison of the maximum load data presented in Figures 13–16, the relevant data from the numerical model were determined specifically accounting for the timeframe during which the maximum impact load was observed in the experimental approach. Corresponding load values (Rcforc) for this time interval were retrieved from the program’s database after the analysis.

Figures 13–16 demonstrate that the maximum impact load values obtained from both the experimental and numerical methods are closely aligned across all configurations. It is important to emphasize that The LSDYNA finite element program averages the force magnitude throughout the time interval to mitigate issues related to instability and contact penetration to the impact

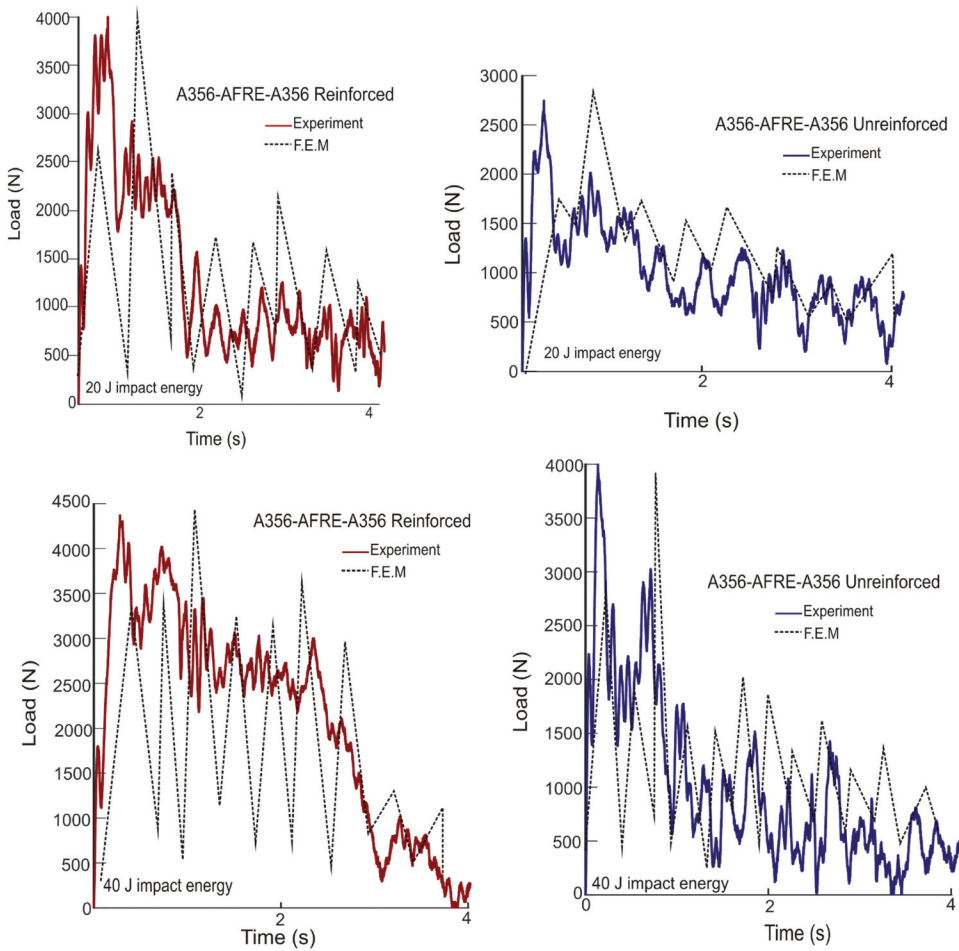


Figure 15. The load-time curves comparison for A356 -AFRE-A356.

simulation. This averaging process produces a smoother and more informative time history of the contact forces.^[27] As a result, the time interval for the maximum load from the numerical model may not precisely correspond with that derived from the experimental approach.

6. Conclusion

This study investigates the behavior of metal-composite double lap joints under various impact energies through both experimental and numerical approaches. A356 aluminum and grain-refined aluminum adherends were used as the metal components. The composite laminates were made from glass/epoxy and aramid/epoxy, utilizing unidirectionally oriented fibers. A total of 8 different configurations of double lap joints were prepared and tested under two different impact energies (20 J and 40 J). The numerical

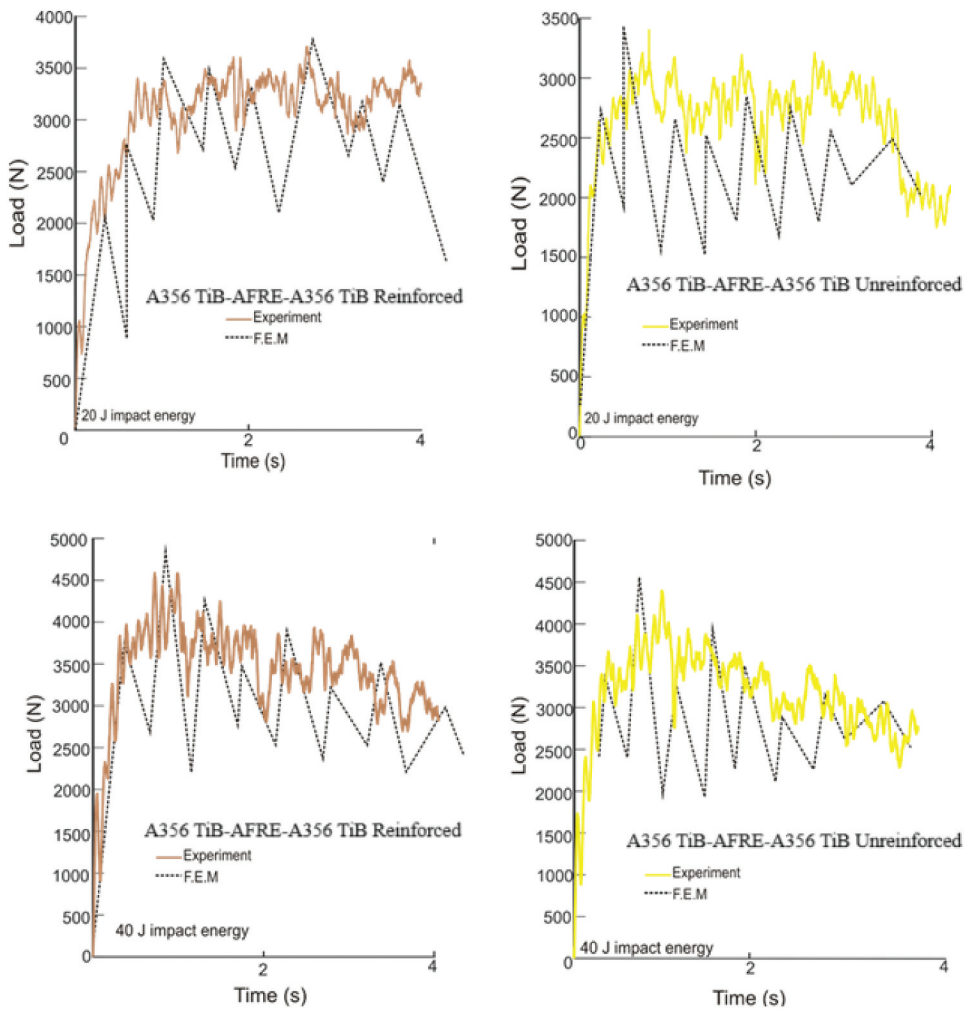


Figure 16. The load-time curves comparison for A356 TiB-AFRE-A356 TiB.

modeling of the adhesive utilizes a six-node pentahedron cohesive element. The results obtained from both the experimental and numerical approaches are summarized as follows

- The A356TiB-GFRE-A356TiB lap joint demonstrated the highest impact load at an energy level under 40 J impact energy. In contrast, at 20 J of impact energy, the A356-AFRE-A356 lap joint exhibited the lowest impact load. Notably, the addition of the thermoplastic material (Copes) to the adhesive formulation enhanced the impact load across all tested connection configurations at both 20 J and 40 J impact energies. This indicates that the impact resistance of the metal composite double lap joint was positively influenced by incorporating Copes.

- Double lap joints made of fine-grain reinforced aluminum adherends demonstrated improved impact resistance at both energy levels. The overall performance of the double lap joint was significantly enhanced by the fine-grained, strengthened aluminum adherends. Furthermore, the GFRE composite laminate showed greater impact load capacity than the AFRE composite laminate in all tested configurations.
- The damage zones identified in the six-node pentahedron element align well with the results from the experimental approach for both types of impact energies. This indicates that the cohesive element used is appropriate for the boundary conditions related to impact loading. Furthermore, the maximum impact load values obtained from both experimental and numerical methods are closely matched across all configurations.

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Engin Erbayrak: Methodology, Finite Element Analysis, Writing – original draft. Murat Colak: Production of materials, review & editing. Cansu Noberi: Production of materials Writing – review & editing.

Author contributions

CRedit: **Engin Erbayrak**: Conceptualization, Software, Validation, Writing – original draft; **Murat Colak**: Conceptualization, Methodology, Writing – original draft; **Cansu Noberi**: Investigation, Writing – original draft.

Disclosure statement

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