Visible Light Curing of Fiberglass-Reinforced Ballistic Panels Based on Epoxy Acrylate Resin

Yunyun Bi, Department of Paper and Bioprocess Engineering, SUNY ESF, Syracuse, NY
Mark S. Driscoll, Department of Chemistry, SUNY ESF, Syracuse, NY
Robert W. Meyer, Department of Paper and Bioprocess Engineering, SUNY ESF, Syracuse, NY
L. Scott Larsen, New York State Energy Research and Development (NYSERDA), Albany, NY

Abstract

Visible light curing of composite is predominantly used in dentistry. This paper introduces a novel industrial application of using blue (470nm) LEDs to photocure fiberglass-reinforced impact-resistant panels that is traditionally manufactured by heat curing. Photopolymerization takes place with blue light radiation from a customized LED array. Lab drop-weight impact tests demonstrated light cured panel withstood over 90% of the test energy of the control panel.

1 Introduction

Fiberglass-reinforced impact-resistant panels (FRIRPs) have been playing important roles in both civil and military applications. FRIRPs are usually made of woven fiberglass and a polymer matrix system, traditionally manufactured by thermal curing. Traditional thermal curing systems require a substantial amount of energy and time for controlled heating and cooling ramps during manufacturing cycles, along with Inevitable Volatile Organic Compounds (VOCs) emission due to the solvents used in the resin formulation.

The radiation curing process significantly minimizes those problems. Curing time required can be as short as fractions of a second in the case of clear acrylate composites. Energy consumption is greatly reduced because less energy is lost compared to thermal curing. In addition, the formulations contain little or no solvent, thus the VOCs emission is negligible.

Visible light offers several significant advantages over other types of radiation sources- Ultraviolet Light (UV), Electron Beam (EB), and X-ray: lower energy consumption, lower cost of equipment, and non-hazardous environment during operation. Along with these benefits came the need to develop visible light curing unit and associated resin system to achieve desired physical and mechanical properties of the finished product, since visible light curing process is primarily used in restorative dentistry but rarely in industrial applications.

A series of preliminary experiments have been conducted to prove that a single or a row of three LED chips can cure a thin layer of epoxy acrylate based resin within seconds, and 10 layers of woven fiberglass prepregs within minutes. An 8” x 10” LED array was later designed and characterized in irradiance distribution in the previous study. The purpose of this research was to develop the procedure for visible light curing of epoxy acrylate based composite and investigate the effect of curing time, concentration of photoinitiator, and different resin system on the mechanical properties.

2 Method

2.1 Materials

This study uses commercial E woven roving fiberglass with a density of 24 ± 10% oz per square yard, kindly provided by Armortex.

The resin system consists of an oligomer, a monomer, a photoinitiator, and an amine synergist (Table 1).

Oligomer	Bisphenol A diglycidyl ether acrylate diluted with tripropylene glycol diacrylate (TPGDA)
Monomer	Isobornyl acrylate (IBOA)
Photoinitiator	Camphorquinone (CQ)
Amine synergist	Dimethylaminoethyl Methacrylate (DMAEMA)

Table 1 Visible Light Curable Resin Formulation

The oligomer Bisphenol A diglycidyl ether acrylate forms the backbone of the polymer network. IBOA was used as monofunctional acrylate monomers and reactive diluent, together with Bisphenol A diglycidyl ether, donated by Rapid Cure Technologies. Camphorquinone has an absorbance peak in the visible light region at 468 nm and is by far most widely used in biomedical applications[1]. The efficiency of camphorquinone alone is insufficient. In dental composites restoratives, it is frequently used with a tertiary amine co-initiator. Various studies[2,3] suggest that a molar ratio of 1:2 (CQ/amine) achieved the best result.

2.2 Procedure

2.2.1 Preparation of resin system

The resin formulation is mixed in a dark room with yellow lighting, and then heated in an oven for 12 hours at 40 degree C to accelerate the dissolution of camphorquinone.

2.2.2 Preparation of specimen

Fiberglass was cut in 8.5 inch squares from continuous woven fiber roving. Each layer was brushed with resin, stacked over each other, and then placed into a transparent plastic bag that does not absorb radiation. Each panel consists of 22 layers of fiberglass.

A two-piece plexiglas of 1 ⅛ inch thick mold fixture held the panel while an electric press applies 0.5 tons load. Three 0.5 inch thick stopper were placed in between the mold, to determine the thickness of the panel. In this process, excess resin and air was squeezed out. The unpolymerized composite material was then irradiated with blue light for 5 or 10 minutes on each side.

2.3 Ballistic test

Lab drop-weight screening test

The drop impact tester simulates a speeding bullet by dropping a weight of 250 lb from a preselected height on the specimen (Figure 1). The projectile is made from a 7/16” x 3” non-deforming hard steel bolt, fixed in a grade 8 bolt, attaching to the bottom of the weight. The impact tester lifts and drops the weight by electromagnetic control. The panel was fixed horizontally in a wooden frame holder by nuts and bolts in all four sides as shown in Figure 1 with a 6” x 6” exposed area.

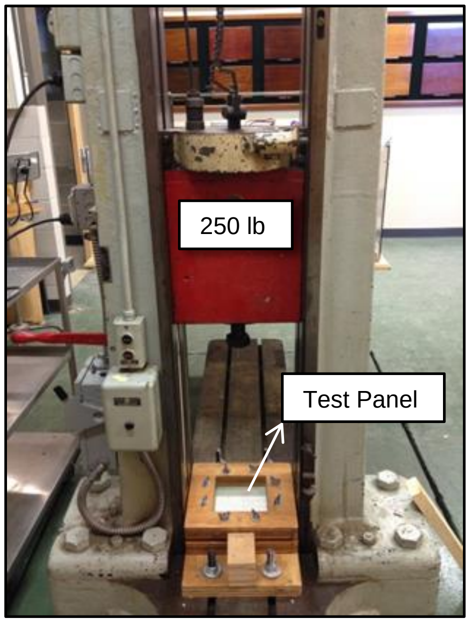

Figure 1 Lab drop-weight impact tester

The impact tests were conducted with drop-weight energy of 800, 750, and 700 ft lb. The indicated energy was obtained by lifting the weight a required distance from the compression surface of the specimen.

After the strike, specimens were examined to determine the extent of penetration and delamination, as well as whether it passes or fails the test based on the criteria in Table 2.

Fail	The bottom layer is broken. The projectile may or may not penetrate through the panel.
Pass	The projectile stops before reaching the bottom layer.

Table 2 Pass/fail criteria for drop impact test.

3 Results

3.1 Lab impact test

The impact tests results are shown in Table 3. The control panel passed at 750 ft lb, while light cured panel passed 700 ft lb, lying within 10% of the control panel. The panel cured for 5 minutes on each side passed 700 ft lb as well, but presented most severe delamination (Figure 2-c). The control panel passing 750 ft lb had the least delamination (Figure 2-a). Figure 3 shows the front and back side of 10 minutes light cured panels after 750 ft lb and 700 ft lb strikes.

Sample	Test Energy (ft lb)	Result
Control	800	Fail
Control	750	Pass
10 minutes light cured panel	750	Fail
10 minutes light cured Panel	700	Pass
5 minutes light cure panel	700	Pass

Table 3 Drop impact test results

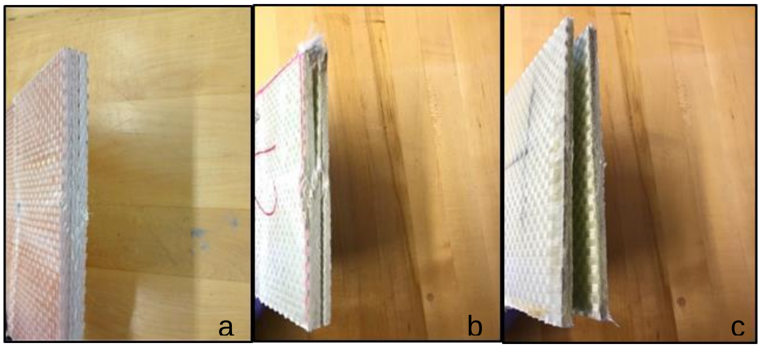

Figure 2 Representation of delamination after passing impact tests: a - Control panel passing 750 ft lb; b - 10 minutes light cured panel passing 700 ft lb; c - 5 minutes light cured panel passing 700 ft lb.

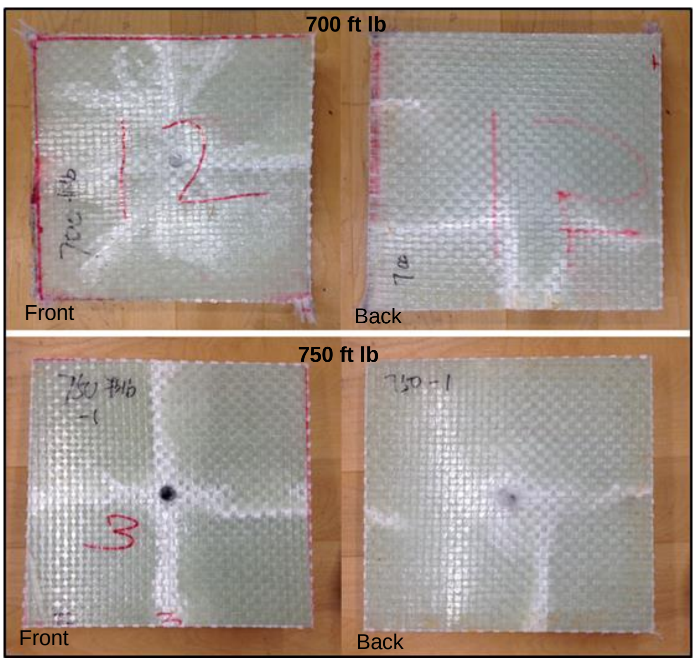

Figure 3 Front and back side of 10 minutes light cured panel passing 700 ft lb and failing 750 ft lb.

4 Discussion

Impact properties represent the capacity of a material to absorb and dissipate energy under low or high velocity impact. When the projectile hits the panel, the fibers under the projectile started to fail by compression. As the impact proceeded through the laminate, the compressive stress exerts pressure on the fibers in the surrounding area, causing compressive deformation. The fibers at the impact point were pushed forwards by the projectile, eventually exited from the panel after the bottom layer was broken by tension, or stopped the projectile when all the kinetic energy was absorbed. Delamination or cracks usually occur in the experimental and control samples in both cases. During the whole impact event, frictional resistance and heat generation is another energy absorbing factor.

Light cured panel passed 700 ft lb drop-weight test, while the controlled panel passed 750 ft lb. That could be attributed to two factors - resin loading and resin type, which significantly influence fiber-matrix interaction. At high levels of adhesion, the failure mode is brittle and relatively little energy is absorbed, while at low levels of adhesion, delamination may occur without significant fiber failures[4]. The controlled panels contain over 30% thermal cured polyester based resin, while the light cured panel is made of epoxy acrylate based resin with a loading of 20-25%. As can be seen from Figure 2, curing time also plays a significant role in impact response. Longer curing time indicates denser crosslink and more complete polymerization, resulting in better adhesion, ultimately less delamination.

It should be noted that even though the projectile has the same diameter as 0.44 Magnum semi wadcutter bullet defined in Underwriters Laboratory 752 (UL 752) level 3 ballistic standards, the impact response is expected to be different because the lead-tipped bullet when hitting the target would absorb extra impact energy due to mushrooming effect, and its high velocity (1350- 1485 ft/sec) may result in different failure mode.

5 Conclusion

A 22 layered fiberglass- reinforced panel can be successfully cured by a blue LED array with irradiance ranging from 200 - 1000 mW/CM^2. Ten minutes curing time on each side is preferable over 5 minutes, because the incomplete cure cause more severe delamination. Lab impact test demonstrated comparable results to control panels.

The effect of resin loading, resin type, and concentration of photoinitiator on impact properties, as well as shooting test are still ongoing, and will be presented once the data is complete.

6 Acknowledgement

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