

Numan Behlül Bektaş* and İnan Ağır

Impact response of composite plates manufactured with stitch-bonded non-crimp glass fiber fabrics

Abstract: This experimental study deals with the impact response of composite plates manufactured with stitch-bonded non-crimp glass fiber fabrics. Three kinds of fabrics – biaxial, triaxial, and quadraxial – are used as reinforcing material. Polyester resin is used as a matrix material in the composition of composite plates. An instrumented drop weight impact testing machine, Instron-Dynatup 9250 HV, is used for impact testing. Impact tests are performed under various impact energies, ranging from damage initiation to final perforation. An energy profiling method, showing the relation between impact energy and absorbed energy, was used together with load-deflection curves to determine the penetration and perforation thresholds of those composites. The failure processes of damaged specimens for different impact energies were evaluated by comparing load-deflection curves and images of damaged samples taken from the impacted and non-impacted sides. All types of composites have obvious penetration and perforation thresholds. The perforation threshold of triaxial/polyester composite is approximately 27% and 22% higher than that of the quadraxial and biaxial/polyester composites, respectively.

Keywords: energy profiling method; impact response of composites; non-crimp fabric composites.

*Corresponding author: Numan Behlül Bektaş, Department of Mechanical Engineering, Pamukkale University, 20070 Denizli, Turkey, e-mail: bbektas@pau.edu.tr

İnan Ağır: Department of Mechanical Engineering, Pamukkale University, 20070 Denizli, Turkey

1 Introduction

The improvement of stitch-bonded, multiaxial reinforcements has allowed for faster fabrication of parts with better physical and mechanical properties. Parts made from these reinforcements have led to economical solutions for a variety of applications, including marine, transportation, infrastructure, sports and recreation, and aerospace. The economical solution begins with engineering the laminate requirements at the point of fabric

manufacture. The strength demands can be engineered right into the reinforcement by considering the fiber weight and fiber angle of any given ply. Stitch-bonding fabric is essentially an automated process and is highly efficient compared with a shop-fabricated laminate with unidirectional or woven fabrics [1].

Stitch-bonded fabrics offer greater range and flexibility compared with woven fabrics, especially in the field of multiaxial (three plies or more) reinforcements. Multiaxial reinforcements can be engineered to meet specific requirements and perform multiple tasks, such as providing good surface finish, impact and abrasion resistance, and structural integrity, all in one fabric [1]. Furthermore, the ability to place fibers on $0^\circ/90^\circ/+45^\circ/-45^\circ$ (see Figure 1) means engineers can design composite laminates to handle loads from both known and unknown directions. Quadraxial reinforcements are closer to traditional building materials such as steel and aluminum, i.e., equal strength in all directions [1].

There are many studies in the literature [2–7] on the impact response of composite materials and structures. A few of them are as follows: Morais et al. [8] studied the effect of laminate thickness on the resistance of carbon, glass, and aramid fabric composites to repeated low-energy impacts. They obtained results for the different fiber-reinforced composites, and the results were correlated with the characteristics of the fibers and fabrics used. Naik et al. [9] investigated the impact behavior and post-impact compressive characteristics of glass-carbon/epoxy hybrid composites with alternate stacking sequences. Caprino and co-authors [10] carried out low-velocity impact tests on carbon-fabric/epoxy laminates with different thicknesses. Ataş and Liu [11] presented experimental investigations on impact response of woven composites with various weaving angles between interlacing yarns. In their works, the effects of the weaving angle on the impact characteristics, such as peak force, contact duration, maximum deflection, and absorbed energy, were examined. They found that the energy absorption capability and perforation threshold of woven composites can be significantly improved by using a small weaving angle between interlacing yarns. Sayer et al. [12] conducted an experimental investigation on the impact behavior of hybrid composite plates. In their work, increasing impact

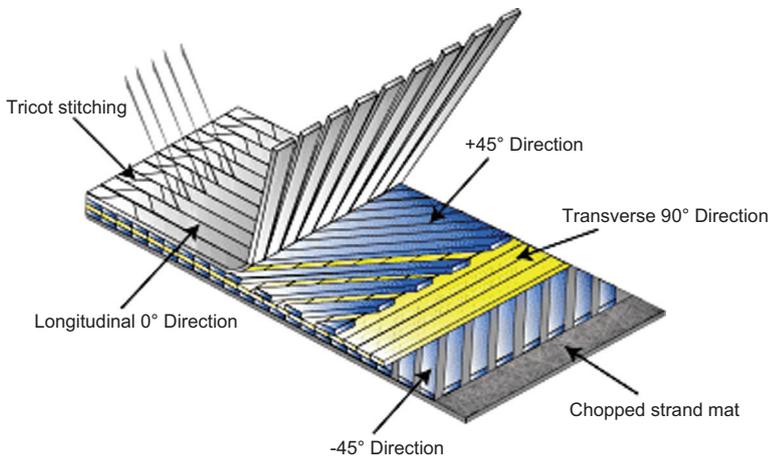


Figure 1 Typical quadraxial ply stack includes 0° , 90° , $+45^\circ$, and -45° plies [1].

energy was applied to two types of hybrid composite plates (glass-carbon/epoxy) until complete perforation of specimens. The perforation threshold of hybrid composite impacted from surface with carbon fibers was found to be approximately 30% higher than that of surface with glass fibers. Sayer et al. [13] investigated the impact response of hybrid composite laminates experimentally. In their work, two different hybrid composite laminates, aramid/glass and aramid/carbon, and two different stacking sequences were selected for impact test. They found the perforation thresholds for $[0/90/45]_s$ aramid/glass and aramid/carbon laminates to be approximately 5% higher than those for their counterparts with the $[0/0/90/90]_s$ stacking sequence.

Studies on the impact response of stitch-bonded non-crimp fabric (NCF) composites are limited in the literature. Many of them are as follows: Onal and Adanur [14] examined the tensile and flexural properties of glass-carbon fiber-reinforced stitched hybrid composites after low-velocity impact. They also investigated the effect of stacking sequence and fabric ply angle with composite axis on the mechanical performance of impacted hybrid composites. It can be seen from this study that the tensile failure mechanism of damaged plies was affected by the interaction of reinforcement property, hybrid order, and ply angle. Lopresto et al. [15] studied stitched carbon fiber-reinforced plastic laminates of various thicknesses under low-velocity impact with reference to the overall force-displacement curve, first failure load, penetration, indentation, and damage extent. They found that the stitched laminates exhibited a penetration energy about 30% lower than their two-dimensional equivalent. They also found that the advantage of stitching in terms of impact damage resistance was evident only for high-thickness composites. The effectiveness of stitching in increasing

the damage resistance and tolerance has been discussed by many authors [16–18]. However, its detrimental role in lowering the material in-plane properties has also been extensively documented [16, 18]. In particular, the studies published have mainly been concerned with the tension, compression, and flexure behavior, whereas fewer data are available on impact response, creep, and fatigue. An experimental investigation on the NCF composites was performed by Dexter and Hasko [19], who carried out a comparison with standard tape composites, highlighting the improved performances of NCFs in terms of compression after impact strength and the limited loss in terms of compression and tension strength with respect to tape laminates. Asp and Juntikka [20] reported a series of high-velocity impact tests using $\varnothing 50$ and $\varnothing 25$ mm ice spheres and 0.32 g granite stones on NCF composite plates. The objective of their study was to monitor ice and stone impact on NCF composite laminates and to investigate the validity of engineering impact resistance models for analysis of ice and stone composite impact. Vallons et al. [21] determined the impact and post-impact static and fatigue tensile properties of a carbon fiber/epoxy NCF composite and compared their properties with those of a carbon fiber/epoxy woven fabric composite, for two impact energies (3.5 and 7 J). They found that the projected damage area after impact was larger for the NCF composite than that for the woven fabric composite for both impact energies.

In this study, increasing impact energy was applied to three types of stitch-bonded NCF composite plates made of biaxial, triaxial, and quadraxial fabrics with polyester resin, and the impact response of these composite plates was investigated. The penetration and perforation thresholds of these composites were determined using an energy profiling method (EPM) with load-deflection curves. To assess the extent of damage modes and damage process,

damaged specimens were also visually inspected and discussed.

2 Materials and methods

2.1 Manufacturing of composite plates

The composite plates were manufactured with stitch-bonded non-crimp glass fiber fabrics supplied from Metyx (İstanbul, Turkey), (Telatex, İstanbul, Turkey) and polyester resin by a vacuum infusion method at the Atard firm in Turkey. Three kinds of fabrics, such as biaxial, triaxial, and quadraxial, were used. A polyester resin (Dewester 196; Dewilux) and a hardener (Dewilux, İzmir, Turkey) with accelerator were used. The mixing ratio for resin-to-hardener in weight was 10:0.15, and for resin-to-accelerator was 10:0.4. The layer configuration and properties of the composite plates are given in Table 1. The biaxial/polyester (BP), triaxial/polyester (TP), and quadraxial/polyester (QP) composites are in total 16, 21, and 16 layers, which are composed of two-by-two, three-by-three, and four-by-four stitch-bonded layers, respectively. Composite plates were manufactured by the vacuum infusion process, which is a technique that uses vacuum pressure to drive resin into a laminate. Stitch-bonded non-crimp glass fiber fabrics were laid dry into the mold and the vacuum was applied before the resin was introduced. The mold was composed by two thick glass plates to achieve smooth surfaces. Once a complete vacuum was achieved, the resin was literally sucked into the fabrics through carefully placed tubing, as seen in Figure 2. After the manufacturing process, the composite specimens with dimensions of 100 mm×100 mm were trimmed from the laminated plates.

2.2 Impact testing

In this study, the Instron-Dynatup 9250 HV impact testing machine (Instron, MA, USA) was used for impact testing.

This testing machine consists of a drop-ping crosshead with its accessories, a pneumatic clamping fixture, a pneumatic rebound brake, and impulse data acquisition system. The weight of the crosshead can be adjusted with drop mass, and the tip of the impactor has a 12.5-mm-diameter hemispherical nose. The self-identifying load-cell capacity is 15.56 kN, and the total mass of the impactor with its accessories was kept constant at 6.32 kg for all tests. The test machine has a pneumatic rebound brake system to prevent repeated impact on specimens. The impulse data acquisition system is a software program that records the electronic signals (load vs. time data and instantaneous velocity at the moment of impact). The software program based on Newton's second law and kinematics is used to convert the load-time data into a load-deflection relation with the assumption that the impactor is rigid. The electronic signals are used by the software to calculate the deflection, tip velocity, and the energy absorbed by specimen. As the present work contains experimental data, the deflection representing the travel of the nose of the impactor during impact events includes both the bending and stretch of the plate.

For a number of impact tests, the impact energies varied from approximately 25 J to 75 J, up to the complete perforation of the specimens. Therefore, it becomes possible to examine the damage mechanisms of stitch-bonded NCF composite plates under various impact energies.

3 Results and discussion

Impact tests were separately performed on three types of composite plates, such as BP, TP, and QP. The layer configuration and properties of these composite plates are given in Table 1.

3.1 Load-deflection (F-d) curves

Figure 3 depicts typical load-deflection (F-d) curves for the BP, TP, and QP composites at the different levels

Table 1 Layer configuration and properties of the composite plates.

Sample ID	Stacking sequence	Nominal thickness (mm)	Unit volume density (g/cm ³)	No. of layers
BP	$[(0,90)/(\pm 45)/(\pm 45)/(90,0)]_s$	4	1.888	16
TP	$[(45,90,-45)/(-45,90,45)/(45,90,-45)/(-45,90,45)/(45,90,-45)/(-45,90,45)/(45,90,-45)]_s$	4	1.858	21
QP	$[(0,-45,90,45)/(45,90,-45,0)]_s$	4	1.800	16

B, biaxial; T, triaxial; Q, quadraxial; P, polyester resin.

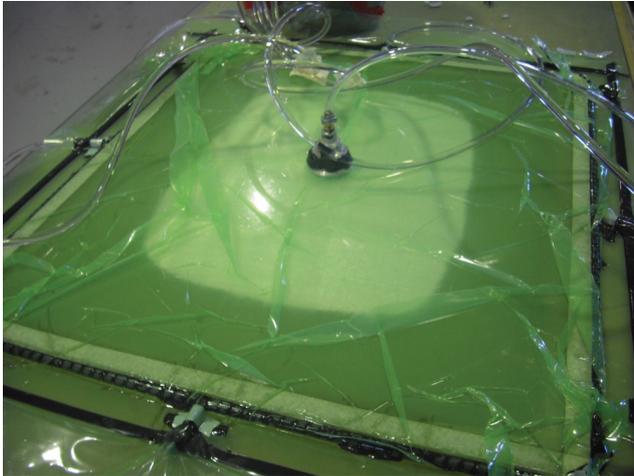


Figure 2 Composite plates manufactured by vacuum infusion process.

of impact energy. Individually, each curve has an ascending section of loading, reached a maximum load value, and has a descending section of unloading. The ascending section of the load-deflection curve is called bending stiffness due to the resistance of the composite to impact loading, and at this section the maximum load value reached the highest maximum load, which is called peak force. The TP composites have the highest peak force at the ascending section, as seen in Figure 3B.

There are three situations in load-deflection curves of those composite plates: rebounding, penetration, and perforation. Also, in general, load-deflection curves can be classified as closed-type curve and open-type curve. The rebounding case results in closed curves denoting the rebounding of the impactor from the specimen surface. The closed-type curves turn back toward the origin of the diagram after the descending section from the maximum load or peak force. These curves are numbered as 1–9 for BP, 1–10 for TP, and 1–10 for QP composites, as seen in Figure 3.

When the impact energy is increased, deflection increases, closed-type curves bound restricted larger areas, and meanwhile the rebounding section becomes smaller. As seen from Figure 3B, specimen 10 is also of a closed-type curve but it is located in the transition point between closed-type and open-type curves. As the impact energy continues to increase, the curve type changes from the closed type to the open type. If a curve is of an open type, the specimen is either penetrated or perforated by the impactor. Thus, specimen 11 represents a penetrated case, while the others represent a perforated case, as seen in Figure 3B.

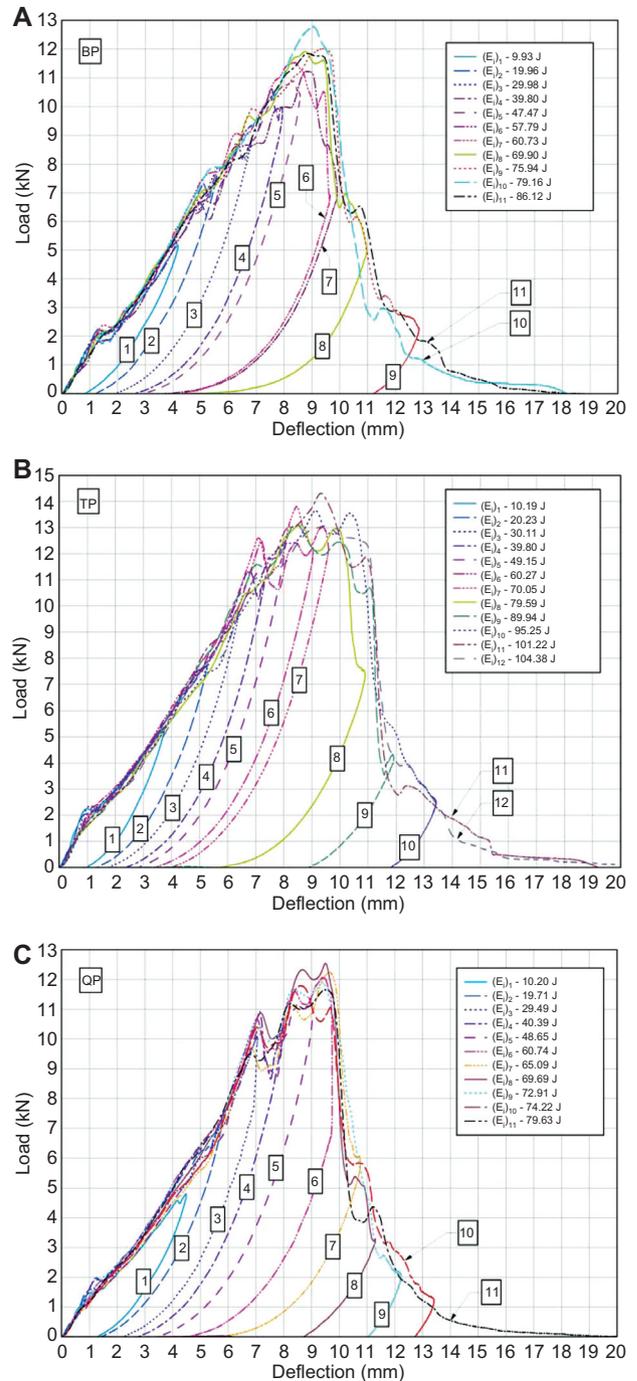


Figure 3 Typical load-deflection (F-d) curves for the (A) BP, (B) TP, and (C) QP composites.

3.2 EPM and impact characteristics

The energy profiling method (EPM) is a diagram that shows the relation between impact energy and the corresponding absorbed energy [22]. This method is useful for comparing the impact and absorbed energies and also for identifying the penetration and perforation thresholds.

Impact energy (E_i) and absorbed energy (E_a) are important parameters for characterizing the response of composite plates. The impact energy (E_i) can be defined as the energy introduced to a specimen from the impactor during an impact event. The absorbed energy (E_a) is defined as the entirety of energy absorbed by the specimen at the end of an impact event [12].

The absorbed energy of a composite specimen can be calculated from the area surrounded by the closed curves for non-penetrated or non-perforated specimen. When the specimen is perforated by the impactor, an open-type load-deflection curve has a friction section induced between the impactor and specimen at the end part of the descending section. This section is called the post-perforation friction section, and this section must be removed from the load-deflection curve to calculate the accurate absorbed energy [12]. Therefore, open-type load-deflection curves should be bounded by an extending line to the horizontal axis, shown as dashed lines in Figure 8.

The energy profile diagrams of composites for BP, TP, and QP specimens are given in Figure 4. As seen from the figure, the energy profile diagrams show the correlation between the impact energy and the absorbed energy. A diagonal line, which is called the equal energy line, is added to diagrams to represent the equality between impact and absorbed energies.

As seen from the diagram, impact, absorbed, and excessive energies are nearly the same up to 50 J impact energy for all types of composites. Above 50 J impact energy, the excessive energies of TP are higher than that of

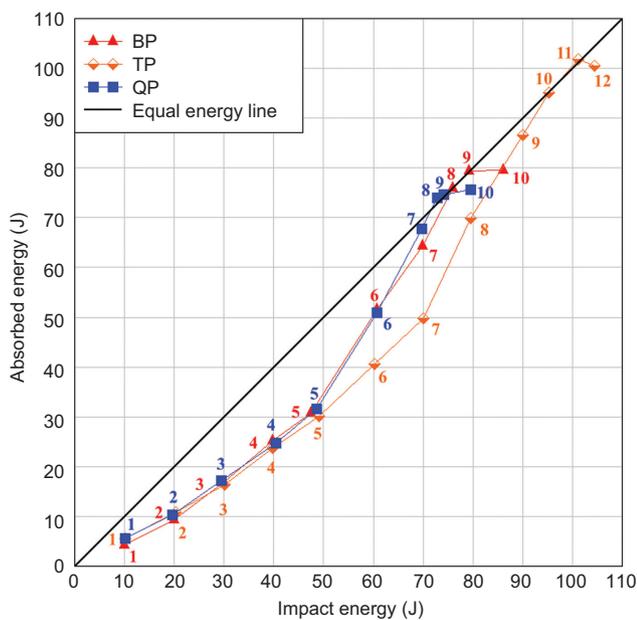


Figure 4 Energy profile diagram.

BP and QP owing to the layer configuration of composites. The excessive energy is the retained energy in the impactor and used to rebound the impactor from the specimen at the end of each contact-impact event. This energy is the difference between impact energy and absorbed energy, or the difference between the data points and the equal-energy line.

In the diagram, up to data point 5, excessive energies are increased; however, above that, up to point 8, they are decreased while impact energies are increased for BP and QP composites. It implies that the damages absorbed less energy up to data point 5, but above that, up to point 8, they absorbed more energy while impact energies are increased. This can be the result of matrix fractures followed by the fiber fractures in specimens. Thus, the absorbed energy becomes equal to the impact energy when it reaches the penetration point. It is designated that there is no excessive impact energy to rebound the impactor from the specimen. At the data point 8, penetrations take place, and then approximately around data point 9 perforations take place for BP and QP composites. The impact energy of BP composite ($E_i=80$ J) is slightly higher than that of QP composite ($E_i=75$ J) when perforations take place.

For TP composite, data points deviate from data points of BP and QP composites at point 5. The excessive energies for TP composites are of the highest value, at data points 5, 6, and 7 as seen in Figure 4. After these points, up to the penetration point (in other words, points 8 to 9), excessive energy decreases when impact energy is increased. At data point 10, penetrations take place and then approximately around data point 11 perforations take place for the TP composite. The TP composite has the highest impact energy, whereas the QP composite has the lowest one.

In Figure 5, the impact characteristics of BP, QP, and TP composites, such as peak force, deflection, and contact

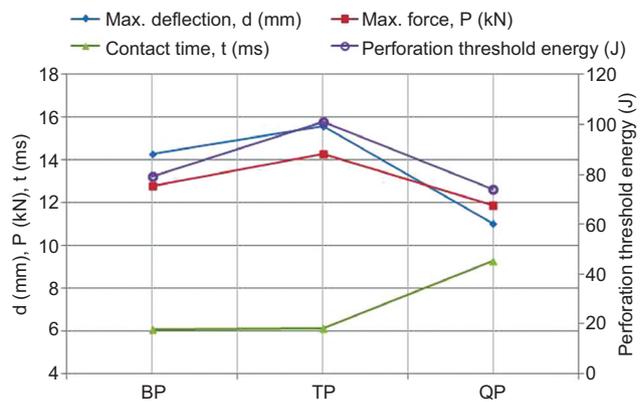


Figure 5 Impact characteristics of composites at perforation threshold energy.

duration, are shown. These parameters are important impact characteristics of composite laminates subjected to impact loading. The values of peak force, deflection, and contact duration increase with increasing the impact energy until the perforation threshold. The perforation threshold is a critical energy level for composites due to the most important damage stage. As seen from Figure 5, TP has the highest impact characteristics as deflection and peak force, but it has low contact duration compared with other composites.

3.3 Damage process

The damage processes of damaged NCF composite specimens were evaluated for the front (impacted) side and the back (non-impacted) side by visual inspection. In general, impact damage modes consist of indentation, matrix cracking, delaminations between adjacent layers, fiber pullout, and fiber breakages. In the following paragraphs, for understanding of damage modes, several images of damaged specimens were compared with the load-deflections curves, and explained, respectively, for BP, QP, and TP composites.

For lower impact energies (less than approximately $E_i=50$ J), the primary damage mode is indentation-induced matrix cracking on impacted surface. There are minor matrix cracks and some delaminations at the impacted side, while fiber pullout starts to take place at the back side of all specimens (Figure 6). As shown in Figure 6, the fiber fractures at the back side of QP composites results in fluctuation in the F-d curve at peak force value is reached, followed by the rebounding of the impactor. However, the fiber fractures at the back side of TP and BP composites do not show any significant fluctuations in F-d curves at peak force is reached. As seen from Figure 6, QP composite shows maximum deflection, whereas TP composite shows minimum deflection at approximately the same impact energies. Also, TP composite depicts maximum load, whereas BP shows minimum load. The absorbed energy of QP composites is slightly higher than the others. As also seen from Figure 6, damages are formed on composites, such as matrix cracking, fiber fracture, fiber pullout, and delamination.

As the impact energy increased up to 70 J, the F-d curves of composites expand in the positive direction of the horizontal axis and damaged composites absorb more impact energy as expected. In Figure 7, owing to the bending and indentation, fiber breakages increased and its progression developed through the thickness of layers. The fiber breakage lowered the bending stiffness

of composites, and it was seen as an oscillation in the F-d curve for TP composites. For QP and BP composites, fiber breakage in layers results in a sudden drop in F-d curve right after the peak force value is reached. As seen from Figure 7, F-d curves of BP and QP composites follow each other and surround nearly the same areas, whereas F-d curve of TP composite surrounds a smaller area. This means that TP composite has less absorbed energy and less damaged area than the others.

As the impact energy continued to increase up to 74, 79, and 101 J, penetration and perforation took place for QP, BP, and TP composites, respectively, as seen in Figure 8. The penetration threshold can be defined as the energy level that the impactor sticks into the specimen for the first time and does not rebound from the specimen surface any more. The perforation threshold can be defined as the energy level that the impactor passes through the thickness of the specimen for the first time resulting in a permanent catastrophic damage to the specimen [12].

As seen in Figure 4, data point 8 for BP and QP composites, and data point 10 for TP composites, represent the penetration thresholds. In this situation, the nose of the impactor sticks into the specimen, and all glass fibers are damaged through the thickness. After data point 9 for BP and QP composites, and data point 11 for TP composites, complete perforations take place, and there is only friction between the impactor and the specimen due to post-perforation. For the complete perforation case, F-d curves and images of damaged specimens are shown in Figure 8. As seen from Figure 8, the TP composite has the highest impact and absorbed energy and also the maximum peak force. The deflections of all composites are nearly the same at peak forces. It can be seen from the damaged specimens that QP composite has less damage than the others.

4 Conclusion

This experimental study deals with the investigation of the impact response and damage process of the three types of stitch-bonded NCF composites plates: BP, TP, and QP. The following conclusions can be drawn from the tests:

- For lower impact energies (up to 50 J), impact events were elastic and excessive impact energies were used for rebounding of the impactor. For all types of composites, absorbed energies are nearly the same. As the damaged specimens were visually inspected, minor matrix cracking, indentation, and some delaminations were observed on the surface of the impacted and non-impacted sides of all specimens.

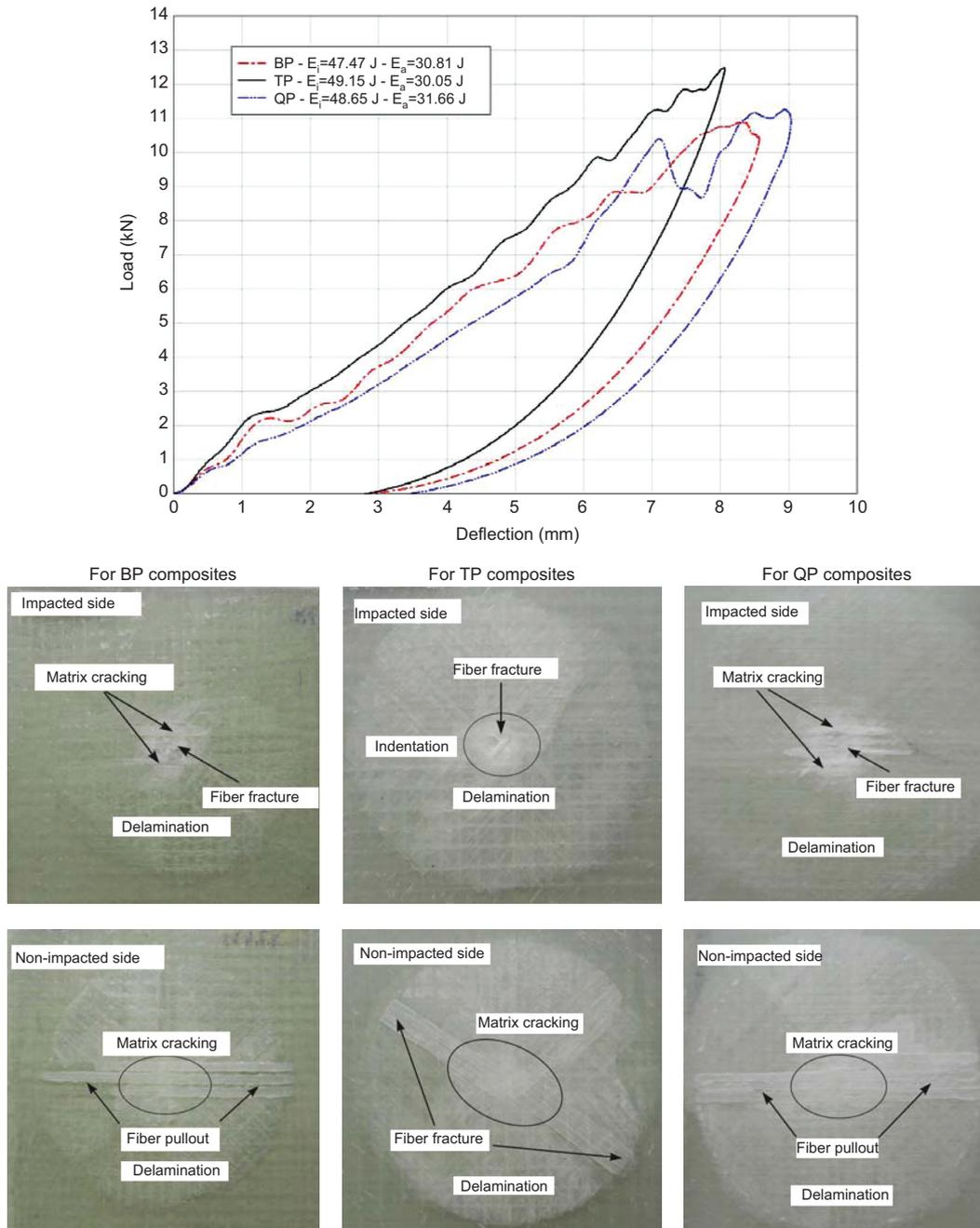


Figure 6 Typical load-deflection (F-d) curves of the BP, TP, and QP composites and images of damaged specimens.

- For higher impact energies (from 50 J to energies for penetration thresholds), when impact energies were increased, absorbed energies were also increased, but excessive impact energies were decreased. At penetration thresholds, excessive energies get zero value and absorbed energies equal to impact energies. As the damaged specimens were visually inspected, major matrix cracking, major fiber fracture and fiber pullout, and also larger delaminations were observed on the surface of the impacted and non-impacted sides of all specimens.
- All types of composites have obvious penetration and perforation thresholds. The perforation threshold of TP composite is approximately 27% and 22% higher than that of the QP and BP composites, respectively.
- The energy absorption capability of BP composite seems to be same as that of the QP composite, but it has slightly higher absorbed energy at perforation

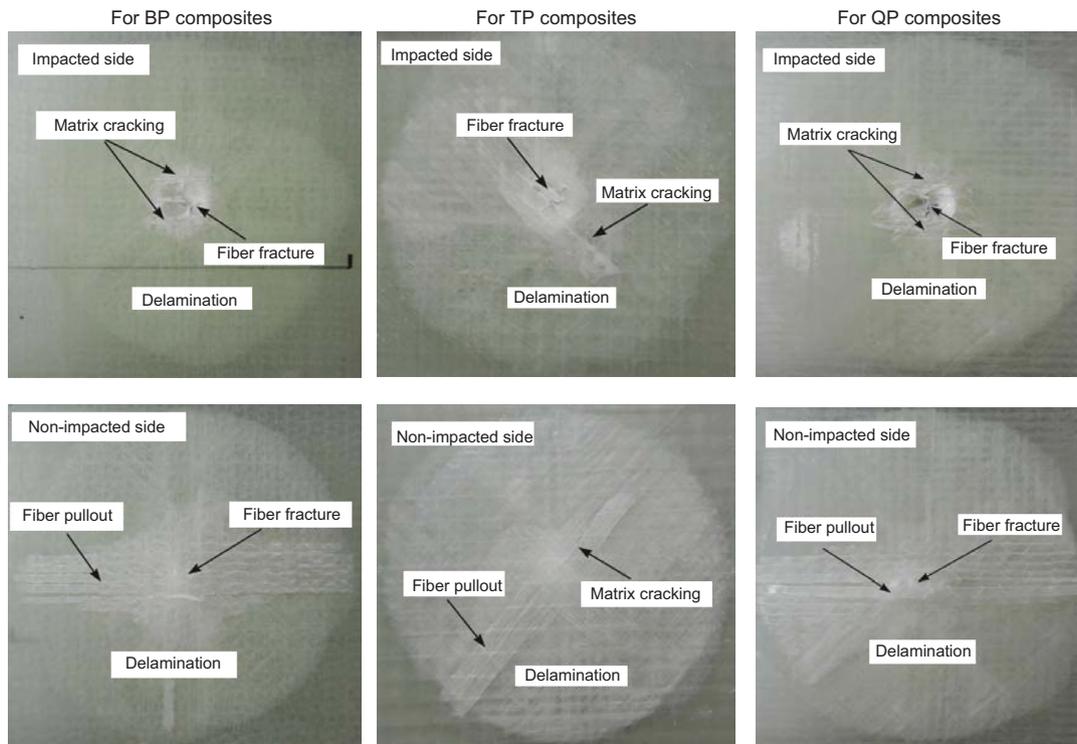
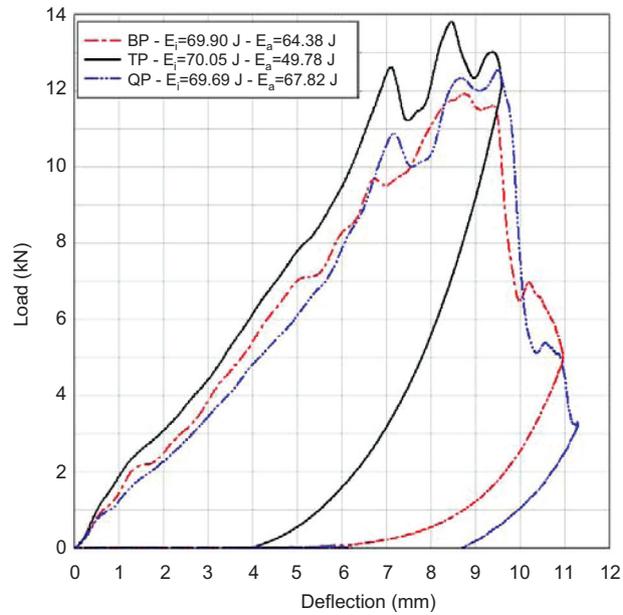


Figure 7 Typical load-deflection (F-d) curves of the BP, TP, and QP composites and images of damaged specimens.

threshold. The TP composite has the highest absorbed energy at perforation threshold.

- The TP composite has the highest impact and absorbed energy and also the maximum peak force. The reason is the number of layers and stacking sequence of TP composites. TP composites have 21 layers, and the fibers crossover in layers as seen
- in Table 1. These increase the bending stiffness so that the penetration and perforation energies are increased.
- The deflections of all composites are nearly the same at peak forces. As the damaged specimens were visually inspected, QP composite has less damage than the others. The reason for this is the high number

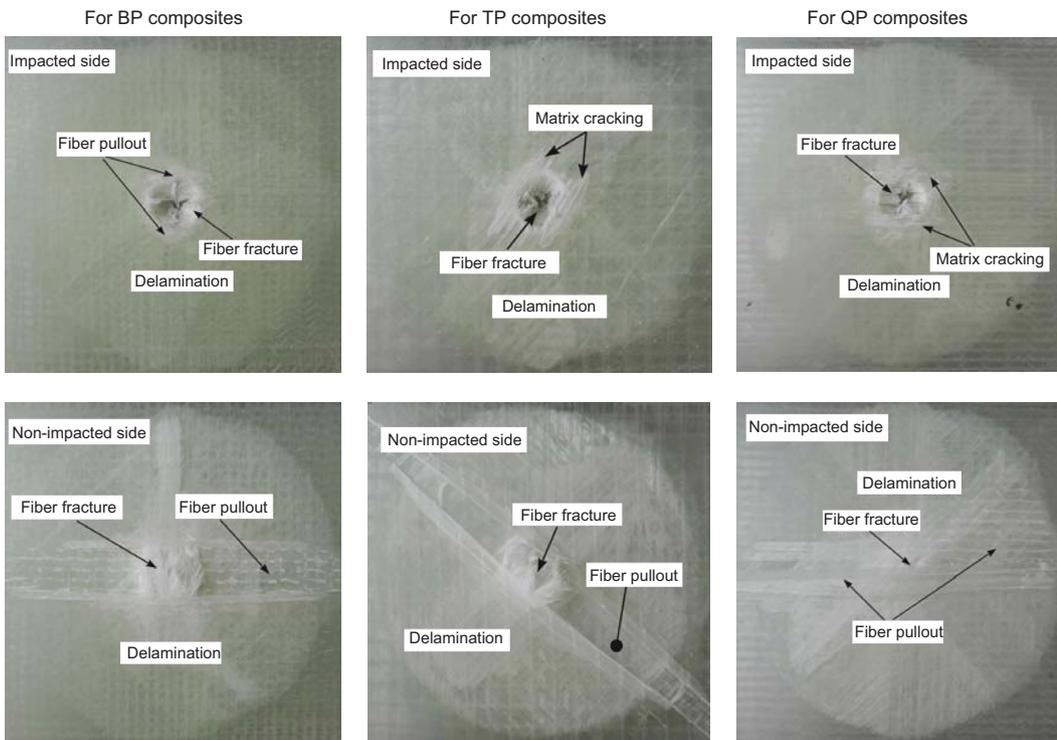
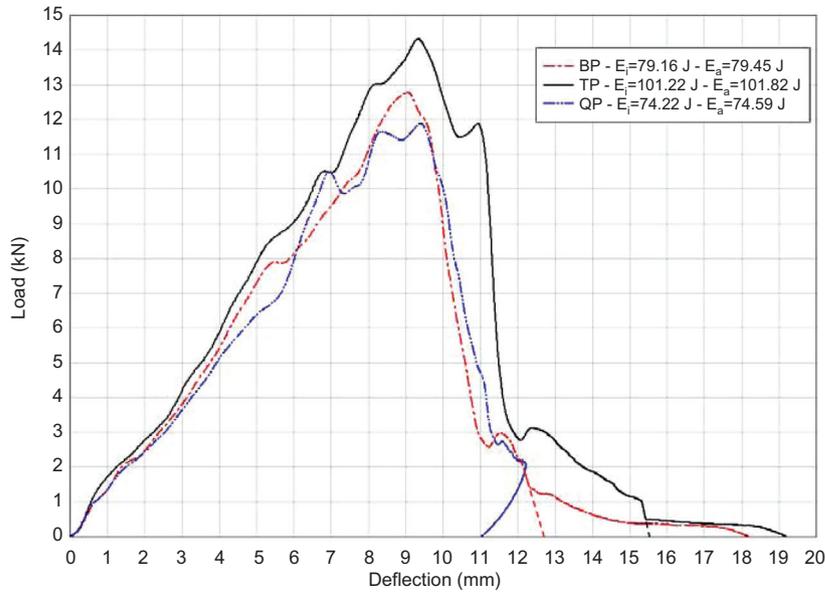


Figure 8 Typical load-deflection (F-d) curves of the BP, TP, and QP composites and images of damaged specimens.

of stitch-bonded layers. QP composite is composed of four-by-four stitch-bonded layers as seen in Table 1. Stitch bonding keeps layers together and minimizes damage propagation.

Therefore, it can be concluded that the number of layers and the stacking sequence or orientation of fibers are the important parameters for the energy absorbing and damage mechanism in the impact behavior of composite

plates manufactured with stitch-bonded non-crimp glass fiber fabrics.

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