TOTAL LIGHT TRANSMITTANCE OF GLASS FIBER-REINFORCED POLYMER LAMINATES FOR MULTIFUNCTIONAL LOAD-BEARING STRUCTURES

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ABSTRACT

Glass fiber-reinforced polymer (GFRP) materials are increasingly used in building construction for the design of multifunctional structures. These composite materials allow the integration of structural functions, building physics functions (mainly thermal insulation) and architectural functions (complex forms and color) in single large-scale building components. GFRP materials also allow the fabrication of translucent structural components with high degree of transparency when optically aligned resins and glass fibers are used, i.e. their refractive indices are identical. In this study the total light transmittance of hand lay-up GFRP laminates for building construction was investigated with a view to two architectural applications: translucent load-bearing structures and the encapsulation of photovoltaic (PV) cells into GFRP building skins of sandwich structures. Spectrophotometric experiments using an integrating sphere set-up were performed on unidirectional and cross-ply GFRP specimens in the range from 20% to 35% fiber volume fraction. Results were compared with the short-circuit currents generated by amorphous silicon (a-Si) PV cells encapsulated in GFRP laminates exposed to artificial sunlight radiation. The total amount of fibers in the laminates was the major parameter influencing light transmittance, with fiber architecture having little effect. 83% of solar irradiance in the band of 300-800 nm reached the surface of a-Si PV cells encapsulated below structural GFRP laminates with a fiber reinforcement weight of 820 g/m^2, demonstrating the feasibility of conceiving multifunctional GFRP structures.

Keywords: Glass fiber-reinforced polymer, Light transmittance, Multifunctional structure, Photovoltaic solar cells

INTRODUCTION

Today, iconic building projects creating lighting effects on their facades are constructed using polymer materials. Visual perception of the building facade is made to change with the illumination conditions, increasing therefore the architectural expression of the building. To this purpose, high light transmittance glass fiber-reinforced polymer (GFRP) laminates are increasingly used due to their low cost, lightweight and impact resistance compared to traditional glass components. Moreover amorphous silicon (a-Si) flexible photovoltaic (PV) solar cells can be encapsulated in the GFRP skins of freeform building envelopes, integrating electric energy production in lightweight and low-cost structures. Reducing the cost of the encapsulation process of PV cells has been a main issue since the early age of photovoltaic energy and for this purpose systems using GFRP composites can constitute a valuable option [1]. The integration of PV cells in multifunctional composite elements has begun to be explored recently for high-tech applications in aerospace [2, 3]. However, in such cases, FRP composites are used as mechanical support for the PV cells and not as the top encapsulant of the cells. For building applications, recent research [4] has explored the thermal and mechanical feasibility of encapsulating PV cells in the translucent skin of structural GFRP/PUR (polyurethane) sandwich structures, however no optical investigation of the light transmittance through structural GFRP encapsulants was performed. For traditional encapsulants of a-Si PV cells, that is, cells covered with a thin layer of EVA adhesive and front sheets of glass or fluoropolymers, transmittance ranges from 0.89 to 0.95 were reported in [5]. This research investigates light transmittance of GFRP laminates used as translucent load-bearing structures and encapsulants of solar cells. In the first application, the percentage of visible light transmitted through GFRP laminates surrounded by air is investigated. In the second application, where the GFRP laminate is in contact with air on one side and laminated onto a solar cell on the other, the percentage of solar irradiance transmitted through the laminate and reaching the surface of a-Si PV cells is studied.

EXPERIMENTAL WORK

Fabrication of GFRP laminates

Unidirectional (UD) and cross-ply (CP) GFRP laminates were fabricated by a hand lay-up process using a UV-stabilized polyester resin and E-glass fibers, both with refractive indices around 1.56. The laminates cured at room temperature (23 ± 2°C) for one day and were then postcured for another day at 60°C. Five UD specimens (fiber reinforcement weight, w, of 410, 820, 1230, 1640 and 3280 g/m^2) and two CP symmetric specimens (of 1230 and 1640 g/m^2) were cut from the hand lay-up laminates. Fiber volume fraction of the specimens ranged from 20% to 35%. Specimens were labeled according to their reinforcement weight and fiber architecture, e.g. 1640CP refers to the specimen reinforced with w = 1640 g/m^2 of E-glass fibers and with cross-ply fiber architecture. In addition, a 1-mm thickness pure resin specimen was fabricated and cured using the same procedure as for the other specimens.

Fabrication of PV modules

Seven PV modules with three serial-connected a-Si PV cells (Flexcell) in each module were fabricated by hand lay-up, as shown in Fig. 1. Additionally, a reference non-encapsulated PV module with three serial-connected bare cells was also fabricated.

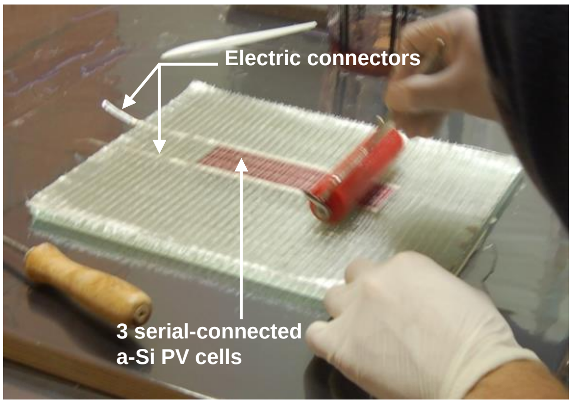

Figure 1: Hand lay-up encapsulation of three serial-connected a-Si PV cells in GFRP

The PV modules consisted of three different components: a rectangular glass pane support (300 x 250 x 10 mm^3), three connected a-Si PV cells (150 x 50 mm^2) and the GFRP encapsulant. One UD layer of E-glass was laminated onto the glass support and the thin PV cells were placed in the wet resin on top of this layer. The upper GFRP encapsulant was laminated over the PV cells. The fiber architecture and reinforcement weight of the upper encapsulant differed for each module according to Table 1 (from 410 to 3280 g/m^2 in UD and CP architecture). The PV modules cured at room temperature (23 ± 2°C) for seven days.

PV cells encapsulant	None	410UD	820UD	1230UD	1640UD	3280UD	1230CP	1640CP
I_{sc} (mA)	187	164	155	152	140	118	-	136
T_{PVexp} (-)	1	0.88	0.83	0.81	0.75	0.63	-	0.73

Table 1: Short circuit currents for PV modules with different fiber architecture of upper encapsulants and corresponding light transmittance

Spectrophotometric set-up

The total hemispherical spectral light transmittance of the seven GFRP and of the 1-mm thickness resin specimens was investigated by spectrophotometry with a 152-mm-diameter integrating sphere as shown in Fig. 2. The measurements were performed using a halogen light source (Osram 64642 HLX, 150 W, 24 V, Xenophot®), an integrating sphere (LOT RT-060-SF) and a spectrophotometer (Oriel, model 77400, MultiSpec 125TM, type 1/8m) measuring from 400 to 800 nm and connected to a computer equipped with InstaSpecTM II software for signal analysis. Specimens were located at the entrance port A of the sphere and crossed by the beam of light at nearly normal incidence (81°). The specimens were oriented with the reinforcement rovings forming an approximate angle of 45° with the horizontal plane (see Fig. 2). Port B of the sphere remained closed. For each GFRP specimen, four measurements at different locations of the specimen were performed and, in the following, the average spectral curves will be presented.

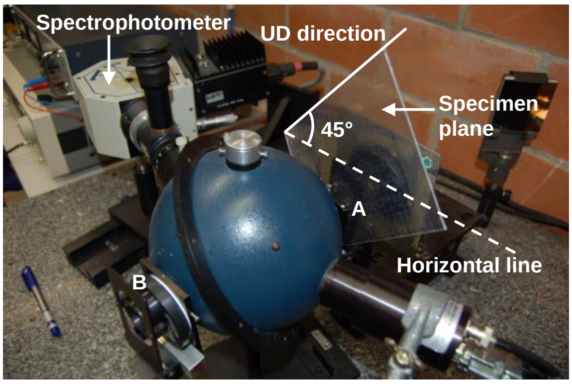

Figure 2: Integrating sphere with GFRP specimen located in port A for total light transmittance experiment

Solar radiation flash set-up

The percentage of solar irradiance reaching the surface of a-Si PV cells encapsulated in GFRP material was investigated subjecting the fabricated PV modules to a standardized radiation flash of 1000 W/m^2 and measuring the generated short circuit current. The flasher reproduced the terrestrial reference hemispherical solar spectral irradiance according to ASTM G173-03 for an air mass (AM) value of 1.5 [6]. The experiments were performed at ambient temperature between 19°C and 20°C.

RESULTS AND DISCUSSION

Spectrophotometric experiments

The measured spectral light transmittance curves of the UD specimens are shown in Fig. 3a. Light transmittance decreased when the reinforcement weight was increased. Light transmittance of UD and CP specimens is compared in Fig. 3b. For CP specimens transmittance was approximately 4% lower than for UD specimens. The transmittance results of the polyester resin specimen are also shown in Fig. 3a. Light absorption in the resin started at 430-nm wavelength and increased linearly until 400 nm. Using another spectrophotometer (Perkin Elmer Lambda 2), measuring regular transmittance from 190 nm to 1100 nm, showed that transmittance disappeared completely at 380 nm, from which point the light was absorbed by the UV additive. The spectral transmittance curve of the resin was therefore linearly extrapolated to zero at 380 nm.

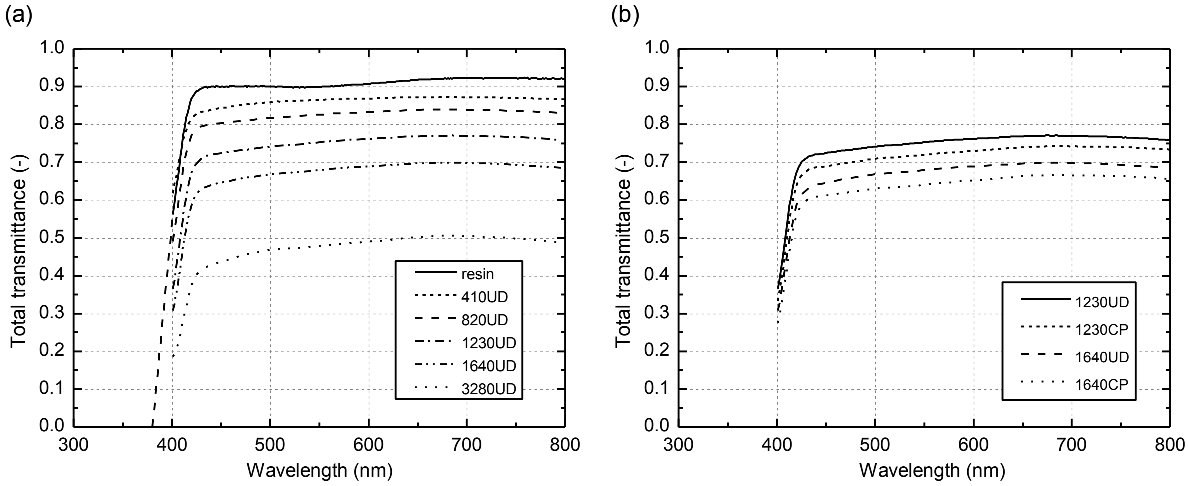

Figure 3: Spectral transmittance of (a) unidirectional specimens at different reinforcement weights and (b) unidirectional and cross-ply specimens

The transmittances at a single wavelength of 555 nm, $T_{t,555exp}$, of the pure resin, and UD specimens are shown in Fig. 4. The 555-nm wavelength was selected because the spectral response of the PV cells and the solar spectral irradiance both have their maximum very close to the 555-nm wavelength.

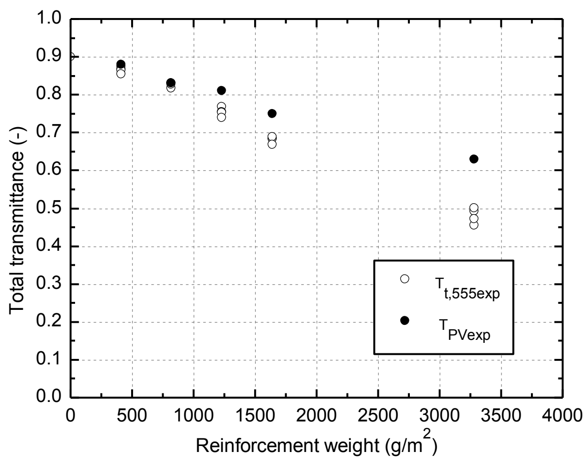

Figure 4: Transmittance measurements at 555-nm wavelength and from solar radiation flash experiments (UD specimens)

Solar radiation flash experiments

The short circuit current, I_{sc}, of a solar cell is directly proportional to the irradiance reaching the surface of the cell [7]. An experimental value of the light transmittance, T_{PVexp}, of the encapsulation system was therefore defined as the ratio between the I_{sc} generated by the encapsulated cells and the I_{sc} generated by the bare cells. The results are shown in Table 1 and Fig. 4. The PV cells with the 1230CP upper encapsulant did not generate any current during the experiment and it was concluded that these cells were damaged during the encapsulation process.

Comparison of experimental results

The light transmittance results obtained from spectrophotometric experiments, $T_{t,555exp}$, and solar radiation flash experiments, T_{PVexp}, are compared in Fig. 4. Both sets of results show that light transmittance significantly decreased when reinforcement weight increased. However, for w > 820 g/m^2, $T_{t,555exp}$ decreased much faster than T_{PVexp}. It was concluded that in the spectrophotometric measurements, for w > 820 g/m^2, not all of the scattered light inside the specimen passed through port A of the integrating sphere. The results obtained from the integrating sphere are therefore reliable only for low scattering specimens. The observed dependence of the transmittance on the reinforcement weight and, to a lesser extent, on the reinforcement architecture (UD or CP) may be attributed to two effects: 1) Even a small mismatch of the refractive indices of fibers and resin reduces transmittance; this reduction increases with increasing reinforcement weight. 2) Hand lamination cannot prevent the inclusion of some air pores, which represent a “material” (air) with a different refractive index. Locations sensitive to such voids are, in particular, crossings of fibers in CP laminates, which explains the slightly lower transmittance of CP compared to UD laminates.

As shown in Table 1, encapsulant 820UD had a transmittance T_{PVexp} = 0.83, which is between 7% and 13% lower than that of traditional encapsulations [5]. The Archinsolar project [8] showed, however, that a 10% loss in efficiency is well accepted for architecturally well integrated PV modules. The slightly lower efficiency of the encapsulation of PV cells into multifunctional GFRP elements with load-bearing capacity presented here thus can be acceptable.

CONCLUSIONS

Total light transmittance of GFRP laminates for building construction applications was measured. The following conclusions were drawn:

- The most important parameter affecting the light transmittance of GFRP is the fiber reinforcement weight of the laminate: transmittance increases with decreasing weight.

- Small-diameter integrating sphere measurements are reliable for low scattering laminates only. Measurements based on the short circuit current generation of encapsulated PV cells lead to more accurate values of GFRP light transmittance, particularly for thicker laminates.

- The solar irradiance in the band of 300-800 nm, reaching a-Si PV cells encapsulated in GFRP, is reduced by approximately 10% compared to traditional encapsulating systems if a structurally significant reinforcement weight of 820 g/m^2 is used for the covering layer. This drawback, however, can be compensated by the possible integration of PV cells into multifunctional load-bearing components, opening up new possibilities in architectural design.

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