A COMPARATIVE ANALYSIS OF HOLLOW AND SOLID GLASS FIBER REINFORCED COMPOSITES

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Abstract

Geometrical properties of hollow and solid glass fibers used for composite reinforcement have been compared as well as the possibility of filling the hollow fibers with fluids. Composite sheets were prepared from epoxy resin reinforced with hollow and solid glass fibers. Mechanical properties were compared by tensile, flexural, compression and Charpy impact tests. It has been observed that the specific strength (the strength divided by the density) was higher for hollow fiber reinforced systems than for solid fiber reinforced ones.

1 Introduction

Nowadays composites exhibit high importance due to their high strength and low density. They are used as structural materials in aerospace, wind energy, transport, sports etc. applications, where it is essential to move the possibly smallest mass in the possibly fastest manner. The failure of composites starts with crack initiation, then under the effect of repeating loads the cracks start to propagate, which is hardly visible by naked eye in the initial phase. The life of parts and products could be much longer if the crack propagation could be arrested already in the initial phase and the material could heal itself. Such self-healing can be realized by microcapsules [1-3], by a vascular system [4-7] or by hollow fibers [8-11]. In all three cases a healing liquid is stored within the material, the liquid container opens under the effect of cracks, the liquid flows to the damaged area thus restoring the continuity of the material. In the case of two component healing liquid it is possible to store one component in hollow fibers, the other one in microcapsules (Figure 1a), or in the case of one component the healing resin might cure in air (Figure 1b). The development of the best known hollow fiber method is attributed in the literature to Bond *et al.*, where in a part of the hollow fibers the resin is located while the hardener is present in another part of the hollow fibers, so if the liquid is released during cracking, the components are mixed and ensure the proper degree of crosslinking (Figure 1c) [12]. Bond and coworkers used repeatedly fibers filled with slowly curing premixed epoxy resin for self-healing to avoid the possibly incomplete mixing. The storage in hollow fibers has the advantage that in addition to the storage of a proper amount of healing liquid they exhibit also reinforcing effect. Production settings and the cross section of the hollow fibers also influence the mechanical properties. The smaller the wall thickness of the hollow fibers, the better the orientation of the molecular chains along the fiber direction during production [13].

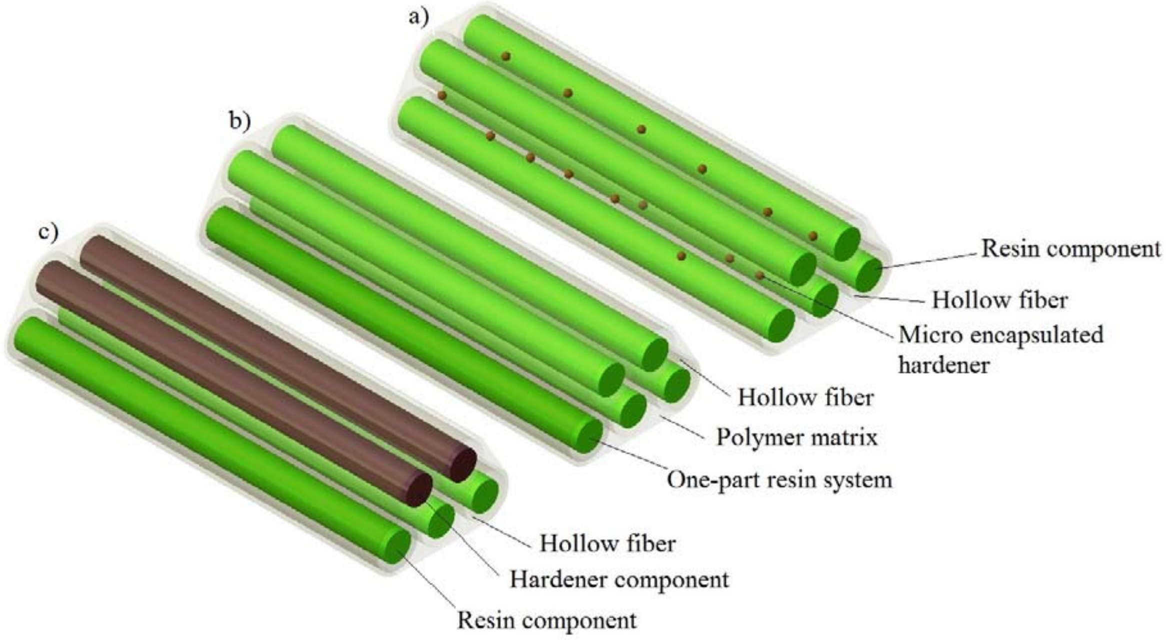

Figure 1. Realization possibilities of self-healing composites reinforced with hollow fibers (a) hollow fibers + microcapsules, (b) one component resin systems, (c) two component resin systems

Rosen *et al.* [14] drew hollow fibers and showed that the strength of the fibers decreases with increasing diameter, and increases with increasing hole volume. By compression studies on composite specimens it was established that the compression strength and elastic modulus of composites reinforced with hollow fibers is higher than those of composites reinforced with traditional fibers, provided that the fibers are parallel with the load. In the case of loads perpendicular to the fiber direction it was concluded that if the ratio of the internal and external diameter of the fibers (hole fraction) is increased above 0.5 the transversal compression strength of the specimens decreases as in these case the fibers fail and not the matrix.

Hucker *et al.* [15] studied the effect of production parameters on the mechanical properties of solid and hollow fibers. Glass preform products were plasticized for fiber production and fibers were drawn from them. The composition of the solid and hollow preform products was almost identical with a minor difference. The larger was the diameter of the fibers to be drawn the lower was the tensile strength of the fibers. The strength of the solid fibers decreased with drawing speed and increased with decreasing temperature.

The goal of this article is to show our preliminary results related to the filling possibilities of the hollow fibers using the capillarity principle. Mechanical properties and energy absorbing capabilities of composites reinforced with hollow and traditional fibers were compared in these preliminary tests.

2 Materials and test methods

2.1 Materials used and preparation of composite sheets

The solid fibers used for composite production were 3b Advantex$^{®}$ and the hollow fibers were the products of R&G Faserverbundwerkstoffe GmbH. Both fibers were made of E-glass, which were checked by inductively coupled optical emission spectrometry (ICP-OES) method. The matrix resin of the composites was Eporezit AH-12 T58 resin (Ipox Chemical).

The glass fibers were wound onto an aluminum plate then the fibers were impregnated by hand lamination. Composite sheets were post-cured at 80°C for 2 hours. The thickness of the sheets produced for the standard tests was1 mm for the tensile tests, while it was 3.5 mm for the solid fiber reinforced composites and 2.5 mm for the hollow fiber reinforced composites.

2.2 Microscopy

Fiber diameters were measured by an Olympus BX 51M optical microscope at 50x magnification with lower illumination. Micrographs were taken using a C-5060 CAMEDIA type digital camera, the fiber diameters were determined by an AnalySIS image analysis program. Studies on single fibers were made on fibers laid onto glass microscopic slides. Glass fiber bundles were embedded into resin and cross sectional surfaces were polished.

2.3 Ash content

One important property of composites is fiber content, as the mechanical properties are largely dependent on this parameter. The fiber content can be determined by ash content determination which was performed according to the EN ISO 3451 standard [16]. Based on the density (ρ) mass percentages were transformed into volume percentages from which the fiber content could be determined. As air is present in the central part of the hollow fibers, its density was calculated form the hole fraction.

2.4 Tensile test

Tensile strength and elastic moduli of the composites parallel with and perpendicularly to the fiber direction were determined by tensile tests. The tests were performed according to the EN ISO 527 standard [17] using a Zwick Z-050 universal tester. Samples of 15x250 mm size were cut from the composites and tabs were glued to their ends to avoid slippage from the clamp and the shear damage of the fibers.

2.5 Compression test

Based on the review of literature [14, 18, 19] the compression properties of the composite sheets were compared by the EN ISO 14126 standard test [20]. The test samples were compressed by a Zwick Z-050 universal tester at a speed of 1 mm/min. Long tabs were glued to the ends of the 110x10 mm specimens to keep the test length at a constant value of 10 mm.

2.6 Three point bending test

Three point bending tests were performed according to the EN ISO 14125 standard [21] on a Zwick Z-050 universal tester at a speed of 1 mm/min. The test specimens were of 15x60 mm size while the span length was 40 mm.

2.7 Charpy impact test

The tests were performed according to the recommendations of the EN ISO 179 standard [22] using a computerized Ceast Resil Impact Junior type pendulum impactor and 25 J hammer. Test data were collected by a DAS 800 equipment.

3. Results and discussion

3.1 Individual fiber tests

The diameter of both solid and hollow fibers was measured equidistantly at three points along their length. In the case of the hollow fibers, when focusing exactly to the half of the fiber diameter both the outer and inner diameters of the fibers were well discernible. In the case of the hollow fibers control tests were also performed on the polished cross sections of the fibers embedded into resins (Figure 2.), which could be compared with the results of the test method using laid fibers (Figure 3.).

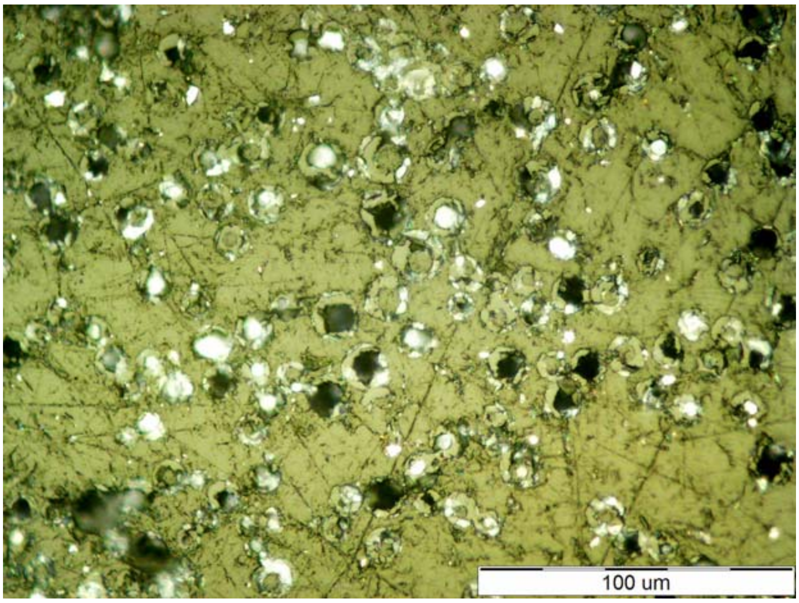

Figure 2. Measuring fiber diameters on polished cross sections

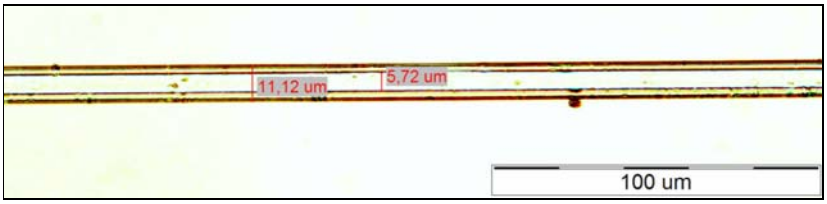

Figure 3. Fiber diameter tests on laid fibers

Diameters measured on polished cross sections and on laid fibers are summarized in Table 1.

	Outer diameter [μm]	**Inner diameter [μm]**
Solid fiber	12.00±0.96	-
Laid hollow fiber	11.65±2.03	6.23±1.21
Polished hollow fiber	11.44±2.40	6.02±1.45

Table 1. Comparison of fiber diameters determined by different methods

It can be seen that the difference between the results obtained by the two test methods for hollow fiber is below 5%, so in the following the diameter tests performed on laid fibers are enough.

Liquid drops were placed on the ends of the hollow fibers and filling phenomena were investigated. Using optical microscopy it was possible to observe the filling rate of the fibers (Figure 4.). It was observed during fiber filling that if the fiber-ends remained non-contaminated the filling process continued until the wall-friction compensated the capillary effect. It was important that no glass splinters are present at the fiber-ends and no contaminant is present at the fiber-ends, as it considerably hinders or even prevents the filling process.

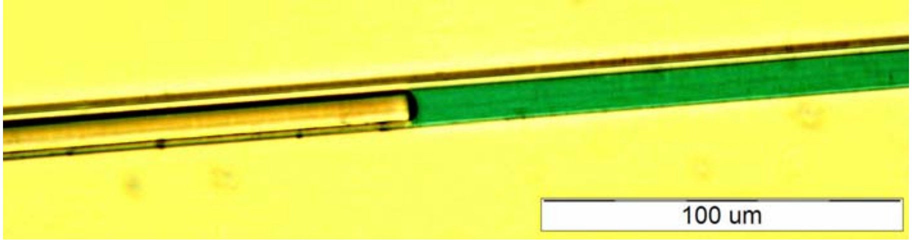

Figure 4. Fiber filling by fluids as observed under optical microscope

3.2 Preliminary results obtained on composites

Based on the fiber content test the fiber contents of sheets of various thicknesses were in the 37-51 vol% interval. Therefore, when comparing the results they were rendered specific by dividing them by the density of the composite. The results of the static mechanical tests are summarized in Table 2. Loading parallel with the fiber direction are denoted as 0° while those perpendicular to it by 90°.

		σ_t [MPa]	E_t [GPa]	σ_c [MPa]	E_c [GPa]	σ_b [MPa]	E_b [GPa]
0°	Specimen reinforced by solid fibers	559.1±47.4	16.0±1.0	286.0±39.2	3.6±0.2	621.5±19.7	25.1±1.1
	Specimen reinforced by hollow fibers	330.2±25.3	13.2±1.1	293.4±29.6	5.4±0.3	661.8±34.1	26.3±1.9
90°	Specimen reinforced by solid fibers	4.8±0.9	4.2±0.4	56.3±9.3	2.2±0.2	30.4±1.8	6.3±0.2
	Specimen reinforced by hollow fibers	14.1±2.0	4.7±0.5	60.4±8.6	2.8±0.2	47.7±3.9	4.8±0.5

Table 2. Results of static mechanical tests (explanation of indices: t-tensile, c-compression, b-bending)

In case of the 0° (fiber) direction the tensile strength and elastic modulus values of specimens reinforced by solid fibers were higher than those with hollow fibers, but after division by the density the specific modulus of elasticity became higher for the hollow fiber reinforcement. At 90° direction the values obtained for the hollow fiber reinforced specimens were higher in each case. As the hollow fiber are much more fragile than the solid fibers, several fibers were broken and disoriented during impregnation, resulting in better properties for the hollow fibers.

In case of the compressive tests at 0°fiber direction the strength is somewhat lower for hollow fibers, but the elastic modulus is higher, and not only for the specific values obtained after division by the density. At 90° direction the values are higher for the hollow fibers because of the broken and disoriented samples.

In the three point bending test all mechanical properties of the composites reinforced by hollow fibers were superior to those with solid fibers, which is due to the higher second order cross sectional moment of the single fibers.

The results of the Charpy impact tests are summarized in Table 3.

	a_{cU} [kJ/mm^2]
Specimen reinforced by solid fibers	352.0±15.5
Specimen reinforced by hollow fibers	209.3±20.0

Table 3. Results of the Charpy impact test

The energy absorption ability of specimens reinforced by solid fibers was higher, which contradicts the expectations. Single fibers did not break as expected, which was due to the fact that the hole volume fraction of the fibers was not high enough. The energy absorption ability of the composites reinforced by hollow fibers could be improved if the hole volume fraction of the fibers could be increased in the manufacturing process.

4 Conclusions

Geometrical properties and filling possibilities of hollow fibers were investigated. It was proved that the fibers can be filled utilizing capillarity. Composite specimens reinforced by hollow and solid fibers were prepared and some preliminary tests were performed on their static mechanical and energy absorption properties. It was shown that the specific mechanical properties (divided by the composite density) of composites reinforced by hollow fibers were higher than those of traditional composites reinforced by solid fibers. Energy absorption ability was lower for hollow fiber reinforced composites which was due to the fact that the fibers did not collapse because of the small fiber diameter, which could have meant large energy absorption. In order to be able to perform the tests again at identical fiber contents, a more reliable technology should be used for producing the specimens instead of hand lamination, allowing more precise adjustment of the fiber content. If the tests are repeated with hollow fibers filled during composite production, the properties of the composites reinforced by hollow fibers are expected to improve further.

Acknowledgements

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