IMPACT DAMAGE AND RESIDUAL STRENGTH OF MUTIAXIAL WARP KNITTED GLASS FABRIC REINFORCED POLYESTER LAMINATE

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SUMMARY: This paper describes an experimental program undertaken to investigate first the low impact energy damage in multiaxial warp knitted glass fabric, which has a guasi-isotropic stitching sequence of 0°/+45°/90°/-45°, reinforced unsaturated polyester composite. Laminates made by 4-blanket, 8-blanket, and 12-blanket glass fabrics were used. The laminates were subjected to falling-weight, non-penetrating impacts at the normalized impact energies from 4 J/blanket to 16 J/blanket. A mechanistic study that impact induced delamination characterized by a butterfly shape was observed on the 4-blanket laminate. A circular shape was observed on the 8-blanket and 12-blanket laminates. The radial matrix cracks were observed on both of the delamination patterns. A conical region under the impact location does not generally break fibres and matrix cracks. Kink band shear failure was found after a compression-after-impact test. Fibre-matrix debonding between two kink band regions was observed, which transferred the compressive strength from one to another. The results show that more blanket of the laminate has high efficiency of impact energy absorption, but it has large delaminated region. The delaminated region affected the residual compressive strength, where residual compressive strength decreases as the impact delaminating region increases.

KEYWORDS: multiaxial warp knitted fabric, impact, and compression after impact.

INTRODUCTION

The increasing desire by industry for composites is to exploit the cost reductions in its manufacturing process. The high cost of the raw materials must be offset by reduced processing and assembly costs for composite. A textile from that is the multiaxial warp knit or non-crimp fabric is being widely considered. Although the textile manufactured non-crimp fabric has shown to result in laminates with in-plane mechanical properties that are somewhat lower than equivalent laminates made from unidirectional prepreg tape, they offer one significant benefit, namely the material's compression-after-impact performance[1].

Typical impact damage appears in the form of matrix cracking, fibre-matrix debonding, delamination, fibre-shear-out, fibre fracture, etc.[2]. In particular, the

internal delaminating often generated due to the relatively low interlaminar shear strength will grow under subsequent compression loading, which leads to a significant strength reduction in post-damage performance. Therefore, it needs to have an understanding of the impact and the compression after impact characteristics of laminates.

The objectives of the work are (1) examine the characteristics of impact damage in ascending order of normalized impact energies up to 16 J, which results in small levels of the impact damage for used laminates, (2) examine the characteristics of compression failure after a non-penetrating impact damage. A quadriaxial warp-knit fabric laminated as a panel is used in this study.

EXPERIMENTS

Material and testing

The material that was investigated consisted of a guadriaxial warp-knit fabric impregnated with an unsaturated polyester resin system. The construction of one blanket (single unit of fabric) of 1141g/m^{-2} warp-knit fabric consists of individual plies knitted together by a low-tex polyester stitching yarn, with the areal weight distribution of glass fibre as follows [0(g/m^{-2}), -45(276g/m^{-2}), 90(283g/m^{-2}), +45(276g/m^{-2})]. The laminates made by 4-blanket, 8-blanket, and 12-blanket glass fabrics, DBLT 1150-E11-1 glass fabric produced by DEVOL AMT AS, were used in this work. Laminates were manufactured by a hand-lay method, which was cured at room temperature for 24 hours. The thickness of 4-blanket, 8-blanket, and 12-blanket laminates, with 24.4%, 29.0%, and 27.8% fibre contents in weight, are 3.5mm, 6.1mm, and 9.6mm, respectively.

Non-penetrating impact tests were conducted using a guided drop-weight test rig with a pair of (remote) adjustable rebound catch blocks to prevent repeat impact. Specimens for the investigation of impact characteristics, 7.62cm wide by 12.7cm long, were cut from the laminates. The specimens were struck once with a 13.12kg impactor with a hemispherical nose. The laminates were subjected to non-penetrating impacts at the normalized impact energies (normalized by the laminate blankets) from 4 J/blanket to 16 J/blanket. The incident impact energy for all specimens are shown in Table 1. The impacts were conducted on a Dynatup Model 8250 at an ambient temperature of 23 . Traces of the impact load history and impact energy (calculated from the load) were stored digitally. Impacted specimens were sectioned and polished and the damage surface examined under a camera with two 500W light sources and a metallographic microscope.

The residual load-carrying capacity of the impacted specimens was determined by end-loaded, side-supported compression testing. The residual compressive strength was evaluated at a speed of 0.05 in/min, which was conducted on a MTS model 458. After compression, sectioning of specimens was carried out for fractographic studies using a camera and a metallographic microscope.

Table 1: Impact energy for the specimens

Sample Code	Impact energy (Joule)
4A	64
4B	48
4C	32
4D	16
8A	128
8B	96
8C	64
8D	32
12A	191
12B	143
12C	96
12D	48

RESULTS AND DISCUSSION

Impact response, energy absorption, and damage characteristics

Typical load-time and energy-time trace for laminates supported at their ends are illustrated in Figure 1. Hertzian failure and shear failure occurred in each blanket depending on the impact energy. They are more likely with higher impact energies. In the specimen 4C, a lower impact level was given and shear failure is not easy to be identified. The rebounding phenomena are observed since all the laminates did not completely fail.

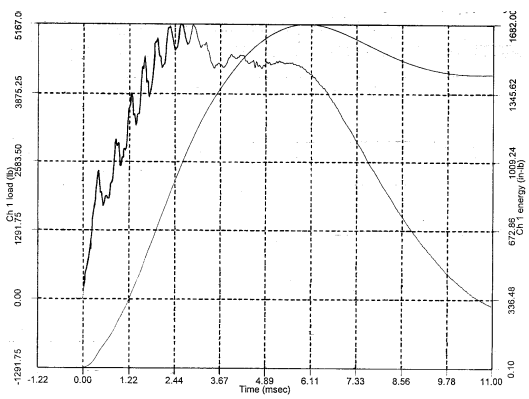


Figure 1: Typical load-time and energy-time traces of laminate

A series of impact tests were conducted on laminates with varying blankets and incident impact energies. Figure 2 illustrates impact load vs. normalized impact energy (normalized by the laminating blankets) for each specimen. The curves show that as the impact energy increased, the impact force increases also. The blankets of laminate increase results in a decrease of impact force. More blanket of the laminate has a higher efficiency of impact energy absorption for each blanket of the laminate. Figure 3 presents a plot of the threshold level and normalized impact energy of 8-blanket and 12-blanket laminates. These data reveal that the threshold level increases as blankets of laminate increase and normalized impact energy levels decrease. The results can be explained by the efficiency of impact energy absorption of each

blanket, where a higher efficiency of each blanket results in a lower threshold level. A rebounding force at all non-penetrating impact tests was found. The ratios of rebounding force to measured impact energy of all tested specimens are shown in Figure 4. These results show that the rebounding ratio decreases as normalized impact energy increases.

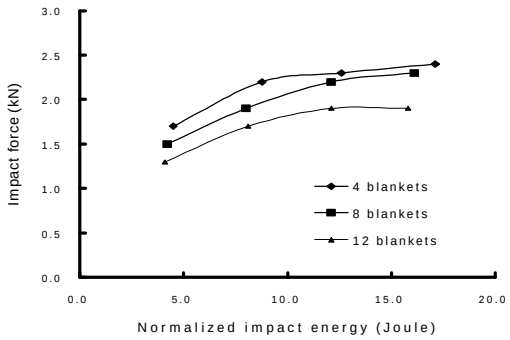


Figure 2: Plot of impact force vs. normalized impact energy

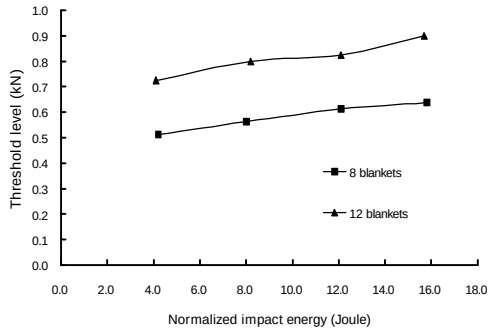


Figure 3: Plot of threshold level vs. normalized impact energy

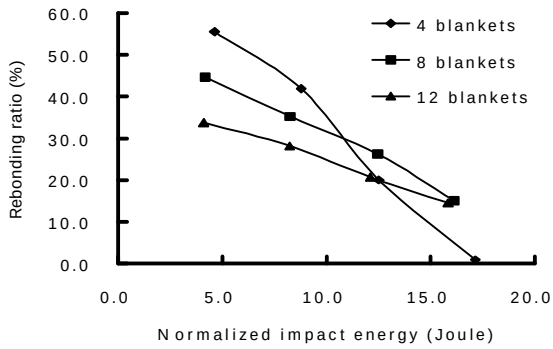
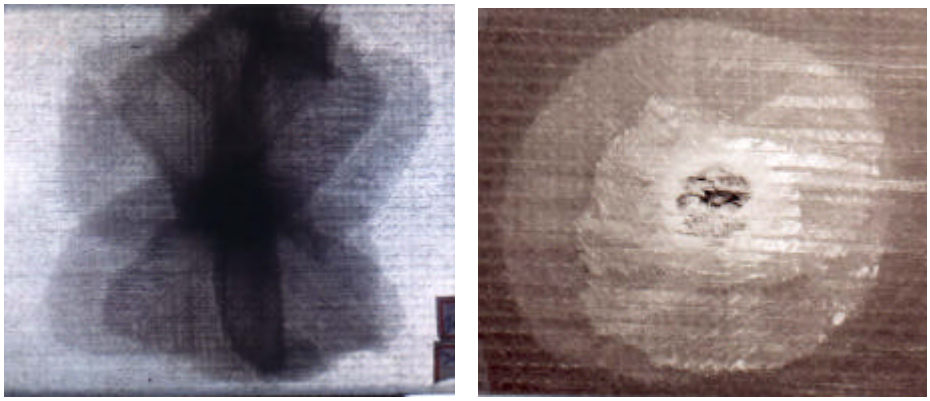


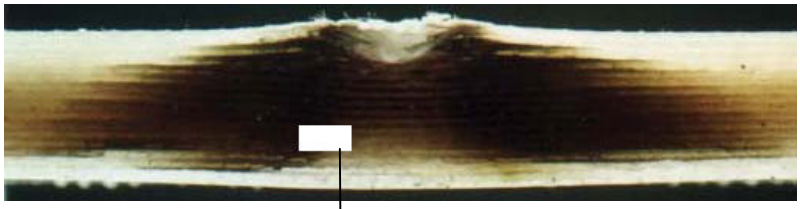
Figure 4: Plot of rebounding ratio vs. normalized impact energy

A number of experimental studies have characterized the impact damage that occurs in laminates. One generic damage characteristic is intra-ply delaminating. In this study, the major delamination that occurs between adjacent blankets is characterized by a butterfly shape with its major axis parallel with the fibre direction of the 4-blanket laminate. Figure 5(a) presents a photograph of the overall delaminated region of the 4-blanket laminate. The image of the delaminated area isolated in each blanket can be seen. Figure 5(b) reveals that, in contrast, delamination with a circular shape was formed in the 8-blanket and 12-blanket laminates. The circular shape of the lower blanket spirals down to the higher blanket and the delaminated area is enlarged from the lower blanket to the higher blanket. Careful inspection of the impacted laminates with the same blankets shows that higher impact energy absorption results in larger delaminated area. The exceptions are found with specimens 4A and 8A. They are nearly penetrated and have a small-delaminated area, although the laminates were supported by high impact energy. In general, a larger delaminated area presents a higher impact damage resistance of the laminate. The comparison of different laminates shows that more blankets of laminate with the same normalized impact energy have a larger delaminated area. Other damage characteristics typically observed in laminates subjected to impacts include a centrally depressed region, radial matrix, and fibre breakage.

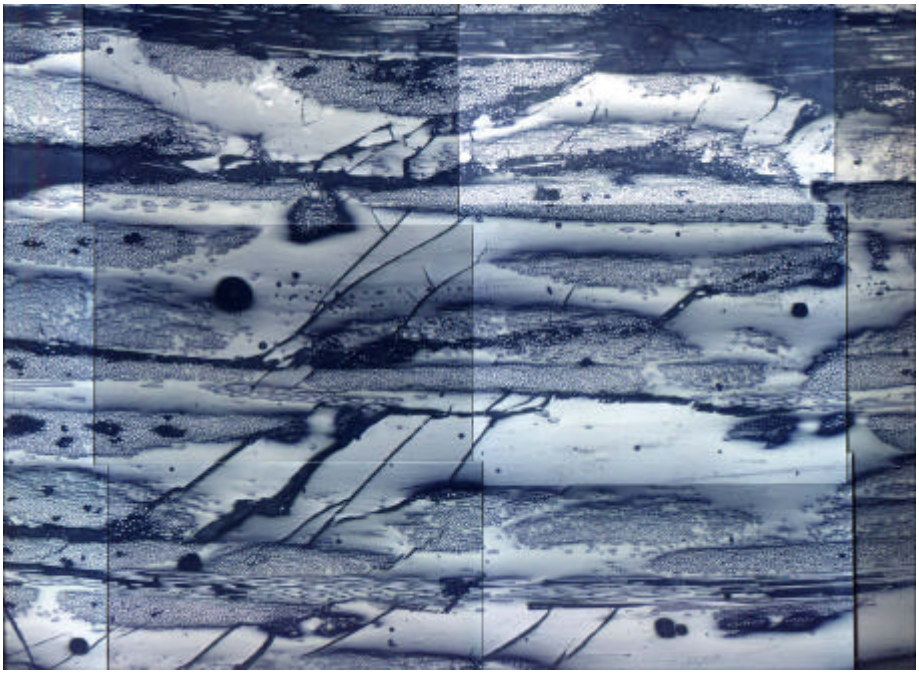


(a) butterfly shape (b) circular shape

Figure 5: Photographs illustrating the intra-blanket delamination



(a) photograph illustrating impact damage region



(b) delamination and matrix microcracks

Figure 6: Photographs illustrating the damage characteristics of non-penetrating impact laminate

The damaged specimens were sectioned and polished, and observed under a metallographic microscope. The radial matrix cracks are generally inclined from the vertical position toward the impact contact region and emanate from the impact location in a radial pattern (see Figure 6). Notice that the cracks appearing in pairs in each blanket of the laminate are offset from a centrally depressed region, and emanate outward along the fibre direction in an antisymmetric pattern with regard to the impact location. A conical region under the impact location, which appears to be circular in plan view, does not generally break fibres and matrix cracks (see Figures 5 and 6). A schematic representation of non-penetrating impact damage of laminate is presented in Figure 7.

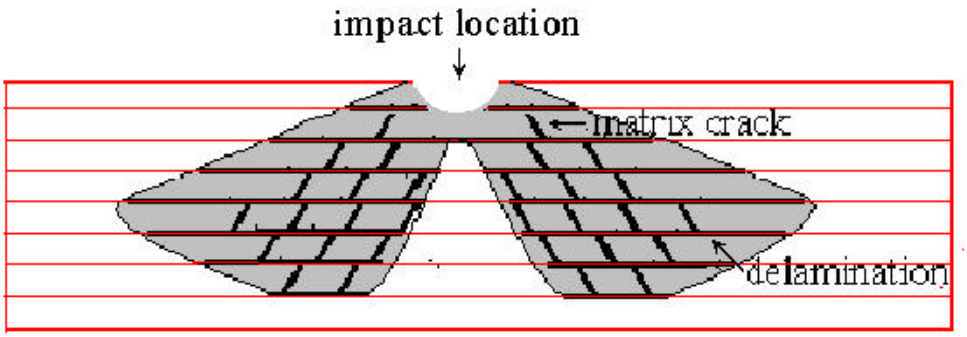


Figure 7: Schematic of non-penetrating impacted laminate with major damage region (denoted with the gray area)

Residual compressive strength and fracture characteristics

Ranking the compression-after-impact strength of the non-penetrating impacted laminates follows. Figure 8 presents a plot of the residual compressive strength vs. normalized impact energy. The results show that the residual compressive strength decreases as the impacted energy increases (except specimens 4D and 8D). However, the blankets of laminate increase as the residual compressive strength decrease. The fracture of compression is more likely to be governed by the impact damage. The impacted laminate with large delaminated area results in a low residual compressive strength

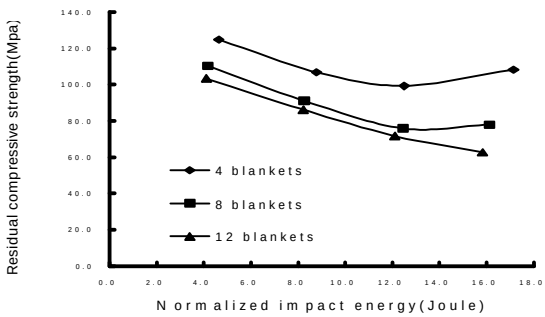
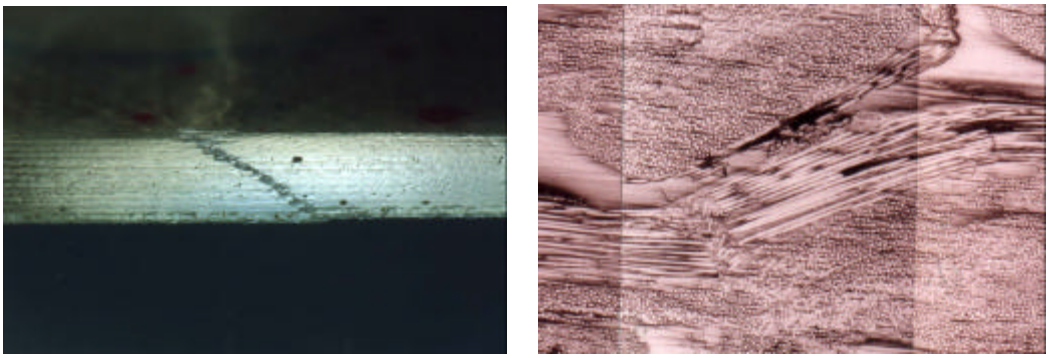


Figure 8: Plot of residual compressive strength vs. normalized impact energy

One generic compressive damage characteristic is shear failure. Figure 9(a) shows

that laminates typically deform by a shear mechanism with kink bands formed at 45° to the load axis. A metallographic photograph of kink band of fibres is shown in Figure 9(b). Figure 10 reveals kink bands shear failure with fibre-matrix debonding. Damage locations of impact on blankets of the laminate are varied, which results in the shear failure initiating at different place. Compressive strength between two kink band regions were offset by fibre-matrix debonding



(a) compressive damage (b) kink band

Figure 9: Photographs showing kink band shear failure

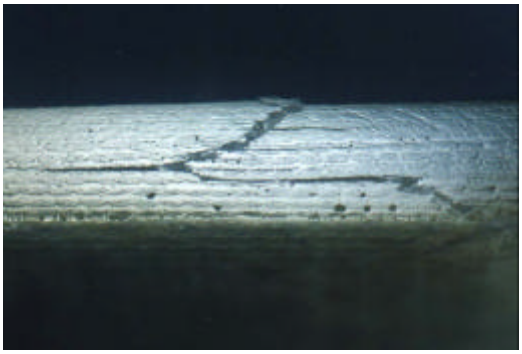


Figure 10: Photograph showing kink band shear failure with debonding

CONCLUSIONS

The results from this investigation show that resistance to non-penetrating impact damage and corresponding residual compressive strength is varied with the laminates. An increase of blankets of the laminate results in an increase of the efficiency of the resistance to impact damage but in a decrease of its residual compressive strength. The impact damage region is one of the important indices to evaluate this property. This suggests that the highest residual compressive strength has been achieved, as the impact damage region is the smallest, which is consistent with our expectations. However, the exact impact damage region is not easy to measure. The calculation of the impacting delaminated area based on the photograph taken from the sectioned and polished damaged specimen could be one of the methods.

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