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Title: Behavior of Quasi-three-dimensional Woven Composites

Authors (names are for example only): Dahsin Liu
Kirit Rosario
Shawn Klann

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ABSTRACT

In view of the fundamental uses of composite materials for in-plane loading and the needs to combat delamination due to accidental out-of-plane loading, quasi-three-dimensional (Q3D) woven composites have been developed in this study. The Q3D woven composites are not three-dimensional woven composites because there is no fiber specifically oriented in the thickness direction. However, the Q3D woven composites are similar to three-dimensional woven composites because all in-plane fibers between adjacent layers are interlocked together to form an overall three-dimensional network. Accordingly, the Q3D woven composites should offer high delamination resistance similar to the three-dimensional woven composites while retain reasonable fiber flatness, and hence high in-plane properties. In justifying the advantages of the Q3D woven composites, several variations of Q3D woven composites are presented. The comparisons of their in-plane stiffness and buckling strength with the laminated and two-dimensional and three-dimensional woven counterparts are performed with the use of compression tests. Moreover, the damage patterns due to low-velocity impact and the residual properties of the impacted specimens are characterized by using the compression after impact (CAI) tests. Experimental results have concluded that the innovative Q3D woven composites with five-harness have similar in-plane stiffness to the laminated composites but have higher damage tolerance than the laminated counterparts.

INTRODUCTION

Delamination has been recognized as one of the major concerns in laminated

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Dahsin Liu, Kirit Rosario and Shawn Klann, Dept. of Mechanical Engineering, Michigan State University, East Lansing, MI 48864, U.S.A.

composite materials [1-7]. Many efforts have been devoted to understanding the cause of delamination, the effects of delamination on the behavior of laminated composites and the techniques to combat delamination. Because delamination is caused by high interlaminar stresses and/or low interlaminar strengths, the fundamental techniques to combat delamination are to reduce the interlaminar stresses and/or to increase the interlaminar strengths. The former can be achieved by reducing the anisotropy of the composite materials, the difference of angle between adjacent plies, the ply thickness and the loading level. The latter, however, can be achieved by increasing the matrix strength, improving the bonding strength between fiber and matrix, and introducing additional reinforcing materials in the thickness direction.

Stitching and z-pinning [1,3,8-10] are the two most commonly used techniques in improving the interlaminar strengths. They introduce reinforcing materials in the thickness direction of laminated composites and have been found to be efficient in improving the interlaminar strengths. However, they also cause high stress concentrations to the composite materials simultaneously. The controversial results consisting of the increase in interlaminar strength and the decrease in in-plane properties have been reported by many researchers.

Instead of introducing the extra reinforcing materials in the thickness direction, manipulating fiber geometry to form through-thickness interlocking, such as two-dimensional weaving, thee-dimensional weaving and braiding [9-15], has also been proved to be effective in improving the delamiantion resistance of composites. Although woven and braided composites are superior to laminated composites in combating delamination, their wavy fibers and through-thickness fibers can also cause reductions in in-plane stiffness and buckling strength and hinder the applications of the woven and braided composites to high-performance structures. As the goal for this study, innovative woven composite materials are introduced in this study to combat delamination while maintaining high in-plane properties.

QUASI-THREE-DIMENSIONAL WOVEN COMPOSITES

In this study, the term 'quasi-three-dimensional (Q3D) weaves' refers to weaves having in-plane yarns in the adjacent layers interlocked one another to form overall three-dimensional networks. These are different from the commonly called three-dimensional (3D) weaves which refer to weaves having in-plane yarns assembled together through the thickness by yarns in the thickness direction. 'Quasi' is used to emphasize that the weaves have no yarns specifically oriented in the thickness direction to tie all the in-plane yarns together, but rather, the in-plane yarns in the adjacent layers are integrated and interwoven together gradually.

Figure 1 shows the commonly called 3D weaves. There are some yarns oriented in the thickness direction. They do not directly contribute to the in-plane strength of the composite material. Also these yarns cause kinks to the in-plane yarns at points where they are inserted. The kinks may become weak points in the composites made from these yarns due to the high stress concentrations and, after addition of matrix, the resin rich pockets.

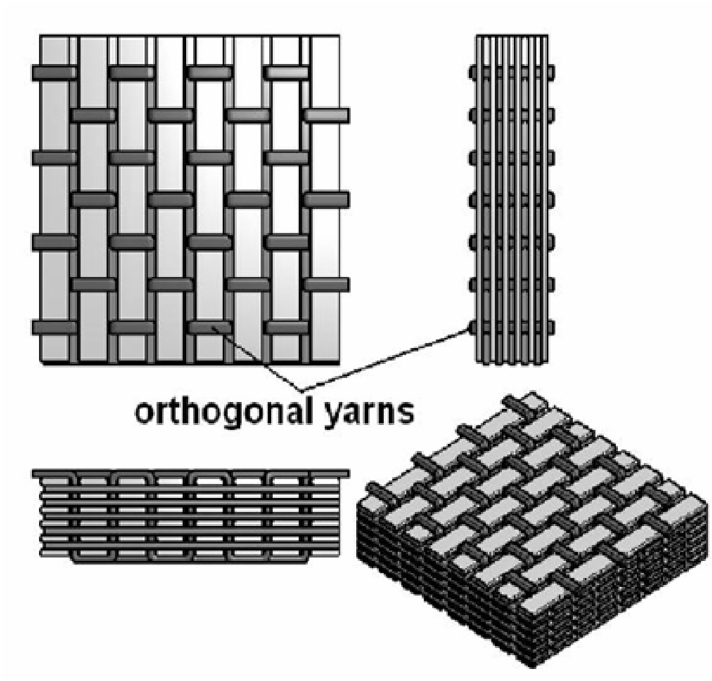

Figure 1. 3D weave.

In a Q3D weave, as shown in Figure 2, all the yarns are primarily located in the plane of the weave. From Figure 2, it can also be seen that the yarns are interlocked not only with the cross yarns of their own layer, but also go deeper into the weave to interlock with the yarn of the adjacent layer. Although undulations of the in-plane yarns can be clearly identified, none of the yarns is specifically oriented in the thickness direction. The contribution of the in-plane yarns to the in-plane properties, hence, can be largely preserved.

All specimens investigated in this study were of [0/90] type, i.e. the warp and fill yarns were orthogonal to each other. For the purpose of comparison, the conventional composites, such as laminated (L) and two-dimensional (2D) woven composites were also investigated. In the description of various weaves in this study, the difference between ply and layer should be mentioned. A ply was a composite sheet with unidirectional fibers and used to build up a laminated (L) specimen. A layer was made of two in-plane sets of yarns, which were orthogonal to each other (warp and fill) and woven together or with neighboring sets of yarns, i.e., a [0/90] pair. Each in-plane yarn that made up this [0/90] pair was referred to as a half-layer.

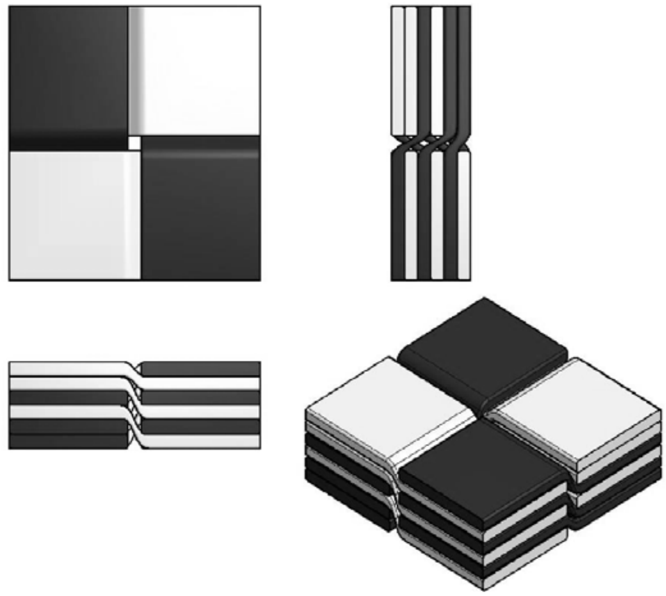

Figure 2. Q3D$[0/90]_3$ weave.

WEAVING PARAMETERS

Level of Integration

This describes whether or not adjacent warp and fill yarns, or adjacent layers, are interconnected by yarn content, and to what level. Laminated (L) samples have no integration between adjacent plies, and are held together only by matrix material. Two dimensionally woven (2D) samples are integrated only within each layer (warp and fill yarns are intertwined), but individual layers are held to each other only by matrix material. These laminated and two-dimensional weaves are depicted in Figure 3 and Figure 4, respectively.

In all Q3D samples, each warp or fill yarn is integrated with the fill or warp yarn above and below it. In this way, each half-layer is held to both neighboring half-layers through yarn links, yielding a continuous, integrated network. The maximum depth of any interlock is three half-layers deep, including the ply in question. Figure 2 shows a two-harness Q3D weave. A slight difference might be noticed in the surface yarns which may only be integrated with the half-layer below i.e. integrated with only one orthogonal half-layer instead of two. This is an unavoidable consequence which is true of one set of fill and one set of warp surface yarns. The difference in the property of the weave caused by this feature may be negligible in cases with a higher number of layers. The level of integration is designated by L, 2D and Q3D.

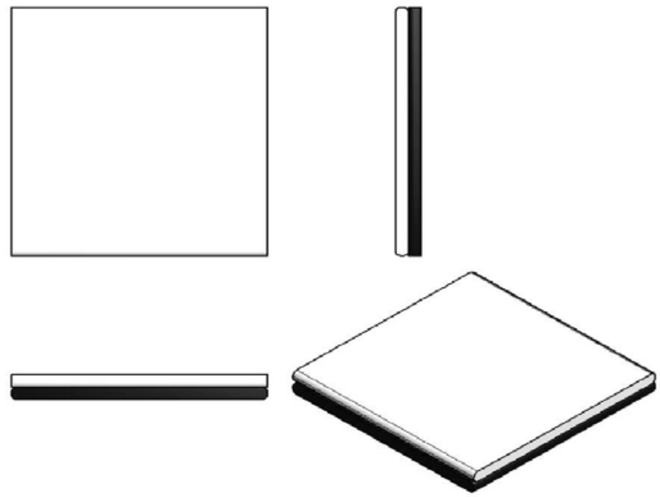

Figure 3. $L[0/90]_1$ weave.

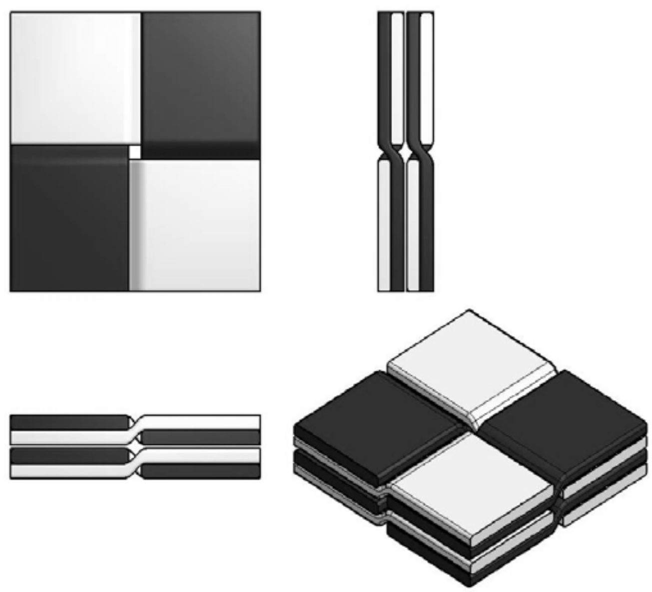

Figure 4. $2D[\underline{0/90}]_2$ weave.

Harness Number

This describes the frequency of interlacing of warp and fill fibers with respect to yarn width. In 2D weaves, the fill or warp fibers interlace alternately over and under every orthogonal warp or fill fiber. This yields a two-harness weave as the pattern is repeated every two yarn widths. In higher harness weaves, yarns interlace less frequently with the orthogonal yarns and have longer regions where they are straight. This can be seen in the three-harness Q3DO3 and five-harness Q3DO5 weaves shown in Figure 5 and Figure 6, respectively. Laminated samples (L) are considered to have infinite harness number. Harness number higher than two is designated by a number just before the [0/90] in the nomenclature.

Number of Layers

This describes the number of [0/90] pairs for L and the number of [0/90] pair for 2D and Q3D that are either stacked one over the other (as in L and 2D), or interwoven (as in all Q3D weaves). It should be noticed that in Q3D weaves, there are in fact, no layer, but a set of orthogonal half-layers. But for clarity of definition, in all weaves, a set of two orthogonal half-layers is counted as one layer. Number of layers is designated by the subscript just after the [0/90] in the nomenclature.

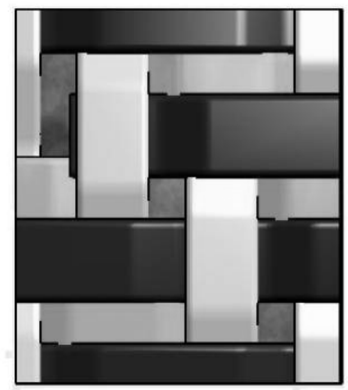

Figure 5. Q3DO3$[0/90]_3$ weave.

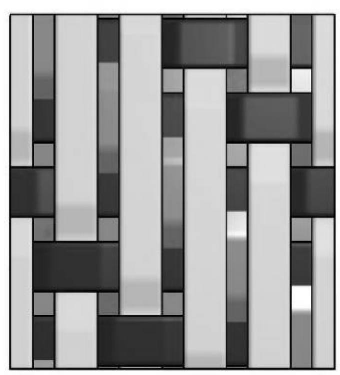

Figure 6. Q3DO5$[0/90]_3$ weave.

An edge replication method was used to evaluate the through-thickness composition of cured samples of each weave to gauge the quality and uniformity of the final products. The method began with cutting an edge of the specimen, sanding it flat with 1200 grit sandpaper (with water to prevent burning the surface), and then polishing it on a polishing felt cloth (placed on a flat glass) with 5-micron and then 3-micron polishing powder mixed with a little water. This yielded a smooth shiny cross-sectional surface. With the use of a syringe, acetone was injected onto the smooth edge. Immediately a piece of edge replication tape was placed on the surface (without any sliding), and pressed against it with a soft rubber block till the acetone evaporated fully. The texture of the cross-section of interest would then be imprinted on the tape, which could be magnified, viewed and printed off from a microfiche reader. Figure 7 shows the edge replications of the five sample groups. The width of samples presented is the maximum that the microfiche reader was capable of displaying. The thicknesses in all cases were 2mm but the diagrams were stretched to make the structure clearer.

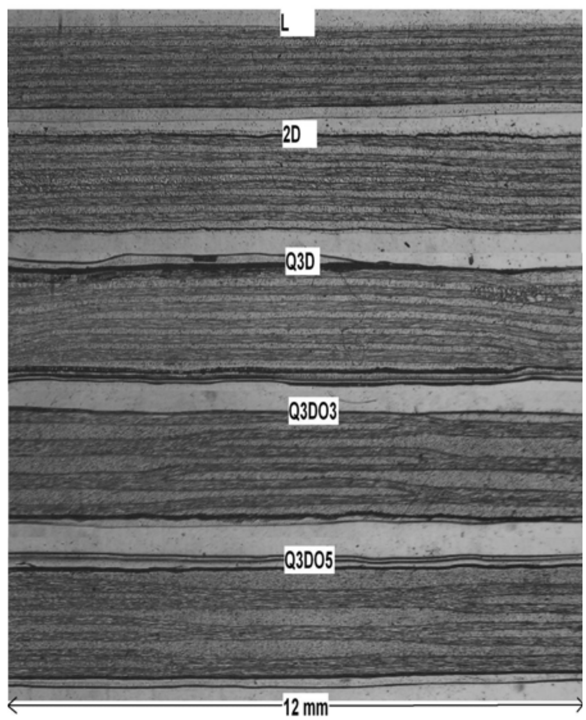

Figure 7. Images of edge replication of different weaves.

EXPERIMENTAL RESULTS

All the sample specimens prepared in this study were tested by a low-velocity drop-weight impact tester. From the load-deflection curves, several quantities were measured. The method of measuring these different quantities as well as their significance was explained in Reference [1,2,4,5]. Average values of these measured quantities for each group are presented in Figure 13.

Load-Deflection Curves

Following are the load-deflection curve groups for the five groups of thin specimens subjected to drop weight impact tests. These are presented to show the distribution or variation within each set, and the general trends in each case. Trend lines that are superimposed on the plot sets highlight these trends.

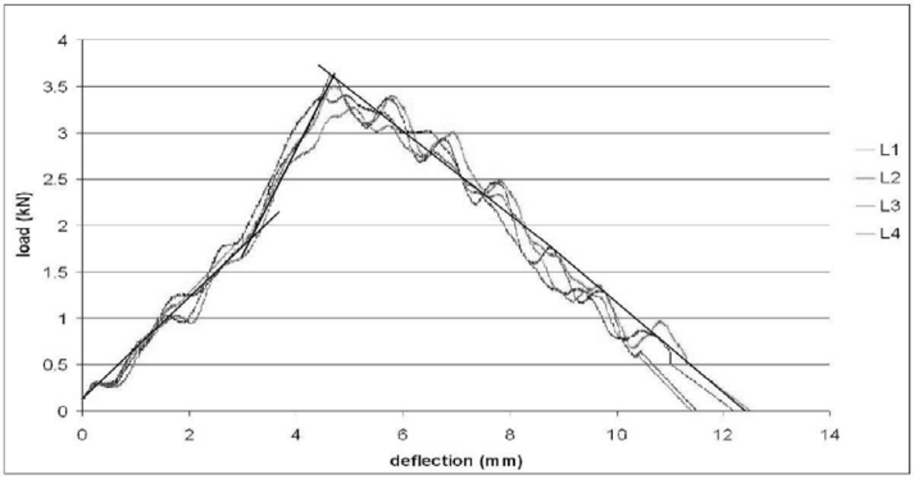

Figure 8. Load-deflection curves for L specimen impact tests.

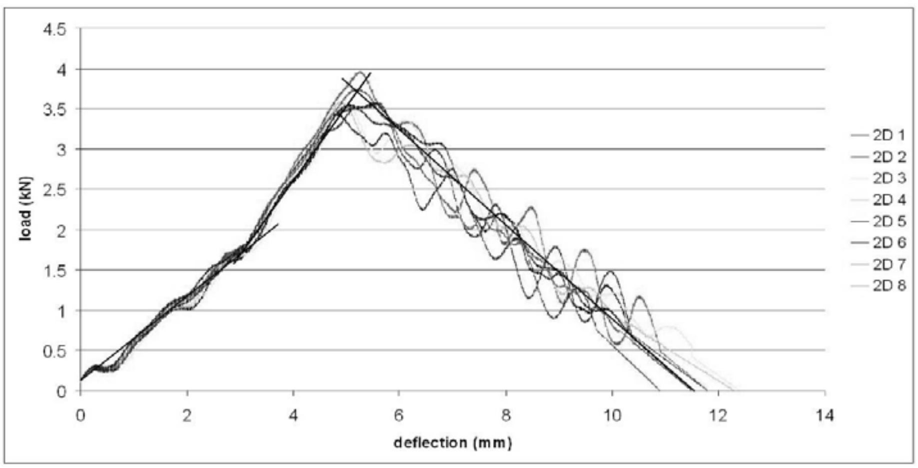

Figure 9. Load-deflection curves for 2D specimen impact tests.

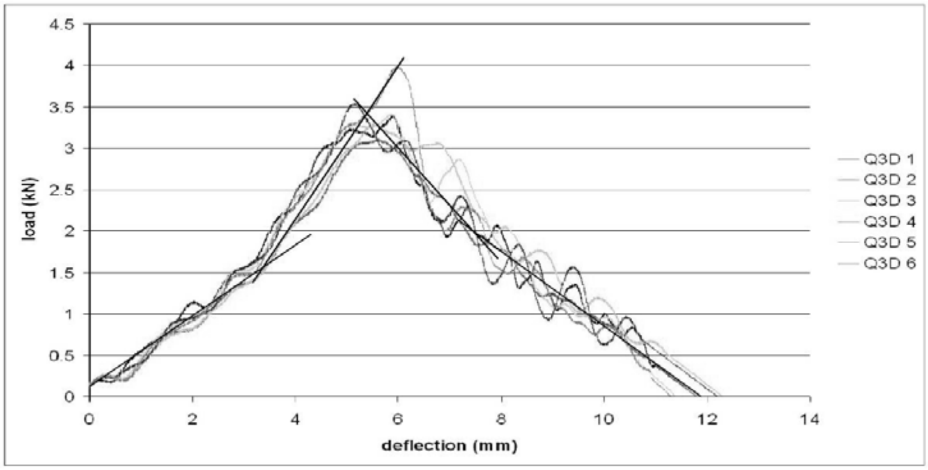

Figure 10. Load-deflection curves for Q3D specimen impact tests.

From the plots of L, 2D and Q3D weaves shown in Figures 8, 9 and 10, respectively, it is seen that the load values increase along the ascending portion until peak load is reached. At this point, the load begins to drop at a significant rate immediately. In the case of the Q3DO3 and Q3DO5 samples shown in Figures 11 and 12, respectively, there is a difference. It can be seen from the trend lines that the load holds at a high value for some period around peak load before significant reduction occurs. This 'plateau' region is circled in the figures. The deflection over which this plateau load is held is higher for the five-harness Q3DO5 samples (2.5mm) than for the three-harness Q3DO3 samples (1mm).

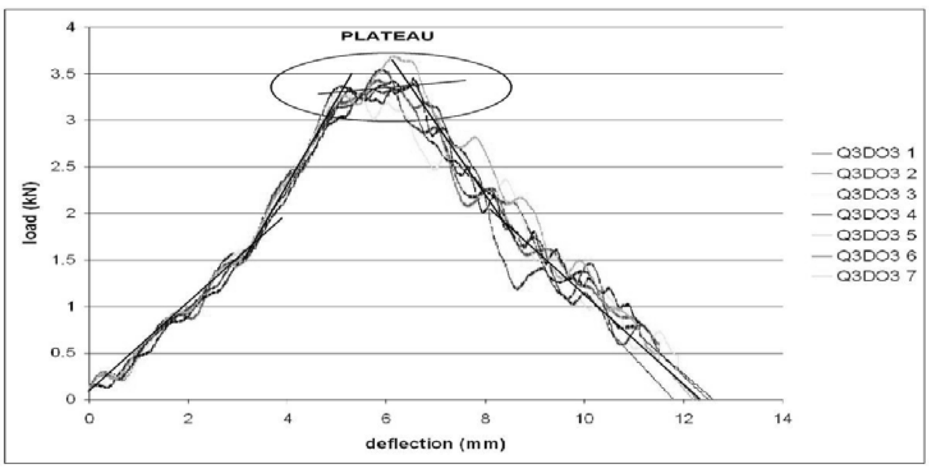

Figure 11. Load-deflection curves for Q3DO3 specimen impact tests.

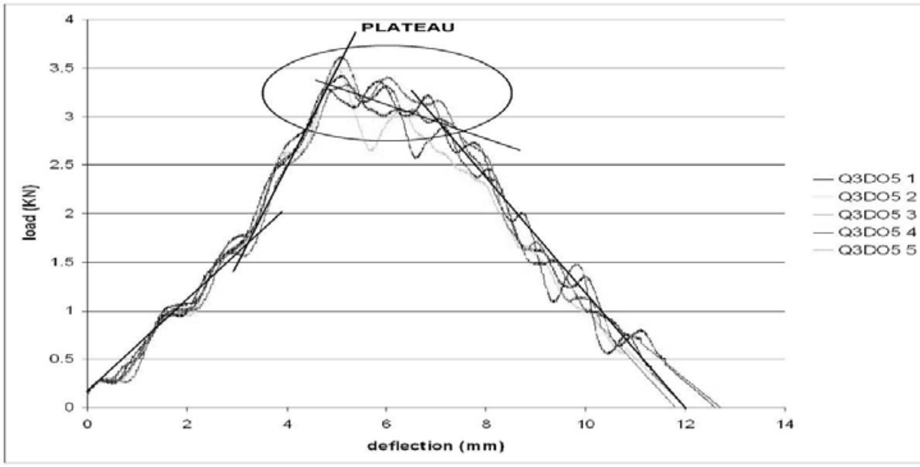

Figure 12. Load-deflection curves for Q3DO5 specimen impact tests.

From the above sets of graphs, one representative plot which best represents each batch (the plot which is most averaged within the group for all sections of the curve), are used to make the comparison plot shown in 13. This is used to contrast the differences between the load-deflection curves of the different sample types as previously explained.

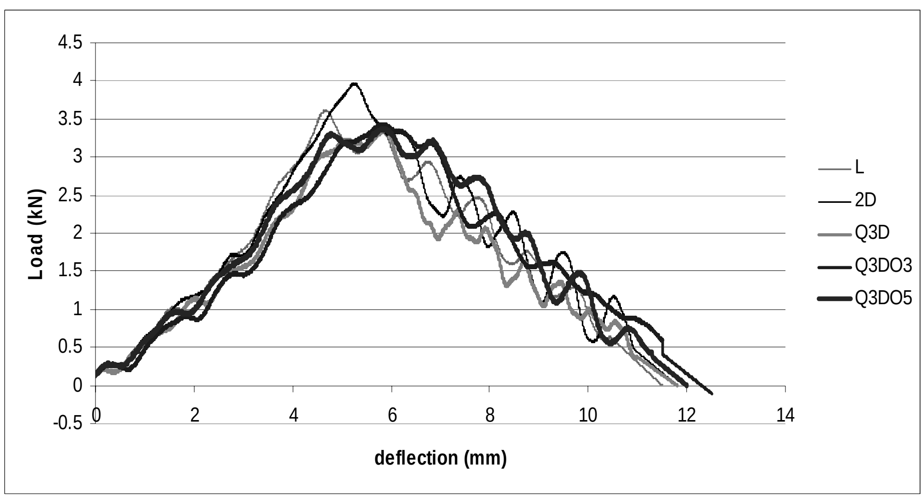

Figure 13. Comparison load-deflection curves.

Impact Characteristics

From the above sets of load-deflection curves, several quantities representing the characteristics of the impact properties of the composites, including stiffness (slope 1 and slope 2), maximum load, maximum deflection, primary damage, secondary damage, absorbed energy, and specific absorbed energy, were measured. Average values of these measured quantities for each group, along with percentage deviations are presented in Table 1.

TABLE 1. IMPACT CHARACTERISTICS

Sample Group	**Thick. mm**	**Absorb. Energy J**	**Max. Load kN**	**Max. Defl. mm**	**Slope 1 kN/mm**	**Slope 2 kN/mm**	**Primary Damage Area mm^2**	**Second. Damage Area mm^2**	**Specific Energy Absorp. mJ/mm^2**
L	2.0	20.62	3.5	11.9	0.56	0.97	157 ±5%	718	8.5 ±8%
2D	2.1	20.10	3.6	11.7	0.52	0.90	158	250	9.6 ±14%
Q3D	2.0	18.24	3.4	11.8	0.46	0.87	134 ±8%	280 ±4%	10.4 ±7%
Q3DO3	2.0	20.71	3.5	12.3	0.57	0.82	128	399	11.4 ±8%
Q3DO5	2.0	20.91	3.5	12.2	0.52	0.86	125 ±4%	428	11.6 ±6%

SUMMARY

Thin samples of 2mm of laminated (L), two-dimensional woven (2D), 2-harness quasi-three-dimensioanl (Q3D), 3-harness quasi-three-dimensional (Q3DO3) and 5-harness quasi-three-dimensioanl (Q3DO5) configurations were prepared by hand weaving and cured at elevated temperatures. Impact tests along with high speed photography were performed on these specimens to measure impact energy, bending stiffness and study damage behavior. Through thickness damage (primary damage) and rear layer surface-damage (secondary damage) were measured using a light table. From these values, specific energy absorption (SEA) was calculated. The following conclusions can be reached:

a. Three harness Q3DO3 and five harness Q3DO5 configurations could match up to energy absorption capabilities of conventional L and 2D configurations for thin specimens due to fiber straining.

b. Q3D weaves showed improved damage and delamination control over conventional configurations. Their primary damage areas in all cases were lower than those of conventional weaves. Compression tests showed the ability of the Q3D weave to contain damage within one unit cell.

c. Accounting for both energy absorption and damage area, specific energy absorption (SEA) was higher for all Q3D weaves as compared to conventional weaves.

d. All Quasi-3D weaves showed a lower percentage loss in strength due to impact damage than conventional weaves in compression tests. This demonstrates higher damage control and higher residual strength after impact.

e. Low harness Q3D weaves (Q3D and Q3DO3) showed favorable yielding kind of bending failure in compression instead of catastrophic shear as seen in other specimens. This kind of failure mode warns of impending failure and retains some strength even after the first breach in structural integrity. This may prove useful in practice as it allows for timely repair.

f. Q3DO5 was found to be the most favorable configuration as it matched the compressive and bending stiffness of conventional 2D weave, showed the highest energy absorption, highest specific energy absorption, low primary damage area and low percentage loss in load bearing ability after impact as compared with the other configurations. This would also be the easiest of the Q3D weaves to produce due to less frequent interlocking of fibers.

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