



Experimental determination of residual flexural strength and critical buckling load of impact-damaged glass/epoxy laminates

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The main objective of this research is to find experimentally the effect of impact damage on the flexural strength of glass fiber/epoxy laminated composite materials at two different test conditions. The other objective is to determine the critical buckling load of laminated composite material after impact loading. Thus, the loss of flexural and buckling performances of the damaged material has been established by comparison with the undamaged material. Initially, angle-ply laminated composite plates with rectangular shaped have been subjected to impact load at different energy levels by using a drop-weight testing machine and impact damage has been created. To find the residual flexural strength, four-point bending tests have been carried out. Four-point bending specimens have been cut from the damaged area of the middle of the laminated plates and have been positioned in two different ways according to the face subjected to the impact. For buckling tests, a unidirectional compression load has been applied to the impacted specimens with the size of 100 mm x150 mm. According to the four-point bending test results, the flexural strengths of the specimens subjected to impact at 10 J and 30 J have decreased approximately 25 and 42%, respectively. Similarly, the reductions in critical buckling loads of specimens subjected to impact at 10 J and 40 J are approximately 16 and 32%, respectively. Consequently, the impact load significantly reduces the flexural and buckling performances of laminated glass/epoxy composites. Furthermore, the positioning of the four-point bending test specimen affects the flexural strength.

Keywords: Glass/epoxy composites, Laminates, Post-impact behavior, Flexural strength, Critical buckling load

1 Introduction

Laminated polymer composite materials used in many different industrial applications may be subjected to in-plane or out-of-plane loads such as tension, compression, shear, bending, buckling or impact. While the laminated composite materials are designed, the static loads to be applied are known and any problem does not occur in the material due to the static loads under operating conditions. However, the out-of-plane impact load, which is an unpredictable dynamic load, can cause a catastrophic damage such as delamination, fiber breaking or matrix cracking in the composite material. Depending on the type of impact damage, there may be a significant reduction in the mechanical properties of composite materials.

The effect of the impact load on the composite material is quite complex. Factors such as impact mass, impact velocity, impactor shape, and support type influence the damage type and residual mechanical properties. In recent years, a lot of investigators have done experimental and numerical

researches with different parameters to determine the residual strength after impact. But a great majority of these researches are about the residual compressive strength after impact¹⁻⁸. All the researches have shown that the compression strength of laminated composites reduced significantly due to the impact damage and Abrate⁹ clarified that the residual compression performance of the impacted composite materials is critical. Actually, all the mechanical properties of the laminated composite materials are somewhat influenced from the impact load. It is an important subject to determine the other loads carrying capacities of the composite material after the accidental impact load. For this reason, it is aimed to determine the flexural and buckling behavior of impacted laminates in this experimental study.

Buckling of composite plates is a stability problem and the significant distortions and damages may occur in the composite material after the buckling. Moreover, if the impact damages such as delamination, fiber breaking or matrix cracking occurred previously in the composite material, it is necessary to determine the buckling behavior of the

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structure and how much load it will carry. In recent years, some researchers have been carrying out experimental and numerical studies on this topic using different composite materials. Cestino *et al.*¹⁰ introduced a methodology on the buckling and tensile responses of laminated composites with impact damage. They considered both uniaxial buckling and in-plane shear buckling for carbon/epoxy composites and then compared the predicted and experimental results. Wang *et al.*¹¹ determined experimentally and numerically the post-buckling characteristics of composites after impact. They applied the impact load to create the pre-damage by using a falling-weight impact machine and then carried out the axial compression tests for two stiffened composite panel. Callioglu and Ergun¹² found the critical buckling loads of impact-damaged laminates for different energy levels. They determined the effect of the thickness and the effect of the application point of impact load on the buckling performance. In additionally, Samuel *et al.*¹³ investigated the effect of low temperatures on the compressive buckling strength of E-glass/epoxy composite beams after low-velocity impact.

Bending load is an important mechanical property in the characterization of laminated composite materials and creates a complex type of stress. When the material subjected to bending, both tensile and compression stresses occur. Determination of bending behavior after impact is an important issue due to the brittle structure of composite materials. Therefore, the researchers are interested in the residual bending properties in recent years. Kwang *et al.*¹⁴ researched the residual flexural strength of carbon fiber/epoxy laminates impacted with high velocity. They used two configurations for the three-point bending test. Firstly, the impacted face was placed on the top side (corresponding to the loading cylinder and subject to compression) and then the impacted face was placed on the bottom side (corresponding to the support cylinders and subject to tension). Their results showed that the position of impacted specimen affects the flexural strength. Mouritz *et al.*¹⁵ found the interlaminar shear strength (ILSS) and residual flexural strength after impact for E-glass/vinyl ester composite stitched with Kevlar at different energy levels. They used the three-point bending tests to determine the flexural strengths for stitched and non-stitched laminates and also investigated the effect of multiple impacts on the ILSS and flexural strengths.

Boucher *et al.*¹⁶ studied experimentally to determine the effect of low-velocity impact damage on the flexural and tensile behavior of cross ply glass/polypropylene laminates. They found different flexural strengths according to the position of three-point bending specimen (impacted face subjected to compression and impacted face subjected to tension) at different impact energy levels. Shim and Young¹⁷ examined the compression and flexural behavior of impacted woven carbon/epoxy laminates by using blunt and sharp impactor. They performed the four-point bending tests to determine the residual flexural strength and then presented a theoretical model. Zhang and Richardson¹⁸ carried out three-point bending tests and found the flexural behavior of pultruded glass/polyester composites after low velocity impact for different energy levels. Nilsson *et al.*¹⁹ determined the post-impact flexural and compression properties of carbon /epoxy laminates with different thicknesses. They carried out the four-point bending tests and placed the specimen in two different positions according to the impacted face. Santiuste *et al.*²⁰ performed three-point bending tests to evaluate flexural strength of plain-woven E-glass/polyester laminated beam after impact loading with Charpy and hemispherical impactor noses. Sarasini *et al.*²¹ investigated the post-impact bending behavior of hybrid laminates by using four-point bending test method. They used aramid and basalt fabrics for fiber material and epoxy resin for matrix material. They also monitored the four-point bending test with acoustic emission to determine the damage mechanism. Liu *et al.*²² found the thickness effect on post-impact flexural behavior of woven carbon fiber/plastic composites with three-point bending test. In addition, Zhang *et al.*²³ determined the effect of environmental factors on the residual flexural performance of carbon/epoxy laminates by using three-point bending tests after impact. Suvarna *et al.*²⁴ carried out low-velocity impact tests at different temperatures and then determined the residual flexural strength of carbon/epoxy laminated composites with three-point bending test at room temperature.

To determine the post-impact mechanical properties, only one ASTM standard is available. This standard belongs to compression after impact strength (ASTM D7137²⁵). The flexural test known as bending test and the buckling test after impact do not yet have an ASTM standard. That's why the different specimen

sizes and the different boundary conditions are used in the experimental studies. In the vast majority of studies performed to determine the flexural strength after impact, the three-point bending test method was used. But, in the three-point bending test, the loading cylinder and the impact damage come face to face and the loading cylinder is directly compress the impact-damaged area. However, in the four-point bending test, the damaged zone remains in the middle of two loading cylinders. Only a few investigators have used the four-point bending test method to determine the flexural properties after impact. In addition, a large part of the experimental works have mainly used carbon fiber and woven fabric. For all these reasons, this experimental study focused on finding the residual flexural strength and the critical buckling load after impact for angle-ply E-glass/epoxy laminates. And furthermore, the four-point bending test method is used for the flexural tests and the specimen is positioned in two different ways according to the impacted face in the tests.

2 Materials and Methods

2.1 Manufacturing of Laminated Plates with Hot Press

The laminated composite plates used in the impact tests and post-impact tests were produced at the IZOREEL Composites Company. The laminates were arranged with hand lay-up method by using unidirectional E-glass fiber and epoxy resin and then subjected to cure process at hot press. While preparing the matrix material, epoxy resin-CIBA GEIGY CY225 and hardener-CIBA GEIGY HY225 were mixed at a specific mass ratio recommended by the supplier company (100 epoxy/80 hardener). The temperature and pressure used for curing process at the hot press were 120 °C and 0.2 MPa, respectively. Following 4 h of curing, the post-cure process continued at 100 °C and at the same pressure for 2 h. After that, it was subjected to room temperature at a pressure of 0.2 MPa. The fiber volume ratio of angle-ply glass/epoxy composite material is 65%, the number of ply is 16 and the fiber orientation is (0°/45°/-45°/90°)₂₅. The average thickness of the produced composite plate is 3.3 mm, and the size of the plate is 100 cm x100 cm before cutting for the impact tests. The composite plates were cut using a diamond tipped saw and the impact test specimens were obtained. The four-point bending test specimens were also cut with the diamond tipped saw after the impact tests.

2.2 Drop-weight Impact Test²⁶

To create impact damage before the flexural and buckling tests, the specimens were subjected to impact loading with Fractovis Plus falling-weight impact machine at the laboratory of Mechanical Engineering Department in Dokuz Eylul University, Izmir. The impact experiments were performed in accordance with ASTM D7136²⁶ standard improved for composite materials with fiber reinforced and polymer resin at ambient temperature. The specimen has a rectangular shape and its dimensions are 150 mm x 100 mm. The hemispherical shaped impactor is made of steel material and has a diameter of 12.7 mm. By using a pneumatic apparatus, the specimen was clamped and the impact load was applied to the midpoint of the 76.2 mm diameter circular area in the middle of the specimen (Fig. 1). After applying the first impact load to the specimen, the repeated impact was hindered. Four different impact energies were selected for drop-weight impact tests (10 J, 20 J, 30 J and 40 J). The impactor mass was constant in all tests as 4.926 kg and the impact velocity was changed (2.02 m/sec for 10 J, 2.85 m/sec for 20 J, 3.49 m/sec for 30 J and 4.03 m/sec for 40 J). The software named *Visual Impact* recorded the energy absorbed, the contact force depending on the time and the deflection of the midpoint of the specimen depending on the time during the test. Every drop-weight impact test was repeated thrice.

2.3 Flexural Test (Four-point bending test)²⁷

Two ASTM standards are available to find the flexural strength of undamaged fiber reinforced composite materials. While the load is applied from two points in the ASTM D6272 test (four-point bending test)²⁷, the load is applied exactly from the

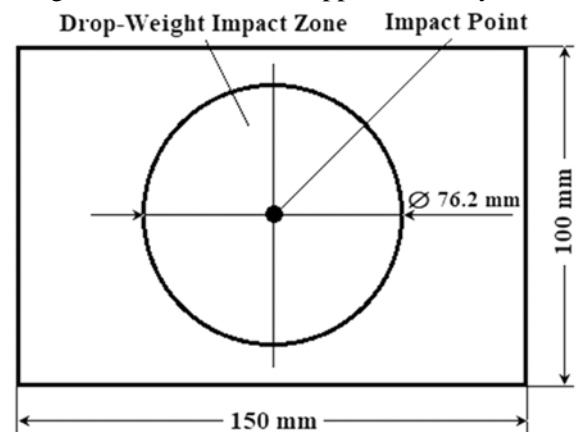


Fig. 1 — Drop-weight impact test specimen.

center of the specimen in the ASTM D790 test (three-point bending test)²⁸. No standard has been developed until now to determine the flexural strength of impact-damaged composite materials. ASTM D6272 standard, known as the four-point bending test method, was chosen as a reference in this experimental study. Because the load cylinder compresses directly the impact-damaged region in the three-point bending tests. In the case of the four-point bending tests, the impact-damaged region remains in the middle of two load cylinders. On the other hand, the bending moment is uniformly distributed between the load cylinders in the four-point bending test.

The interval between the support cylinders is suggested as 16 times the laminate thickness in the ASTM standard. This ratio is called as support span/thickness ratio (s/t). However, the researchers have chosen different s/t ratios for the impact-damaged composite materials. Shim and Yang¹⁷ chose s/t ratio as 60:1 for the four-point bending test of impacted woven carbon/epoxy laminates. Sarasini *et al.*²¹ selected s/t ratio of 23:1 to find the residual bending strength of hybrid composite materials (aramid-basalt fabrics/epoxy) at the four-point bending tests. Chenghong *et al.*²⁹ preferred this ratio as 20:1 for the impact-damaged unidirectional laminates (glass/epoxy, aramid/epoxy and basalt/epoxy) at the three-point bending test. In this experimental study, the s/t ratio for impact-damaged E-glass/epoxy laminate was chosen as 20:1 considering the literature review and impact test specimen sizes. The four-point bending test specimen was cut from the impact specimen of 150 mm x 100 mm as shown in Fig. 2. The obtained four-point bending test specimen width and length are 40 mm and 100 mm, respectively. In all tests, the interval between the loading cylinders was set as half of the interval between the support cylinders. By using the four-point bending test apparatus shown in Fig. 3, all flexural tests were carried out on the Shimadzu AG-X-250 tension-compression test machine at ambient temperature at the Mechanical Engineering Department in Sivas Cumhuriyet University. The speed of universal test machine was 2.5 mm/min. The impact-damaged specimens were positioned on the supports in two different ways (Fig. 4). Firstly, the face hit by the impactor was placed on the top side and corresponded to the side of the loading cylinders (Fig. 4a). In this position, the impacted face was subjected to compression. In Fig. 4b, the face hit by

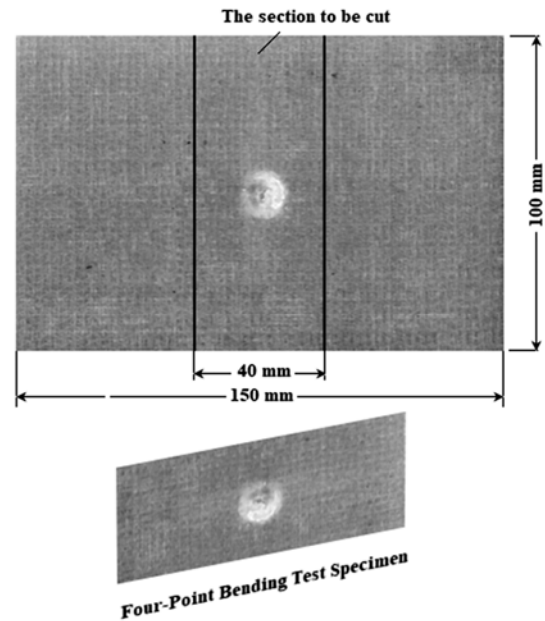


Fig. 2 — Cutting of the four-point bending test specimen from the impact test specimen.



Fig. 3 — Flexural test with four-point bending fixture.

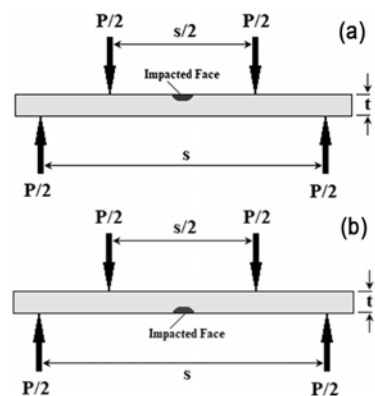


Fig. 4 — Positions of the four-point bending test specimen (a) Impacted face on the top side - subject to compression and (b) Impacted face on the bottom side - subject to tension.

the impactor was placed on the bottom side and corresponded to the side of the support cylinders. In this position, the impacted face was subjected to tension. Thus, the effect of placing the specimen was investigated. The flexural strength ($\sigma_{flexural}$) or in other words, the bending strength was calculated according to Eq.(1):

$$\sigma_{flexural} = \frac{3 F_{max} s}{4 w t^2} \quad \dots (1)$$

where, F_{max} is the maximum force applied to the specimen, s is the interval between the support cylinders, w is the specimen's width and t is the specimen's thickness. Three different impact energies were selected for the flexural tests (10 J, 20 J and 30 J). Every four-point bending test was repeated thrice.

2.4 Buckling Test

As is known, the uniaxial buckling test of laminated composite plates after impact does not have a standard. For this reason, the impact test specimens were used as the buckling test specimens without cutting in this study. That is, the post-impact buckling test specimen width and length are 100 mm and 150 mm, respectively. The buckling specimens were fastened to the fixture seen at Fig.5a. While the one edge of 100 mm of specimen was fastened as clamped, the uniaxial compressive load was applied from the opposite edge and the other two edges of 150 mm were free (Fig. 5b). All post-impact buckling tests were performed with the Shimadzu AG-X-250 test machine at ambient temperature and at a speed of 1 mm/min. After the first buckling of the laminated plate, the experiment was terminated. The post-impact buckling tests were conducted at four different impact energy levels (10 J, 20 J, 30 J and 40 J). Every buckling test was repeated thrice.

3 Results and Discussion

3.1 Impact Test Results

Three different energy levels were used to investigate the effect of impact energy on the flexural strength (10 J, 20 J and 30 J) and four different energy levels were used to examine the effect of impact energy on the critical buckling load (10 J, 20 J, 30 J and 40 J). Since each experiment was repeated three times and two positions were used for the flexural strength, a total of 30 impact tests were carried out. In all selected energy levels, the hemispherical impactor head crashed to the specimens and then bounced and

returned. No perforation occurred in the laminated composite specimens. The diagram between the impact energy and the absorbed energy is given in Fig. 6. The maximum and minimum absorbed energy values among the series of impact tests were selected for the diagram. All impact energies are greater than the absorbed energies and this energy profile diagram indicates the rebounding situation for all laminates³⁰.

Figures 7 and 8 show the contact force-time graphs and the contact force-deflection graphs, respectively. The deflection values belong to the midpoint of the composite specimen. As the energy increases, the oscillations (ups and downs) in the contact force-time graphs increase. Especially at the 40 J, there are a lot of oscillations in the upper part of the curve. These oscillations indicate that the damages occurring in the laminated composite material increase. Similar fluctuations are also seen in the contact force-deflection graphs. In all of the contact force-deflection graphs, the loading section of curve is

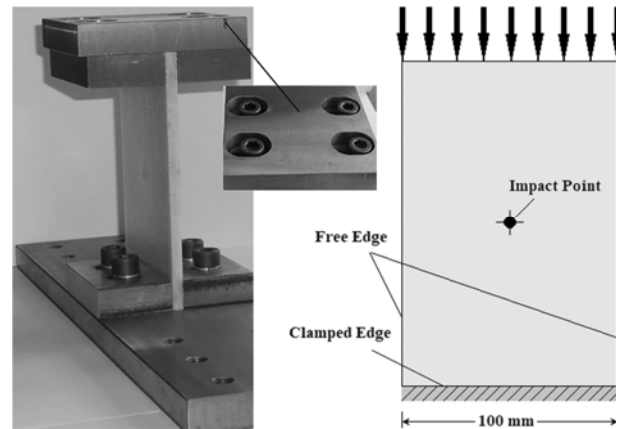


Fig. 5 — Buckling test specimen (a) Fixture and (b) Boundary conditions.

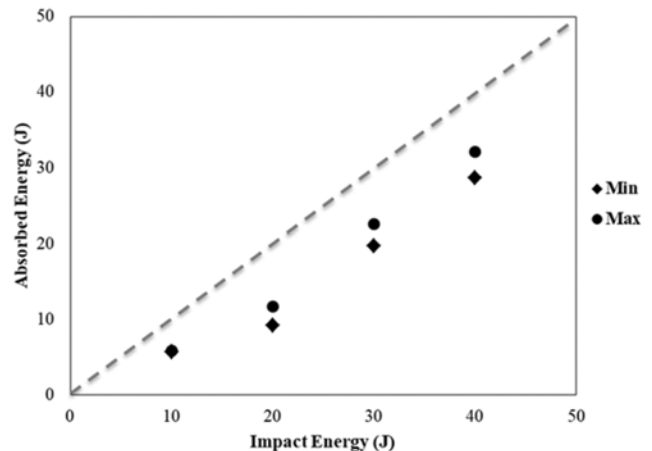


Fig. 6 — Absorbed energies at the impact tests.

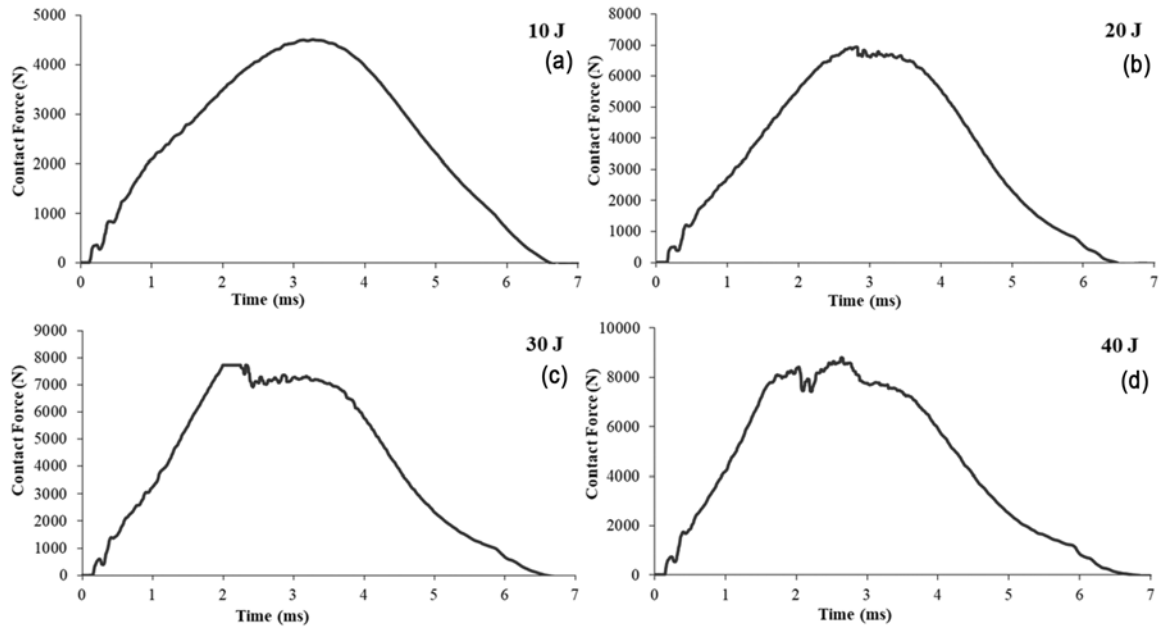


Fig. 7 — Contact force-time graphics (a) 10 J, (b) 20 J, (c) 30 J and (d) 40 J.

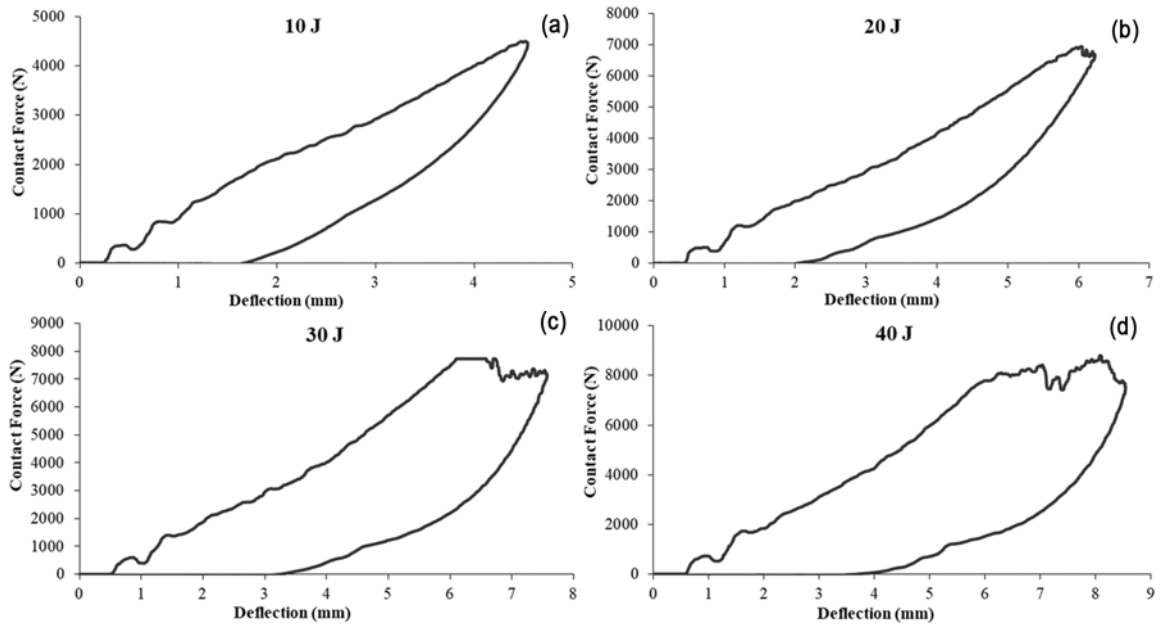


Fig. 8 — Contact force-deflection graphics (a) 10 J, (b) 20 J, (c) 30 J and (d) 40 J.

generally parallel to the unloading section. In all energy levels, the contact force finally reaches zero.

3.2 Flexural Test Results

To determine the effect of impact damage on the flexural strength of E-glass/epoxy laminates, the four-point bending tests after impact were carried out and the force-displacement graphs obtained from the tests were given in Fig. 9. When the impacted face is on

the top side and subjected to compression, the force-displacement curves of the impacted specimens for three different energy levels are fairly close each other. The region subjected to compression in this position was also exposed to compression in the previous impact test, and the region subjected to tension in this position was also exposed to tension in the previous impact test. When the impacted face is on the bottom side and corresponded to the side of the

support cylinders, the force-displacement curves are separated from each other. The region subjected to tension in this position was exposed to compression in the previous impact test, and the region subjected to compression in this position was exposed to tension in the previous impact test. The absorbed energies obtained from the impact tests and the flexural strengths calculated from the four-point bending tests of each specimen are given in Table 1. The reductions in the flexural strengths for both placement cases are shown as a percentage in Fig. 10. Although there is no significant difference in the flexural strengths between two placement cases at 20 J, there is a considerable difference at the results of 10 J and 30 J. There is more reduction in the flexural strength when the impacted face is on the top side at 10 J. However, there is more reduction in the flexural strength when the impacted face is on the bottom side at 30 J. It is thought that the change of the damage type occurring in the material as the impact energy increases can be caused to this reverse situation. At low impact energy levels, only matrix cracks and delamination damages occur. But as the impact energy level increases, the fiber fractures can occur inside the laminate. While

the energy absorbed for 10 J is approximately 55% of the impact energy, the energy absorbed for 30 J is about 70% of the impact energy. As a result, there is a reduction of approximately 25% and 42% in the flexural strength for 10 J and 30 J, respectively. If the residual flexural strength of laminated composites is to be determined, the four-point bending test must be carried out by using both placement cases.

The microscope images obtained from the four-point bending tests of intact and impact-damaged specimens are given in Fig. 11. As the impact energy increases, the matrix cracks increase. Fiber fractures are seen in the specimen-30 J top. This is because the tension side in this specimen has been subjected to tension during impact loading and fiber fractures occurred in this region. On the other hand, the large cracks are seen in the specimen-30 J bottom.

3.3 Buckling Test Results

In order to investigate the effect of impact energy on the critical buckling load, four different impact energies were selected by using the constant impactor mass and the variable impact velocity (10 J, 20 J, 30 J and 40 J). For the residual critical buckling load of the laminated composite, the force-displacement graph was used instead of the maximum force obtained from the uniaxial buckling test. The point at which linearity ends in the force-displacement graph, that is, the end of the Hooke line gives the critical buckling load as shown in Fig. 12. The global buckling occurred in all intact and impact-damaged composite specimens and the experiments were terminated following the first buckling of specimen. The absorbed energies

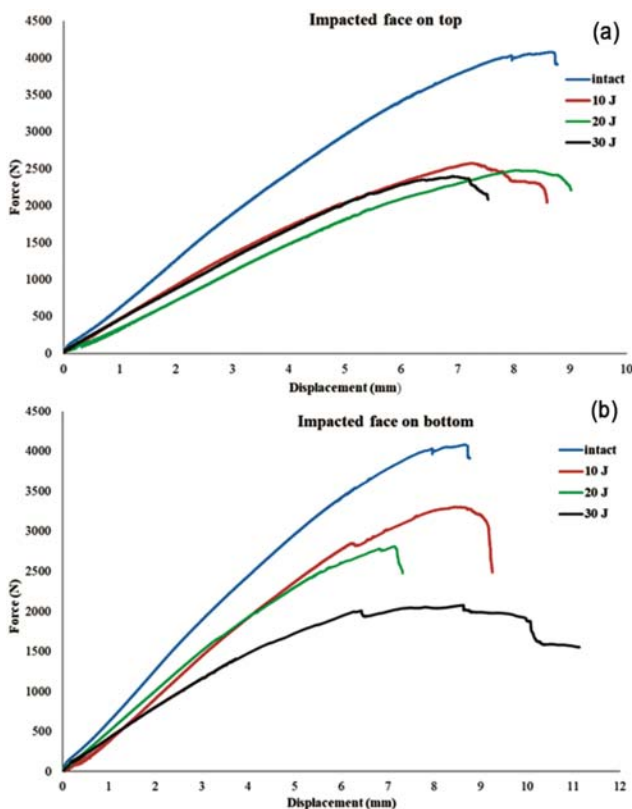


Fig. 9 — Force-displacement graphics for flexural tests (a) Impacted face on top and (b) Impacted face on bottom.

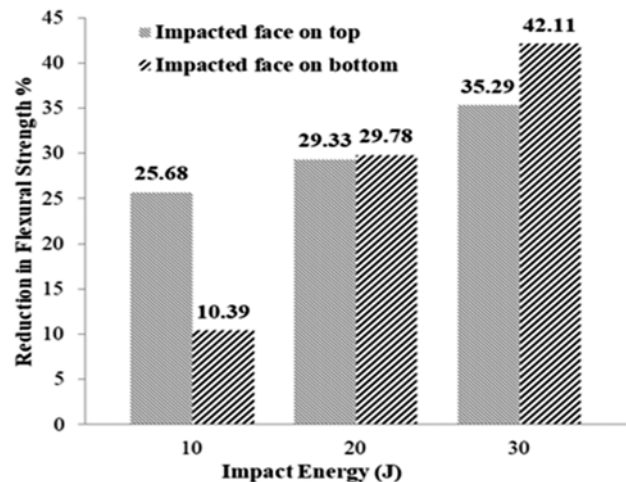


Fig. 10 — Reductions in the flexural strengths of the impacted specimens.

Table 1 — Flexural strengths of the impacted laminates.

	Impact Energy (J)	Width (mm)	Thickness (mm)	Absorbed Energy (J)	Flexural Strength (MPa)
<i>intact</i>	0	41	3.35	-	465.81
	0	42	3.30	-	486.01
	0	42	3.41	-	467.80
				Mean value	473.21
				Standard deviation	11.13
<i>impacted face on top</i>	10	40	3.32	5.72	351.95
	10	39	3.24	5.68	354.34
	10	39	3.15	5.66	348.82
				Mean value	351.70
				Standard deviation	2.77
<i>impacted face on bottom</i>	10	40	3.32	5.71	439.22
	10	41	3.23	5.74	405.47
	10	39	3.29	5.80	427.44
				Mean value	424.04
				Standard deviation	17.13
<i>impacted face on top</i>	20	39	3.15	10.63	336.33
	20	41	3.22	10.17	338.29
	20	40	3.40	10.71	328.66
				Mean value	334.43
				Standard deviation	5.09
<i>impacted face on bottom</i>	20	40	3.41	9.16	341.00
	20	41	3.26	10.30	338.78
	20	41	3.32	10.23	317.16
				Mean value	332.31
				Standard deviation	13.17
<i>impacted face on top</i>	30	39	3.40	21.36	303.92
	30	40	3.21	21.73	305.25
	30	40	3.30	20.58	309.53
				Mean value	306.23
				Standard deviation	2.93
<i>impacted face on bottom</i>	30	40	3.37	21.15	291.59
	30	39	3.39	22.59	266.71
	30	38	3.30	19.67	263.58
				Mean value	273.96
				Standard deviation	15.35

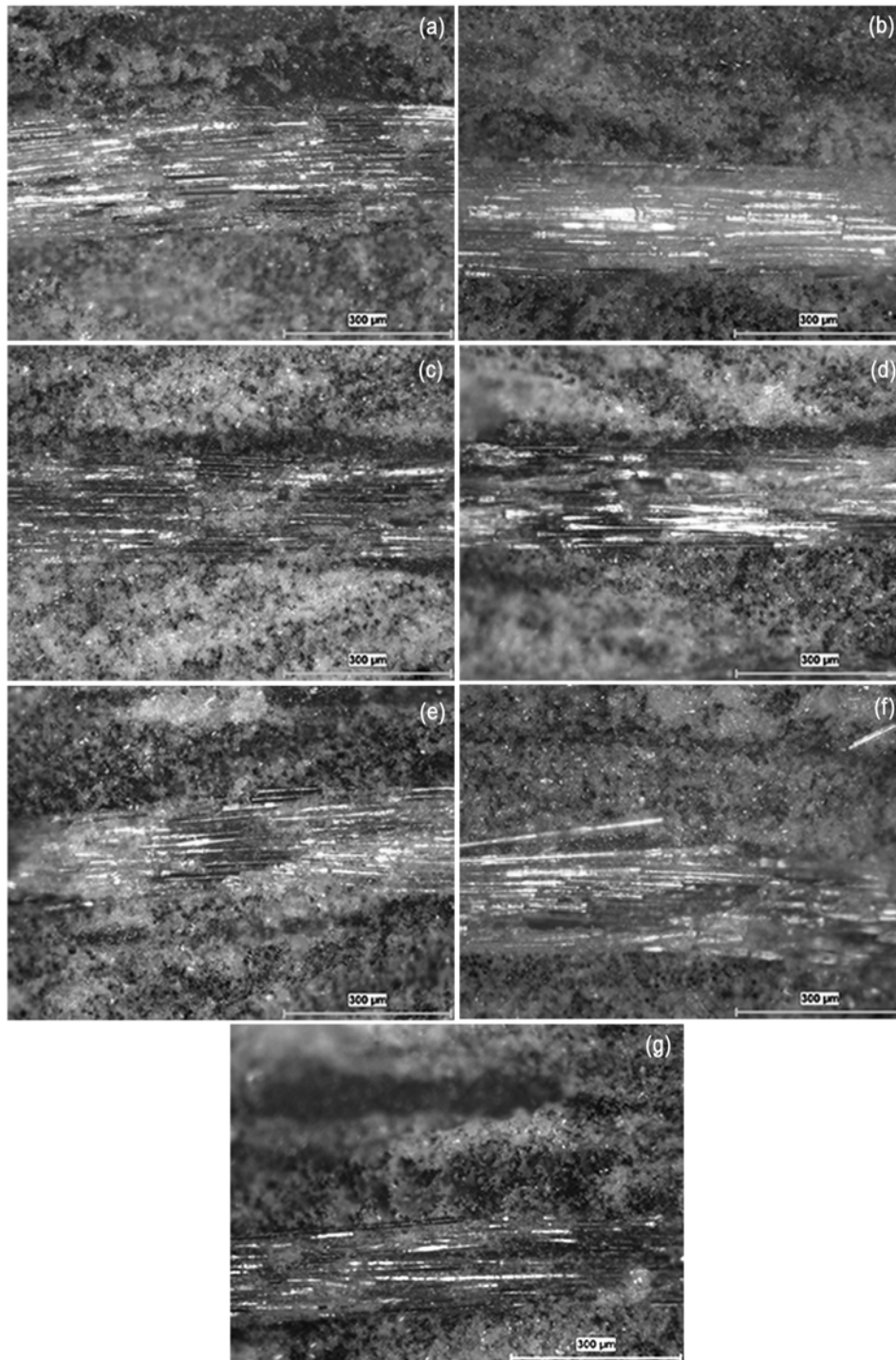


Fig. 11 — Microscope images (a) Intact, (b)10 J-impacted face on top, (c) 10 J-impacted face on bottom, (d) 20 J-impacted face on top, (e) 20 J-impacted face on bottom, (f) 30 J-impacted face on top and (g) 30 J-impacted face on bottom.

obtained from the impact tests of each specimen and the critical buckling loads of intact and impacted laminates are seen in Table 2. The reductions in the critical buckling loads for different impact energies

are shown as a percentage in Fig.13. There is no significant difference among the critical loads after 10 J. While the residual critical buckling loads tend to decrease up to 30 J, there is a slight increase at 40 J.

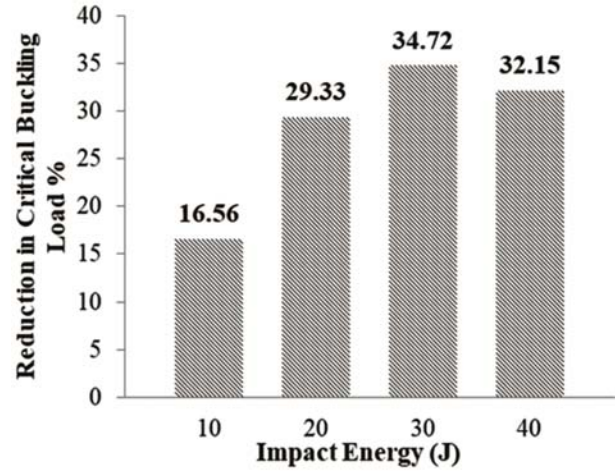
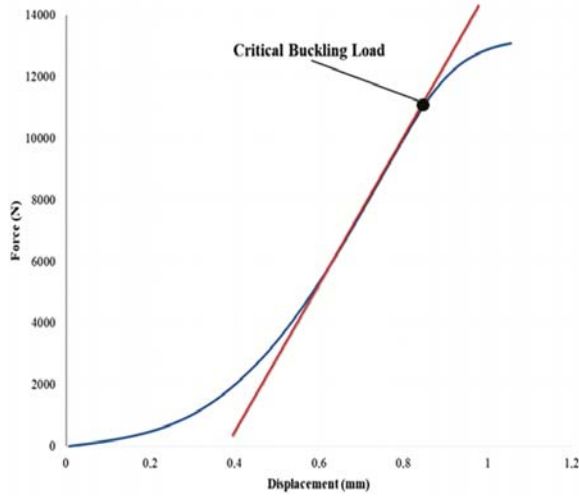


Fig. 12 — Finding the critical buckling load from test results.

Fig. 13 — Reductions in the critical buckling loads of the impacted specimens.

Table 2 — Critical buckling loads of the impacted laminates.

Impact Energy (J)	Thickness (mm)	Absorbed Energy (J)	Critical Buckling Load (kN)
0	3.35	-	16.31
0	3.35	-	16.00
0	3.45	-	16.59
		Mean value	16.30
		Standard deviation	0.30
10	3.30	5.76	13.70
10	3.30	5.72	13.27
10	3.40	5.90	13.84
		Mean value	13.60
		Standard deviation	0.30
20	3.20	11.66	11.85
20	3.20	11.43	11.38
20	3.40	11.34	11.34
		Mean value	11.52
		Standard deviation	0.28
30	3.20	21.86	10.89
30	3.35	19.67	10.54
30	3.30	19.72	10.50
		Mean value	10.64
		Standard deviation	0.21
40	3.45	32.15	10.71
40	3.45	30.23	11.61
40	3.30	28.59	10.86
		Mean value	11.06
		Standard deviation	0.48

The change of the residual buckling loads in this investigation can be clarified by the fact that the progress of delamination. The size of interlaminar damage can be different at low and high impact speeds. At low impact speeds, the more layers may be separated from each other or the separated field may be larger. Because of these interlaminar damages caused by the impact load, the stability of laminated composite plate will be more quickly disrupted and the reduction in uniaxial buckling load will be increased.

4 Conclusions

In this research, the residual flexural strengths and the critical buckling loads after impact were determined experimentally for angle-ply laminated glass fiber/epoxy composites. The results obtained are listed following:

- (i) The reduction in the flexural strength is 25.68% for 10 J, 29.78% for 20 J and 42.11% for 30 J, respectively.
- (ii) In the four-point bending tests, the position of the specimen affects the flexural strength value. When the impacted face is in the tension zone (on the bottom side) at the four-point bending test for 10 J, the flexural strength value is higher. On the contrary, when the impacted face is in the compression zone (on the top side) for 30 J, the flexural strength value is higher. However, the results are almost identical for both placements at 20 J. The difference among the results can be explained by the change of the damage type according to the impact energy level. Therefore, when the flexural strength is determined after the impact, two positions should be considered.
- (iii) The minimum reduction in the critical buckling load is obtained at 10 J (16.56%) while the maximum reduction is obtained at 30 J (34.72%).
- (iv) The critical buckling load decreases as the energy level increases up to 30 J. However, the critical buckling load increased slightly at 40 J. The reason for these results can be the change in the type of damage and the size of the delamination area at different energy levels.

The results obtained give information about the remaining bending and buckling performances after impact for the composite communities. Thus, it is possible to decide whether to repair, replace or

continue to use the laminated composite material with impact damage. In further studies, the four-point bending and buckling tests can likewise be repeated for different materials such as hybrid composite or micro/nanoparticle added composites to determine the loss of flexural and buckling performances. These studies may include the effect of different environmental conditions such as temperature or seawater.

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