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The flexural behaviors of the impacted composite single-lap adhesive joints

Abstract: This experimental study deals with the flexural behaviors of composite single-lap adhesive joints after impact tests. Increasing impact energies are applied at the center of the composite plates having three different overlap lengths. It is shown that the overlap lengths and impact energy levels affect considerably the impact responses of the composite single-lap joints. It is also shown that the bending stiffness of the composite increases with increasing overlap length. For this reason, after the impact tests, how these effects influence the flexural behaviors of the impacted composite lap joints was also investigated. The flexural loads of the impacted and non-impacted composite single-lap joints were determined and compared with each other. It is shown that the residual flexural loads after impact increase with increasing overlap lengths but decrease with increasing impact energy.

Keywords: impact behavior; joints/joining; mechanical testing; polymer-matrix composites; strength.

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1 Introduction

Fiber-reinforced polymer composites are increasingly being used for different applications as a substitute for traditional materials due to multiple reasons including their long performance life and low maintenance properties. Nevertheless, accidental low-energy impacts caused by dropping tools during maintenance, transportation debris and hailstones can lead to significant strength reduction and localized damage in composites. The results of such minor impact damage between the laminates may vary from surface damage to complete penetration depending on the magnitude of impact loading conditions. The failure modes of damaged composite laminates include fiber breakage, matrix cracking, fiber-matrix debonding and delamination. Among these, delamination causes the most detrimental results on composite stiffness and strength [1–5]. Hence, impact event is very important in design.

Adhesively bonded joints are also widely used in a variety of industrial and engineering activities because the adhesive bonding has some advantages with regard to mechanically fastened joints such as a decrease in stress concentration, a high strength-to-weight ratio, a capacity to join different adherends, a capacity to join thin-sheet materials and good corrosion resistance [6]. Their overall strength depends on the properties of the adhesives. Thus, some researchers have studied the damage mechanism of the composite and lap joint structures. Kim and Chung [7] have investigated the impact load, the absorbed energy and the damaged area according to different energy levels and stacking sequences for woven composite laminates, which were used for a railway vehicle. Datta et al. [8] have done repeated drop tests for glass/epoxy composite laminates to investigate the effects of variable impact energy and laminate thickness.

In the past few years, the failure analysis of composite joints has been performed by combining continuum damage mechanics and finite element (FE) analysis. But, finally, the FE models must be validated by mechanical tests. Several studies on failure analysis of single-lap joints are mentioned in the following paragraphs. Sawa and Suga [9] have measured the stress distributions in single-lap joints subjected to static load by photoelasticity and examined the effects of Young's modulus ratio of dissimilar adherends and the adherend thickness on joint strength. Moreover, FE method (FEM) analyses of the impacted joints were carried out. It was seen that the joint strength increased when Young's modulus of the adherends and the adherend thickness increased. Higuchi et al. [10] have analyzed the stress wave propagations and stress distributions in single-lap joints using an elastic three-dimensional (3D) FEM (DYNA3D). One end of one of the adherends in the single-lap adhesive joint was fixed, and the other adherend to which a bar was connected was impacted by the weight. They observed that the maximum stress increased as the overlap length, the adhesive thickness and the adherend thickness decreased, whereas Young's modulus of the adherends increased. Apalak and Yildirim [11] have investigated the effect of adhesive thickness on the transverse low-speed impact behavior of adhesively bonded similar and dissimilar clamped plates using 3D explicit FEM. They found that the stiff plate resulted in a shorter contact time, a higher contact load and lower plastic dissipation energy, and the impact energy was absorbed by the adhesive layer rather than by the front and back plates, whereas lower stiff plates dissipate it as much as the adhesive layer. Ribeiro et al. [12] have modeled the stress distribution in single-lap adhesive joints by a numerical strategy. They found that the results of the 3D model were more compatible than those of a 2D model on the basis of the experimental results.

Xu and Wei [6] have characterized the overall strengths and the critical displacements of metallic bonded single-lap joints. The results showed that the overall strength of the joints was significantly dependent on the adhesive properties, which were characterized by the strength and energy rate mixities of the adhesive. Furthermore, the shear adhesive stress components played a dominant role in both the damage initiation and the evolution in the adhesives, which were also affected by the overlap length of the joints. Park and Kim [13] have specifically focused on the high-velocity transverse impact of composite joints by hailstones. Impact tests with ice spheres on composite lap joints were conducted to determine the failure threshold energy describing damage initiation. The damage area vs. impact energy was found to increase dramatically for impacts beyond the failure threshold. Ma et al. [14] have conducted an experimental study on carbon fiber-reinforced plastic (CFRP)/Al adhesively bonded single-lap joints. Experimental results showed that structural failure of joints occurred in the adhesive layer or the bonded interface; failure loads and impact resistance of the joint increased as the overlap length increased; the load-carrying capacity of impacted joints declined significantly due to internal damage of the adhesive layer.

To understand the effect of an impact, a common method is to define the residual strength of a composite that has been previously impacted with a lower energy. Bending after impact (BAI) and compression after impact (CAI) tests are used to obtain the retained strength of composite materials. Tetsusei et al. [15] have established a convenient evaluation method for the residual strength after low-energy impact in CFRP laminates by FEM. They have developed a numerical simulation program on damage development considering the angles of transverse cracks to the loading direction based on damage mechanics. The numerical results of the residual strength after the occurrence of damages have a good agreement with experimental results. It was recognized from those results that the proposed numerical method (BAI) was more convenient than CAI.

The transversal impact causes visible damage and delamination in the plate, affecting significantly its mechanical properties and being the reason for a high reduction of compression strength [16, 17]. Onal and Adanur [4] have studied the effect of stacking sequence on the tensile and flexural properties of stitched hybrid composites after low-velocity impact. They found that the incorporation of glass fibers in carbon-reinforced structures improved the impact properties and increased the strain to failure. They also observed the tensile failure mechanism for different hybrid structures. Vachon et al. [18] have presented a study of the effect of stitched reinforcements on impact-induced damage and damage propagation under flexural load. The specimens were subjected to low-velocity impact loading prior to being tested under a three-point bending load. They used a 3D FE model for predicting the propagation of the delamination around the stitched reinforcements during post-impact bending. Nilsson et al. [19] have experimentally detected the strength of bending loaded impacted composite panels having two different thicknesses. They have demonstrated that damage distribution through the thickness affected the bending properties of the laminate and the failure load was lower when the side with the largest delamination was loaded in compression; they have also demonstrated that the far-field failure strain was higher at bending compared to compression loading. Yang et al. [20] have studied the mechanical properties and failure mechanisms of through-the-thickness stitched plain weave glass fabric/epoxy composites. They found that *Z*-directional stitching increased the delamination resistance and lowered the bending strength of the composites. Composites made from through-the-thickness stitched fabrics have demonstrated improved compression after impact behavior as compared to unstitched fabrics.

Analysis of the impact in adhesive joints has been based on the analysis of the effect of a transversal impact on a single-lap joint using CFRP as an adherend [21]. The adhesive is modeled as an elastic-plastic material with kinematic hardening exposed to a transversal impact over the adhesive region. It is found with the use of a dynamic FEM that such conditions produce a mixed mode load, but as the crack propagates through the adhesive, mode II becomes the main loading mode. Sayman et al. [22] have investigated the load-carrying capacity of a single-lap joint bonded by an adhesive by experimental method. They have used glass fiber-epoxy composites as adherends and Loctite 9466 A&B2 as an adhesive material. Their results show that load-carrying capacity decreases at 5, 10 and 15 J but increases for 20 J.

As can be seen in the literature, there are several studies on failure analysis of single-lap joints by using

FEM; however, there are few articles on the impact damage mechanisms of glass/epoxy composite lap joints. To our knowledge, there is no study on the impact behaviors of glass/epoxy composite lap joints with different overlap lengths. A significant decrease in strength of composite structures occurs as a small body hits somewhere near the center region of the adhesively bonded composite single-lap joints. Therefore, this experimental study presents the bending behaviors after impact of the composite single-lap joints. The increasing impact energies, which ranged from approximately 10 to 30 J, are applied at the center point of the composite plates having three different overlap lengths. First, the impact behaviors of the composite lap joints are determined and discussed. After the impact tests, the effects of the different energy levels and overlap lengths on the flexural behaviors of the impacted composite lap joints are investigated. Also, comparing with non-impacted lap joints, variation of their flexural loads is presented graphically.

2 Composite lap joints

The glass fiber/epoxy composite plates are manufactured by Izoreel firm, Izmir, Turkey, from unidirectional E-glass fabrics (600 tex in 0° direction, 200 tex in 90° direction and 76 dtex for stitch) and epoxy resin by the hand lay-up method. An epoxy resin matrix based on CY225 epoxy prepolymer and HY225 hardener is used in the production of the composite plates. The mixing ratio for resin to hardener by weight is 10:2 and the fiber volume fraction of the plate is approximately 50%. The glass/epoxy composite plates with six layers and same directions are cured in a lamination press at a constant pressure of 0.3 MPa and a temperature of 120°C for 2 h. Then, the composite plates are cooled down to room temperature while maintaining the pressure. After the manufacturing process, all the plates 130 mm in length and 40 mm in width were cut by water jet in 0° direction from the fabricated composite plates. The thicknesses of the composite plates with six layers are measured as 1.2±0.03 mm after the process of trimming.

Afterward, the surfaces of the composite plates were prepared using the cleaning technique specified in ASTMD2651-01 [23]. The surface preparation starts by removal of ink markings or stamped identifications from the plates by wiping with a cloth wetted with acetone. Then, vapor degreasing with 1,1,1-trichloroethane is done. This is carried out in a deep tank with provision for heating a chlorinated solvent to 82–87°C. Plates are suspended in the vapor zone above the hot liquid and allowed to remain until condensation and runoff is obtained (at approximately 5 min). The plates are then raised above the tank and allowed to dry thoroughly. Following the vapor degreasing, the plates are cleaned mechanically. The composite plates are then bonded in three different overlap lengths. After the bonding process of the plates, they are cured for 2 h under the curing temperature of 120°C at a pressure of 3 bars. In order to compare the data to be obtained from the experiments, the overlap lengths of the composite plates are taken as 20, 40 and 60 mm as shown in Figure 1, represented by LJ-20, LJ-40 and LJ-60, respectively. FM73 film adhesive having a thickness of 0.15 mm is used in bonding of the composite adherends. This adhesive is supplied by CYCTEC® firm, NJ, USA.

In order to compare the data to be obtained from the three-point bending test specimens, the loading span (LS) is taken 160 mm for all composite single-lap joints.

3 Materials and methods

3.1 Impact test

The impact tests are carried out by using an Instron®-Dynatup® 9250 HV model instrumented drop weight impact testing machine equipped with a Dynatup 930-I impulse data acquisition system. The data acquisition system, which is a software program, records the electronic signals and converts them into the impact parameters (such as load, deflection, time, energy and velocity). This testing machine has a dropping crosshead (impactor), a pneumatic clamping fixture and a pneumatic rebound brake to prevent repeated impact. The tube of the impactor has a hemispherical tip with a diameter of 12.5 mm. The total mass of the impactor is approximately 6.32 kg. The composite single-lap joints are clamped with the pneumatic fixture with an impact window with a diameter of 30 mm and the desired impact energy is applied. Three composite lap joints for each type are impacted at

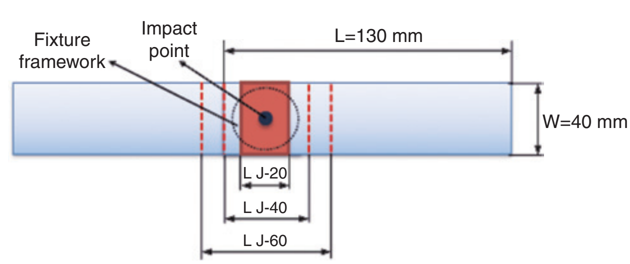

Figure 1 The composite single-lap joints.

their center with three different energy levels of 10, 20 and 30 J to take their average values. All the tests are approximately carried out at room temperature of 23°C.

3.2 Three-point bending tests

The residual flexural behavior of the composite single-lap joints impacted at their center points and different impact energy levels is evaluated by three-point bending tests under static conditions. The three-point bending load is applied at the displacement rate of 2 mm/min on the impacted surface of the lap joints so that the impacted surface undergoes a compression stress. The tests are performed using an Instron 8801 universal testing machine with a load cell of 50 kN. The schematic view of the composite lap joints used in the tests is shown in Figure 2. The cylindrical supports and loading nose are 25 mm in diameter. In this figure, LS refers to the loading span (160 mm). In order to evaluate the residual flexural behaviors of the impacted lap joints, it is necessary to know the behaviors of the non-impacted composite single-lap joints. For this reason, three specimens are tested in bending for both the impacted and non-impacted lap joints, and the average of their ultimate load values is considered as the flexural load. The displacement values at the points where maximum bending loads occur are found to be between 35 and 40 mm.

4 Results and discussion

To determine the residual flexural behaviors of the impacted composite adhesive-bonded single-lap joints, the composite lap joints having three different overlap lengths are first impacted at different energy levels. After the impact test, three-point bending test on the impacted composite lap joints are conducted. The flexural behaviors of the impacted composite single-lap joints are obtained according to the increasing impact energy levels. Also, for comparison, the test is made on non-impacted composite lap joints.

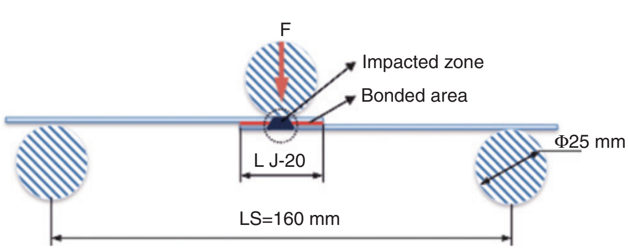

Figure 2 Three-point bending test after impact of the composite single-lap joints.

4.1 Impact behaviors of composite single-lap joints

The composite adhesively bonded single-lap joints are impacted at the center of the composite lap joints with different overlap lengths with the impact testing machine (Instron Dynatup 9250 HV). Impact tests were conducted at energy levels ranging from 10 to 30 J. During the impact event, it is shown that some of the composite single-lap joints were completely perforated at the energy levels applied (for example, LJ-20). As the impactor passes through the thickness of the adherends, the perforation threshold defined as the minimum impact energy level and a permanent catastrophic damage in both adherends occur.

The correlation between impact energy and absorbed energy can be seen in the energy profile diagram (EPD). This diagram is useful for comparing the impact and absorbed energies that are used to evaluate the impact response of composites and to identify the penetration and perforation thresholds. The impact energy (E_i) is the energy introduced from the impactor to the composite lap joint. The absorbed energy (E_a) is the total energy absorbed by the composite at the end of the impact event (when the impactor loses contact with the specimen) and is calculated from the area under the load-deflection curve.

The EPD of LJ-20, LJ-40 and LJ-60 composite lap joints is shown in Figure 3. As can be seen from the figure, a diagonal line is drawn in the diagram to represent the equality between impact and absorbed energies. The data points of composites with LJ-20 (between 10 and 20 J) are found

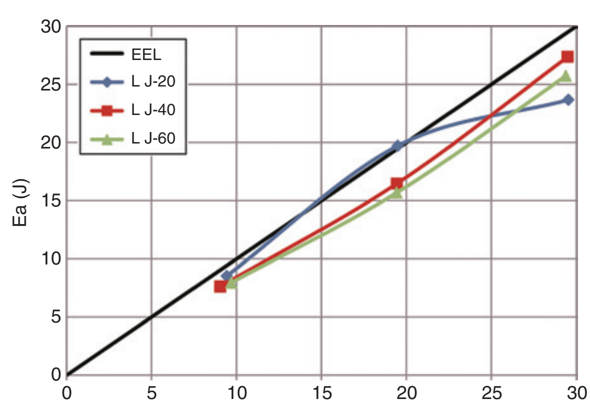

Figure 3 EPD diagram of composite single-lap joints.

to be closer to the diagonal line (equal energy line; EEL) as compared to the other lap joints. The absorbed energy of LJ-20 composites is higher than those of the other composite lap joints. As it reaches the penetration point, the absorbed energy becomes equal to the impact energy. As a result, the penetration threshold of the LJ-20 composite is smaller than those of other composite lap joints. The penetration and perforation thresholds of composite plates are affected by increasing overlap length. The perforation threshold is a critical energy level because crucial damage in the composites occurs in the stage, and it is observed that damage formation in composites increases until the perforation threshold, and permanent damage occurs at this energy level. Therefore, as the perforation threshold occurs at impact energy between 20 and 30 J for the LJ-20 composite, it does not occur for other composite lap joints at the energy levels applied. However, it approaches the penetration thresholds of LJ-40 and LJ-60 composites. Consequently, LJ-20 composites experience larger damaged zones in both adherends and adhesive layer than those in LJ-40 and LJ-60 composites.

In the following paragraphs, impact responses of the composite lap joints are compared. The impact load, deflection and contact time are the important impact characteristics of the composite single-lap adhesively bonded joints subjected to impact loading. During the impact event, these characteristics yield the impact behaviors of the composite lap joints. The impact characteristics vs. impact energy for LJ-60 composite are shown in Figure 4. This figure shows the variation of load values with impact energy in the composite lap joint. The contact (peak) load values of the composite lap joints indicate a sudden increase up to 20 J. The load values remains almost constant after the impact energy level. The reason for this is that damage like fiber breakages occur heavily in the first adherend, and the impairment in the adhesive at the impact zone of the adherends occurs so that the impactor reaches the first adherend, starts to leave the adhesive from the adherends and then penetrates to the second adherend (see Figure 5A). The resistance of the composite lap joints

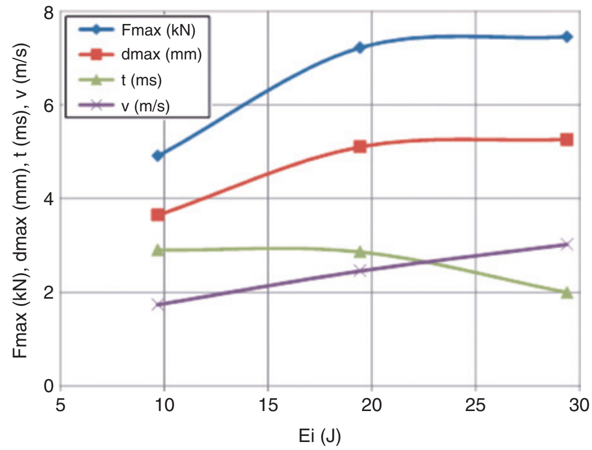

Figure 4 Variation of the maximum load, maximum deflection, contact time and impact velocity vs. impact energy of LJ-60 composite.

shows a significant decrease due to matrix cracking and delamination accumulation. The fiber breakages that occur at both the front and the back surfaces (see Figure 5A and B) and through the thickness of adherends are the main cause of increasing of the deflection until 20 J. Thus, in the contact load-deflection curves, a plateau occurs when the impactor reaches the adherends of the composite lap joint. After 20 J, a slight increase in displacement values during the peak load occurs (5.2 mm), but total deflection is actually very large (6.8 mm) due to the plateau. The contact time between the impactor and the composite lap joints are shown almost constant up to 20 J, but after 20 J, it decreases at the peak point due to the plateau again. However, with increasing damage state, softening of the specimen typically occurs and the total contact time generally becomes longer than that of a non-damaging or low-damage state. As expected, the impact velocity increases with increasing impact energy and is the same for all the composite lap joints in the same impact energy.

Figure 5A and B shows damages in LJ-20, LJ-40 and LJ-60 composites under the impact energy of 30 J, and LJ-60 composite under the impact energy of 10, 20 and

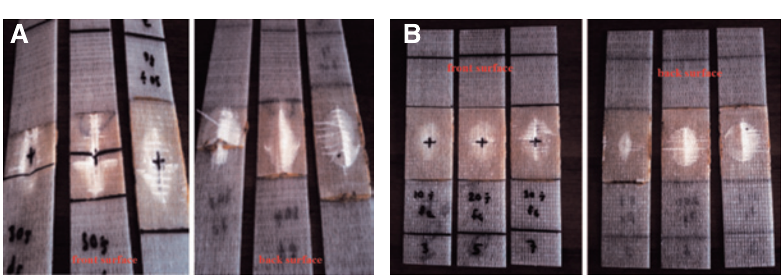

Figure 5 Damages in the front and back surfaces of (A) LJ-20, LJ-40 and LJ-60 for 30 J and (B) LJ-60 composite for 10, 20 and 30 J.

30 J. As mentioned above, when there are indentations and minor matrix cracking in the first adherends of the lap joints, the minor matrix cracking in the back side of and the minor delamination inside the second adherend occurs in the lower energy levels. whereas by increasing the energy level, damages such as fiber breakages and matrix cracking at both the impact and the back sides occur heavily for all lap joints. Especially for LJ-20 composite, the impairment in the adhesive at the impact zone of the adherends and the stratification in the sample occurs due to the accumulation of matrix cracks, fiber breakages and delamination. Thus, the damages cause a decrease in the strength of the composite lap joints.

Figure 6 shows load-deflection curves of the composite plates having 20-, 40- and 60-mm overlap lengths subjected to impact energy of 10 J. The load-deflection (F-d) curve is a response of the composite lap joints to the impact loading. It is seen from the figure that each curve has a loading section, reaches a contact load value and has an unloading section. The loading section occurs due to the resistance of composite to the impact loading. The slope of the section represents the bending stiffness of the composite lap joints. Although the composite plates with LJ-20 have the lowest slope, the slope of the composite lap joints increases with increasing overlap lengths. As the overlap length increases, contact load increases but deflection decreases. While the impactor is reaching the adherends of the LJ-20 composite, the plateau occurs in the contact load-deflection curves of the composite, where damage accumulates. The unloading section of the load-deflection curves represents the impactor rebounding from the composite's surface. F-d curves are obtained in the closed form until the perforation threshold of the LJ-20 composite. Then, the F-d curve is not closed anymore.

Figure 7 depicts variations of the load vs. contact time in the composite lap joints subjected to impact energy of 10 J. With increasing overlap length, contact loads increase, whereas contact durations decrease. However, the contact times of the LJ-40 and LJ-60 composites are very close to each other. Little change is seen at the contact time due to the fiber breakages in the adherends.

Figure 8 illustrates the variations of the impact energy vs. contact time in the composite lap joints subjected to impact energy of 10 J. Although the composite lap joints are approximately subjected to the same impact energies,

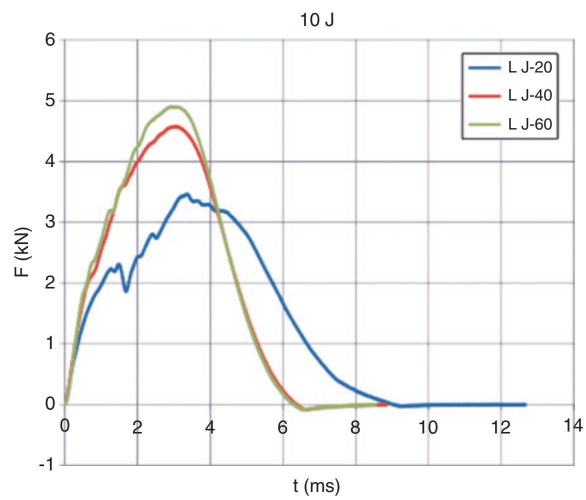

Figure 7 Variation of the contact load vs. contact time of composite single-lap joints.

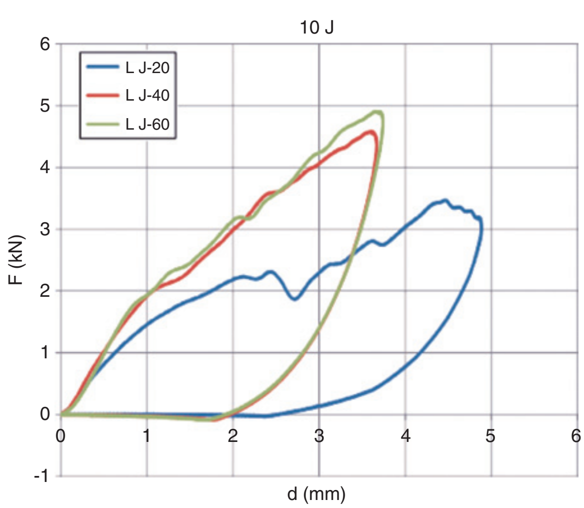

Figure 6 The contact load-deflection curves of composite single-lap joints.

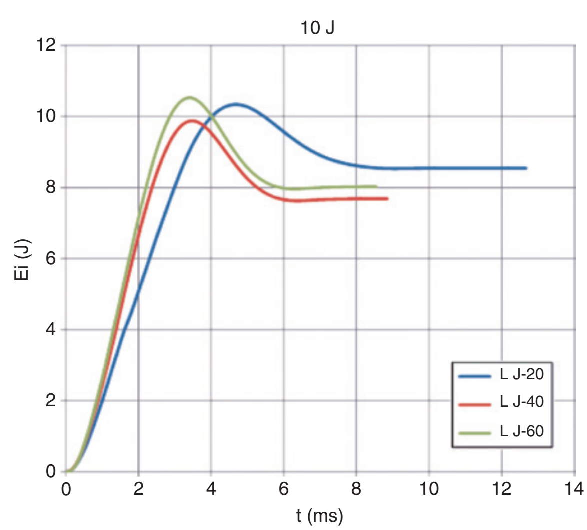

Figure 8 Variation of the impact energy vs. contact time of composite single-lap joints.

their absorbed and excessive energies are not the same. It is known that the excessive energy is the difference between the impact and the absorbed energies. It is observed that the absorbed energy of the LJ-20 composite is the highest; on the contrary, its excessive energy is the lowest because the perforation of this composite lap joint is close to each other. Absorbed and excessive energies of other composite lap joints are very close to each other.

4.2 Flexural behaviors of composite single-lap joints

After the impact test, three-point bending test on the impacted and non-impacted composite lap joints is conducted with the Instron 8801 testing machine. The residual flexural behaviors of the impacted and non-impacted composite lap joints are compared.

Figure 9 shows the variation of the flexural loads vs. the impact energy levels in the composite single-lap joints. As expected, the lowest flexural load occurs in the composite plates having overlap length of 20 mm and impacted about 30 J at the center point. However, the flexural load value of the LJ-20 composite impacted at the energy level of 10 J is found to be the maximum compared to both non-impacted and impacted composites at the other energy levels. It is shown that the flexural load values of the non-impacted LJ-40 and LJ-60 composite plates are higher than those of impacted composite plates. The flexural loads increase with the increase in overlap length. On the contrary, the flexural loads diminish gradually with increasing impact energy level except for the LJ-60 composite impacted at 30 J. A clear indication of the damage due to the bending loads is not seen with the naked eye at either the impact or the non-impact surfaces.

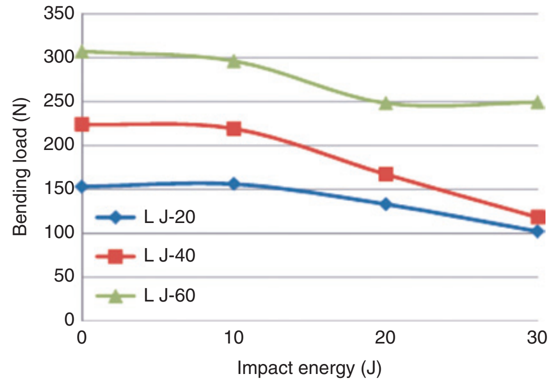

Figure 9 Variation of the bending loads according to impact energy in the composite lap joints.

5 Conclusions

The flexural behaviors of the composite single-lap adhesive joints impacted at different energy levels at their center are experimentally analyzed. First, impact responses of the single-lap joint are determined, and then, as BAI was more convenient than CAI [15], three-point bending tests are performed on the impacted composite lap joints. The following results are obtained:

1. Overlap length considerably affects the impact responses of the composite single-lap joints.
2. Penetration and perforation threshold values of the composites having smaller overlap length are found to be smaller.
3. By increasing overlap length, contact load considerably increases, whereas deflection and contact duration decrease.
4. The absorbed energy of composites having smaller overlap length is the largest, but their excessive energy is the lowest.
5. The residual flexural loads after impact increase with increasing overlap lengths.
6. The residual flexural loads after impact decrease with increasing impact energy and the change in them is smaller at higher energy levels.

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