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# Manufacturing of glass ribbon reinforced transparent composites using the autoclave process

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MANUFACTURING OF GLASS RIBBON REINFORCED TRANSPARENT

COMPOSITES USING THE AUTOCLAVE PROCESS

by

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## ABSTRACT

Clear transparent panels have many applications ranging from windows on an aircraft to protective safety guards on industrial equipment. Glass ribbon reinforced transparent composites are light weight, load bearing and have a high impact resistance.

A transparent composite is based on the concept of matching the refractive index of the glass ribbon with that of a resin system. It is not necessary that the resin refractive index match the glass refractive index before the cure cycle, only that the refractive indexes match after curing.

Transparent composites have a high impact resistance that would be mechanically ideal for aircraft windows and canopies. In the present synthesis of transparent composites, pre-impregnated tapes are used to manufacture parts using the autoclave process. The autoclave is a pressure vessel that has heaters and coolers to maintain a consistent temperature and pressure throughout the cure cycle. The cure cycle is comprised of a series of constant and varying temperature and pressure segments for specific time periods. The performance of the manufactured parts was demonstrated by conducting tensile, flexural and impact tests. The objective of this research is to manufacture a transparent panel that will have high impact resistance, be light in weight and be high in strength; not to sacrifice desirable characteristics to obtain an absolutely limpid panel. Future development of transparent composites will include the synthesis of curved shapes for aircraft canopies or helmets for astronauts.

## ACKNOWLEDGEMENTS

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# 1. INTRODUCTION

A composite can be manufactured using any fiber and matrix combination. A sidewalk is a useful example of a composite; the steel rebar makes up the reinforcement of the composite and the concrete makes up the matrix. Usually, when composites are mentioned, fiberglass or carbon fibers are at the forefront of the discussion.

Previously, transparent composites have been comprised of polycarbonate materials. Wright et al., 1993, studied the impact of cylindrical projectiles on polycarbonate plates of varying thickness [1]. For transparent armor applications, laminates are usually manufactured from polycarbonate, poly(methyl methacrylate) (PMMA), ceramics and glass [2-4]. Sarva et al., 2004 utilized the contrast in mechanical response between polycarbonate and PMMA to develop a material assembly design with strong improvements in energy absorption capability under impact load [5].

Glass ribbon reinforced transparent composites are light weight, load bearing and have a high impact resistance. Transparent composites are thinner and stronger than current glass and polyurethane laminates. The cost of putting windows on aircraft is very high. If the load of the surrounding structure can be transferred through the window, a lot of structure can be eliminated, leading to a weight savings; in turn adding to fuel efficiency and monetary savings. If a face shield or body shield can be manufactured thinner and lighter, there will be a substantial energy savings; in turn leading to higher endurance of the soldier or police officer. The objective of this research is to manufacture a transparent panel that will have high impact resistance, be light in weight and have high strength; not to obtain an absolutely limpid panel which would sacrifice the desirable characteristics of the panel.

Currently, to make a transparent composite, it is important to start with transparent materials of excellent homogeneity. In a transparent composite the refractive index of the matrix and the fibers must match. If not, the composite will be severely distorted due to refraction and scattering. Eliminating this distortion provides transparent composites that should be ideal for face shields, body armor or windows in aircraft and cars. In this work, glass ribbons were used for the reinforcement. The ribbons have a rectangular cross section, which scatters the light waves much less than curved fibers [10].

There are several processes used to manufacture composites. Some, such as vacuum assisted resin transfer molding (VARTM), can be used at room temperature to cure when there is no need to add heat. VARTM and pultrusion also use heaters to cure the resin systems involved. When pressure, vacuum and heat are needed an autoclave is the only manufacturing process capable of effectively completing the cure. An autoclave uses different combinations of heat, pressure and vacuum. These curing conditions are subject to change due to the cure cycle of the specific polymer resin system.

# 2. AUTOCLAVE

An autoclave is used for various kinds of research, such as corrosion of zirconium for the nuclear industry, architectural concrete for the building industry and composite fabrication of aircraft parts [6-8]. The primary function of an autoclave is to apply pressure and high temperatures to parts in its interior. A vacuum bag can even be used to contol the differential pressure on the parts. Several parts can be made at the same time as long as they have the same temperature and pressure cycle and provided there is enough capacity for all the parts. Autoclaves consist of a pressure vessel, heaters, coolers and vacuum pumps. All these components allow consistent temperature and pressure throughout the cure cycle. Autoclaves come in a variety of shapes and sizes, but the most common are cylindrical pressure vessels with sealed ends, as shown in Figure 2.1.

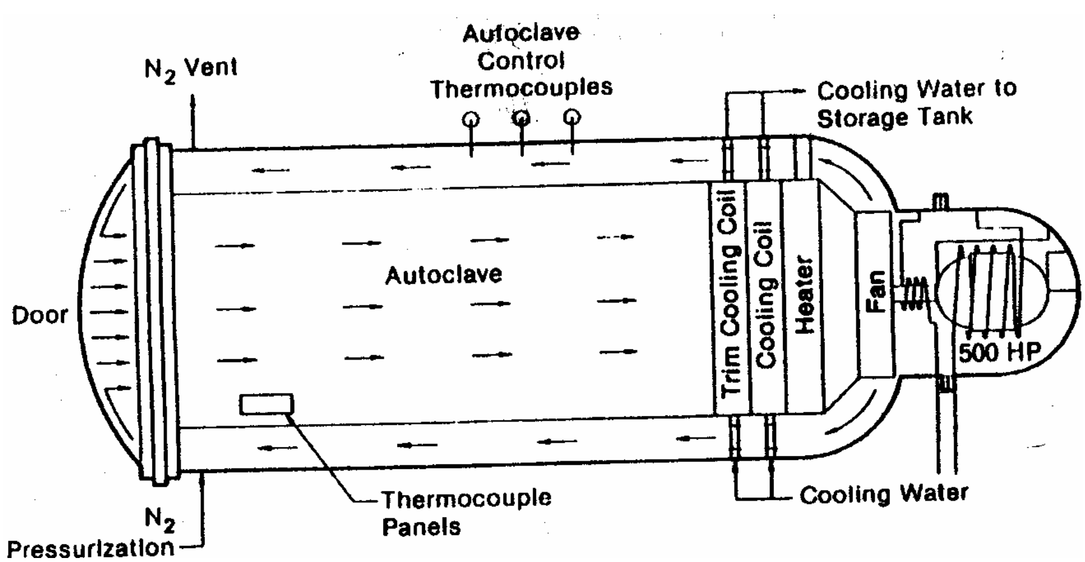


Figure 2.1: Schematic of an Autoclave

Many complex shapes can be made using an autoclave; the die is a very important component of that process. The composite lay-up will take the form of any die it is vacuum bagged against so that if the die is well made, with proper dimensions and texture, the surface of the composite will need no additional processing to be put into use. Dies can me made from aluminum, steel, glass or other materials. It is important to choose a die that will not cause residual stresses due to thermal expansion. Surface roughness is also a concern when choosing a die. If the product is a transparent composite panel, then an absolutely smooth surface is necessary. If the product is a carbon fiber skin panel, a rough surface suitable for painting is preferable.

In the lay-up and bagging operation, if a thick panel is being made, it is necessary to debulk the laminate every five layers so that voids do not occur in the finished panel. Debulking is the act of vacuum bagging the sample and turning on the vacuum for short periods to compress the sample. This will allow compaction of the layers so that resin pressure gradients through the thickness of the laminate are reduced. If the resin pressure is lower than the void pressure, a void will occur [9].

During the cure cycle, as the temperature and pressure increases, the resin will become less viscous and flow. As the resin flows it will “wet” all the surrounding fibers and then congeal. If done properly the bleeder ply will bleed off enough of the resin to allow for an appropriate fiber volume fraction but not leave the fibers too “dry”. When the panel has cured the temperature and pressure will be lowered at constant rates until it can be allowed back into ambient conditions. This process is intended to give a strong, dense, void-free composite part that can be used for the intended application.

Fibers come in many different weaves. They can be unidirectional or woven in such a way as to give an appropriate amount of tensile strength in a specific direction. Strength can be added in any planer direction by rotating the fibers to the required direction. Pre-impregnated weaves have the resin applied during manufacturing and must be refrigerated or the resin will cure improperly. The room temperature shelf life of a pre-impregnated weave varies depending on the resin, but is usually only a few days. The procedure for a typical bagging lay-up is shown in Figure 2.2.

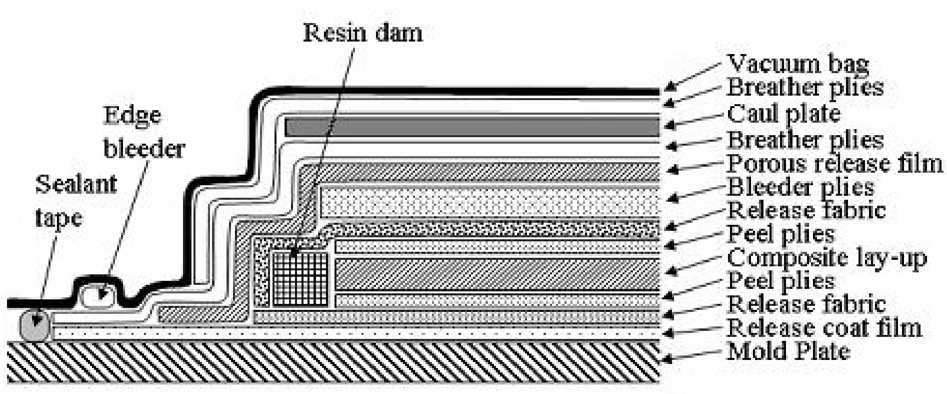


Figure 2.2: Typical Bagging and Lay-Up Schematic

Vacuum bagging was done to apply pressure to the part and to hold its shape during the cure cycle. Vacuum bagging was accomplished by placing a plastic sheet over the lay-up and sealing it with tacky tape. A vacuum pump was turned on so that the air inside the lay-up was evacuated. Figure 2.3 shows the autoclave at the University of Missouri-Rolla (UMR).

Figure 2.3: Autoclave at UMR

# 3. TRANSPARENT COMPOSITES

Transparent composites have potential use as aircraft windows. Glass ribbons are incorporated into the polymer matrix to give a composite material. The composite produced is much lighter than regular window material and has four to five times the strength of the plastic material. Transparent composites can be obtained if the refractive index of both the ribbon and the matrix match. The refractive index of the matrix can be modified to match that of the glass ribbon by changing the composition and/or degree of polymerization of the polymer matrix. Various processing factors such as the amount of initiator, cross-linker, curing temperature and time must be carefully controlled to obtain a given refractive index.

Another method is to use a polymer matrix with its given refractive index and to modify the refractive index of the glass ribbons. The refractive index of the glass ribbons depends on its chemical composition and thermal history. Annealing can also increase the refractive index of chilled glass and could be potentially useful in fabricating transparent composites [10-13].

The scattering of light by particles can been described by two different approaches: 1) the geometric optics approach and 2) the wave theory approach. Each has its own range of applicability depending upon factors such as particle size, shape, refractive index, number and position of scatterers. Figure 3.1 shows monochromatic light rays that have been refracted because the matrix and ribbon of a composite have different refractive indexes which is dictated by Snell's law:

$$n_1 * \sin(\theta_1) = n_2 * \sin(\theta_2) \quad (1)$$

where $n_1$ is the refractive index of material 1, $\theta_1$ is the angle from perpendicular to material 1 to the incident ray, $n_2$ is the refractive index of material 2 and $\theta_2$ is the angle from perpendicular to material 2 to the refracted ray. A diagram of Snell's Law is shown in Figure 3.2.

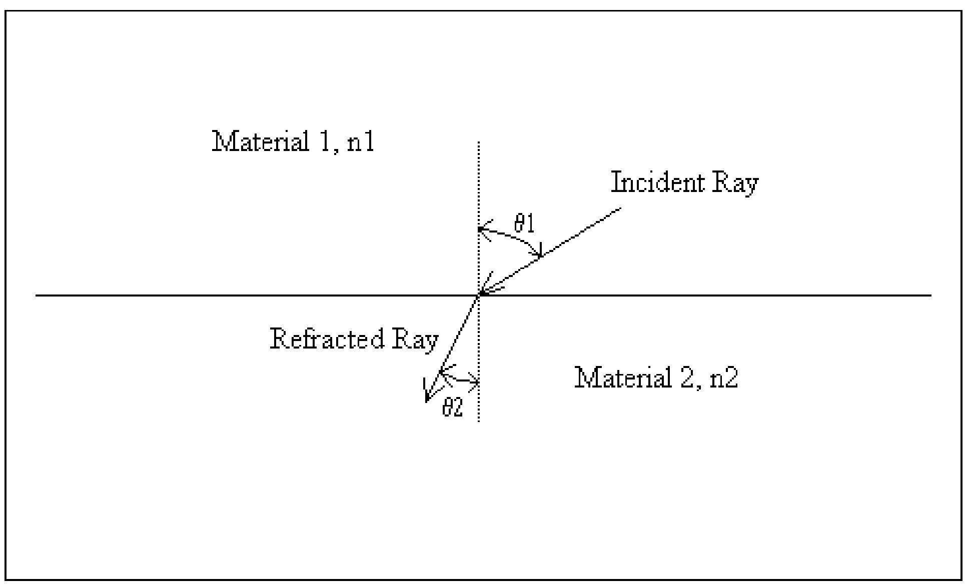


Figure 3.2: Diagram of Snell's Law

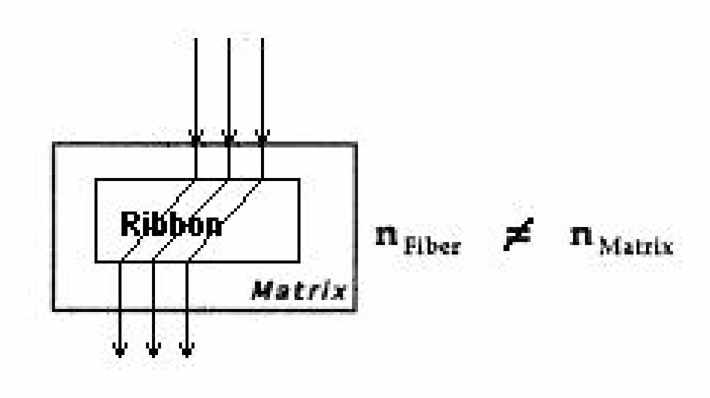


Figure 3.1: Refraction of Monochromatic Light within a Single Ribbon Composite

Figure 3.3 shows the transmittance of monochromatic light as it passes through the matrix and the ribbon without any refraction.

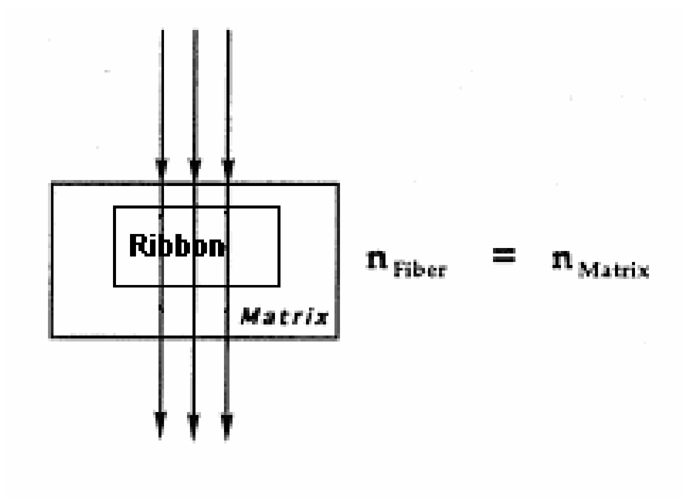


Figure 3.3: Transmission of Monochromatic Light through a Single Ribbon Composite

Future development of transparent composites will include curved shapes such as canopies for fighter planes or helmets for astronauts and; eventually, shapes as complex as lighting fixtures can be achieved.

# 4. MANUFACTURING

## 4.1 SYSTEMS OF RESIN AND OTHER MATERIALS

The pre-impregnated glass ribbon reinforced transparent composites were obtained from MO-SCI Corporation. The glass ribbons were Corning 0211 glass which have and ultimate tensile strength of 900MPa (130ksi) and a refractive index of 1.523. The vacuum bag was Stretchlon 800 by AIRTECH. This vacuum bag will withstand a temperature up to 200°C (400°F) and will elongate up to 400%. It is not affected by humidity and always stays soft with no cracking. The pre-impregnated composite used was an epoxy resin coated glass ribbon with a total thickness of 25μm (0.001in). The breather cloth was Econoweave 44 by AIRTECH. This is a recycled non-woven polyester breather designed for ambient or oven cures. The maximum usage temperature is 190°C (375ºF) and the approximate weight is 135g/m$^2$ (4oz/yd$^2$). The mold release agents used were Chemlease® 15 sealer, Chemlease® 2161 semi-permanent release agent and Chemlease® mold cleaner from Chem Trend. The sealant tape was AT-200Y from AIRTECH, which is designed to hold both the vacuum bagging material and the base material. A glass mold was used to lay-up the parts. Some samples used off-the-shelf Mylar between the mold and the lay-up to ensure surface integrity. The autoclave was pressurized using nitrogen gas.

## 4.2 RIBBON PRODUCTION

Bulk glass was melted in an electrically heated platinum bushing. The glass was heated for three hours at 1300°C (2375°F) to remove bubbles from the melt and then cooled to 1200°C (2200°F). Ribbons were started by touching a glass rod to the molten glass flowing from nozzles in the bottom of the bushing. The sizes of these glass ribbons ranged from 10μm to 25μm. A stream of forced air was used to cool the nozzles during the fining process to prevent the glass from flowing prematurely. The ribbons were quickly cooled after being pulled from the melt. The ribbons were pulled across a coating wheel, through a hot furnace and then attached to a spinning take-up wheel. The coating wheel consisted of a rotating grooved brass cylinder suspended in a water-cooling bath of silane solution. The wheel was designed with grooves, one for each ribbon, narrow enough so that they are filled with coating solution by the rotation of the wheel, which ensures complete coating of the ribbon surface during pulling. The coating bath is cooled with chilled water to prevent changes in silane concentration due to solvent evaporation by neighboring hot ribbons. Figure 4.1 shows the apparatus used for making the glass ribbons. The coated and dried ribbons are placed in an airtight and heat-sealed polyester bag to protect them from moisture.

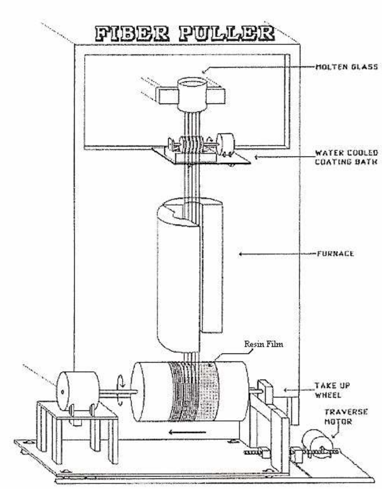


Figure 4.1: Ribbon Pulling Machine

**4.3 MOLD PREPARATION**

A glass mold surface was used to lay-up the pre-impregnated composites. Chemlease® mold cleaner was applied to the mold surface with clean 100% cotton cloths. While the mold cleaner was still wet, the mold was vigorously wiped dry with a second clean cotton cloth. The mold was wiped several times until all residues such as dirt, dust and moisture were removed. The mold was then ready for application of sealer and release agent. Chemlease® 15 sealer was applied to the mold surface with a clean cotton cloth. The surface of the mold was wiped with a second clean cotton cloth using a circular motion from the outside working inwards. The procedure was repeated until the entire mold surface had been covered. Then the mold sealer was allowed to cure for 30 minutes before applying the mold release. Chemlease® 2161 semi-permanent release agent was applied to the mold surface with no more than a few square feet at a time. This procedure was repeated for four to five coats, allowing 10 minute drying periods between each complete coat.

The pre-impregnated transparent composites were cut into plies and stacked in several layers on the glass mold. Some of the samples created had Mylar between the pre-impregnated composite and the mold. The samples with Mylar used aluminum plates for molds and the Mylar was to protect the surface integrity of the sample. The pre-impregnated composites were then covered with another glass mold on the top. A peeling cloth was placed over the glass mold followed by a breather cloth. One vacuum line was attached at the top of the mold. The whole configuration was then covered using a vacuum plastic bag. Prior to placing the configuration inside the autoclave, a vacuum was applied to the mold for a few minutes to debulk the lay-up. The whole configuration was then carefully placed inside the autoclave for curing.

## 4.4 CURE CYCLE

A cure cycle for composite parts is a series of pressure and temperature variations that allow the resin and fibers to cure into a rigid structure. Figure 4.2 shows the cure cycle for a typical autoclave manufactured transparent composite. There are temperature and pressure increases, decreases and hold segments in the cure cycle. The figure shows that the autoclave is pressurized to 690kPa (100psi) and heated at 11°C (20°F) per minute to 60°C (140°F). Then the temperature and pressure is held constant for two hours. The autoclave is heated again at 11°C (20°F) per minute to 121°C (250°F). The temperature and pressure is again held constant for two hours, cooled at 5.5°C (10°F) per minute to 32°C (90°F) and pressure dumped. Each resin system has its own cure cycle. If a cure cycle is used that is not specific to the resin system, the composite will not be properly cured. This will then cause an undesired opacity or have some other weakness.

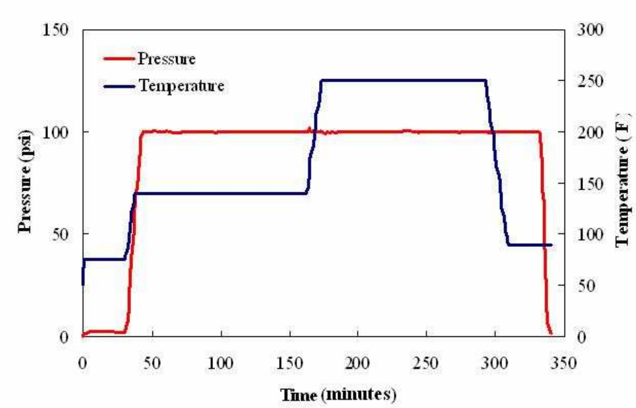


Figure 4.2: Cure Cycle for Transparent Composites

Several glass ribbon-reinforced transparent composites were manufactured using the autoclave molding process. The transparency of the samples is assessed subjectively by placing the panel over text with the intent to read the words without squinting. Figure 4.3 shows one of the UMR technicians holding up a manufactured transparent panel. The results of this work helped to eliminate much of the guesswork involved with making transparent composite panels using the autoclave molding process.

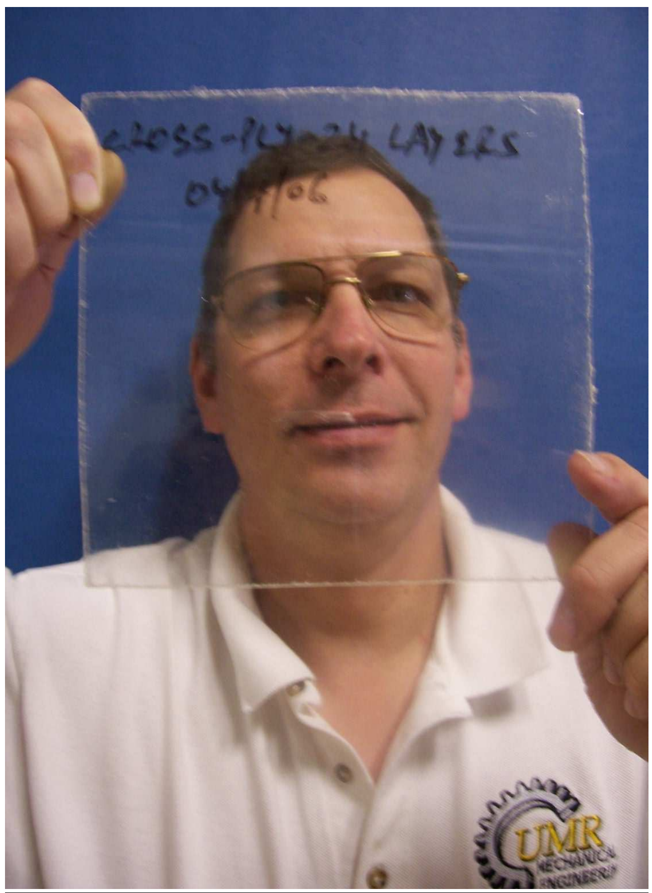


Figure 4.3: Glass Ribbon Reinforced Transparent Panel Manufactured at UMR

# 5. TESTING AND RESULTS

## 5.1 FIBER VOLUME FRACTION (ASTM C 3171)

The samples were cut into rectangles using a standard band saw found in the Mechanical Engineering Machine Shop. Small rectangles allow for easy measurement using vernier calipers. The sample edges were checked and found to be free of delamination and stray ribbons. The samples were weighed on a scale to the nearest 0.0001g. The filter-lined crucible that was used in the vacuum filtration was also weighed to the nearest 0.0001g. The filter weight was needed to subtract from the combined filter and ribbon weight.

A 250mL Erlenmeyer flask was used in a hot water bath and held using a clamp and ring stand. The bath was ensured not to exceed 80°C (175°F). The sample was placed inside the flask and 30mL of 70% nitric acid were added. A condenser column was attached to the flask as shown in Figure 5.1. The column allowed any material that splashed up during the reaction to be washed back into the flask.

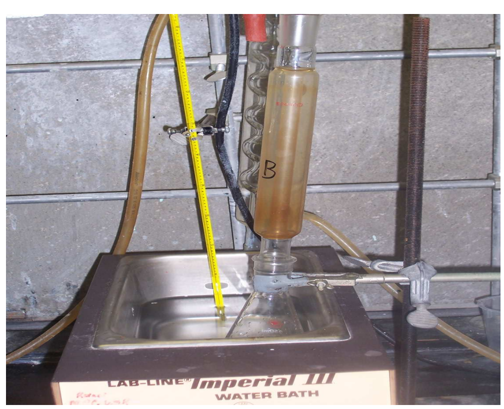


Figure 5.1: Water Bath, Clamped Flask and Condenser Column

The maximum time for the complete digestion of the composite was six hours. Once the digestion was complete, the condenser column was removed. The sample mixture was then filtered using a sintered crucible under a vacuum, as shown in Figure 5.2. All the contents of the flask were removed from the flask; a wash bottle was used as necessary.

Figure 5.2: Vacuum Filtration of the Sample

According to the American Society for Testing and Materials (ASTM) standard C 3171 the weight percent of reinforcement in the specimen, $W_r$, is calculated using the equation:

$$W_r = (M_f/M_i)*100 \quad (2)$$

where $M_f$ is the final mass of the specimen after digestion in grams and $M_i$ is the initial mass of the specimen in grams.

Also, the ASTM standard specifies the volume percent of reinforcement in the specimen, $V_r$, is calculated using the equation:

$$V_r = (M_f/M_i)*100*\rho_c/\rho_r \quad (3)$$

where $M_f$ is the final mass of the specimen after digestion in grams, $M_i$ is the initial mass of the specimen in grams, $\rho_c$ is the density of the specimen in g/mL and $\rho_r$ is the density of the reinforcement in g/mL. The results of the fiber volume fraction testing are given in Table 5.1.

Table 5.1: Volume Percent of Reinforcement in the Specimen

| Sample | Volume ($mm^3$) | $\rho_c$ (g/ml) | $V_r$ (%) |
|---|---|---|---|
| 24 Layers | 415.126 | 0.001444 | 23.22 |
| 24 Layers | 405.285 | 0.001454 | 23.91 |
| 30 Layers | 580.893 | 0.001448 | 20.49 |
| 30 Layers | 595.505 | 0.001422 | 20.60 |

**5.2 TENSILE**

Tension tests were performed on the neat resin and ribbon reinforced transparent composite samples. Tests were conducted in accordance with ASTM standards. Four specimens were tested and the average values are reported. Dog bone (ASTM D 638) molded samples were used for the neat resin samples while straight edge (ASTM D 3039) specimens were used for the transparent composite specimens. Figure 5.3 shows the tensile test setup used.

Figure 5.3: Tensile Testing Setup

Figure 5.4 shows the stress versus strain curve for the neat epoxy resin samples. The curve is smooth up to its maximum stress; then it fractures which is an indication that there is no useful data beyond this maximum.

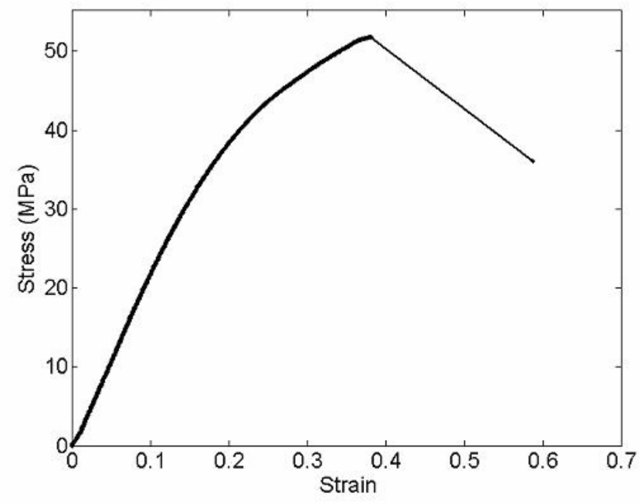


Figure 5.4: Tensile Test for the Neat Epoxy Resin Samples

Figure 5.5 shows the stress versus strain curves for neat epoxy resin and two 20 layer cross-ply composite samples. The figure also shows that the modulus of elasticity was much higher for the composite compared to the neat resin.

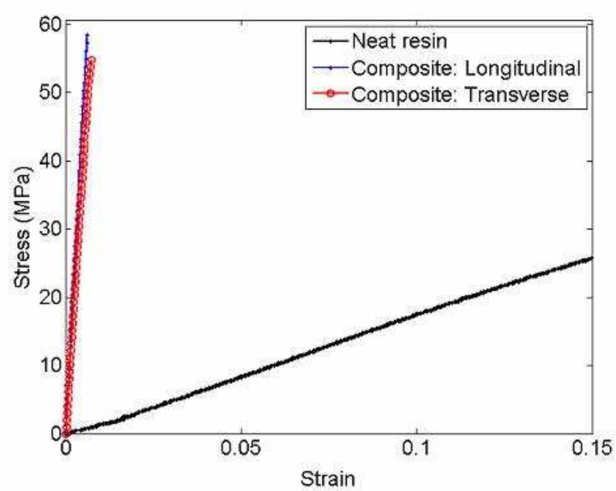


Figure 5.5: Tensile Test for Neat Epoxy Resin and Composite Samples

Figure 5.6 shows the stress versus strain curves for neat epoxy resin and composite samples and that if a composite has more layers it will take more stress for the same amount of strain. The figure also indicates that the composite is a significant improvement over the neat resin.

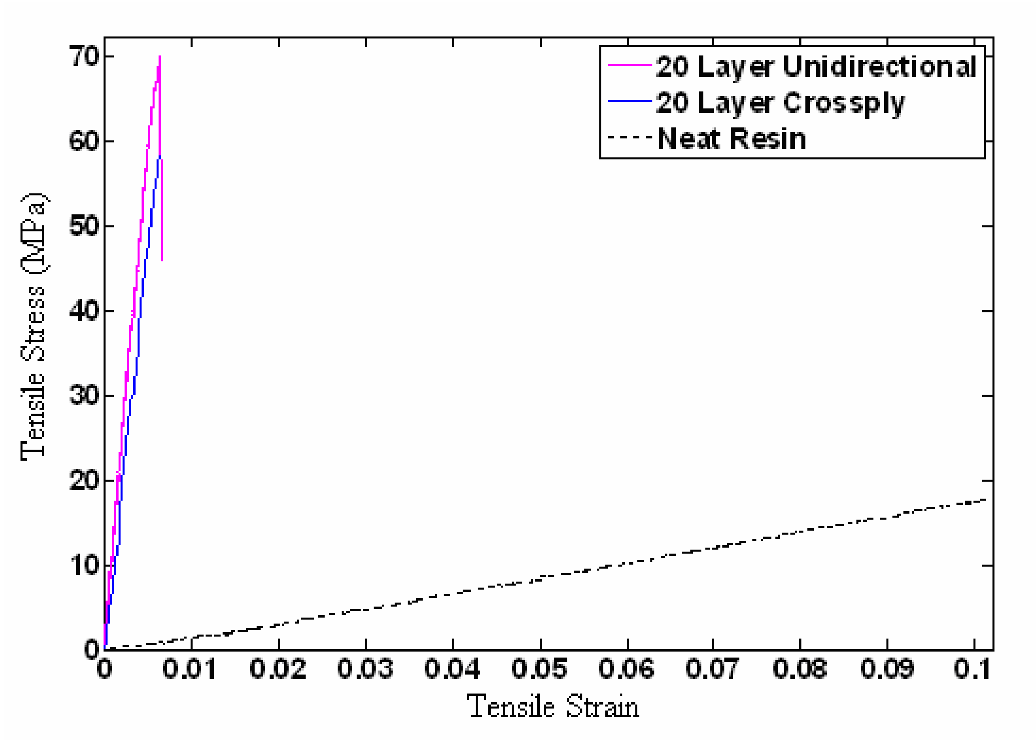


Figure 5.6: Tensile Test for Neat Epoxy Resin and Composite Samples

Figure 5.7 shows the stress versus strain curves for neat epoxy resin and composite samples and that if a composite has more layers it will take more stress for the same amount of strain. It also shows that the composite is a significant improvement over the neat resin.

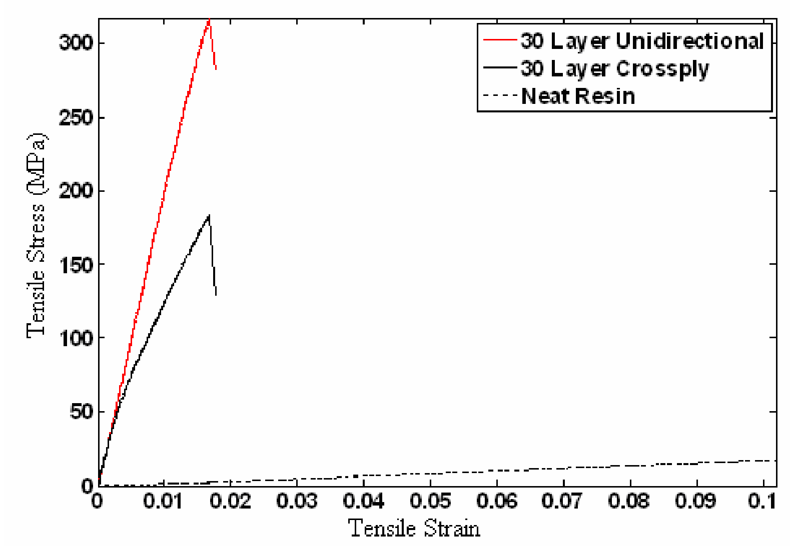


Figure 5.7: Tensile Test for Neat Epoxy Resin and Composite Samples

The tensile modulus and strength of the neat resin as well as the transparent ribbon reinforced composite samples are listed in Table 5.2. It is clear that the transparent composites have a significant increase in modulus when compared to the neat resin sample. Also, an increase in the tensile strength is observed for the transparent composites.

Table 5.2: Tensile Properties for Glass Ribbon Reinforced Optically Transparent Composites

| Sample | Tensile Modulus (MPa) | Tensile Strength (MPa) |
|---|---|---|
| Neat Epoxy Polymer | 200.51 ± 4.5 | 52 ± 2.8 |
| $[0/90]_{20}$ – Longitudinal | 9,615.7 ± 125.4 | 58.6 ± 3.5 |
| $[\text{Unidirectional}]_{30}$ – Longitudinal | 19,470 | 316.8 |
| $[0/90]_{30}$ – Longitudinal | 10,700 | 183.4 |

**5.3 FLEXURAL (ASTM D 790)**

The flexural tests were carried out per ASTM D 790 on an Instron Universal testing machine. Flexural modulus and flexural strength were evaluated. All the tests were performed at a crosshead speed of 0.5mm per minute. At least five specimens were tested for each different resin system and the average values were reported with corresponding error bars at ±1 standard deviation from the mean. A picture of the test setup is shown in Figure 5.8.

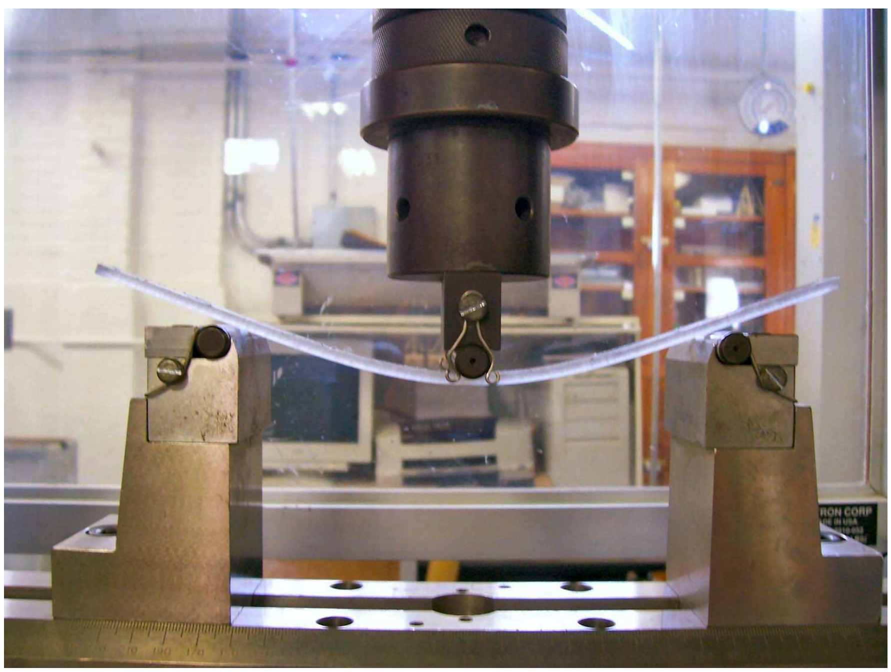

Figure 5.8: Flexural Test Setup

Figure 5.9 shows the load versus deflection from the flexural tests on the epoxy resin samples and that if a composite has more layers it will deflect less before fracture during a flexural test.

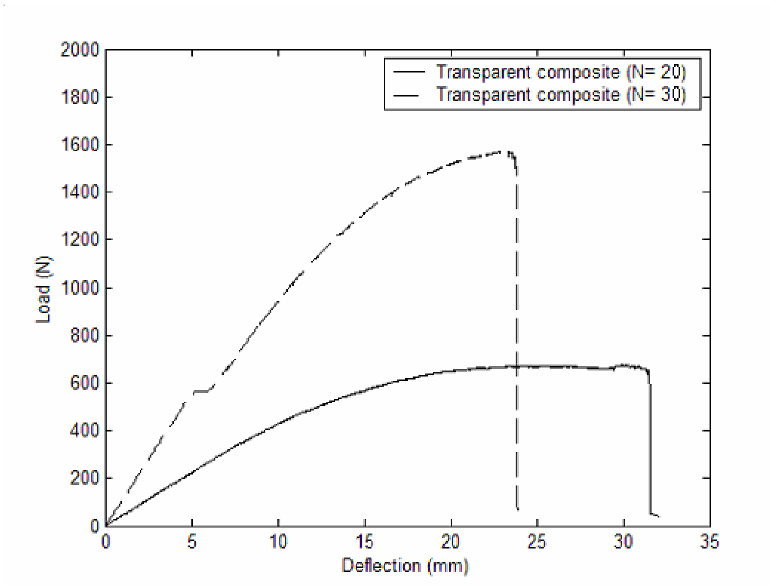


Figure 5.9: Flexural Test of Epoxy Resin Composite Samples

Figure 5.10 shows the stress versus strain curves from the flexural tests and that if a composite has more layers it will take more stress and strain.

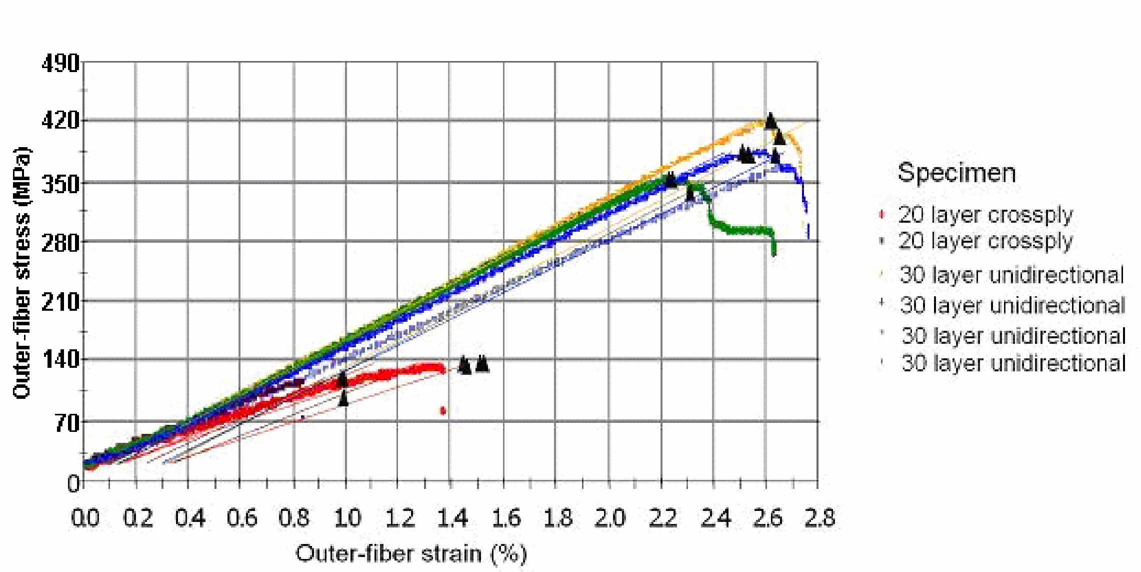


Figure 5.10: Flexural Test Data of Epoxy Composite Samples

Figure 5.11 shows the stress versus strain curves from the flexural tests and that if a composite has more layers it will take more stress to induce the same amount of strain and that the composites are a significant improvement over the neat resin.

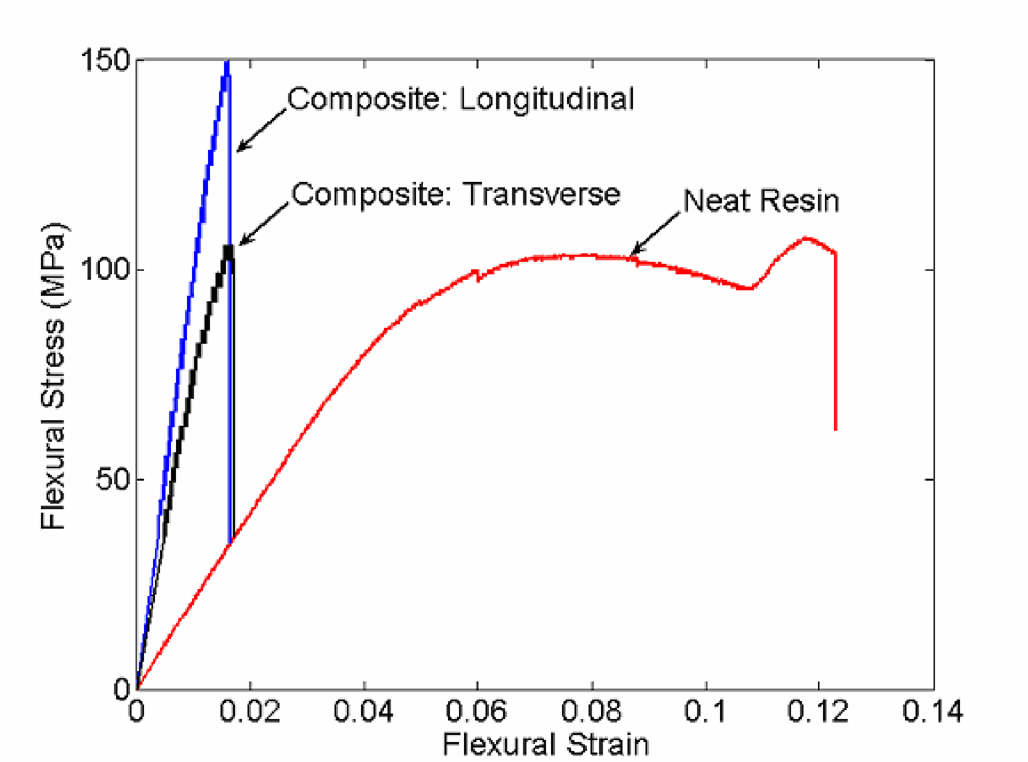


Figure 5.11: Flexural Test of Neat Epoxy Resin and Composite Samples

Figure 5.12 shows the stress versus strain curves from the flexural tests on the epoxy resin samples, that if a composite has more layers it will deflect less before fracture during a flexural test and that the composite is a significant improvement over the neat resin.

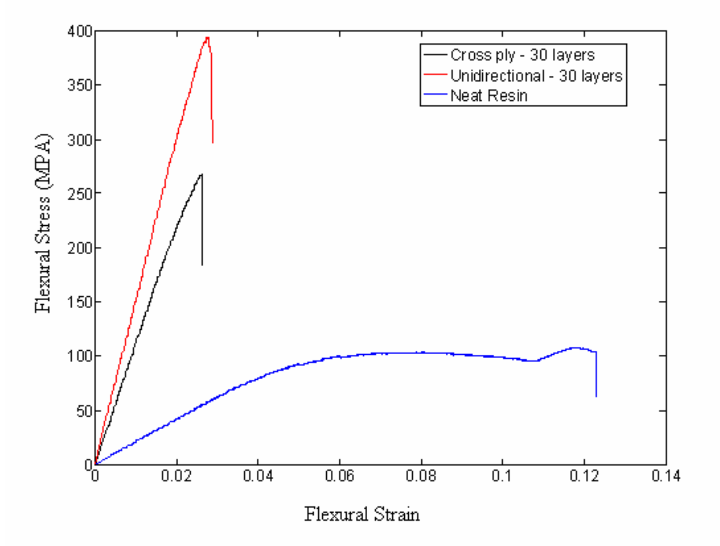


Figure 5.12: Flexural Test of Neat Epoxy Resin and Composite Samples

Figure 5.13 shows the stress versus strain curves from the flexural tests on the epoxy resin samples and that if a composite has more layers it will deflect less before fracture during a flexural test and that the composite is a significant improvement over the neat resin.

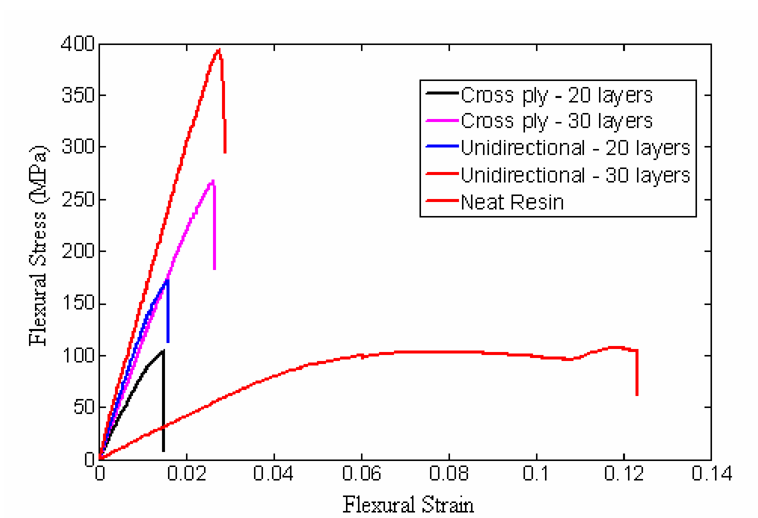


Figure 5.13: Flexural Test of Neat Epoxy Resin and Composite Samples

Table 5.3 shows some of the properties of ribbon reinforced transparent composites obtained from the flexural testing.

Table 5.3: Flexural Properties for Glass Ribbon Reinforced Optically Transparent Composites

| Sample | Flexural Strength (MPa) | Flexural Modulus (GPa) |
|---|---|---|
| Neat Epoxy Polymer | 104.1± 2.8 | 2.06 ± 0.45 |
| $[0/90]_{20}$ – Longitudinal | 148.9 ± 3.4 | 9.1 ± 0.65 |
| $[\text{Unidirectional}]_{30}$ – Longitudinal | 383.41 ± 28.27 | 15.48 ± 1.02 |
| $[0/90]_{30}$ – Longitudinal | 261.1 ± 5.79 | 10.12 ± 0.21 |

## 5.4 IMPACT

A Dynatup Instron Model 9250 Impact Testing Machine shown in Figure 5.14 with impulse control and data system was used to carry out the low velocity impact tests. The maximum physical drop height of the machine is 1.25m (49.2in) and can simulate a maximum drop height of 20.4m (803.1in). The impact test instrument has a motor and twin screw drive for rapid crosshead retrieval after impact. The impulse control and data system includes an impulse software controller panel for test configuration and high-speed impulse signal conditioning unit. The impulse data software can calculate total energy, contact force, impactor displacement and impactor velocity as a function of time. A typical impact test lasted for around seven milliseconds. The measurement of contact force, transient deflection and impact energy can be used to assess the extent of damage in composite structures. The fixture in the impact-testing machine has the capability to test 7in x 10in specimens supported over a 5in x 5in opening. As the samples were 2in x 2in, a fixture with an opening of 1.75in x 1.75in was used for the impact tests. The fixture opening was kept at 1.75in to ensure that the test specimens were clamped along all four edges. The impactor had a mass of 6.88kg (15.2lbs) and a diameter of 0.0127m (0.5in). An energy level of 5J was analyzed.

Three specimens were tested for the resin formulation at that energy level. The specimen was first clamped in the fixture. The impactor mass was then raised to the desired drop height corresponding to the energy of impact. The impactor was then dropped onto the clamped specimen. The impulse control data acquisition system was triggered to start acquiring data when the impactor made contact with the specimen.

Figure 5.14: Impact Testing Machine at UMR

Figure 5.15 shows the contact force versus time from the impact tests at 5J on the epoxy resin composite samples. The figure shows that the more layers a transparent composite has the better it can resist a transverse force during an impact test.

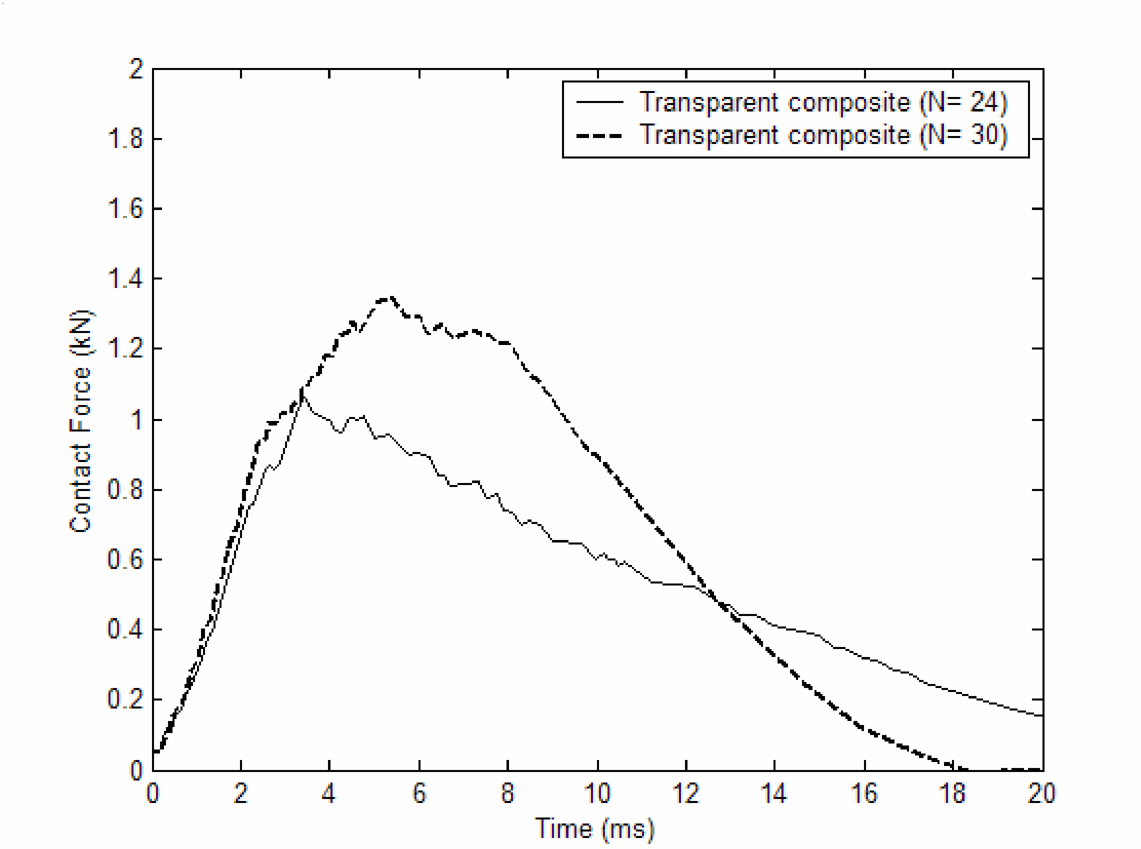


Figure 5.15: Impact Test at 5J for Epoxy Resin Coated Glass

Figure 5.16 shows the energy absorbed versus time from the impact tests at 5J on the epoxy resin composite samples. The figure shows that the 30 layer composite absorbed only four joules of energy during the impact test and that the 24 layer composite absorbed all five joules.

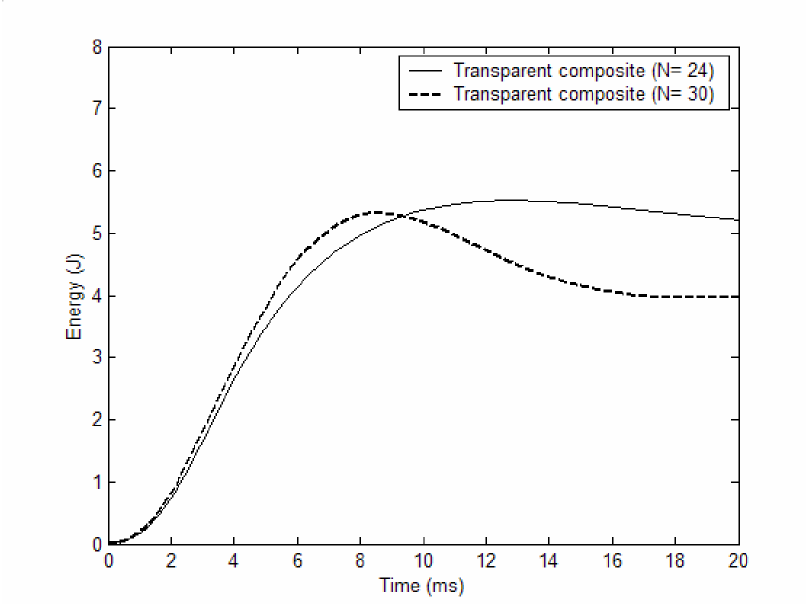


Figure 5.16: Impact Test at 5J for Epoxy Resin Coated Glass

Figure 5.17 shows the velocity of the impactor versus time from the impact tests at 5J on the epoxy resin samples. The figure shows that the more layers a composite has the lower its velocity will be during an impact test.

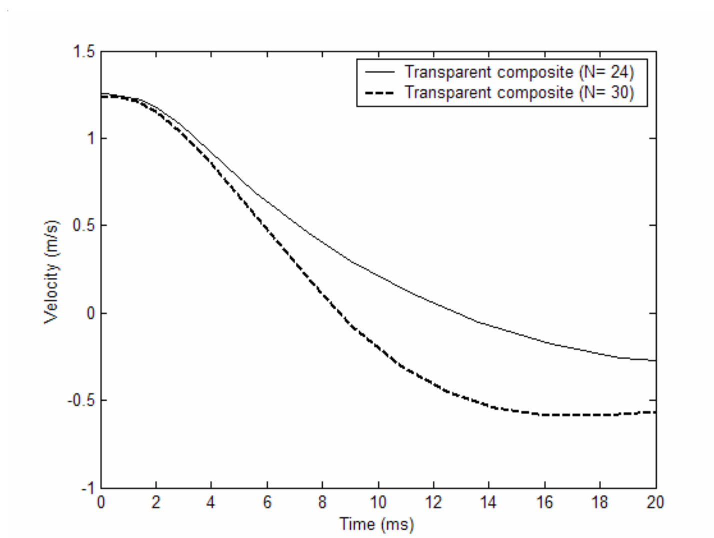


Figure 5.17: Impact Test at 5J for Epoxy Resin Coated Glass

Figure 5.18 shows the displacement of the impactor versus time from the impact tests at 5J on the epoxy resin samples. The figure also shows that if a composite has more layers it will be displaced less during an impact test.

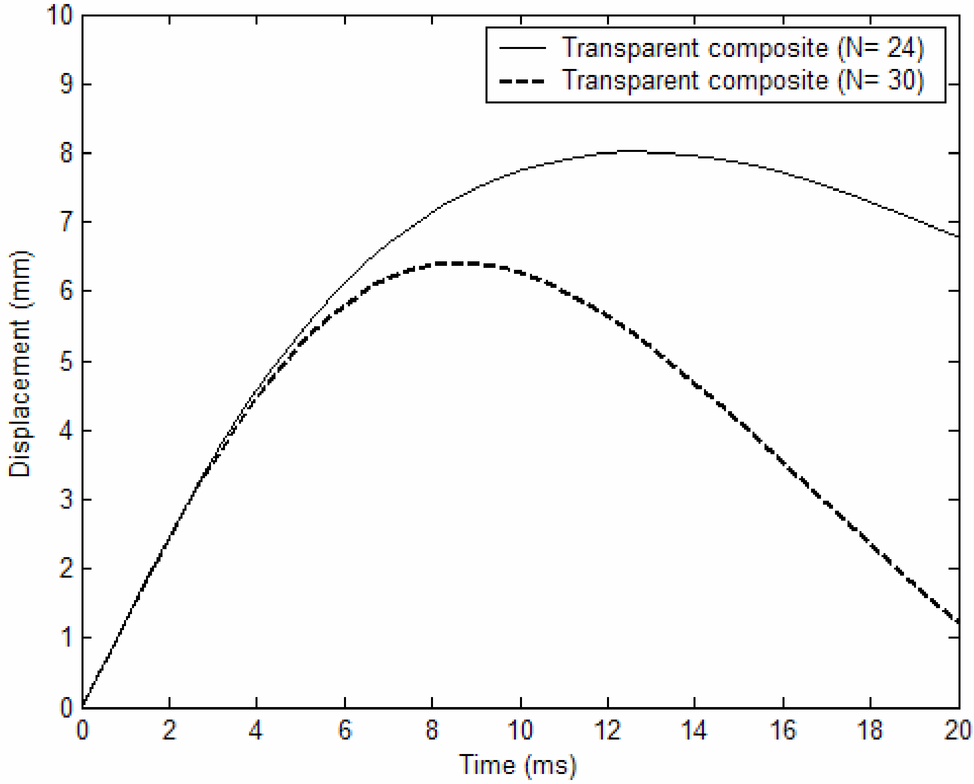


Figure 5.18: Impact Test at 5J for Epoxy Resin Coated Glass

Figure 5.19 shows the damage caused by impact testing on the samples. The damage inflicted on the 24 layer sample is much greater than the damage done to the 30 layer sample. The ribbons are easily seen after the testing is complete. The exposed ribbons makes the damaged areas easily detectable during inspection so that repairs can be arranged.


Figure 5.19: Front View of the Damage Caused by Impact Testing

# 6. CHALLENGES AND RECOMMENDATIONS

With any new project there are always some unforeseen obstacles that occur. Since the autoclave was refurbished several details have needed resolution. Some of the samples used aluminum plates for support. Mylar covered the plates to give the samples a smooth surface. Other samples had breather between the glass molding and a flat aluminum plate. Still, others had glass molding for support and an aluminum flat plate underneath. The samples with glass molding had glass plates on top to distribute the pressure evenly. The Mylar samples had aluminum covered Mylar on top to distribute the pressure evenly. Several of the glass moldings cracked or shattered during the curing cycle of the resin. The next run of the autoclave had the ramp up and ramp down parts of the cure cycle slowed down to 2.2°C (4°F) per minute. The aluminum plates with Mylar did not give the clarity that was desired in the sample. Because of this, all glass moldings are now being used. Pyrex glass also proved to be vulnerable to rapid temperature changes and have shattered or broken. It is important to use only one caul plate, flat and weighted plate, per sample; one caul plate for several samples will not distribute the weight properly and will cause the moldings to break. Glass plates of the same size are also necessary because the gaps between the caul plate and the lower molding are too big. Support of the bag can be obtained by placing some breather material between the bag and the plates but it is always a risk that the bag will stretch beyond capacity and burst. Problems can also arise when liquid nitrogen runs out. If even one bag bursts or tears, a 226.8kg (500lbs) bottle of liquid nitrogen can be spent before the cycle is complete. This is due to the fact that there is not enough nitrogen to keep up with the vacuum suction.

An air compressor has been used to substitute the nitrogen pressure. The air compressor was able to maintain the pressure in the autoclave adequately, but is not an appropriate substitute for pressurizing the autoclave.

## 7. CONCLUSIONS

Glass ribbon reinforce transparent composites that are light in weight, load bearing and have a high impact resistance have been manufactured using the autoclave process. The ribbon reinforcement helped make it possible to get the clarity required. The testing showed that the composite is a great improvement over the neat resin and that for greater strength and stiffness a greater number of layers in the axial direction will be required. The testing also shows that the transparent composites have a high impact resistance. Aircraft that have transparent composite windows will be lighter and more fuel efficient than commercial aircraft currently in use. A police officer or soldier utilizing transparent composite shielding will have a longer endurance than a person using current methods for protection.

The objective of this research was to manufacture a transparent panel that has high impact resistance, is light in weight and is high in strength which also has enough transparency to clearly see objects and text on the opposing side. Curved shapes present another call for research, the convex or concave shape of the composite will cause light to converge or diverge as it is transmitted. The convergence or divergence will cause light to shift in a manner that will distort objects on the opposing side. Future development of transparent composites will include curved shapes such as canopies for fighter planes or helmets for astronauts and; eventually, shapes as complex as lighting fixtures can be achieved.

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