DAMAGE TOLERANCE ENHANCEMENT USING CONTINUOUS FIBER REINFORCEMENTS CO-MOLDED WITH LONG FIBER REINFORCED THERMOPLASTICS

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Abstract

An important advantage when designing with fiber filled composites is the ability to incorporate ribs and bosses directly into the part. Rib or grid stiffened polymer matrix composites are featured in automobile, marine, transportation and aircraft applications in recent years due to their high impact and fatigue resistance, high strength and stiffness to weight ratios and damage tolerance. An innovative method of incorporating ribbed features in molded parts is using unidirectional tapes that are co-molded with a skin. This work focuses on enhancing the damage tolerance of co-molded Long Fiber Thermoplastics (LFTs) with pre-consolidated sections of continuous reinforced thermoplastics tapes.

Introduction

Thermoplastic matrix composites are receiving increasing interest in recent years due to several advantages including high volume process ability, recyclability, superior damage tolerance, fracture toughness, and ability to produce complex shapes (1). Among thermoplastic composites, Long Fiber Thermoplastics (LFTs) are finding increased use in the automotive and transportation sector due to their superior specific strength and modulus resulting in substantial weight savings, combined with relative ease of fabrication and handling (2). Rib or grid stiffened polymer matrix composites are incorporated into design to increase the structural rigidity, torsion resistance and the overall stiffness of the molded part without increase in the thickness of the molded part (3, 4). However, in typical LFT processing by extrusion-compression molding, the ribs can pose complexity in terms of fiber flow into ribs and cavities. The addition of rib creates a relatively thick region at the intersection of the rib with the primary wall. Thick region can cause sink marks at the part surface, which is a result of polymer shrinkage during solidification (5).

In the present work, an approach of co-molding LFTs with pre-consolidated continuous reinforced unidirectional tapes has been adopted (6). The LFTs provide good design freedom, and enable low cost mass production of complex structural lightweight parts such as side doors, underbody panels, and front end bumper modules in automotive applications. The continuous reinforcements replace the rib structures and provide excellent mechanical characteristics and can be inserted three dimensionally.

Methodology

25 mm (1") long E-glass /Polypropylene (E-glass/PP) LFT (40% by weight fiber w/w) pellets and S2-glass/Polypropylene (S2-glass/PP) continuous tape material (70% by weight fiber w/w) were used to produce the E-LFT composite. While studies are also underway with E-glass/PP tape, the present paper reports the use of S2-glass/PP continuous tape. S2-glass possesses higher mechanical properties than E-glass and the rationale for using S2-glass for the continuous tape was to enhance the damage tolerance and load bearing, yet maintaining an overall low thickness profile. Adequate interface bonding between the LFT substrate and the pre-consolidated continuous unidirectional tape is important for effective load transfer in case of the E-LFT composite. The interface bonding is a function of several variables including constituent weight fraction of the LFT substrate and the tapes, type of matrix for both, initial thickness of the tapes, and processing conditions (tool temperature, LFT charge temperature, pre-heating of the tapes, tonnage pressure for consolidation) to name a few. The current work has been carried out in two stages explained below; the second stage depending on the outcome of the first.

Effect of Tape Thickness on Flexural Properties of E-LFT:

The first part of the study focuses on the effect of initial thickness of the tape on the final mechanical properties of the E-LFT. To effectively process E-LFT, the pre-consolidated tapes have to be pre-heated before co-molding with LFT's. Initial trials revealed that the tapes tend to displace (fiber wash effect) when pre-heated to an excess temperature, or debond at the LFT substrate-tape interface when pre-heated to less than optimal temperature. The processing conditions were optimized by various trials to obtain E-LFT with minimal fiber wash and adequate interface bonding to the LFT substrate. The thickness of the tape was varied from 1.50, 2.00 and 2.50 mm while maintaining the width of the tape to be constant at 12.75 mm. Three point flexural tests (ASTM D-790) were performed. The E-LFT with the optimized mechanical properties with respect to thickness was used to for the second stage of the work.

Performance Evaluation Between E-LFT and LFT with and without Ribs:

The E-LFT with the optimized mechanical properties obtained from first stage was used in the second stage work. Four sets of specimens were examined for static properties. These specimen types are summarized in Table 1. The physical dimensions of the specimens and corresponding flexural rigidity are listed in the Table. The four specimen types are shown in Figure 1.

Table 1. Dimension of various specimens examined for flexural properties

Specimen	Physical Dimensions		Specimen Width (mm)	Flexural Rigidity (N mm^2)
	Rib / Tape Height (mm) x Width (mm)	Skin Thickness (mm)		
A (LFT Rib - 1*)	6.35 x 6.35	5.00	25.40	$1.01*10^7$
B (LFT Rib - 2*)	3.00 x 3.00	5.00	25.40	$2.96*10^6$
C (LFT - No Ribs**)	N/A	5.75	25.40	$2.93*10^6$
D (E-LFT***)	2.00 x 12.70	5.00	25.40	$3.29*10^6$

* height and width correspond to the rib dimensions

** regular rectangular beam without ribs

*** height and width correspond to the pre-consolidated tape dimensions

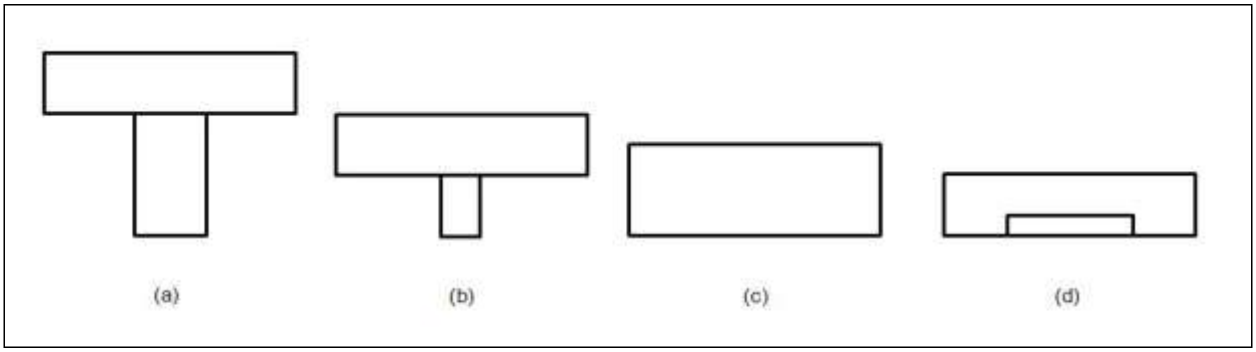

Figure 1: Schematic of the cross section of various specimens (a) & (b) LFT with varying rib dimensions, (c) LFT without ribs and (d) E-LFT with unidirectional pre-consolidated tapes.

The specimens (a), (b), (c) and (d) of Figure 1 are referred to as A, B, C and D from this point on in the manuscript. Three point flexural tests were performed according to ASTM D-790 to compare the static properties. The flexural rigidity (EI) for B, C and D was kept as close to each other as possible in order to compare the flexural properties described in Section 4.2. The specimen type A has the same skin dimensions as that of B except that the rib dimensions were twice that of B. The specimen A was considered to investigate the effect of increasing rib dimensions on the flexural properties. Effect of constant span to depth ratio and constant span length was also examined.

Processing of LFT With / Without Ribs and E-LFT

Processing of LFT Ribbed and Flat LFT Specimens:

The LFT specimens were fabricated by the extrusion-compression molding process. A steel tool of 266.7 x 304.8 mm with engraved ribs of dimensions of 6.35 x 6.35 mm was used to fabricate the LFT ribbed specimens. The tool was mounted on a hydraulic press equipped with heated platens and a plasticator was used to extrude the LFT molten charge. The tool was preheated to a temperature of 120 - 130 oC and the LFT molten charge was extruded at 235 ^{o}C. The amount of fiber filled polymer charge (charge length) was adjusted to fill the mold completely and results in a skin thickness of approximately 5 mm. Some of the A specimens were machined (mechanically milled) to obtain specimens B of smaller rib dimensions of 3.00 x 3.00 mm. For type C a steel tool of 304.8 x 304.8 mm without any ribs was used for processing. The processing parameters were maintained same except for the charge length. The approximate thickness of flat specimens was 5.75 mm.

Processing of E-LFT with Unidirectional Pre-Consolidated Tapes:

The E-LFT specimens were processed in two steps. The first step involves fabrication of consolidated unidirectional S2-glass/PP by compression molding. S2-glass/PP Polystrand® with fiber weight fraction of 80% (w/w), 304.8 mm wide, were film stacked with alternate layers of neat PP film to reduce the fiber weight fraction to 70% (w/w). The neat PP films and S2-glass/PP were cut to dimensions (304.8 x 304.8 mm) stacked in a closed tool. Pressure of 10 metric tons and temperature (165 ^{o}C) was applied to consolidate the laminates. Unidirectional consolidated strips of width 12.70 mm were cut with a tile saw. The fiber weight fractions in the consolidated unidirectional tapes were obtained by burn-off and measured to be 70% by weight of fiber. The second step involves the co-molding of pre-consolidated unidirectional sections with LFT. The 12.70 mm unidirectional strips were carefully placed in a pre-heated tool maintained at 120 - 130 ^{o}C for approximately 10 minutes. Six strips were used in each trial. The molten charge was then extruded and carefully placed inside the tool and a pressure of 20 metric tons was applied to co-mold the LFT with the unidirectional tape sections.

Results and Discussion

Comparison of Flexural Results for Different Tape Thickness:

As mentioned above the effect of pre-consolidated tape thickness on E-LFT was examined by three point flexural test. Three different tape thicknesses 1.50, 2.00 and 2.50 mm was examined. The overall thickness of all the E-LFT specimens (i.e. tape + LFT) was 5.00 mm. Three specimens in each of the thicknesses were tested. Figure 2 compares the flexural stress versus displacement. Results show that the stiffness of the specimen increases with tape thickness while the specimen with 2.00 mm thick tape exhibited the maximum flexural stress (142.99 MPa). The stress versus displacement plot shows that there is an initial load drop followed by a gradual increase in load. The results of the flexural tests are summarized in Table 2. For the case of specimen with 1.50 mm, the stiffness provided by the tape to the specimen is comparatively lower than the rest, and thereby forcing the substrate to bend more. The specimen not only fails at lower load but with higher displacement. Therefore the second stage of load increase happens at much higher displacement, leading to possible debonding of the tape from the substrate on the specimen edges. In the case of higher tape thickness of 2.50 mm, it is evident from the Figure 4 that although the initial stiffness is higher, the tapes tend to debond from the substrate at much lower load. As all the specimens were processed at the same condition, it appears that the not enough bonding was achieved with the current processing condition. It is clear from the results that E-LFT with a tape thickness of 2.00 mm had the maximum flexural stress, with minimum percentage load drop and maximum recovery after initial drop in load. Based on the above results, for performance evaluation studies E-LFT with tape thickness of 2.00 mm is considered.

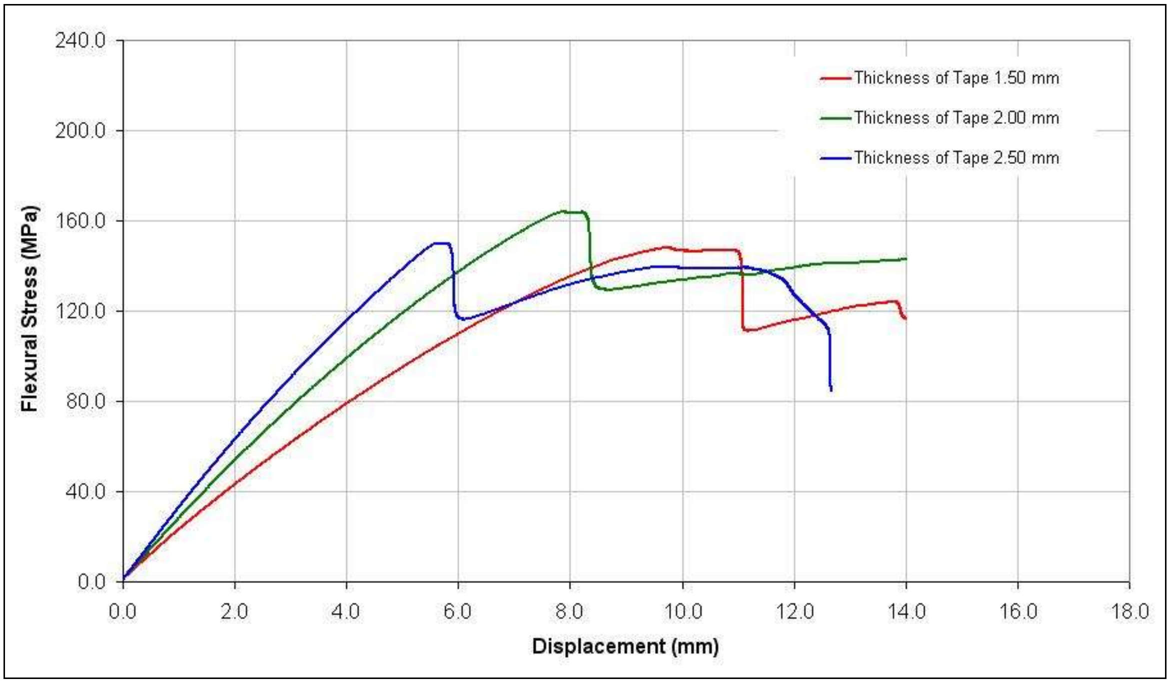

Figure 2: Comparison of flexural stress versus displacement for E-LFT with varying tape thickness.

Table 2. Comparison of flexural properties of ELFT with varying tape thickness

Tape Thickness (mm)	Flexural Stress (MPa)	First Max Stress (MPa)	Percentage Drop (%)	Percentage Recovered (%)	Second Max Stress (MPa)
1.50	147.88	148.12	24.95	65.15	124.04
2.00	160.36	163.83	21.03	60.48	142.99
2.50	151.37	149.76	22.38	29.89	139.74

Comparison of Mechanical Properties Between LFT with / without Ribs and E-LFT:

As stated earlier, specimen types B, C and D had comparable flexural rigidity. The effect of rib dimensions (at constant skin thickness) on the mechanical properties was examined with specimens A and B. The effect of maintaining a fixed span to depth ratio (aspect ratio of 16) and constant span length (span length of 128 mm) was also examined.

Comparison of Flexural Properties at Constant Span to Depth Ratio:

Since all the specimens are of different thicknesses, flexural properties were determined at constant span to depth ratio. Except for specimen A all other specimens were tested at span to depth ratio of 16. For the case of specimen type A, (skin depth + rib depth = 11.35 mm) the aspect ratio was limited by maximum allowable span on the fixture used for testing. Hence the A type specimens were tested at maximum allowable span length on the fixture, and the corresponding allowable span to depth ratio was 13.16. The average aspect ratio, flexural stress and displacement at peak stress are summarized in Table 3. The percentage increase in stress and displacement has been calculated with specimen B as the standard. Figure 3 compares the flexural stress versus displacement at constant span to depth ratio. The results indicate that except for the D specimens, all the other types exhibit brittle failure (drop in load at initiation of a crack) at a lower flexural stress. Due to the stress concentration on the tension side, specimens A, B, and C failed at lower load levels. For specimen D, since the unidirectional tapes were on the tension side, these specimens were able to withstand higher loads. The initial drop in load for specimen D indicates that there was momentary debonding of the tape and LFT at point of loading. Once the LFT substrate made contact with the tape, the load from the substrate was transferred to the tape, enabling the specimens to withstand the loading and subsequently showed an increase in stress levels. There was no visual evidence of failure of unidirectional tapes (externally on the tension side) for the specimens tested for specimen D, while cracks were could be noticed through the thickness on the LFT substrate.

Table 3. Comparison of flexural properties at constant span to depth ratio (aspect ratio)

Specimen	Aspect Ratio	Flex Stress (MPa)	Max Displacement (mm)	Percentage Increase Stress	Percentage Increase Displacement
A	13.16	117.31	7.59	65.83	44.85
B	16.00	70.74	5.24	0.00	0.00
C	16.00	99.15	9.63	40.16	83.78
D	16.00	160.36	7.82	126.69	49.24

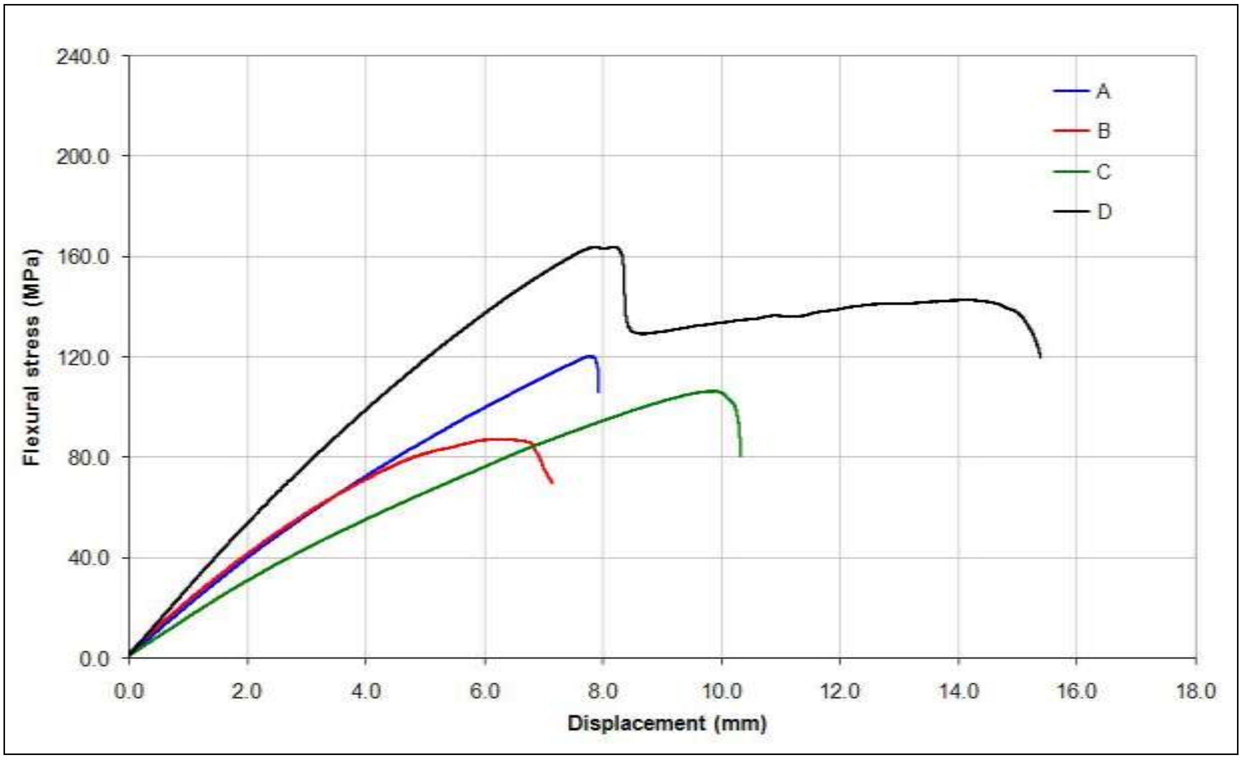

Figure 3: Comparison of flexural stress versus displacement for constant span to depth ratio of 16.

Comparison of Dynamic Properties Between LFT with / without Ribs and E-LFT:

Samples were tested for low velocity impact resistance using an instrumented drop weight test. The impactor (tup and mass) was dropped from a height of 40 cms to achieve an impacting energy of 25 J. The tup diameter was 19.2 mm and total impact mass used including tup was 3.37 kg. The average size of the samples was 140 mm x 140 mm. For the case of ribbed and tape stiffened samples, the samples were impacted at the impacted in the center of two ribs and tapes respectively. Load and energy as a function of time were recorded and compared for all the samples.

It was observed that the damage due to impact were localized for all the samples, hence the load data obtained were normalized with respect to the overall thickness of the sample. Figure 4 compares the normalized load vs. time data obtained for a drop height of 40 cms. It can be observed that tape stiffened sample D exhibits the maximum load with highest energy absorption. On impact the samples tend to deflect more which aids to the final energy absorption. Table 4 summarizes the dynamic results obtained for all the samples.

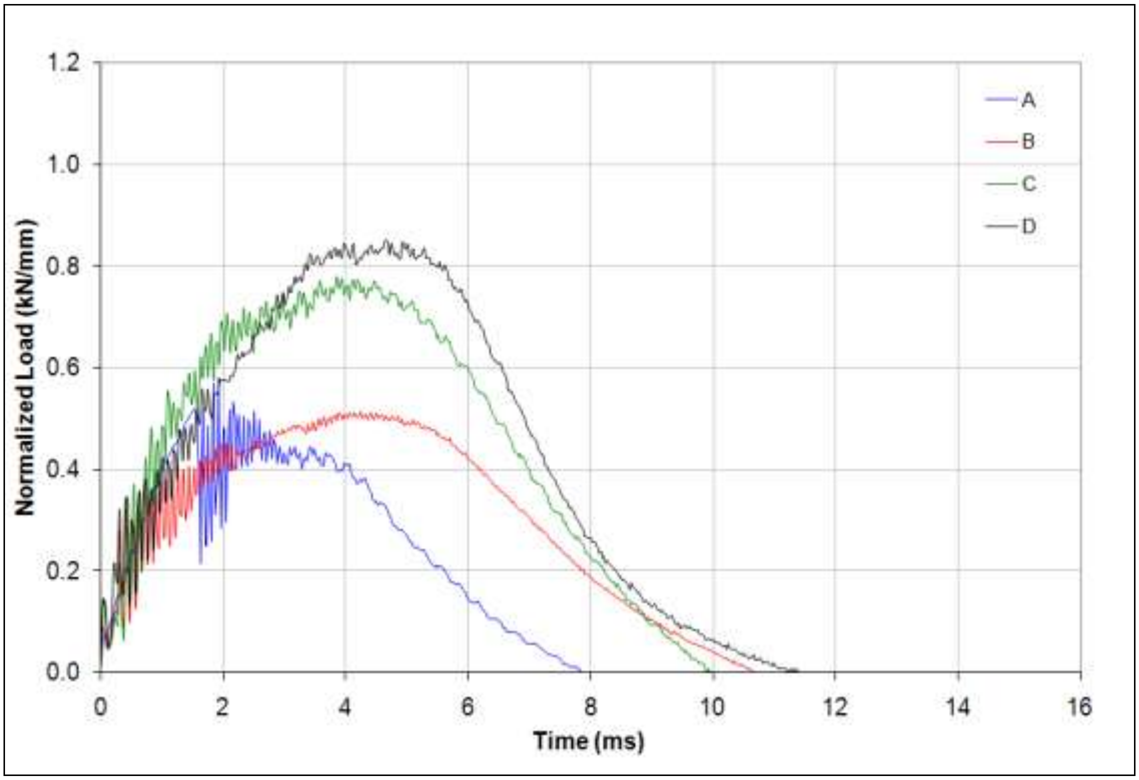

Figure 4: Comparison of normalized load versus time for drop height of 40 cms.

Table 4. Comparison of low velocity impact properties at constant drop height of 40 cms and impact energy of 25 J

Sample	Height (cm)	Impact Energy (J)	Energy$_{Max\ Load}$ (J)	Normalized Max Load (kN/mm)	Time$_{Max\ Load}$ (msec)	Deflection$_{Max\ Load}$ (mm)
A	40	25.01	16.24	0.58	1.93	4.71
B	40	24.49	23.44	0.51	4.25	8.33
C	40	24.62	22.61	0.78	3.86	8.02
D	40	24.58	23.74	0.85	4.66	9.35

Summary

Long fiber thermoplastics can be successfully co-molded with continuous unidirectional tapes without major changes in processing methodology. E-LFT specimens have enhanced flexural properties compared to LFTs with and without ribs for equivalent flexural rigidity. The mode of failure in static loading is more ductile as opposed to a brittle failure that is exhibited in regular LFT specimens. E-LFT specimens show a second stage of increase in load after the initial failure, a unique distinct phenomenon true only in E-LFT. Both maximum flexural stress and displacement of E-LFT specimens are higher than all the LFT specimens. Future studies are ongoing for investigating the impact response of the LFTs and comparison to E-LFTs

References

[1] U. K. Vaidya and S. Pillay, "Cost-effective structural thermoplastic composites for automotive and transportation", Soc. for the Advancement of Material and Process Engineering, Baltimore, MD, United States, (2007).

[2] Häuptli A. and Winski J., "Direct processing of long fibre reinforced thermoplastics: selecting a feeding system", Plastics, Additives and Compounding, 5, 5, 36-39, (2003).

[3] H.-J. Chen and S. W. Tsai, "Analysis and optimum design of composite grid structures", Journal of Composite Materials, 30, 4, 503-534, (1996).

[4] P. Jadhav, M. P. Raju and R. F. Gibson, "Energy absorption and damage evaluation of grid stiffened composite panels under transverse loading", Composites Part B: Engineering, 37, 2-3, 191-199, (2006).

[5] B. Davis, P. Gramann, T. Osswald and A. Rios, "Compression Molding", Hasner Publishers, Cincinnati, Ohio, USA, (2003).

[6] A. Ruegg, N. Stotzner, D. Jaggi and S. Ziegler, "A new mass production process for lightweight structural parts and their application-field", Annual Technical Conference - ANTEC, Conference Proceedings, Chicago, IL., United States, (2004).