Enhancement of Composite Performance by Hollow Polyester Fibers

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***Abstract*—The effects of hollow glass fibers (HGF) on tensile and compression strength and bulk properties of polymeric composites have been studied. In this research, the improvement of impact behavior of composites using hollow polyester fibers is investigated. The damage tolerance of composites reinforced by unidirectional hollow ductile fibers is compared with solid fibers reinforced composites under drop weight impact tests. It is found that hollow fibers composites despite the lower modulus in comparison to solid ones are more impact resistant. It is also found that the force at the crack initiation of composites composed of hollow fibers is 9.5% higher than the other one. It is notable that the damage tolerance is increased to 71% in the hollow fiber specimens.**

Key words: Hollow fiber, composite, crack initiation, impact behavior, absorbed energy

I. INTRODUCTION

The hollow structure of hollow glass fibers (HGFs) is responsible for significant improvement in dielectric, thermo-insulating, acoustic insulation and some mechanical properties in comparison to standard solid glass fibers in composite materials. The first investigation on hollow fibers was conducted by Rosen *et. al* [1] to evaluate the improvement in bulk properties obtained by utilizing HGF as the reinforcing material for polymeric composites. Various experiments were designed to compare the mechanical properties of hollow fiber reinforced plastics with solid fiber ones. A considerable improvement in specific longitudinal compressive strength was observed in hollow fiber specimens compared with solid ones. The most disappointing result for early HGF composites was the very low transverse compression strength which caused failure in the testing machine grips for tensile tests. Therefore, it was concluded by Rosen and Dow [2] that HGF is useful only for shell buckling applications for which material density is of prime importance, as for monocoque construction. Results in the case of longitudinal compression were confirmed in the recent work where techniques have been developed to produce HGFs in the range of different outside and inside diameters [3]. The specific compression strength of HGF composite specimens reached to its maximum level at the fiber hollowness fraction of 22%.

In another attempt to improve the mechanical properties of composite materials, it was theoretically and experimentally shown that HGF laminates have a flexural rigidity considerably higher than solid ones [4]. This was achieved by fabricating the composite specimens with the same mass per unit length for proper evaluation. Thus, the thickness and accordingly the cross-section second moment of area was increased for samples containing hollow fibers. It was also stated in another study on the flexural rigidity of HGF composites that the micro-honeycomb structure made from hollow hexagonal glass filaments has a higher rigidity-to-weight compared to the solid fiber composite [5].

Boniface and his colleagues [6] expressed that although there is no improvement in the compression and tensile modulus/strength of composites containing hollow glass fibres in comparison to composites with solid ones, the compression strength is 20% higher than solid fiber reinforced samples after impact test.

HGFs have been also used in an investigation to reduce the real component of permittivity of hybrid composites based on high dielectric Nicalon fibers. It was derived from the test results that HGF/Nicalon hybrid composites do offer potential advantages for structural applications where microwave transparency and high stiffness are both required [7].

In a series of studies done at Bristol University, resin filled by HGF was used as a material to store healing components. The flexural and compression results from impact tests on laminates showed that a significant fraction of lost strength can be restored by the self-repairing effect of the repair agent stored within hollow fibers [8-10].

Similar study has been done on carbon fiber reinforced composite. The hollow glass fibers containing self-healing materials were applied through the free space between carbon fibers in the composite. Results showed that the flexural strength decreased only 3% after impact test compared to its strength before the test [11].

However, it is seen that hollow fibers could not obtain the researchers attention to do a comprehensive study on HGFs composites. The few researches on hollow fibers have been only concentrated on glass fibers as well. As

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mentioned above, HGFs have considerably improved the compression strength of composite in fibers direction, but they have not shown appropriate performance in other properties specially impact behavior.
In the present study, the impact behavior of hollow and solid fully-drawn polyester fiber reinforced composites is compared as an important mechanical property of composite materials. In general, the main difference between polyester and glass fibers can be attributed to the degree of polyester fibers ductility which is higher than glass fibers [12]. This kind of ductile fibers can overcome the problem of localized breakage of glass fibers through transverse compression and impact. The ductility of polyester fibers can help composites to be deflected easily with less damage when encountering impact events. The local elastic and plastic deformation of hollow fiber composite causes the energy of a striker to be absorbed with minimum damage.

II. EXPERIMENTAL

A. *Materials*

Yarns used for the experimental work were composed of 72 fully-drawn hollow and solid polyester circular filaments with equal outside diameter and different linear density. In comparative researches on hollow and solid fiber composites, two methods for fiber selection were suggested. In the first method, which is demonstrated in Figure (1-a), fibers with different outside diameters and same mass per unit length (denier) were implemented. Therefore, in order to achieve an identical fiber volume fraction at a constant composite cross-section area, the number of required solid fibers was more than hollow ones since the overall cross-section area of a solid filament was less than a hollow filament. This method was not used in this study since the accurate control and reproducibility of specimens is technically difficult. In addition, the overall fiber-matrix interface area, which affected the mechanical properties of composites, varied due to the dissimilar number and dimension of filaments.

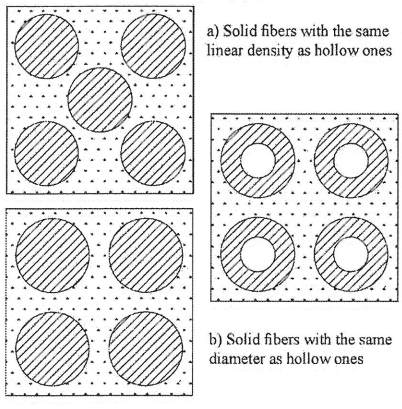

Fig. 1. Cross-section of hollow fiber composite in comparison with a) Solid fibers with same linear density, and b) Solid fibers with same diameter.

In the alternative technique (Figure 1-b), which was used in this investigation, fibers with the same outside diameters were used. Therefore, the effect of hollow canals on composite impact behavior was observed directly and independently.

Some physical and mechanical properties of the utilized yarns and filaments are calculated and listed in Table I.

The solvent-free epoxy resin (polypox VE 01416/5) with the viscosity of 3350 mPa.s was employed as the matrix.

TABLE I
PHYSICAL AND MECHANICAL PROPERTIES OF YARNS AND FILAMENTS

Material	Linear density (denier)	Effective cross-section area (μm^2)	Elastic modulus (Gpa)	Fiber outside diameter (μm)	Hollow section diameter (μm)
Hollow filaments	256.3	20417.94	4.6	20.5	7.72
Solid filaments	298.6	23771.52	4.6	20.5	-

B. *Composite Fabrication*

In an attempt to fabricate composite test specimens uniformly, the strand of fibers was unidirectionally wound over a ten-centimeter diameter mandrel after impregnation in a resin bath on an industrial filament winding device. Once the mandrel was completely covered to the desired thickness, the mandrel was placed in an oven for one hour at 60°C temperature to cure the resin. Eventually, three cylindrical tubes with 4.5 mm in wall thickness made up of solid and hollow fibers and their hybrid were pulled out of the mandrels.

The composite cylinders were cut to 2 cm width rings by a fine band saw appropriate for cutting plastics. Each ring was then, cut into four equal convex pieces in order to prepare proper samples for three-point bending impact test. The specimens were preserved in an incubator at the normal condition to avoid undesired changes in humidity and temperature.

C. *Experimental Details*

Instron Dynatup 8250 drop-weight impact machine which is shown in Figure 2 was employed to perform the low-energy/low-velocity impact test on the simply supported specimens.

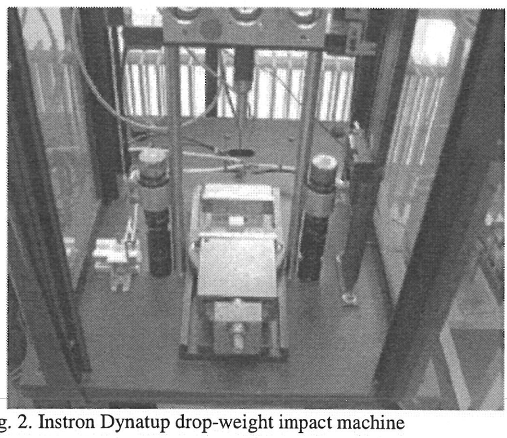

Fig. 2. Instron Dynatup drop-weight impact machine

The schematic representation of the impact test set-up is illustrated in Figure 3.

For each composite sample, eight specimens reinforced by solid, hollow and hybrid fibers were subjected to impact test by a cylindrical head striker in 5 mm radius. The striker was dropped from five different heights with the same weight (2655 gr) to achieve different impact energies.

The contact force during impact test was measured with a 5 kN Kistler force cell (9001A) located on the falling tup and recorded with a Yokogawa DL 1540 digital oscilloscope. The displacement of the head was measured using a Meter Drive ZAM 301 AAS linear encoder with the resolution of 0.1 mm. The support-to-support span was 60 mm in width.

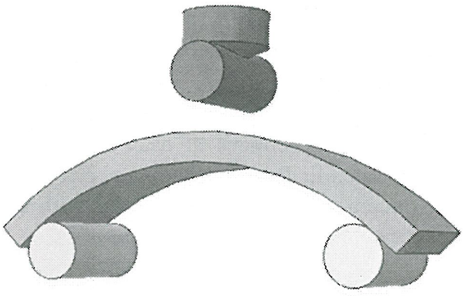

Fig. 3. Schematic representation of three point bending impact set-up.

III. Results and Discussion

A. Composite Fabrication

Table II shows some features of three different fabricated composites. It should be noted that all samples were prepared with the same fiber volume fraction ratio (v_f) of 71±2%. The total area of hollow channels in hollow and hybrid samples was taken into account in the fiber volume fraction. The hollow spaces cause 9% and 4.6% reduction in the specific gravity of hollow and hybrid fiber samples, respectively.

B. Impact Tests

The impact effect on all damaged samples was in the form of a crack through the thickness (Figure 4-a) and along the fiber direction being easily detected by a stereo microscope at its bottom surface (Figure 4-b).

It was observed that the crack was initiated from the point at its distal side opposite to the projectile/specimen contact line (Figure 5). The crack propagated afterward along the fiber direction and through the sample thickness. It should be mentioned that the damage through thickness did not reach the contact line of the striker with the composite. Also, along fibers direction, the crack did not run the full length of the sample.

The microscopic image of the crack at the cross-section of the impacted specimens demonstrates that the most prevailing mode of failure is the interface failure in such composites (Figure 6).

Figure 7 shows the load-deflection curves of all three samples. The impact energy which represents the maximum energy transferred to a plate by the striker during the impact test was calculated from the surface area under load-deflection curves to the maximum deflection. The absorbed energy was obtained from the surface area enclosed in the load-deflection curves.

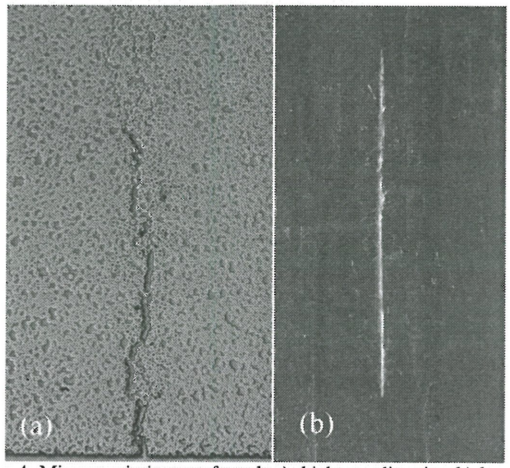

Fig. 4. Microscopic image of crack a) thickness direction b) longitudinal direction

Fig. 5. Schematic representation of crack position.

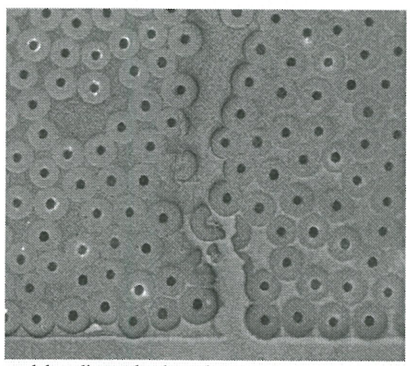

Fig. 6. Interface debonding at back surface of cracked hollow specimen.

TABLE II
SOME PHYSICAL AND GEOMETRICAL FEATURES OF COMPOSITES

Material	Ratio of hollow/solid	Density (g/cm^3)	Volume fraction (%)				Thickness (mm)
			Fiber	Hollow space	Resin	Void	
Hollow fibers composite	100/0	1.183	62.12	9.1	27.12	1.66	
Hybrid fibers composite	50/50	1.24	66.8	4.6	27.1	1.5	4.5
Solid fibers composite	0/100	1.3	71.36	0	27.03	1.61	

Results of impact test are presented in Table III.

The absorbed energy value of specimens under impact forces and before the crack initiation is a criterion to investigate composites characteristics.

Since all three sample types were fabricated with same fiber volume fraction, the empty canals deduced the weight of samples composed of hollow fibers. This would make it difficult to compare the results of solid, hollow and hybrid composites. As a basic principle, it can be declared that the best comparison is among specimens with an equal weight of fiber materials. Hence in this study, some mechanical properties of specimens were normalized by their densities.

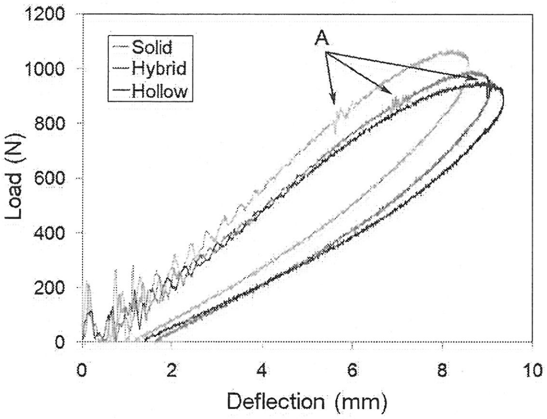

Fig. 7. Load-deflection profile of solid, hollow and hybrid cracked specimens.

TABLE III
RESULTS OF ABSORBED ENERGY OBTAINED FROM IMPACT TEST

Impact Energy (J)	Absorbed energy (J)			Specific absorbed energy (J/r*)		
	Hollow	Hybrid	Solid	Hollow	Hybrid	Solid
1.58	0.55	0.55	0.56	0.46	0.44	0.43
2.91	1.035	0.98	1.026	0.87	0.80	0.79
4.23	1.74	1.65	1.66	1.46	1.33	1.27
5.01	2.24	2.15	2.12	1.89	1.73	1.63
5.60	2.67	2.59	2.49	2.26	2.09	1.91

* r=density

Figure 8 demonstrates that the specific energy absorption in the hollow fiber samples is higher than the two others (The specific energy absorption is defined as the value of energy absorption which has been normalized by density).

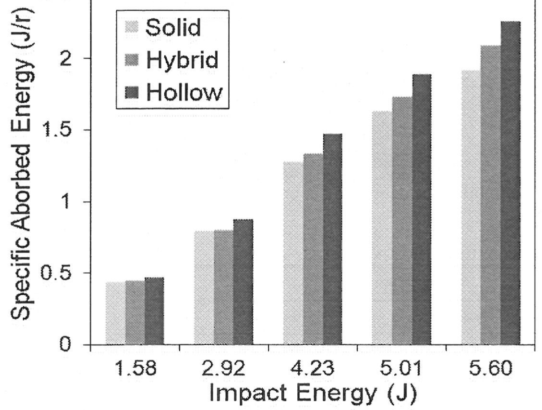

Fig. 8. Specific absorbed energy.

Findings of this study verify that the impact energy is initially absorbed by the elastic deformation prior to the energy value at which the crack is initiated. An abnormal fluctuation observed in the load-displacement profile of all cracked samples (Figure 7) is the evidence of crack initiation.

There is no considerable mutation in the trend after point (A) in Figure 7. This is due to the fact that the crack is perpendicular to the deflection direction and cannot play any momentous role in the bending behavior and consequently in the energy absorption process.

From the above discussions it can be concluded that the superiority of hollow fiber composites in energy absorption, which could be observed in Figure 8, is mainly due to the hollow fibers' slight elastic elliptical deformation which occurs in micro scale and led to energy dissipation in the form of heat.

Another criterion for comparison in this study is the number of damaged specimens at each level of impact energy. As illustrated in Table IV, the number of damaged specimens is increased for all three samples with increase in impact energy.

TABLE IV
PERCENTAGE OF DAMAGED SPECIMENS

Impact Energy (J)	Damaged Specimens (%)		
	Hollow	Hybrid	Solid
1.58	0	0	25
2.92	0	0	50
4.23	12.5	50	100
5.01	50	100	100
5.60	100	100	100

The most significant result that can be noted in Table IV is the different number of cracked specimens of composites composed of hollow, solid and hybrid fibers. It is found that a single crack is created in 50% of solid fiber composites at the impact energy of 2.91J, while this damage percentage was obtained at 4.2J and 5J for hybrid and hollow fibers composites, respectively. It means that, hollow fibers composites are more impact resistant in comparison to solid ones. The importance of this difference in the number of damaged specimens is because of the lower modulus of composites composed of hollow fibers compared to solid ones (Figures 8 and 9).

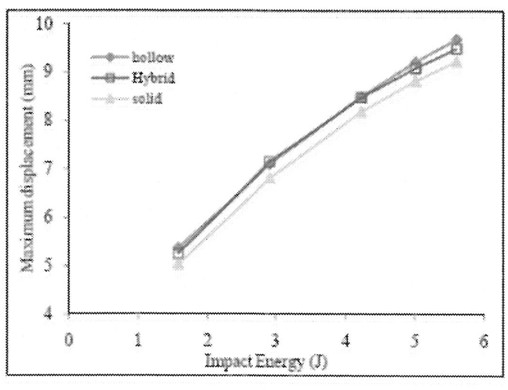

Fig. 9. Maximum deflection-impact energy curves for three different samples.

The important explanation for this phenomenon concerns the flexibility of hollow fibers. The cylindrical thermoplastic hollow fibers can be easily deformed to an elliptical shape. This ability leads to a decrease in stress concentration at the interface and consequently a decrease in the interface cracking which is the most prevailing mode of failure in this research.

Naturally, thermoplastic fibers are plastically deformed before fracture. It is believed that the deformation of thermoplastic fibers is the key factor to improve the energy absorption of composites [13]. This plastic deformation, which appears as compression at upper face and tension at lower face in both transversal and longitudinal directions, occurs more easily in the case of hollow fiber composites.

Results of maximum force and deflection of all samples are listed in Table V.

TABLE V
RESULTS OF MAXIMUM LOAD-DEFLECTION OF COMPOSITES UNDER IMPACT TEST

Impact Energy (J)	Maximum deflection (mm)			Maximum force (N)		
	Hollow	Hybrid	Solid	Hollow	Hybrid	Solid
1.58	5.4	5.3	5.0	603.9	609.4	644.55
2.91	7.2	7.2	6.8	786.5	785.2	839.1
4.23	8.5	8.5	8.2	908.8	940	982.4
5.01	9.2	9.1	8.8	972.4	1023.4	1067.6
5.60	9.7	9.5	9.2	1003.2	1062.51	1116.57

The higher slope of load-deflection curve and the higher value of maximum force for specimens containing solid fibers which is shown in Figure 10 prove the higher modulus and therefore flexural stiffness of these composites in comparison to hollow fibers composites.

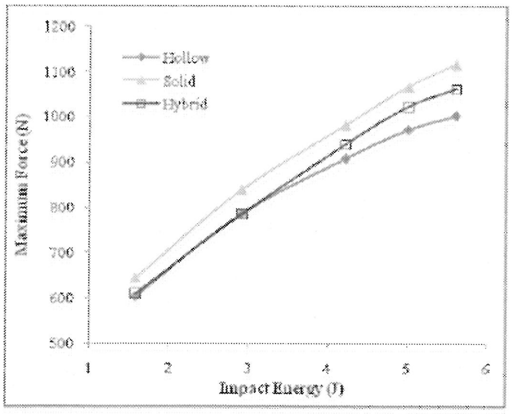

Fig. 10. Maximum force against impact energy curves.

According to Table VI, it seems that the force at the crack initiation can be assumed as a criterion for comparison of hollow fibers composites superiority in case of impact resistance.

TABLE VI
CRACK INITIATION FORCE OF COMPOSITES UNDER IMPACT TEST.

Impact Energy (J)	Force at the crack initiation (N)		
	Hollow	Hybrid	Solid
1.58	-	-	-
2.92	-	-	625.5
4.23	896	856	803
5.01	954	929.75	875.25
5.60	974.25	953.27	901.3

The average value of difference between the force at the crack initiation of composites composed of hollow and solid fibers was computed about 9.5% (see Figure 11).

IV. CONCLUSIONS

In the present study, hollow and solid ductile fibers were used to fabricate unidirectional convex composite laminates. The use of hollow fibers led to 9% reduction in the laminate density. The damage tolerance was dramatically increased (71%) in the hollow fiber specimens due to the decrease in the stress concentration at the interface.

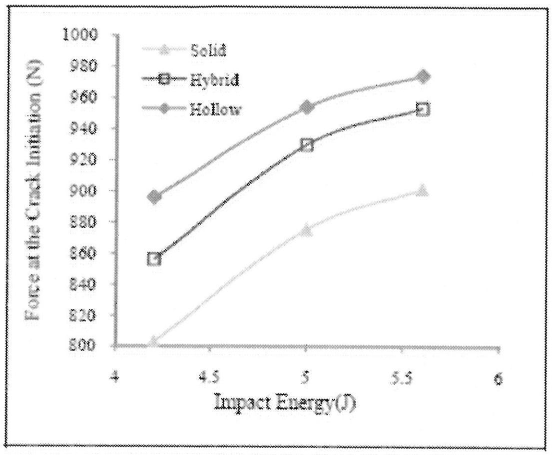

Fig. 11. Crack initiation force-impact energy curves of three composites samples.

Contrary to hollow glass fibers, which were crushed because of transverse compression, hollow polyester fibers were easily deformed without any damages owing to their ductile natures. Hollow polyester cylinders were deformed to elliptical shapes when they were subjected to the transverse compression at their contact sides with the striker and the transverse tension at their bottom surfaces. This ability makes hollow ductile fibers as an appropriate option for producing reinforced composite materials, especially for surface layers.

Acknowledgements

The authors would like to thank G. J. Nevenzel from Production Technology Group of the University of Twente for his help and J. H. M. Fliervoet the process specialist of Future Pipe Industries of Netherlands for providing composites specimens for the experimental phase.

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