DAMAGE REPAIR OF LOW VELOCITY IMPACTED WOVEN THERMOPLASTIC COMPOSITES

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Abstract

In this study, the low velocity impact behavior of three layer thermoplastic laminates consisting of woven glass fiber and polypropylene has been investigated. Panels with dimensions of 100 x 100 mm were subjected to impact energies between 4 and 16 Joules using an instrumented dropping weight impact tower. Results suggested that the woven thermoplastic composites exhibit good energy absorbing properties with approximately 73 % of the impact energy being absorbed after a 16 Joule impact. The impact damaged plates were cut into 100 x 20 mm coupons and tested under four point bending (4PB). The result showed a reduction in flexural strength of approximately 27 % after a 16 Joule impact. Following this a simple compression molding damage repair process was applied to the low velocity impact damaged laminates. Repaired samples were tested under 4PB and results showed a significant recovery of flexural strength to approximately 98 % of the undamaged strength. These results suggest that a simple one step process could be used to successfully repair impact damaged thermoplastic composites.

Introduction

Polymer matrix composites (PMCs) are expanding its use in aerospace and marine industries, as well as other areas due to their high specific strength, stiffness and superior fatigue characteristics. Additional advantages of polymer matrix composites include low density, low cost, recyclability, biodegradability and non abrasiveness [1, 2]. These composites can also be tailored to provide other attractive properties, such as high thermal or electric conductivity and low coefficient of thermal expansion [2]**.** Thermoplastic composites, when compared to thermoset offer a number of advantages including long shelf life, short processing time and ability to be remelted and reprocessed. For most thermoplastic composites, the shelf life is unlimited and the process time in terms of minutes rather than hours for the thermoset counterparts [3]. In addition the excess of scrap thermoplastic material can be reused and the voids or defects can be eliminated by reconsolidation. Thermoplastics have the ability to be processed at various heating and cooling rates due to the absence of the exotherm experienced by thermosets [4]. Furthermore, thermoplastic composites exhibit values of toughness up to ten times higher than those offered by the thermosets and exhibit lower shear and compression strength [3]. Therefore, the final selection depends mainly on the application, particularly in terms of stresses or strains involved, time under load, environmental conditions and solvents involved [3]. Composite structures are subjected to varying working conditions, they are known to be susceptible to impact damage by foreign objects and damage can occur at several scales within the composite material. The invisible damage can cause serious variations in properties of the composite. Therefore, it is very important to study the damage suffered by the composites under the impact loading conditions and more importantly, the after impact damage repair. Low velocity impact testing involves performing tests at relatively low incident energies where composites are partially damaged but still capable of performing their primary function to certain extent [5].

Typical damage produced by a low velocity impact includes matrix cracking, delamination, debonding and fiber breakage. Cantwell and Morton [6] also found that composites are capable of absorbing energy and dissipating it by variety of fracture and elastic processes when subjected to a low velocity impact. The ability of these materials to absorb energy elastically depends on mechanical properties of matrix and fibers, interfacial strength, velocity of impact and size of the component. Polymer matrix composites are known to be highly susceptible to internal damage caused by transverse loads even under low velocity impact [7]. For the effective use of polymer matrix composites in higher performance applications it is important to understand the cause of damage formation under low velocity impact conditions as well as the improvement of the damage resistant characteristics of the composites.

Composites based on woven fibers show less internal damage for a given impact energy than those based on unidirectional tapes. This is because damage growth between layers is constrained by the weave [8]. Woven composites offer high fracture toughness and ease of handling compared to unidirectional composites. The transverse tensile strength of the woven fiber composites is much higher than that offered by the unidirectional counterparts [9]. The increased use of laminated composites has instigated ways to repair the damaged caused by a low velocity impact. There are several possible methods of repairing a damaged composite such as non patch, patch and bonded repairs [8]. Non patch repairs consist of filler or plotting repairs and fusion repair. Filler repair is used for minor indentations in laminates provided that there is no internal damage. Here, the defective region is filled with resin. Fusion repair utilizes the advantage that thermoplastics are fusible and is implemented by applying heat and pressure to the delaminated region. Patch repairs are intended to restore the load path removed by damage, without changing the original loading condition [8]. Bolted repairs are highly suited for the repair of thick composite skins. These repairs are simple to apply by technicians familiar with standard repairs to metallic airframe structures, require no drying, and involve minimal removal of the parent structure. Bonded repairs are capable of restoring the original strength of the composite but require high degree of skills, extensive bonding facilities and longer time to complete repair. Bonded external-patch repairs are generally restricted to thin-skin applications (for example, up to 16 plies, around 2-mm-thick carbon/epoxy), whereas flush or bolted external patches are applicable to repairs for thick sections [8].

The aim of this work is to investigate the low velocity impact properties and the damage repair of woven glass fiber poly propylene (GFPP) laminates. Composite plates will be subjected to impact energies between 4 and 16 joules using an instrumented dropping weight impact tower. Impacted samples will be tested under a four point bending (4PB) loading conditions to evaluate the effect of impact energy on flexural properties. Finally, the possibility of repairing such damage using a simple compression molding process will be investigated. Damage repaired samples will be subjected to 4PB to evaluate the level of flexural strength recovery after repair.

Experimental Procedure

The composite panels tested in this research project were based on a woven glass fiber polypropylene with fiber content of approximately 60 % by weight. Twintex® PP-60, developed and patented by Vetrotex, is a prepreg made by the commingling of continuous glass filaments and PP filaments. Here, the commingling occurs during the glass fiberizing process, which guarantees a homogeneous distribution of two types of filament at an industrial price. Panels with dimensions of 240 x 200 mm were manufactured stacking three layers of the woven prepeg placed in a picture frame mold. The mold was then placed in an air circulating oven, heated to 180 ºC and then removed for cold stamping in a cold press under a force of 4 tones (Figure 1a). Once the mold had cooled below 55ºC, the panels were removed from the mold and visually inspected for defects. The manufactured panels were cut in to laminates with dimensions of 100 x 100 mm using circular cutting diamond wheel. The low velocity impact tests were conducted using an Instron Dynatup instrumented dropping weight impact tower shown in Figure 1b. Here, an impact carriage with 10 mm diameter hemispherical head was released from different heights to generate impact energies between 4 to 16 joules. The GFPP laminates were simply supported on a circular support and impacted at the center. During impact, the absorbed energy, Impact energy vs. time, load vs. displacement, velocity vs. time and impact energy vs. time histories were recorded using the Dynatup load cell, position, time and velocity sensors.

(a) Cold stamping press (b) Instrumented Impact tower

Figure 1: (a) Cold stamping process in a cold press and (b) Instrumented dropping weight impact tower.

In order to determine the before and after low velocity impact flexural properties of the woven GFPP, four point bend (4PB) testing was conducted following the ASTM D6272 – 02 test procedure. Coupons with dimensions 100 x 20 mm were prepared for four point bend testing in a dual column Instron 4469 screw driven universal testing machine. The support span i.e. the distance between the supporting cylinders (L) was 60 mm and the load span, i.e. the distance between the loading cylinders (P) was 30 mm (Figure 2) [10].

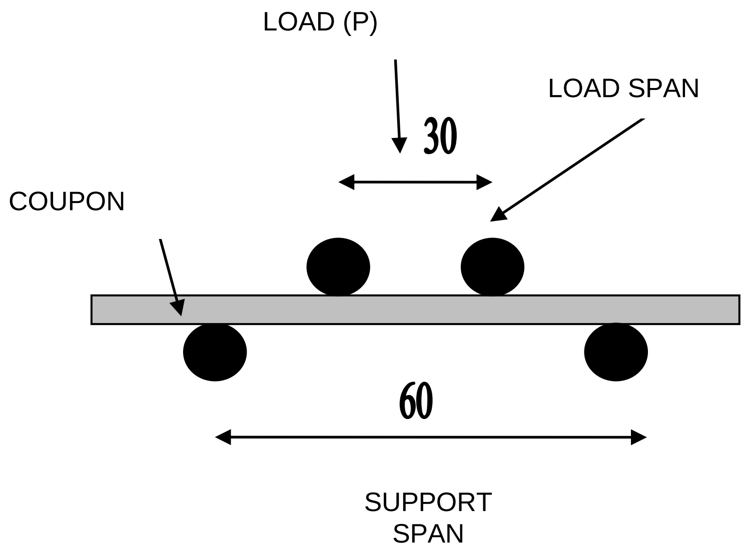

Figure 2: Schematic illustration of a composite coupon loaded in four point bending (4PB).

Quasi-static testing was conducted at a cross head displacement rate of 1mm/min and the load vs. displacement data was recorded. The data collected was used to plot a stress vs. strain curves where values of stress and strain were calculated using [10]:

$$S = \left(\frac{3PL}{4bd^2}\right) * [1 - \left(10.91 * D * \frac{d}{L^2}\right)] \quad (1)$$

and

$$r = \frac{4.36Dd}{L^2} \quad (2)$$

Where, S is the stress (in MPa) in the outer fiber throughout the load span; r is the maximum strain (in mm/mm) in the outer fibers; L denotes the support span (in mm); P is the load at a given point on the load deflection curve (in N); D stands for deflection or displacement (in mm); b is width of the coupon beams (in mm) and d is the depth of the beam (in mm).

In order to investigate the damage repair characteristics of the thermoplastic composites, laminates subjected to an impact energy of 16 joules were prepared for damage repair. Here, a simple one step compression molding process was used following the original manufacturing process parameters. In the repair process, the damaged coupons were placed in the picture frame mold, heated in an air circulating oven up to a temperature of 180 ^{o}C and stamped in a cold press under a force of four tones. The original matrix resin with no additional material identical to the parent material was used. Finally, coupons with dimensions of 100 X 20 mm were cut from the damage repaired laminates and subjected to 4PB testing to evaluate the load of the flexural strength recovery.

Results and Discussion

The low velocity impact behavior of three layer thermoplastic laminates consisting of woven glass fiber and polypropylene was investigated. Panels with dimensions of 100 x 100 mm were subjected to impact energies between 4 and 16 Joules using an instrumented dropping weight impact tower. At least four samples were tested for each impact energy. Figure 3 shows typical variations of incident velocity vs. time for the woven composites subjected to such loading conditions. It is worth noting that this figure shows the first 15 milliseconds of the impact event before a second impact due to bouncing of the impactor occurs. From the figure, it is clear that for the 16 joule impact energy the impacting head reaches a velocity of approximately 2.25 m/s before impacting the specimen. In addition, as soon as the specimen is touched the velocity of the impactor decreases continuously until a velocity of 0 m/s has been achieved. At this time the impactor has reached its maximum displacement.

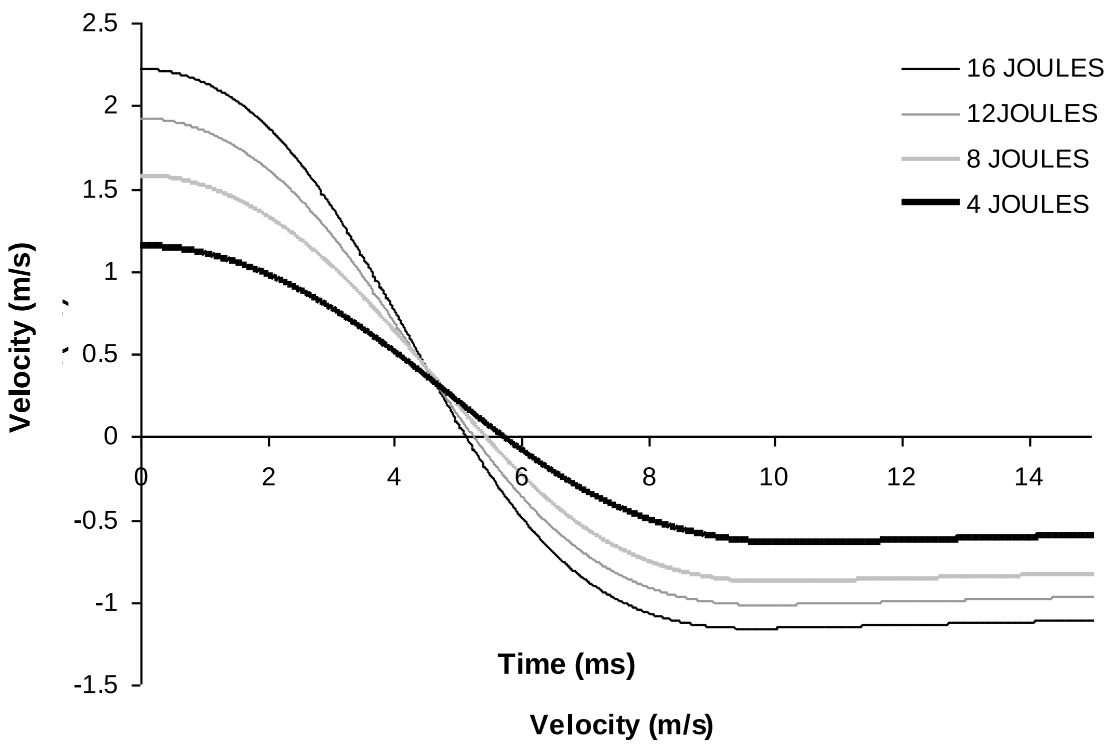

Figure 3: Variation of velocity vs. time for impact energies between 4 and 16 joules under low velocity impact loading conditions on woven GFPP laminates.

Following this, the velocity follows a negative scale reaching a velocity of approximately -1.2 m/s after approximately 9.5 ms as a result of the impactor bouncing back suggesting that some amount of incident energy was still being carried by the impactor after hitting the three layered laminate. Then, the velocity increases again after bouncing for a second impact. At this point the test is stopped.

Figure 4 shows the variation of impact energy with time. From the figure it is clear that at higher impact energies the peak energy was reached at a shorter time. This is a result of the higher velocity of the impactor. It can also been seen that after approximately 10 ms the energy stabilizes which indicates bouncing of the impactor.

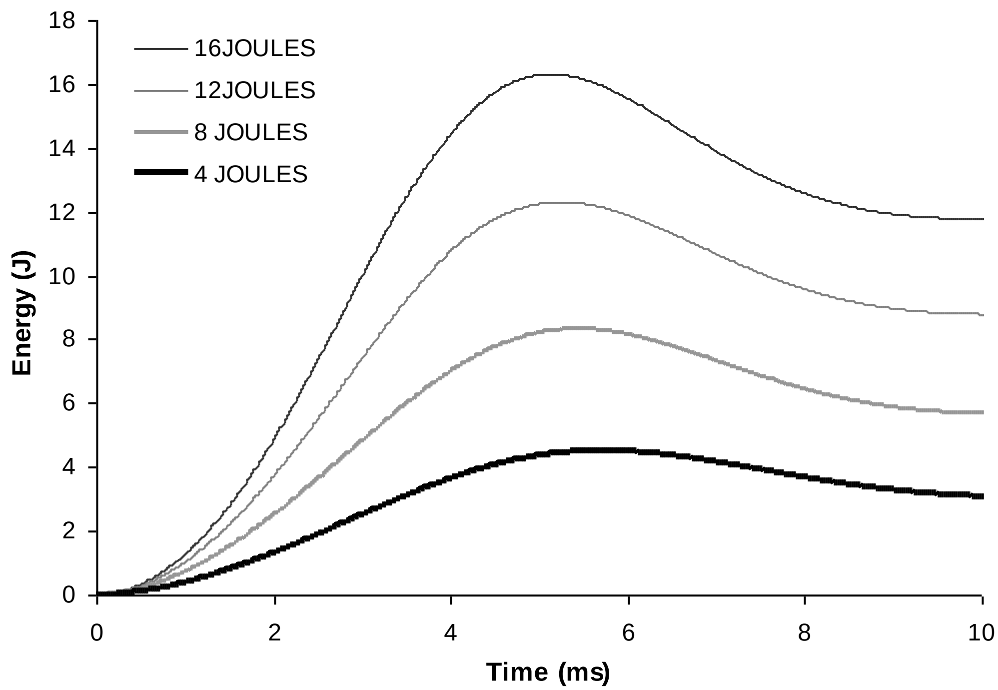

Figure 4: Variation of impact energy vs. time, for the plain woven GFPP laminates.

Figure 5 highlights the variation of load with time after impact energies between 4 and 16 joules were employed to hit the thermoplastic woven laminates. As seen previously, the figures show that the peak loads were reached earlier with higher impact energies. In addition it is also clear that as the impact energy increase the maximum load also increased. It is interesting to see that at the lowest impact energy the loading and unloading regions are more or less symmetrical and as the impact energies increases the unloading regions decrease suggesting further reductions in the load baring capabilities of the laminate. Figure 6 shows typical load vs. displacement curves for the thermoplastic laminates subjected to impact energies between 4 and 16 joules. Clearly, the area under the curves increases with impact energies indicating an increase in energy absorbed by the thermoplastic woven laminates. In addition, all samples exhibit a very similar initial response before the maximum load is reached. Here, loads of approximate 2, 3, 3.75 and 4.4 kN were achieved after impact energies of 4,8,12 and 16 joules respectively.

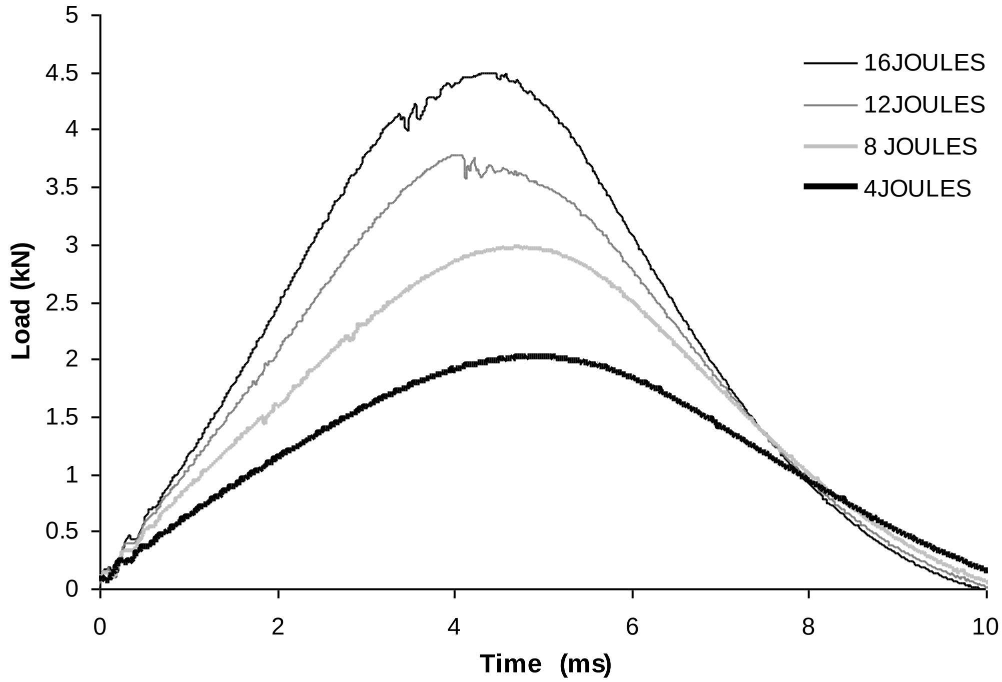

Figure 5: Typical load vs. time curves for the woven laminates subjected to low velocity impact.

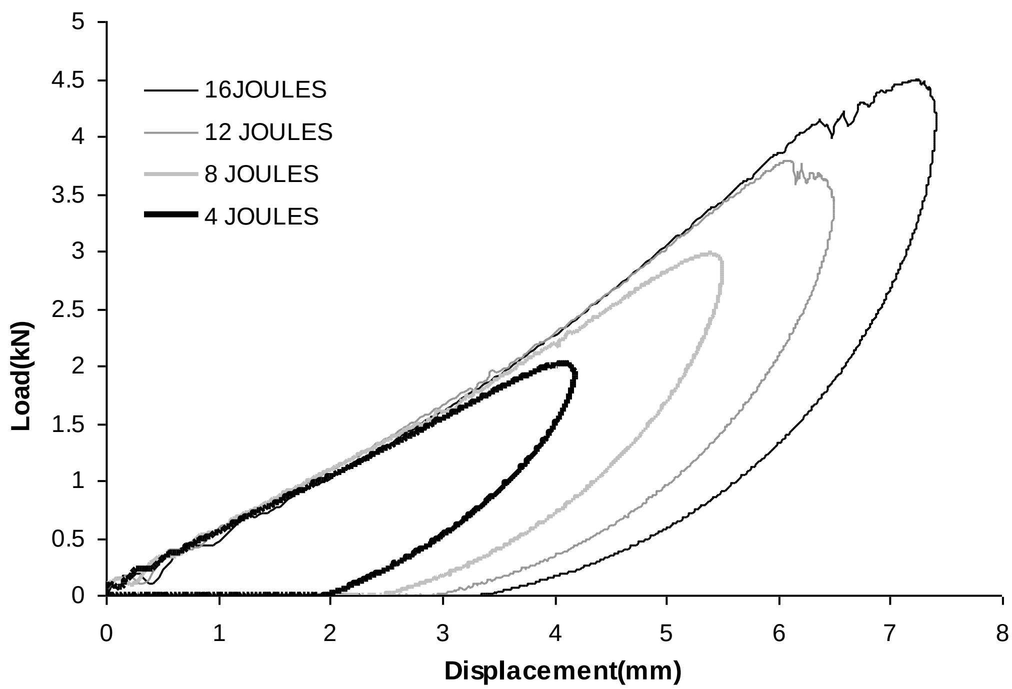

Figure 6: Typical load vs. displacement curves for the woven GFPP laminates subjected to impact between 4 and 16 joules.

The energy absorption properties of the woven thermoplastic GFPP laminates are shown in Figure 7. These values were calculated by the Instron software and validated using an incident and residual energy balance. Here, it is clear that as the impact energy of the impactor is increased, the thermoplastic laminates begin to dissipate significant amounts of the incident energy in permanent failure mechanisms such as localized delamination, further debonding and matrix cracking. At the highest impact energy, almost 73% of the kinetic energy of the impactor has been absorbed by the target, suggesting that these laminates offer a great potential for use in energy absorbing structures.

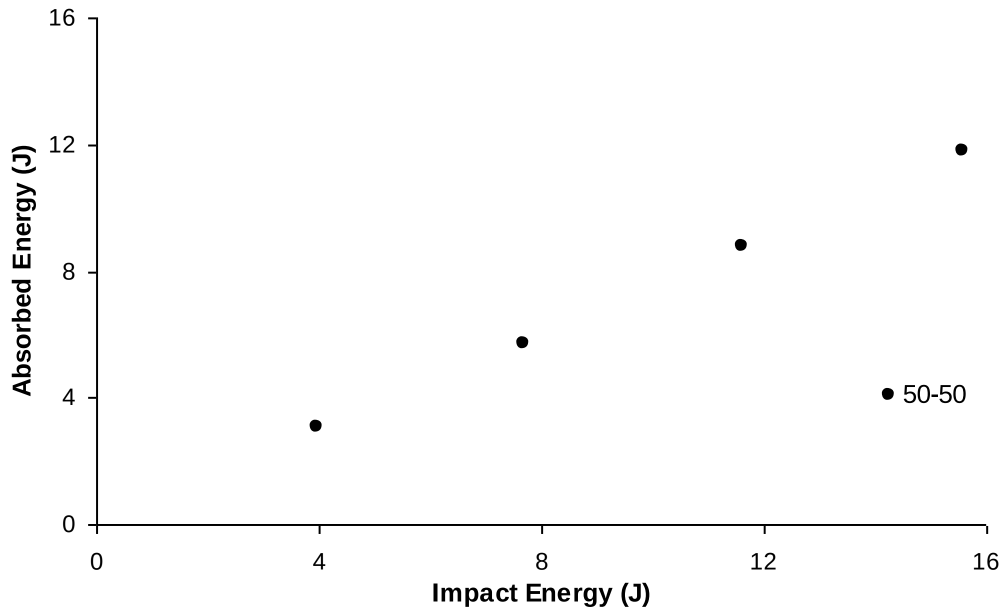

Figure 7: Energy absorption properties of woven GFPP laminate subjected to impact of energies between 4 and 16 joules.

In order to evaluate the effect of low velocity impact on the woven composite, the low velocity impact damaged laminates were cut into 100 X 20 mm coupons and tested under 4PB loading conditions. At least four samples were tested for each impact energy. Figure 8 shows typical load vs. displacement curves of the impacted specimens under four point bending. Here, a reduction in specimen stiffness is apparent as the impact energy is increased. Furthermore, it is clear that the maximum after impact flexural load is also decreasing as the impact energy increases. In order to get a better understanding of the change in after impact flexural strength of the thermoplastic laminates, Figure 9 shows typical flexural stress vs. strain curves of thermoplastic laminates subjecyed to impact energies ranging from 4 to 16 Joules. Included in the figure is the behavior of the undamaged laminates. From the plot it is evident that the reduction in flexural strength after an impact of 16 joules energy is approximately 27 % and continues to decrease as the value of the impact energy increases. These results show that the reduction in flexural strength varies directly with the impact energy. Typical maximum values of flexural strength under impact energies of 4 to 16 Joules varied from 105 MPa to 85 MPa respectively.

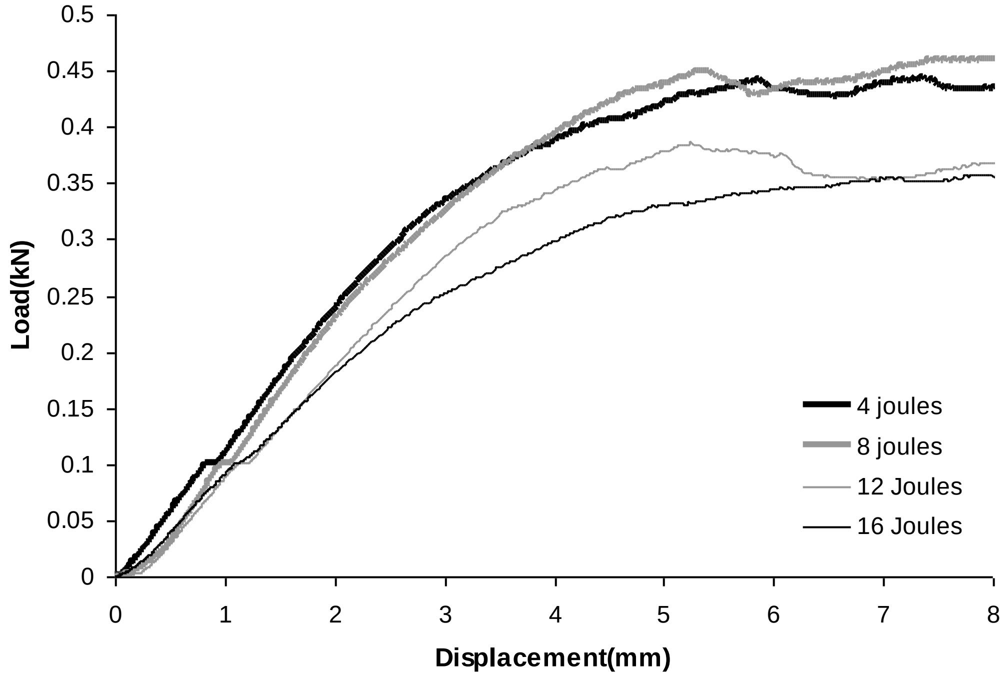

Figure 8: Typical load vs. displacement curves of impacted laminates under 4PB loading conditions.

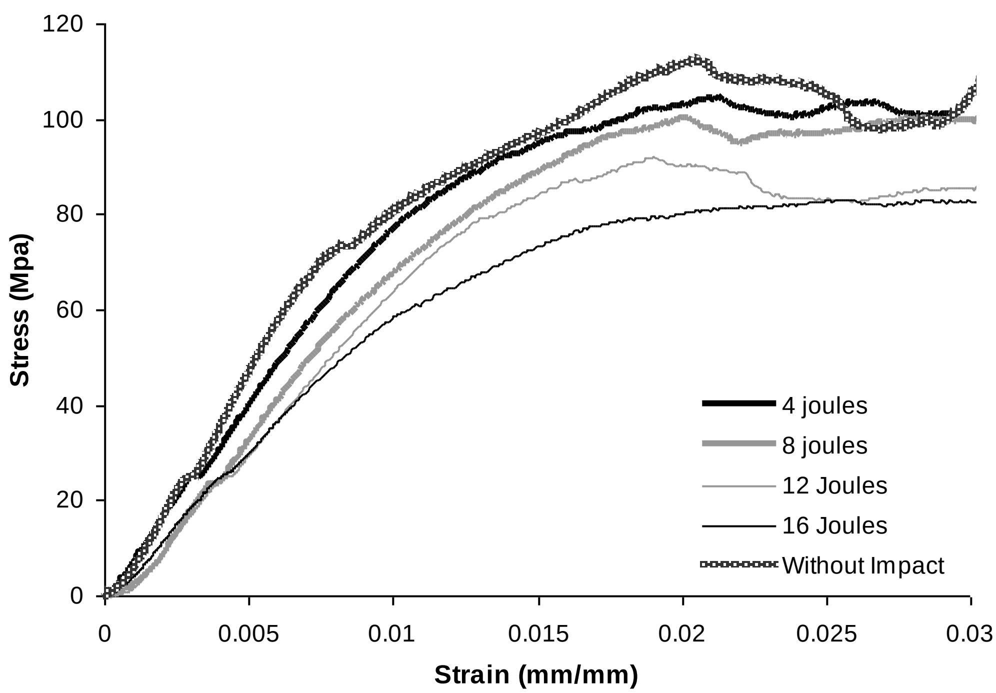

Figure 9: A typical stress vs. strain plot curves of impacted laminates under (4PB) loading conditions.

Finally, in an attempt to revert the damage observed after low velocity impact, a simple compression molding damage repair process was applied to the 16 Joule impacted laminates. After this, samples of 100 X 20 mm were cut from the repaired laminates and subjected to 4PB loading conditions. Figure 10 shows typical stress vs. strain curves for the thermoplastic woven laminates without any damage, after a 16 joule impact and after the repair process was applied to the impacted specimen. From this figure it is clear that the initial slope, the associated stiffness and flexural strength have been recovered after the repair procedure. This result suggests that a simple one step process could be successfully used to repair impact damage thermoplastic woven composites.

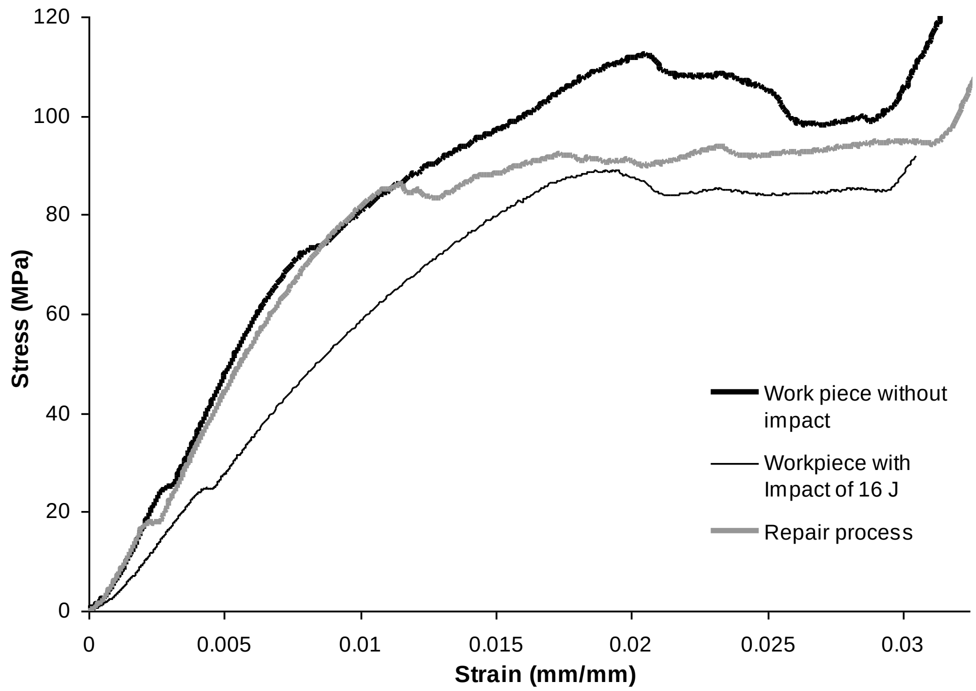

Figure 10: Stress vs. strain curves for woven laminates showing the effect of damage repair after impact.

Conclusions

Thermoplastic woven laminates have been subjected to low velocity impact loading conditions. Experimental results highlighted the excellent energy absorbing capabilities of the GFPP composite. 4PB testing showed a reduction in flexural strength of approximately 27 % after a 16 Joule impact. Finally, a simple one step compression molding process was successfully used to repair the impact damaged laminates. Repaired samples showed a significant recovery of flexural strength to approximately 98 % of the undamaged strength.

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