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An investigation on the mechanical behavior of mixed adhesively bonded composite joints subjected to transverse pre-impact following by axial post-tensile

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ABSTRACT

In this study, mixed adhesive joints were formed to create a more homogeneous stress distribution in order to increase the failure load that the joints could bear. Single-lap joints (SLJs) made of glass fiber-reinforced plastic (GFRP) composites were formed using a rigid adhesive (Araldite AV138) in the middle and a more flexible adhesive (3 M DP8005) at the ends of the joint. Rigid and flexible adhesives were applied to the surface with $l_f/l_r = 1$ and $l_f/l_r = 0.5$ bond-length ratio (l_f is bond length for the flexible adhesive and l_r is bond length for the rigid adhesive). Mono adhesive joints were also created using the same adhesives. Tensile tests at 1 mm/min were carried out without applying pre-impact to some joints and applying 2.5, 3.5, 7.5, and 10 J transverse impacts to other joints to reveal how joint strength changes with the potential impacts to which adhesive joints might be exposed. Mixed adhesive joints bore more load under impact and non-impact conditions compared to mono adhesive joints. The impacts applied in these tests increased the load-bearing capacity of mono DP8005 adhesive joints. The largest decrease of strength after impact was observed for the mixed adhesive joints with $l_f/l_r = 0.5$ bond-length ratio.

1. Introduction

With the rapid development of novel engineering materials, multiple-material structures have become more common than conventional ones to achieve desired strengths. The use of composite materials has been widespread in aviation, marine, and civil transport vehicles in recent years. The high strength and rigidity of these materials allow the production of lightweight, high-performance vehicles. Adhesive bonding in joining composite materials with each other or with other materials is a commonly used method due to several advantages. Stress concentrations in adhesive joints mostly occur at the ends of overlaps, and peeling failure starts from such ends extending toward the center of the joint. The strength of a joint can also be improved by using a rigid adhesive in the center and flexible adhesives at the ends of the bonding region. The joints in which adhesives are used in this way are referred to in the literature as mixed adhesive, module graded, bi-adhesive, and hybrid adhesive joints. Thus, the stress concentrations at the ends of the bonding region are reduced with the flexible adhesive, creating a homogeneous distribution along the overlap that results in a joint with increased failure load [1–3].

Pires et al. [2] bonded aluminum specimens by using rigid adhesives in the center and flexible adhesives at the ends of the overlap. The results of the tensile test at a speed of 1 mm/min showed that mixed adhesive joints had 22% higher strength according to mono adhesive joints. The results were also compared with those of finite element analysis. Silva and Lopes [3] conducted an experimental study by using a rigid adhesive in the center and three flexible adhesives at the ends of SLJs. The mixed adhesive method was found to provide higher joint strength compared to individually used adhesives in cases where the joint strength of the flexible adhesive was lower than that of the rigid adhesive. Fitton and Broughton [4] emphasized that a suitable combination of variable modulus adhesives could reduce the stress concentrations in joints with carbon fiber-reinforced polymer (CFRP) materials and that various modes of failure could occur. Silva and Adams [5] evaluated the strengths of double-lap joints (DLJs) formed with mixed adhesive through tensile tests at − 55, 22, 100, and 200 °C, considering the operating temperature range and materials of a supersonic aircraft body. They concluded that mixed adhesive joints provided higher joint

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strength, especially at higher temperatures. Neves et al. [6] developed an analytical model using joint parameters such as combinations of adhesives and geometric factors, focusing on the distribution of stress to achieve the maximum joint strength in joints with mixed adhesives. Kong et al. [7] carried out a simulation of tensile and cleavage tests of mixed adhesive joints using the three-dimensional finite elements method. They emphasized that maximum stresses along the overlap axis could be reduced if appropriate bond-length ratios were used in joints with high- and low-modulus adhesives. Moreover, they suggested that changes in modes of loading should be taken into consideration when optimizing mixed adhesive joints. Kumar and Pandey [8] investigated the effect of adhesive layer thickness in mixed adhesive joints. The stress distribution was analyzed numerically for adhesive thicknesses of 0.1–0.4 mm. They noted that the maximum peeling and shear stresses at the overlap ends decreased with increasing adhesive thickness. Similar results were found in the study conducted by Carbas et al. [9], in which the effect of adhesive thickness on mixed adhesive joints was experimentally investigated. Özer and Öz [10] carried out three-dimensional finite element analysis with four different bond-length ratios in double-lap mixed adhesive joints. It was concluded that shear and peeling stresses could be reduced through the optimization of bond-length ratio in mixed adhesive joints. The results of the finite element analysis were consistent with analytical solutions. Bavi et al. [11] optimized the geometry of the overlap in mixed adhesive SLJs and DLJs using modified versions of the Bees and Genetic Algorithm. Variables such as bond length, adhesive thickness, and adherend thickness were evaluated. Analytical and experimental results were consistent with each other. Silva et al. [12] investigated mixed adhesive joints formed by a combination of four adhesives through tensile tests at 1 mm/min and impact tests at 40 J. It was concluded that the use of the mixed adhesive technique improved tensile strength and impact resistance by enhancing the flexibility of the joints. Öz and Özer [13] used two flexible adhesives at the ends of the overlap together with rigid adhesives in the center for the bonding of high-strength steel samples. Tensile tests were carried out at 1 mm/min. They noted that high shear strength could be achieved by increasing the flexibility of the adhesives. Stein et al. [14] investigated mixed adhesive joints by means of analytical and finite element methods. They proposed an analytical approach in which peeling and shear stresses on SLJs of steel, aluminum, and GFRP materials could be calculated and compared with previous studies. They reported that a more homogeneous stress distribution and reduced stress concentrations could be achieved with mixed adhesive joints. Machado et al. [15] created mixed adhesive joints with two rigid and three flexible adhesives and carried out tensile tests at speeds of 1 mm/min and 100 mm/min in their experimental study. They concluded that the use of a rigid adhesive in the center and a flexible adhesive at the ends of an overlap could prevent or delay delamination failure by reducing peeling stresses in the critical regions causing delamination. Subsequently, they worked on the development of numerical models to simulate their experimental studies [16]. The numerical studies also showed that the use of mixed adhesives provided improved joint strength under the same stress conditions. The authors carried out tests at − 30 °C and 80 °C to investigate the effect of temperature on mixed adhesive joints under the same material and stress conditions in another study [17]. They showed that the joints were able to bear higher failure load and absorb higher energy at 80 °C than at − 30 °C. However, the best results were generated at room temperature in the specified temperature range. Zaeri and Googarchin [18] investigated the effect of environmental factors on mixed adhesive joints. Samples were conditioned under 4 levels of humidity for 0, 35, 80, and 270 days, after which they were subjected to tensile tests at speeds of 1 mm/min and 100 mm/min. The results of the tests showed that mixed adhesive joints had higher failure load in dry environments, with more decrease in static failure load in humid environments compared to mono adhesive joints. The analytical estimations of failure load were similar to the experimental observations in dry settings. Ramezani et al. [19] carried out tensile tests at 1 mm/min for various configurations of adhesive thickness, adherend thickness, and adhesive ratios in mixed adhesive joints and analyzed them simultaneously with a digital image correlation technique. It was concluded that the effect of bond-length ratio on peeling stress increased with increasing adhesive thickness and decreased with increasing thickness of the adherend.

Adhesive joints are not exposed to static or impact loads in only the axial direction. They can also be exposed to loads perpendicular to the axis. It is necessary to find a satisfactory answer to the questions of how much the joint strength will change and whether it will be sufficient in the event of crashes or impacts to the joint in such cases. Responses of joints such as energy absorption, crack progression, and failure mechanisms were investigated by applying various impact energy levels in transverse low-velocity impact tests on joints with mono adhesives in previous studies.

Vaidya et al. [20] investigated transverse impact responses experimentally and numerically in the adhesive overlap joints of composite materials. They found that nonplanar loads created higher peel stress on the adhesive layer compared to planar loads. Sayman et al. [21] investigated the effects of impacts on single-lap composite adhesive joints by carrying out tensile tests subsequent to axial impacts on the joints at various temperatures. In another study [22], effects of transverse impacts on the failure of different composite joints were analyzed. It was revealed that the load-bearing capacity decreased when impact energy was increased from 5 J to 15 J, while the load-bearing capacity increased at 20 J due to the perforation failure of the adhesive. Akderya et al. [23] investigated the effects of thermal aging and impact load on the tensile properties of adhered composite joints in an experimental study. They noted that thermal aging at − 18 °C increased load-bearing capacity while impacts reduced the joint strength. Ozdemir et al. [24] investigated the effects of fabric reinforcements on failure responses of the bonding surface and transverse impact behavior in joints where GFRP and aluminum materials were adhesively bonded. They noted that the load-bearing capacities of all joints decreased substantially when the samples were subjected to impact load with energy level of 2.5 J. Wu et al. [25] carried out low-velocity transverse impact (1.1–4.5 J) tests to investigate failure modes under impact loads on adhesively bonded SLJs of CFRP adherends with various overlap lengths and widths. The results of transverse impact tests suggested that the length of the crack and the energy absorption increased with increasing impact energy. Callıoglu and Ergun [26] investigated transverse impact behaviors in SLJs of GFRP adherends. Impact responses such as contact load, torsion, and contact duration as well as failure modes of the joints were determined and discussed. It was concluded that overlap length and impact energy affected the impact reactions of the joints significantly. Liu et al. [27] investigated the effects of impact surface and impact energy on SLJs. Tensile tests were carried out at a speed of 1.3 mm/min after impacts were applied at different energy levels. The results showed that the impact surfaces of CFRP materials provided better structural integrity and higher joint strength compared to the impact surfaces of aluminum materials.

There are many extensive studies on the bonding of composite materials. Mixed adhesive joints were evaluated under axial static and impact loads. Mono adhesive joints were used in studies where transverse impacts were investigated. However, there are no studies in the available literature on the mechanical behaviors of joints bonded with mixed adhesives after transverse impacts. In this study, GFRP materials will be adhesively bonded with rigid and flexible adhesives with different properties within the same overlap. Rigid adhesives will be applied in the central region of the overlap, while flexible adhesives with two different ratios will be applied to the ends of the overlap. These adhesive joints will be subjected to drop-weight impact tests with various energy levels perpendicular to the overlap, followed by tensile tests. The experimental results will be evaluated and the overall results of the study will be discussed.

2. Experimental procedure

2.1. Materials

GFRP plates with thicknesses of 2 mm were used to form SLJs. The GFRP plates were manufactured by the hand lay-up method. The lay-up configuration of the composite was considered as 30 layer [0°/90°] woven glass fibre fabrics having a density of 80 g/m^2. An epoxy resin matrix based on CY225 epoxy prepolymer and HY225 hardener were used in the production of the composite plates. The mixing ratio for resin to hardener by weight is 10:2. The GFRP plates were cured in a lamination press, at a constant 0.3 MPa pressure and 120 °C temperature for 2 h. The technical specifications obtained from the manufacturer are given in Table 1.

Adhesives with two different properties were used for the mono and mixed adhesive joints in the tests. Araldite AV138/HV998, an epoxy with very rigid and brittle mechanical behavior, is a commonly used adhesive for bonding CFRP and GFRP. Another adhesive is 3 M DP8005, which is a two-component acrylic adhesive with flexible and ductile properties. The properties of these adhesives were determined in the studies conducted by Silva et al. [28,29] and are given in Table 2.

2.2. Specimen geometry

Overlap lengths of 25 mm [4,12,15,17,20,22,24,27] and/or 50 mm [3,4,10–13] were used in many studies analyzing SLJs. Pre-tests were conducted for both overlap lengths. Specimens with overlap length and width of 25 mm failed in transverse impact tests. An overlap length of I = 50 mm and width of b = 25 mm were used for both mono and mixed adhesive bonding to increase the bonding area in order to evaluate responses at various energy levels. Another important parameter for mixed adhesive joint geometries is the ratio of the surface area covered by each adhesive. There are studies in the literature [4,11–13,15,17] in which adhesives were used with various ratios. Bond lengths were designated as l_f for the flexible adhesive and l_r for the rigid adhesive. These adhesives were applied to the substrate with ratios of $l_f/l_r = 1$ and $l_f/l_r = 0.5$ along the bonding line. The rigid adhesive was used in the center of the overlap, while the flexible adhesive was used at the ends of the overlap.

In previous studies on mixed adhesive joints [12,15,17,27,32], the optimum adhesive thickness value was taken as 0.2 mm. Higher adhesive thicknesses will increase the thickness of the overlap region, which will cause an increase in the bending moment value in the joint. This moment value will reduce the joint strength by increasing the peeling stresses at the overlap ends. Therefore, taking into account the experience in previous studies, double-sided tape with thickness of 0.2 mm was used to separate the adhesives in the overlap. The tape not only prevented the intermingling of the adhesives; it also enabled a fixed bonding thickness in all joints. In addition, mono adhesive joints in which only a rigid or a flexible adhesive was applied along the overlap were formed. Fig. 1 shows the joint geometry.

2.3. Manufacturing of specimens

Composite plates with dimensions of 1000 × 1250 mm^2 were cut with a water jet into plates of 125 × 25 mm^2 while taking fiber orientation into consideration. All specimens with smooth surfaces were roughened with 100-mesh sandpaper applied perpendicular to the axis. Due attention was paid to roughening the resin layer on the surface without penetrating into the fibers. The experimental samples' surface roughness was measured with a Mahr Perthometer M2 (Mahr GmbH, Göttingen, Germany). Sanding was done to ensure that the Ra roughness value taken from three different points on each test sample was between 1.9 and 2.1 μm. An overlap region of 50 mm was marked considering the ratios of $l_f/l_r = 1$ and $l_f/l_r = 0.5$ to determine the regions of the adhesives in the mixed adhesive joints. The overlap region was then washed with acetone to remove possible residues on the surface. Tapes with thickness of 0.2 mm were applied to the lower adherend as very narrow strips approximately 0.3 mm in width. The rigid adhesive was applied to the center first, followed by application of the flexible adhesive to the ends. The upper adherend was then lapped onto the lower adherend. A tape with thickness of 0.2 mm was also used for fixed bonding thickness in mono adhesive joints. Metal blocks weighing 300 g were placed on the joints to discharge excess adhesive and then the discharged adhesive was removed. Five adhesive joints were formed for each group of tests. All specimens were tested after being conditioned at room temperature for 1 week. Fig. 2 shows the types of adhesive joints prepared.

Table 1
Adherend properties.

Fiber orientation	Woven
Resin type	Epoxy
Fiber content by weight, %	76
Fiber content by volume %	65
Tensile strenght (Mpa)	310
Density (g/cm^3)	1,8

Table 2
Adhesive properties.

Properties	AV138/HV998	DP8005
Young's modulus (MPa)	4890	590
Shear modulus (MPa)	1560	159
Tensile strength (MPa)	41.0	6.3
Shear strength (MPa)	30.2	8.4

2.4. Test procedure

2.4.1. Low-velocity pre-impact test

Transverse impacts with different energy levels were first applied to the mono and mixed adhesive joints. The impact tests were carried out with an Instron-Dynatup 9250 HV drop-weight impact tester. The mass of the impactor, with a hemispherical tip of 12.5 mm in diameter, was 5.92 kg. The tester could produce impact load with varying energy levels by changing the drop height of the impactor. The pneumatic grip system of the tester prevented repeated impacts on the specimens. The ends of overlaps were kept free to observe how the flexible DP8005 adhesive at the ends of mixed adhesive joints controlled any bending and how it contributed to the joint during impact. Therefore, test specimens with overlap length of 50 mm were fixed onto frames 60 mm long and 40 mm wide using a pneumatic grip as shown in Fig. 3. Transverse impacts with energy levels of 2.5, 3.5, 5, 7.5 and 10 J adjusted to land directly in the center of the overlap were applied.

2.4.2. Tensile test

The test specimens were subjected to tensile tests after impact tests. The static tensile tests with tensile velocity of 1 mm/min were carried out using the Instron 8801 tensile tester with 50-kN capacity. Tensile tests under the same conditions were also applied to test specimens that had not previously been impact-tested in order to evaluate the effect of impact. Details of these tests are given in Table 3.

3. Results and discussion

The aim of this study was to experimentally evaluate how mixed adhesive joints, which are formed to reduce stress concentrations at the ends of overlaps, affect the load carrying capacity of the joints because of impacts that they may be exposed. For this purpose, transverse impacts at energy levels of 2.5, 3.5, 5, 7.5, 10 J were applied to the lap joints. Following the application of the pre-impacts, mono and mixed joints were tensile- tested. Mono and mixed adhesive joints with and without

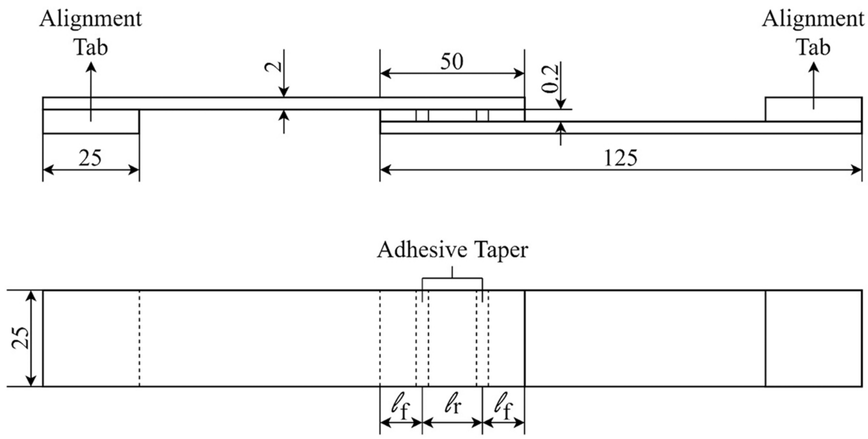

Fig. 1. Dimensions and geometries of adhesive joints (Not to scale and unit mm).

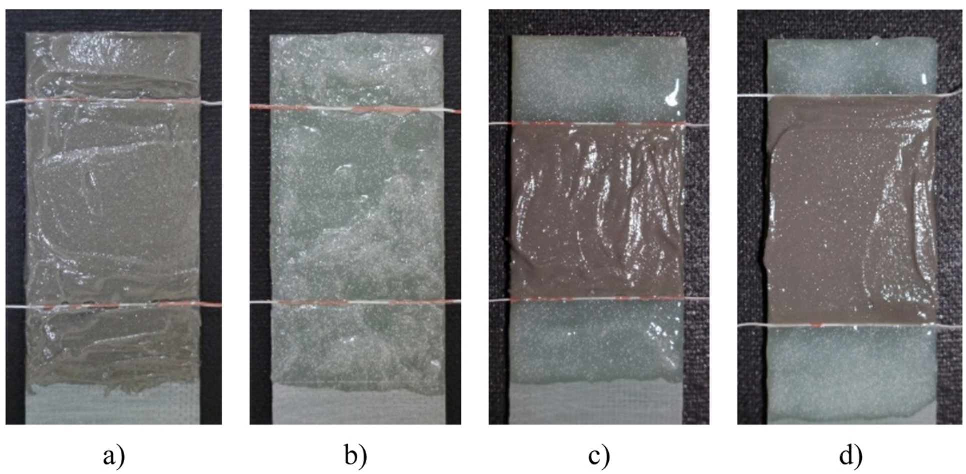

Fig. 2. Type of adhesive joints, (a) Mono AV138, (b) Mono DP8005, (c) $l_f/l_r = 1$ mixed adhesive, (d) $l_f/l_r = 0.5$ mixed adhesive.

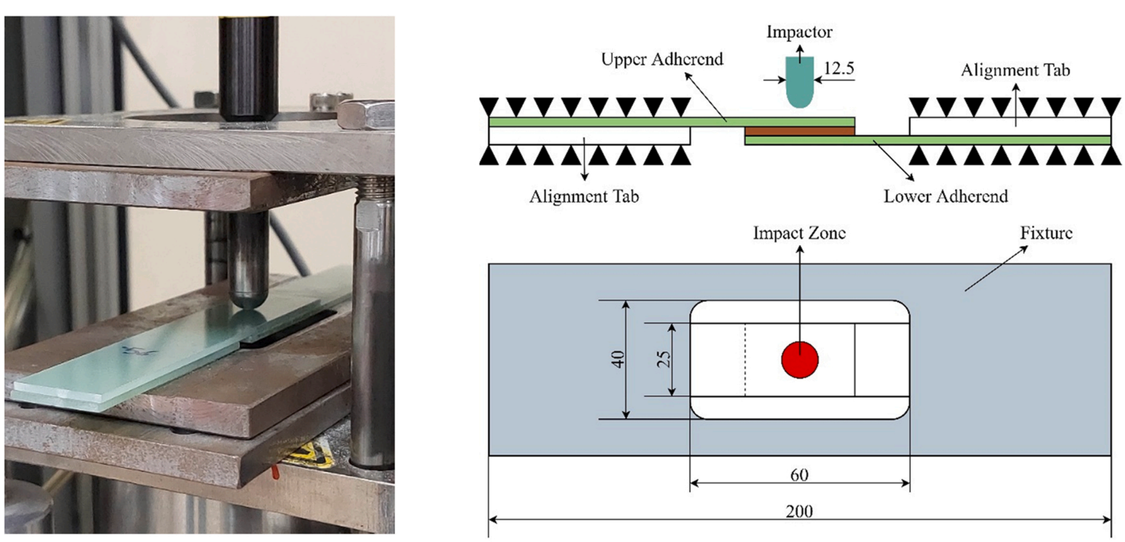

Fig. 3. Impact experiment setup and schematic of the specimen and the clamping system.

pre-impacts were comparatively evaluated.

3.1. Results of transverse impact tests

The responses of mono and mixed adhesive SLJs to impacts were first evaluated in this study. Overall impact responses and the energy

Table 3
Experimental details of the adhesive joints.

SLJ type	Impact energy (J)	Tension velocity (mm/min)
Mono AV138	0, 2.5	1
Mono DP8005	0, 2.5, 3.5, 5, 7.5, 10	1
Mixed $l_f/l_r = 1$	0, 2.5, 3.5, 5, 7.5, 10	1
Mixed $l_f/l_r = 0.5$	0, 2.5, 3.5, 5, 7.5, 10	1

absorbed by the joints are discussed using contact force-deflection curves and post-impact failure images.

Contact force-deflection curves are graphics that provide significant information on the impact behaviors of lap joints during impact. Contact force can be defined as the compression load applied by specimens onto the impact frame. Fig. 4 shows the contact force-deflection curves for mono and mixed adhesive joints under different impact energy levels. Significant peelings occurred at the overlap end parts of the adhesive when transverse impact with an energy level of 2.5 J was applied to joints in which only AV138, a rigid adhesive, was applied. This indicated that the adhesive could not absorb higher levels of energy. Therefore, no other impacts with other energy levels were applied. AV138, having an elongation at break of 0.8%, did not allow plastic deformations. The maximum contact force and the deflection achieved after transverse impact of 2.5 J were 1.77 kN and 2.42 mm, respectively (Fig. 4a). An unloading process of sorts where the force dropped to zero after reaching the maximum was observed in this case. The cause of this sudden drop without any change in deflection was the separation of composite adherends at the ends of the overlap, disrupting the integrity of the joint. Graphics b, c, and d in Fig. 4 show that each curve has an ascending section of loading and a descending section of unloading decreasing after reaching a maximum load value called the contact force. These ascending sections of the curves in the graphics were due to the resistance of the composite material and the adhesive to the impact force. The slope of the ascending section is defined as bending rigidity [30]. The contact forces equivalent to different deflection values of the joints at an energy level of 7.5 J are given as examples in Table 4. The

Table 4
The contact forces equivalent to different deflection values of the joints at an energy level of 7.5 J.

Deflection (mm)	Contact force (kN)		
	Mono DP8005	Mixed l_f/l_r= 1	Mixed l_f/l_r= 0.5
1	0.89	0.91	0.90
2	1.70	1.72	1.73
3	2.34	2.37	2.40
4	2.68	2.80	2.88

values in this table indicate that the smallest contact force at the same deflection value occurred in the joints where the flexible adhesive DP8005 was used as a mono adhesive, while the largest contact force at the same deflection value occurred in mixed adhesive joints where the rigid adhesive AV138 was used in higher percentages with a mix ratio of $l_f/l_r = 0.5$. A larger contact force at the same deflection value means increased slope of the curve in the ascending section, meaning increased bending rigidity of the joint.

The contact forces and deflections in joints increased along with the increasing energy levels of the impacts applied. The largest contact force was measured after the impact with energy of 7.5 J in mixed ($l_f/l_r = 0.5$, $l_f/l_r = 1$) and mono DP8005 adhesive joints, respectively. The contact force increased with the increasing ratio of the rigid adhesive used in the mix ratio. The descending sections of unloading in the curves in the graphics represent rebounding from the material surface of impactor. The contact force-deflection curves obtained after different energy levels were applied for all mono DP8005 and mixed adhesive joints were in closed form. In other words, the structural integrity of the joints was maintained without any failure. The joints where only AV138 was used were detached in the bonding region after impact of 2.5 J, while the mixed adhesive joints where a flexible adhesive was used at the ends and a rigid adhesive was used in the center with a ratio of $l_f/l_r = 0.5$ remained intact against impacts with an energy level of 7.5 J. When the rigid AV138 adhesive, which has a high shear stress but does not allow displacements in shear, is used with DP8005, which is a flexible

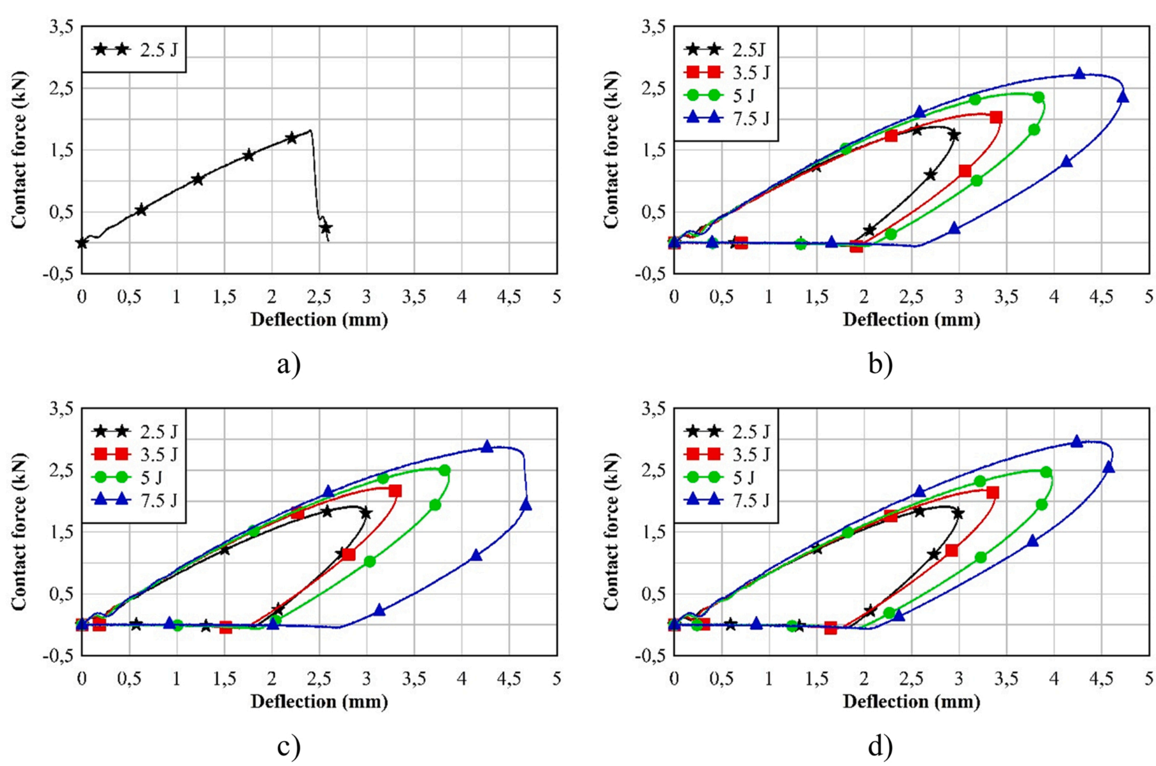

Fig. 4. Contact force–deflection curves according to various energy levels: (a) Mono AV138, (b) Mono DP8005, (c) Mixed $l_f/l_r = 1$, (d) Mixed $l_f/l_r = 0.5$.

adhesive that allows displacements in shear, the joints formed were able to absorb higher impacts. The contact force-deflection curves obtained after impacts with energy levels of 2.5, 3.5, and 5 J were quite similar for the mono DP8005 and mixed adhesive joints (Fig. 4b, c, d). However, there were more distinct differences by adhesive mix ratio for impact energy of 7.5 J. The closed areas created by the curves in the contact force-deflection graphics represent the energy absorbed by the joints [31]. The absorbed energy values for each sample are given in Table 5. When the values in the table are examined, it is seen that the mono DP8005 absorbs more energy at every energy level up to 7.5 J impact, thanks to its flexible structure. At 7.5 J energy level, the mixed adhesive joint with $l_f/l_r = 1$ ratio absorbed the most energy. Contrary to other energy levels, the joints using only DP8005 absorbed less energy after the applied 7.5 J impact compared to the mixed adhesive joint with the ratio $l_f/l_r = 1$. Thus, it is understood that rigid adhesive has a support to absorb impact. However, as the amount of rigid adhesive used increased ($l_f/l_r = 0.5$), the energy value absorbed by the joint decreased again. Because the increase in the rate of rigid adhesive in the middle region means that the rigid adhesive approaches the joint ends. For this reason, the rigid adhesive is affected by the stretching that will occur at the ends of the joint, and a decrease in the energy absorbed by the joint has been observed. The deflection value for the mixed adhesive joint with ratio of $l_f/l_r = 0.5$ at the moment when the contact force dropped to zero was 2 mm (Fig. 4d). The deflections in mono DP8005 and mixed adhesive joints at $l_f/l_r = 1$ at the moment when the contact force dropped to zero were about 2.6 mm (Fig. 4b, c). Therefore, the energy absorbed after impact at 7.5 J was lower for the mixed adhesive joint with a ratio of $l_f/l_r = 0.5$ compared to the mono DP8005 and mixed adhesive joints with ratio of $l_f/l_r = 1$. This was due to the higher ratio of rigid adhesive used in the bonding region. As material failure or overlap separation occurred in all specimens to which impacts with an energy level of 10 J were applied, these findings were not taken into consideration.

3.2. Static tensile test results

In the second stage of the experimental study, tensile tests of mono and mixed adhesive joints without impact and with transverse impact were carried out with varying energy levels. Load-displacement curves were plotted and failure load values were compared. The modes of failure were evaluated by recording images of the adherend surfaces after tensile tests.

Fig. 5 shows the load-displacement curves obtained from the non-impact and post-impact tensile tests of the adhesive joints where only AV138 was used. A failure load of about 8 kN was measured in the tensile tests carried out without applying impact. In addition, the displacement value at this failure load was about 1.5 mm. Following transverse impact with an energy level of 2.5 J, 3 specimens were completely detached at the bonding region while peelings occurred at the ends of the joints in 2 specimens. The failure load in the tensile tests of the specimens that had not detached completely after impact decreased to 2.6 kN. The adhesive joints where AV138 was used lost 67% of their strength after impact with an energy level of 2.5 J.

Table 5
The absorbed energy values for each sample.

Joint type	Energy level (J)	Absorbed energy (J)				
		1	2	3	4	5
Mono AV138	2.5	2,85	3,07	3,24	3,19	3,05
Mono DP8005	2.5	2,75	3,13	2,61	2,58	2,89
	3.5	3,15	3,12	3,10	3,20	3,23
	5	4,23	4,21	4,22	4,51	4,30
	7.5	6,35	6,43	6,20	6,58	6,76
Mixed lf/lr= 1	2.5	2,45	2,46	2,47	2,54	2,52
	3.5	2,98	3,05	3,00	3,01	3,07
	5	5,11	3,98	3,97	4,13	4,16
	7.5	7,10	6,59	7,12	6,88	8,43
Mixed lf/lr= 0.5	2.5	2,48	2,44	2,41	2,56	2,46
	3.5	3,07	3,05	3,00	3,05	2,95
	5	3,86	4,11	4,00	3,98	4,02
	7.5	6,15	5,70	6,90	5,76	6,88

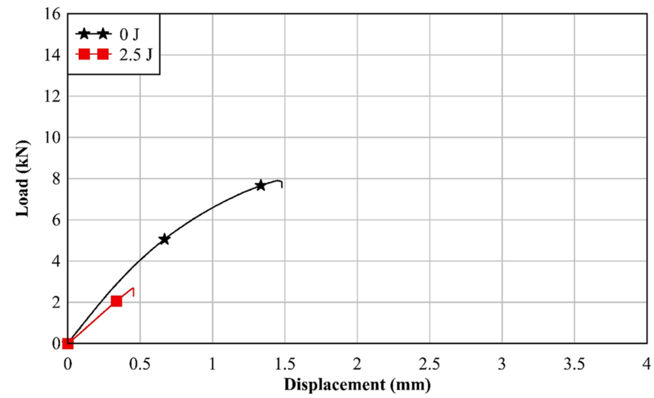

Fig. 5. Load–displacement curves of mono adhesive joints with AV138 for non-impact and post-impact conditions.

Fig. 6 shows the load-displacement curves obtained from the non-impact and post-impact tensile tests of the adhesive joints where the DP8005 adhesive was used. Surprisingly, the smallest failure load was measured for non-impact specimens while the load-bearing capacities of the specimens increased after transverse impact. The joints had the largest failure loads after impact with an energy level of 3.5 J. This value is approximately 44% higher than the load-bearing capacity of the non-impact specimens. Even though the load-bearing capacities of the joints decreased after impacts above 3.5 J, they still had higher values than in the non-impact state. Moreover, the displacement values for the failure loads of the joints to which impacts of 2.5 J and 3.5 J were applied were higher compared to the non-impact state, while the displacement values decreased in the other impact energies compared to the non-impact state. In the literature, as a result of the tensile tests performed after the transverse impact, cases where the load bearing capacity of the joints increased. It was observed in studies by Liu et al. [27] and Sayman et al. [22] evaluating the effects of transfer impacts with varying energy levels that load-bearing capacities were higher in tensile tests of single-lap mono adhesive joints exposed to impacts of 10 J and 20 J compared to the non-impact state. They noted that local pits penetrating into the bonding region from the contact point of the impactor occurred upon impact, which caused the mechanical interlocking of the adhesive and the adherend, resulting in an increased failure load of the joint by creating a resistance to shear. In the present study, no pits occurred on the material surface even after impacts with energy level of 7.5 J, which was the highest energy level that was applied. When the interfaces were

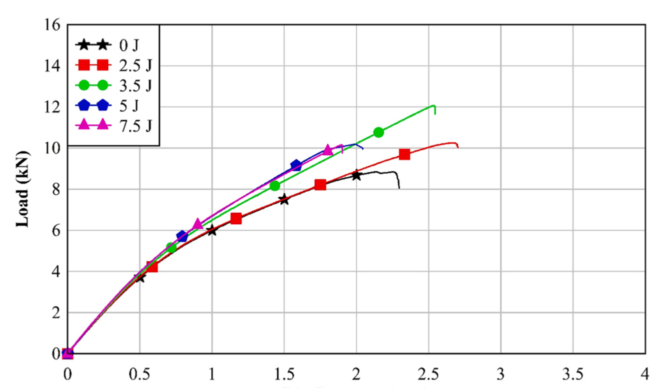

Fig. 6. Load–displacement curves of mono adhesive joints with DP8005 for non-impact and post-impact conditions.

examined after tensile tests, no interpenetration of adherends and adhesives was observed. Therefore, the increase in the load-bearing capacities shown in Fig. 6 cannot be interpreted as having been caused by mechanical interlocking.

The classification of adhesives by chemical composition describes adhesives in the broadest sense as being either thermosetting, thermoplastic, elastomeric, or alloys (hybrids) of these. Thermosetting adhesives are materials that cannot be heated and softened repeatedly after their initial cure. Once cured and crosslinked, the bond can be softened somewhat by heat, but it cannot be remelted or restored to the flowable state that existed before curing [33]. Epoxy and acrylic adhesives are classified as thermosetting adhesive [33–36]. Adhesives become thermosetting after curing. Thermosets are polymers with a crosslinked or a network structure. One of the most important techniques used to improve mechanical strength and tensile modulus is to permanently deform the polymer in tension. During drawing the molecular chains slip past one another and become highly oriented. The chains positioned diagonally in the lamellae within the internal structure of polymeric materials flow over each other upon plastic deformation (through drawing), resulting in tilted lamellae; thus, folded chains are better aligned to the drawing axis and any further displacement is prevented by the weak secondary bonds or van der Waals forces. Thus, the tensile strength increases in the direction of drawing in which orientation occurs [37]. Shear stresses occurred on the adhesive layer due to the bending caused by the impacts applied in the tests. Such shear stresses might have caused the alignment of molecule chains of the adhesives that became thermosetting as described above. The increased strength found in tensile tests applied after impact compared to the non-impact state might be attributed to the resistance created by aligned molecule chains, and three-point bending tests were carried out to create bending stress and thus shear stress on the joints in order to confirm that such increased strength occurred in this way. With this aim, mono DP8005 adhesive joints were created again. Since deflection of approximately 3 mm occurred upon pre-impact of 2.5 J, the joints were loaded so as to create 3-mm deflection in the three-point bending test and then a tensile test was carried out. In this case, increased failure load was observed. The failure load obtained in the tensile test carried out after impact of 2.5 J was almost the same as the failure load obtained in the tensile test carried out after the three-point bending test. It is safe to say that the shear stresses created by bending during impact caused the diagonal chains to align in the lamellae of the cured adhesive, resulting in increased tensile strength of the joints.

Figs. 7 and 8 show the curves produced in the tensile tests of the mixed adhesive joints in which adhesives with varying ratios were used. When non-impact conditions were evaluated, it was observed that the failure loads of mixed adhesive joints were measurably higher compared to the joints in which AV138 or DP8005 was used alone. The increase in strength was over 60%. The lower plastic deformation capability under tensile load of rigid adhesive AV138, which actually has high load-bearing capacity, and its sensitivity to peeling stresses and structural failures can explain the small failure load measured for mono AV138 adhesive joints. However, the load-displacement behavior of DP8005 is different from that of AV138. Although the failure load of the mono DP8005 adhesive joint was smaller than that of mono AV138 adhesive joints, the mono DP8005 adhesive joint had higher ductility and flexibility compared to AV138 [3,12,13,15]. It was observed that the failure load of the joints increased when DP8005, a flexible adhesive allowing plastic deformations in overlap, was used together with AV138. This confirms the conclusion of Banea and da Silva [38], who suggested that the strength of an adhesive joint does not depend on only the shear strength of the adhesive but also on its ductility and flexibility.

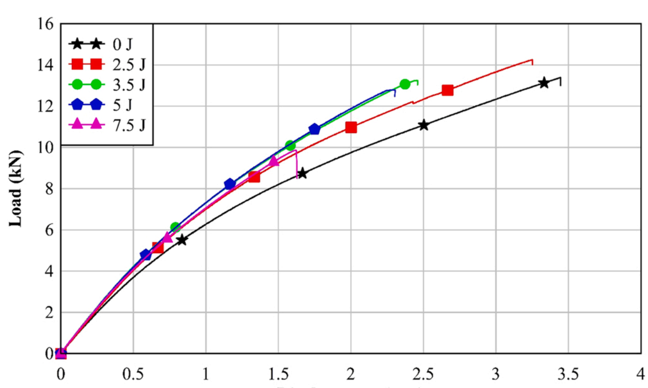

Fig. 7. Load–displacement curves of mixed adhesive joints with $l_f/l_r = 1$ratio for non-impact and post-impact conditions.

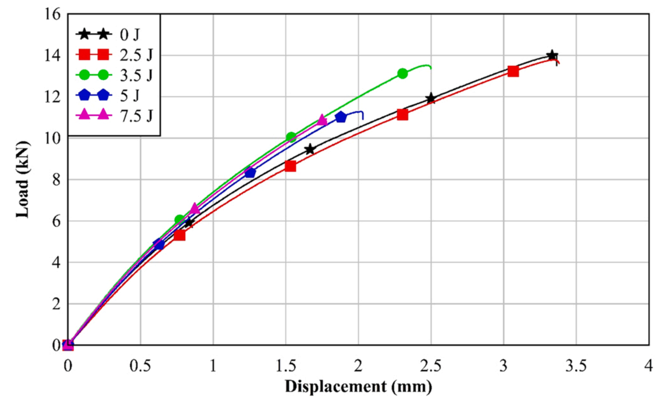

Fig. 8. Load–displacement curves of mixed adhesive joints with $l_f/l_r = 0.5$ ratio for non-impact and post-impact conditions.

It is seen in Figs. 6–8 that the slopes of the load-displacement curves produced in the tensile tests carried out with transverse impacts at varying energy levels are different. The slopes of the load-displacement curves of mono and mixed adhesive joints exposed to impacts with energy levels of 3.5, 5 and 7.5 J were quite similar, while they were higher compared to non-impact joints. The transverse impacts increased the rigidity of the joints. However, the largest displacement until the moment of failure in mixed adhesive joints was observed for non-impact specimens. The displacement values at the moment of failure were likely to decrease with increasing energy levels of the applied transverse impacts. The area of failure increased with increased pre-impact; thus, the axial fracture displacement decreased along with the increasing energy of the pre-impact.

Fig. 9 shows the change of failure load values achieved in tensile tests after impact and non-impact for all types of joints. This graphic provides a more clear illustration of the change in failure loads of the joints. The behaviors among joint types by energy levels of applied transverse impact are described above. It was observed that mixed adhesive joints with a ratio of $l_f/l_r = 0.5$ had higher load-bearing capacity compared to mixed adhesive joints with a ratio of $l_f/l_r = 1$ under non-impact

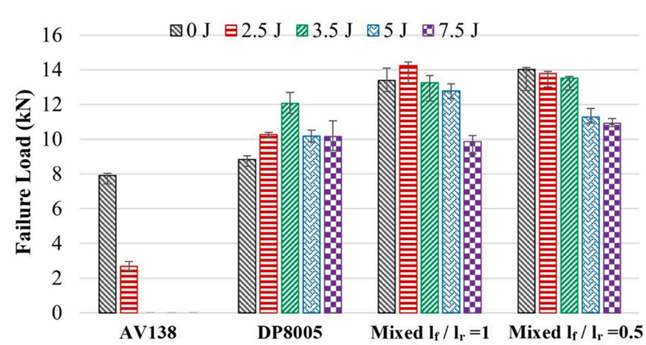

Fig. 9. Comparison of failure loads obtained from tensile test results.

conditions. The failure load value decreased with the increasing percentage of flexible adhesive in the mix ratio. Studies in the literature investigating the effect of adhesive ratio in the overlap of mixed adhesive joints on joint strength have yielded similar results. On the contrary, when the joints were compared in terms of strength after transverse impact, it was observed that the mixed adhesive joints with ratio of $l_f/l_r = 1$ provided higher joint strength. Joints of this type were less affected by the impacts since the flexible adhesive DP8005 was used in greater portions at the ends of the overlaps. This indicates the effect of the mix ratio and operating conditions of the joint on failure load for mixed adhesive joints. Therefore, the selection of the ratio of adhesives to be used in the overlap of mixed adhesive joints is significant. The decrease in failure load after impacts of 5 J and 7.5 J for all joints can be explained by the local breakage of bonding between the adhesive and the adherend in the impact area. This was particularly clear in mixed adhesive joints. The rigid adhesive AV138 applied to the center of the overlap exposed to impact was detached either partially or completely from the adherend depending on the energy level of the impact. Fig. 10 shows that AV138 was mostly detached from the adherend after impact with an energy level of 7.5 J, and the joint was bonded by DP8005 applied to the ends of the overlap.

3.3. Fracture surface

Fig. 11 shows the fracture surfaces of the test specimens obtained after the tensile tests carried out following transverse impacts with various energy levels. Local adhesion and cohesion failures occurred depending on the adhesives used in the joints.

Since tensile tests could not be carried out for mono adhesive joints of the rigid adhesive AV138 as they did not withstand transverse impacts, their fracture surfaces are not shown here. When joint prepared with DP-8005 was examined, the formation and propagation of crack occurred along the mid-plane of the adhesive bondline. Failure behavior observed in DP-8005 is in accordance with general behavior reported in literature for high-ductility flexible adhesives [38]. Cohesion failure mostly occurred for mono joints with DP8005 and parts of mixed joints where DP8005 was used. The adhesive was present on both surfaces. Cohesive failure shows that the surface preparation technique applied to adherend surfaces was sufficient and curing periods were proper. It extended the duration of failure by not being detached from the surfaces instantly upon impact or tension due to being a flexible adhesive. The adhesive created a layered failure surface by piling up due to the shear during tensioning. This form of failure has been observed at every energy level.

In areas where the AV138 is used for mixed adhesive joints crack started near the interface and then changed its propagation direction from the upper interface to the lower interface. It is known that this type of crack propagation was seen mainly in the brittle adhesives [3]. This failure type is more evident at 2.5, 3.5 and 5 J energy levels. The residues of AV138 on the upper adherend decreased with the increased impact energy levels applied to the mixed joints at both ratios. AV138 was detached from the adherend surface upon application of the transverse impact. This was observed more clearly for the energy levels of 7.5 J. Almost no AV138 adhesive remained on the upper adherend, especially after transverse impact of 7.5 J. The rigid adhesive AV138 shattered and remained on the lower adherend. This type of failure was caused by the rigidity of the adhesive. Almost complete adhesion failure occurred at 7.5 J, while an increasing trend towards cohesion failure was observed in regions with AV138 as the energy level decreased.

4. Conclusion

The bonding performances of mono and mixed adhesive joints created by using GFRP composite materials were evaluated experimentally through tensile tests carried out after applying transverse impacts. Mixed adhesive joints were created by applying a rigid adhesive (AV138) to the center and a flexible adhesive (DP8005) to the ends of overlaps with two mix ratios. Drop-weight impact tests of these joints were carried out with impacts with energy levels of 2.5, 3.5, 5, 7.5, and 10 J applied perpendicular to the overlap. Tensile tests were carried out after the impacts. The main conclusions obtained from this study are as follows:

- The strength of an adhesive joint does not depend on only the shear strength of the adhesive, but also on its ductility and flexibility. Joints created using the rigid adhesive AV138, which has a high shear strength but does not allow plastic deformation in shear, together with the flexible adhesive DP8005, which allows plastic deformation in shear, can achieve larger failure loads and absorb higher-energy impacts.
- In mono DP8005 adhesive joints, the failure loads achieved in the tensile tests carried out after impacts with different energy levels were higher compared to non-impact tensile tests.
- It was observed that mixed adhesive joints with a ratio of $l_f/l_r = 0.5$ had higher load-bearing capacity compared to mixed adhesive joints with a ratio of $l_f/l_r = 1$ under non-impact conditions. The failure load

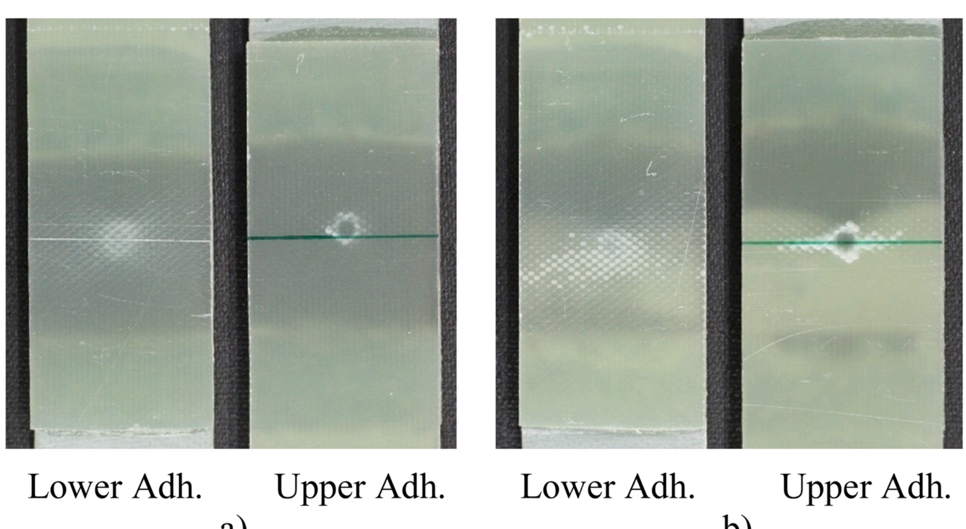

Fig. 10. Failure in $l_f/l_r = 1$ mixed adhesive joints after pre-impact, (a) 5 J, (b) 7.5 J.

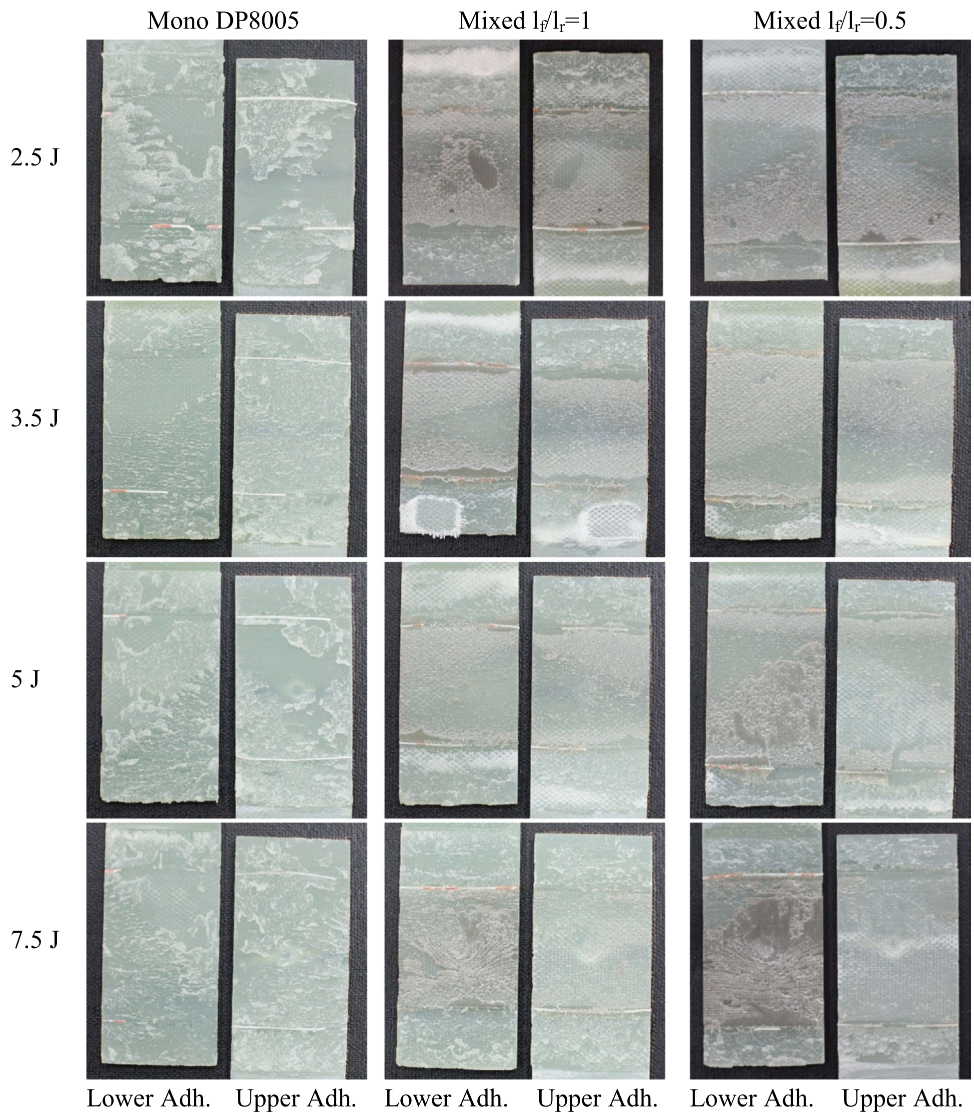

Fig. 11. Failure type of adhesive joints after tensile tests.

value decreased with the increasing percentage of flexible adhesive in the mix ratio.

- In mixed adhesive joints with $l_f/l_r = 1$ ratio, the failure load after 2.5 J was higher compared to the non-impact state, while it was lower for the other values. In mixed adhesive joints with $l_f/l_r = 0.5$, the failure load after all impact conditions was lower compared to the non-impact state.
- When compared in terms of strength after transverse impact, it was observed that the mixed adhesive joints with a ratio of $l_f/l_r = 1$ provided higher joint strength. Using a higher percentage of flexible adhesive provided a reduced effect of impacts on the joint.
- The ratio of application of adhesives and operating conditions affect the failure load that mixed adhesive joints can bear. Therefore, the selection of the ratio of adhesives used in the overlap of mixed adhesive joints is significant.
- All types of joints failed due to adherend damage and/or cleavage at overlap after transverse impacts with an energy level of 10 J.

CRediT authorship contribution statement

Yunus Emre Toğar: Writing – original draft preparation, Visualization, Investigation. **Murat Özenç:** Supervision, Conceptualization, Validation, Investigation, Project administration, Writing – review & editing.

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.

Data Availability

No data was used for the research described in the article.

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References

[1] S. Temiz, Application of bi-adhesive in double-strap joints subjected to bending moment, J. Adhes. Sci. Technol. 20 (14) (2006) 1547–1560.
[2] I. Pires, L. Quintino, J.F. Durodola, A. Beevers, Performance of bi-adhesive bonded aluminium lap joints, Int. J. Adhes. Adhes. 23 (3) (2003) 215–223.

[3] L.F.M. Da Silva, M.J.C. Lopes, Joint strength optimization by the mixed-adhesive technique, Int. J. Adhes. Adhes. 29 (5) (2009) 509–514.
[4] M. Fitton, J. Broughton, Variable modulus adhesives: an approach to optimised joint performance, Int. J. Adhes. Adhes. 25 (4) (2005) 329–336.
[5] L.F.M. Silva, R.D. Adams, Adhesive joints at high and low temperatures using similar and dissimilar adherends and dual adhesives, Int. J. Adhes. Adhes. 27 (3) (2007) 216–226.
[6] P.J.C. Das Neves, L.F.M. da Silva, R.D. Adams, Analysis of mixed adhesive bonded joints part II: parametric study, J. Adhes. Sci. Technol. 23 (1) (2009) 35–61.
[7] F.R. Kong, M. You, X.L. Zheng, Three-Dimensional finite element analysis of the stress distribution in bi-adhesive bonded joints, J. Adhes. 84 (2) (2008) 105–124.
[8] S. Kumar, P.C. Pandey, Behaviour of Bi-adhesive joints, J. Adhes. Sci. Technol. 24 (7) (2010) 1251–1281.
[9] R.J.C. Carbas, L.F.M. da Silva, G.W. Critchlow, Adhesively bonded functionally graded joints by induction heating, Int. J. Adhes. Adhes. 48 (2014) 110–118.
[10] H. Özer, Ö. Öz, Three dimensional finite element analysis of bi-adhesively bonded double lap joint, Int. J. Adhes. Adhes. 37 (2012) 50–55.
[11] O. Bavi, N. Bavi, M. Shishesaz, Geometrical optimization of the overlap in mixed adhesive lap joints, J. Adhes. 89 (12) (2013) 948–972.
[12] M.R.G. Silva, E.A.S. Marques, L.F.M. da Silva, Behaviour under impact of mixed adhesive joints for the automotive industry, Lat. Am. J. Solids Struct. 13 (5) (2016) 835–853.
[13] Ö. Öz, H. Özer, An experimental investigation on the failure loads of the mono and bi-adhesive joints, J. Adhes. Sci. Technol. 31 (19–20) (2017) 2251–2270.
[14] N. Stein, J. Felger, W. Becker, Analytical models for functionally graded adhesive single lap joints: a comparative study, Int. J. Adhes. Adhes. 76 (2017) 70–82.
[15] J.J.M. Machado, P.M.R. Gamarra, E.A.S. Marques, L.F.M. da Silva, Improvement in impact strength of composite joints for the automotive industry, Compos. Part B: Eng. 138 (2018) 243–255.
[16] J.J.M. Machado, P.M.R. Gamarra, E.A.S. Marques, L.F.M. da Silva, Numerical study of the behaviour of composite mixed adhesive joints under impact strength for the automotive industry, Compos. Struct. 185 (2018) 373–380.
[17] J.J.M. Machado, E.A.S. Marques, L.F.M. da Silva, Influence of low and high temperature on mixed adhesive joints under quasi-static and impact conditions, Compos. Struct. 194 (2018) 68–79.
[18] A.R. Zaeri, H.S. Googarchin, Experimental investigation on environmental degradation of automotive mixed-adhesive joints, Int. J. Adhes. Adhes. 89 (2019) 19–29.
[19] F. Ramezani, M.R. Ayatollahi, A. Akhavan-Safar, L.F.M. da Silva, A comprehensive experimental study on bi-adhesive single lap joints using DIC technique, Int. J. Adhes. Adhes. 102 (2020), 102674.
[20] U.K. Vaidya, A.R.S. Gautam, M. Hosur, P. Dutta, Experimental–numerical studies of transverse impact response of adhesively bonded lap joints in composite structures, Int. J. Adhes. Adhes. 26 (2006) 184–198.
[21] O. Sayman, I.F. Soykok, T. Dogan, A. Dogan, V. Arikan, Effects of axial impacts at different temperatures on failure response of adhesively bonded woven fabric glass fiber/epoxy composite joints, J. Compos. Mater. 49 (11) (2015) 1331e44.
[22] O. Sayman, V. Arikan, A. Dogan, F. Soykok, T. Dogan, Failure analysis of adhesively bonded composite joints under transverse impact and different temperatures, Compos. Part B: Eng. 54 (1) (2013) 409–414.
[23] T. Akderya, U. Kemiklioglu, O. Sayman, Effects of thermal ageing and impact loading on tensile properties of adhesively bonded fibre/epoxy composite joints, Compos. Part B: Eng. 95 (2016) 117–122.
[24] O. Ozdemir, N. Oztoprak, An investigation into the effects of fabric reinforcements in the bonding surface on failure response and transverse impact behavior of adhesively bonded dissimilar joints, Compos. Part B: Eng. 126 (2017) 72–80.
[25] W. Wu, Q. Liu, Z. Zong, G. Sun, Q. Li, Experimental investigation into transverse crashworthiness of CFRP adhesively bonded joints in vehicle structure, Compos. Struct. (106) (2013) 581–589.
[26] H. Callioglu, E. Ergun, An assesment of the impacted composite single-lap adhesıve joints, J. Mech. 31 (4) (2015) 433–439.
[27] X. Liu, X. Shao, Q. Li, G. Sun, Failure mechanisms in carbon fiber reinforced plastics (CFRP) / aluminum (Al) adhesive bonds subjected to low-velocity transverse pre-impact following by axial post-tension, Compos. Part B: Eng. 172 (2019) 339–351.
[28] L.F.M. da Silva, R. da Silva, J. Chousal, A. Pinto, Alternative methods to measure the adhesive shear displacement in the thick adherend shear test, J. Adhes. Sci. Technol. 22 (1) (2008) 15–29.
[29] L.F.M. da Silva, F. De Magalhaes, F. Chaves, M. De Moura, Mode II fracture toughness of a brittle and a ductile adhesive as a function of the adhesive thickness, J. Adhes. 86 (9) (2010) 891–905.
[30] S. Abrate, Impact on composite structures, Cambridge University Press, Cambridge, 1998.
[31] T. Mitrevski, I.H. Marshall, R. Thomson, R. Jones, B. Whittingham, The effect of impactor shape on the impact response of composite laminates, Compos. Struct. 67 (2) (2005) 139–148.
[32] M.R.G. da Silva, Impact of mixed adhesive joints for the automotive industry (Master Thesis), Faculty of Engineering of the University of Porto, 2015.
[33] E.M. Petrie, Handbook of Adhesives and Sealants, McGraw-Hill, New York, 2000.
[34] R.D. Adams, Adhesive Bonding Science, Technology and Applications, Woodhead Publishing Limited, Cambridge, 2005.
[35] S. Ebnesajjad, Adhesives Technology Handbook (Copyright by), William Andrew Inc, 2008.
[36] A.J. Kinloch, Adhesion and Adhesives Science and Technology (published by), Chapman & Hall, 1987.
[37] W.D. Callister, D.G. Rethwisch, Materials Science and Engineering, Wiley, 2006.
[38] M.D. Banea, L.F.M. da Silva, R.D.S.G. Campilho, The effect of adhesive thickness on the mechanical behavior of a structural polyurethane adhesive, J. Adhes. 91 (2015) 331–346.