FAILURE OF TRANSPARENT POLYMER COMPOSITE LAMINATED GLASS PANELS UNDER IMPACT LOADING

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ABSTRACT

Historically, windows and other facilities during hurricanes have experienced significant damage exposing the occupants and the building envelope to uncomfortable and dangerous conditions. A new approach to the design of window glass panels with hurricane damage resistance has been carried out in this research work. This has been achieved by developing transparent fiber reinforced polyester composites as the interlayer in the laminated glass panel. Transparency in the composite interlayer has been achieved by matching the refractive indices of the glass fibers with the polyester resin. The composite interlayer provides a higher strength, stiffness and damage resistance compared to the traditional PVB interlayer. The panels have been evaluated by conducting 3-point bend tests to determine bending stiffness, lap shear tests to determine the bond strength of the adhesive that is being used to bond the interlayer to the glass, and large missile impact loading tests to study their expected damage behavior during a hurricane.
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CHAPTER 1

INTRODUCTION
INTRODUCTION

Project Objectives:
The conventional Laminated glass consists of a plastic interlayer made of polyvinyl butyral (PVB) bonded together between two panes of glass under heat and pressure. The laminates are prepared by the use of two sheets of heat-strengthened, annealed or tempered glass. Annealed glass is the most common glazing material used in residential windows. It has good thermal stress resistance and generally shatters producing large shards of glass. Tempered glass is produced by heating annealed glass and then rapidly cooling the glass by blowing air on both surfaces of the glass which gives additional strength, resistance to thermal stress and impact resistance due to compressive residual stress generation. Tempered glass is stronger than annealed glass of the same size and thickness. When tempered glass is broken it breaks into very small pieces. One problem that exists with tempered glass is spontaneous breakage. When broken it crumbles into tiny cubes and presents minimal potential to produce injury due to sharp shards.

The typical breaking stress is 6,000 psi for annealed glass and 24,000 psi for tempered glass [1]. The typical impact velocity causing fracture of glass using a 2gm steel ball for missile impact normal to the surface is 130 ft/sec at 30 impacts. Since tempered glass breaks into relatively small and harmless fragments this reduces the likelihood of injury to people as there are no jagged edges or sharp shards. The building industry uses tempered glass in most of their applications as it is very effective and also very economical. Heat strengthened glass is about twice as strong as annealed glass of the same size and thickness. Heat-strengthened glass is produced by heat treating annealed
glass under regulated thermal conditions. In this process, annealed glass is carefully heated in a furnace and then quickly air-cooled. This sudden cooling causes a compression envelope around the glass surface and edges, along with a balanced tension stress within the glass itself. This equilibrium of stresses increases the strength of the glass to approximately two times that of the original annealed product [2]. One of the benefits of using heat strengthened glass is that it is far less susceptible to spontaneous breakage. The use of heat strengthened glass is recommended for skylights. It offers increased resistance to impact, wind loads and thermal stress breakage. Heat strengthened glass generally fractures in a manner similar to annealed glass. Heat-strengthened glass is widely used in constructing laminated glass for additional strength such as in overhead and sloped glazing. Heat treated glass will withstand greater thermal shock than the same thickness and configuration of annealed glass. Thermal shock results when a rapid temperature change between the surface and core of the glass occurs. When this temperature differential is of sufficient magnitude the glass will fracture. To fracture 1/4" (6 mm) annealed glass the average temperature differential should be approximately 100°F (38°C). To fracture 1/4" (6 mm) heat-strengthened and tempered glass, the average temperature differential should be about 250°F (121°C) and 400°F (204°C) respectively [3].

The goals of this research work are to use the glass fiber reinforced polyester matrix composite as an interlayer in laminated window panels and study the failure of these laminated panels under impact loading. In this research the glass fiber reinforced polyester resin composite and polyurethane adhesive has been used to achieve greater
strength and durability. These are prepared for better properties so that they can withstand flying debris during hurricane force winds and thereby act as a protective shield.

**Introduction to Composite Materials:**

Composite materials are engineered materials made from two or more constituent materials on a macroscopic scale with significantly different physical or chemical properties and which remain separate and distinct within the finished structure. Some of the major advantages of composites are that they are economical, light in weight, have high strength and stiffness, are weather resistant, corrosion resistant, have low thermal conductivity and high dielectric strength. Generally, a composite material is composed of reinforcement (fibers, particles, flakes, or fillers) embedded in a matrix (polymers, metals, or ceramics). The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix. When designed properly the new combined material exhibits better strength. Based on the form of reinforcement, composites are classified as fiber reinforced particulate, flake and filler composites as shown in Figure 1.

Glass reinforced plastic is a fiber reinforced plastic made of a plastic, reinforced by fine fibers made of glass. The reinforcement is provided by fine threads or fibers of glass often woven into a sort of cloth and the matrix is a plastic. The plastics are polymers that hold the reinforcement together and help to determine the physical properties of the end product.
The threads of glass in fiberglass are very strong under tension but they are also brittle and will snap if bent sharply. The matrix not only holds the fibers together, it also protects them from damage by sharing any stress among them. The matrix is soft enough to be shaped with tools and can be softened by the use of suitable solvents. Fibers have a very high modulus along their axis but have a low modulus perpendicular to their axis.

For the matrix, thermosetting plastics also called resins are used. Thermosetting plastics are liquid when prepared but harden and become rigid when they are heated or chemically cured. These plastics also resist wear and attack by chemicals making them very durable, even when exposed to extreme environments. Thermoplastic resins can be repeatedly melted and solidified by heating and cooling so that any scrap generated in processing can be reused. No chemical change generally takes place during their formation. Resins (liquid plastics, i.e. epoxies, polyesters and vinyl esters) are commonly
used in many applications when wetting out fiber reinforcing in order to saturate the fibers and form an FRP (fiber reinforced plastic) part. Fiber adhesion and the wetting of the fibers is a critical step in the production of a quality part. Polyesters are one of the least expensive resins available. Polyester resins are best compatible with fiberglass fibers. Well formulated epoxies yield greatest degree of bond strength and toughness. Resins with low viscosity and accurately tailored gel and cure times are considered to be very ideal for use.

The strength of the composite depends on many factors such as the fiber length, fiber volume/fiber fraction, its bonding characteristics with the matrix and its orientation with respect to the stress direction. In order to improve the wetting of the fibers with the matrix coupling agents such as silanes are used and coatings are applied which also promotes covalent bonding across the fiber/matrix interface. The glass fiber reinforced plastics incorporate fibers in various formats such as multidirectional and unidirectional, continuous strand mat, chopped strand, long and short fibers. Mariatti and Chum [4] have shown that unidirectional laminated composites are preferred for high performance structural applications due to their high specific strength and high specific stiffness. The optimum design of composite laminated materials has been a subject of research for many years.

The most commonly used fibers are E-glass, S-glass, Carbon and Boron fibers. Carbon and Boron fibers are very expensive. The use of E-glass as the reinforcement material in polymer matrix composites is extremely common. Optimal strength properties are gained
when straight, continuous fibers are aligned parallel in a single direction. S-glass is generally used for polymer matrix composites that require improved mechanical properties compared to E-glass based composites. This is often the case when the material is operated under more extreme conditions.

Some of the key properties of the use of E-glass are that it has low cost, high strength, high stiffness, good chemical resistance and ability to maintain strength properties over a wide range of conditions. E-glass fibers are used when high tensile strength and good chemical resistance are required, which makes these fibers a preference in structural applications. Table 1 gives some typical properties of E-glass and S-glass fibers.

<table>
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<th>Tensile Strength (kpsi)</th>
<th>Tensile Modulus (Mpsi)</th>
<th>Strain (%)</th>
<th>Tensile Ratio</th>
<th>Diameter Range (μm)</th>
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<td>E-glass</td>
<td>0.094</td>
<td>500</td>
<td>11</td>
<td>4.76</td>
<td>1.1</td>
<td>3-20</td>
<td>1.55</td>
<td>0.75-1.00</td>
</tr>
<tr>
<td>S-glass</td>
<td>0.09</td>
<td>700</td>
<td>14</td>
<td>5.15</td>
<td>1.5</td>
<td>8-13</td>
<td>1.54</td>
<td>6.00-8.00</td>
</tr>
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Since composites have high strength, stiffness, corrosion resistance, light weight, weather resistant and high dielectric strength extensive research is carried out by utilizing these characteristics in improving the material science and manufacturing processes. The use of composites because of their characteristics in aerospace, marine, automobile, civil and nuclear fields has become a major issue. In the United States, composites manufacturing is a 25 billion dollar a year industry. According to the American Composites Manufacturers Association (ACMA), about 90% of all composites produced are comprised of glass fiber and either polyester or vinyl ester resin. 65% of composites are manufactured using the open molding method. The fiber reinforced plastic market was estimated at almost 1.04 million metric tonnes (2.3 billion lbs) in 2002, and is expected to increase by 15% in volume by 2007. These figures are forecast in a study released from Business Communications Co, Inc, Composites: Resins, Fillers, Reinforcements, Natural Fibers and Nano composites (Report number RP-178). According to the report the market for fiber reinforced plastics will grow at an average annual growth rate (AAGR) of 3% and also increasing to 1.2 million tonnes in 2007. The emergence of several new technologies warrants a reappraisal of the reinforced plastics market. The use of composites in automotive applications account for 719 million pounds and are expected to rise at an AAGR of 2.5 % by 2007. Construction applications will rise at an AAGR of 2.7% by 2007 as shown in Fig 2.

A hurricane’s turbulent winds and strong gusts of air often carry windborne debris which can slam into glass windows and doors. Once the window panels are broken the
protective exterior envelope of a building is compromised allowing strong winds to rush into the building creating internal pressurization within the structure.

The trapped wind forces then push upward on the roof and can cause the roof to be blown away. Laminated glass windows made with a plastic interlayer can help to maintain the important exterior envelope of a building. Ideally upon impact the glass may crack on the impacted side but the pieces tend to adhere to the plastic interlayer material which does not puncture and thus protects the building from strong wind forces. Monolithic glass panels break easily during strong wind storms and the broken glass themselves become windborne debris which causes destruction and is hazardous. In case of laminated glass panels since the broken glass plies still adhere to the polymer interlayer they do not become windborne debris but often the interlayer is punctured.

Figure 2. Fiber reinforced plastics market by application, 2002
Figure 3 shows the basic structures of a monolithic and a laminated glass with a PVB interlayer.

The conventional Laminated glass consists of a plastic interlayer made of polyvinyl butyral (PVB) bonded together between two panes of glass under heat and pressure. This glass provides high durability and high performance preserving the aesthetic appearance of the glass. It reduces the danger of flying or falling glass, resists penetration and forced entry and blocks out unwanted external noise. An important characteristic of laminated glass is that even though the outer glass ply fractures upon impact the inner ply remains intact and protects the buildings.
This research emphasizes the use of glass fiber reinforced polyester matrix composite as an interlayer in window panels to achieve greater strength, durability and impact resistance. The failure analysis of these panels under impact loading has been studied and their mechanical properties determined so that the laminated panels could be used as a substitute for exterior glass panels in architectural structures for protection against strong windstorms and also the impact from windborne debris.

Hurricanes are the costliest and deadliest disasters in the United States. Hurricanes have winds of at least 74 miles per hour. When they come onto land, the heavy rain, strong winds and heavy waves can damage buildings and can lead to destruction of property and life. Previous research into long term trends in hurricane caused damage along the U.S. coast has suggested that damage has been quickly increasing within the last two decades. There has been severe destruction to property and life due to hurricanes over the coastline of United States. Data on the economic impacts of hurricanes are published annually in Monthly Weather Review. The National Oceanic and Atmospheric Administration (NOAA) have been studying the effects of hurricanes from a century. Figure 4 tells the impact of hurricanes on society [5]. The loss in property due to hurricanes is in billions of U.S. Dollars and is highest among all other natural disasters.
Figure 4. Destruction caused due to hurricanes on property and life

All Hurricanes are dangerous but some are more so than others. The way storm surge wind and other factors combine determine the hurricanes destructive power. To make comparisons easier and to make the predicted hazards of approaching hurricanes clearer to emergency managers, National Oceanic and Atmospheric Administration's hurricane forecasters use a disaster potential scale which assigns storms to five categories. This can
be used to give an estimate of the potential property damage and flooding expected along the coast with a hurricane. This scale is known as the Saffir-Simpson scale and is shown in Figure 5. The Saffir-Simpson Hurricane Scale is a 1-5 rating based on the hurricane's present intensity. This is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale as storm surge values are highly dependent on the slope of the continental shelf and the shape of the coastline in the landfall region.

![Figure 5. The Saffir-Simpson Scale](image)

In an effort to improve the quality of housing the building industry recognized the need to evaluate the actual performance of residential construction during hurricanes. Since the disaster caused by Hurricane Andrew in 1992, protection of glazing (i.e. windows and...
doors on the exterior of homes and other buildings) from wind borne debris damage has received much attention. Glass breakage in residential buildings during Hurricane Andrew was extensive [6]. Hurricane Andrew produced wind of gusts of up to 165 mph. On the other hand, glass breakage in Hurricane Opal was minimal with design level wind gusts of about 110 mph over much of the affected housing population. Hurricane Opal provided a unique opportunity to assess the damage to residential construction under conditions similar to the expected design conditions [7]. Debris impact on glass is a very important design consideration for any structure that is designed to resist a hurricane event. Many types of objects including gravel, 2” x 4” wooden members, and sheets of plywood can be picked up and carried by hurricane force winds. The consequence of impact of these types of objects to the building envelope can be quite extreme. If a building envelope component is not designed to resist the penetration of windborne debris, the debris and the building components that are carried with it can severely injure anyone inside the building. An opening on the windward wall of a building of only 5% is enough to allow full internal pressurization that effectively doubles the pressures acting to lift the roof and push the side walls outward [7]. In extensive wind damage surveys conducted throughout the 1970s, a common pattern was observed [7]. Small debris, principally roof gravel, can be carried into all elevations of building facades at velocities sufficiently large to break glass. In an effort to simulate wind debris risk, wind exposure and shielding were found to have a pronounced effect on relative reliability estimates. In addition, roof shingles were found to be a dominant source of wind borne debris in residential settings. The most recent national model building codes have adopted ASTM E1996 [8] and ASTM E1886 [9] as the acceptance criteria for window and door
protection systems or impact resistant glass. The consideration of wind borne debris has become an important aspect of design for coastal regions of the country where buildings are subjected to severe wind events such as hurricanes. Also a lot of improvements in hurricane forecasting, awareness and emergency preparedness have resulted in a decline in the numbers relating to the loss of life due to hurricanes. The hurricanes act in unique ways to cause damage to buildings and this peculiar behavior of the effects of hurricanes leads to the modification of the test standards constantly based on the ongoing research and experiences.

The damage caused by wind borne debris has been under intense focus to study the impact of hurricanes on architectural glazing systems. Hurricane winds are known to be more turbulent and last for longer durations. These winds have caused a lot of damage to the buildings. The intensity of the effects can be known by studying the impact of various hurricanes that struck United States over a few decades. In the last decade there has been severe and widespread damage caused by some deadly hurricanes. Some of the devastating hurricanes were Hurricane Fran (1996) in North Carolina, Hurricane Bret (1999) in Texas, Hurricane Charley (2004) in Florida, Hurricane Katrina (2005) in Florida and Hurricane Rita (2005) in Florida. These hurricanes caused extensive damage to life and property. It was reported that 80% of the glass that broke in Texas was due to wind borne debris. The same was true to the glass broken in parts of Florida and North Carolina. Figure 6 shows some devastating pictures of the recent hurricanes on buildings [10].
Debris impact resistance is an important consideration when designing for hurricanes. There are a number of different codes and standards that have established criteria for building envelope components to be deemed “debris impact resistant.” The procedure to determine the debris impact resistance and subsequent cyclic pressure loading resistance of building envelope components are known. Depending upon the installed height of the component above the ground and the wind zone classification of the building, the components are subjected to small or large missile impacts followed by cyclic pressure loading. The Florida Building Code (SBCCI, 2001) requires that all building envelope components located up to and including 30 ft above the ground are required to pass the large missile impact test in which the specimen is impacted with a 9 lb. wooden member having nominal cross-sectional dimensions of 2" x 4" traveling horizontally with a constant velocity of 50 ft/s (34 mph).
Building envelope components located at heights greater than 30 ft above the ground are required to pass the small missile impact test, in which the specimen is impacted with 10 solid steel balls, each weighing 2 grams, traveling at 130 ft/s (89 mph).

The quality of high strength coupled with extended fatigue life and light weight have led to the use of composite materials in several industries. However, these materials are very sensitive to the damage caused by impacts. Indeed, impact damage modes like delamination can seriously affect the engineering properties of a composite structure. Azouaoui et al. [11] conducted impact fatigue tests of glass/epoxy composite plates subjected to impact loading to study the damage under the effect of impact at low velocity. Several studies have been made on the damage induced by impact. These studies led to classification of the damage into three categories: matrix cracks, delamination and fiber breakage [12]. The composite used was R368 Epoxy resin reinforced with E-glass fibers. They observed that delamination occurred in the first cycles of shock loading. Delamination occurred initially in the interface furthest away from the impact point (i.e., interface of the last layer) and then new delaminated surfaces were created in other interfaces. Thus slowly multiplication of delaminations was observed. It led to the saturation of the delaminations and the next phase was observed that is the ply cracking with fiber breakage [13].
Consider a ply of a fabric reinforced material as shown in Figure 7. Each fabric warp or Weft layer can be treated as an equivalent unidirectional layer, i.e. the fabric layer is Treated as 0/90 cross-ply composite. The main types of damage which have been observed in beam impact tests are matrix cracks normal to the x-axis and matrix cracks that are not normal to the x-axis. These matrix cracks can be seen clearly in figure 7. For the fabric reinforced epoxy composite as used in the tests on small beams three types of damages were observed in the tests: damage related to matrix cracks, damage related to fiber breakage and damage due to delaminations [14]. Impact tests were carried on glass fabric reinforced epoxy (SRGFE) composites. Most tests were carried out on an 8-ply and 16-ply material.

Figure 7. Schematic view of damage variables in a composite panel under impact
The specimens were struck at their centre by a steel cylinder (diameter 1cm) launched by a pneumatic gun, the velocities being in the range 6–33 m/s and the mass ranging from 9.46 g to 49 g. The first damage consisted of distributed cracking in the matrix. A large number of minute cracks were formed, perpendicular to the principal tensile stress. Matrix cracks gradually developed across the whole thickness and the whole length of the specimen. The final stage of damage was fiber breakage, accompanied by disintegration of the matrix. The development of fiber damage was accompanied by irreversible deformation and energy dissipation. Dechaene and Degrieck [15] proposed a lamina based damage model for a woven fabric. The arbitrary structure of interest can be modeled initially using a Finite Element pre-processor to represent the geometrical shape of the composite structure. Once the composite structure has been idealized with a Finite Element mesh, an analysis program, such as DYNA3D, can be used to simulate any impact loading scenarios of interest. Results from such a complex analysis can be viewed on many commercially available post-processors which can produce a graphical representation of damage in each element of the Finite Element mesh. Johnson and Simon [16] proposed another damage model for fiber reinforced composites. The model contains elastic damage in the fiber directions, with an elastic plastic model for inelastic shear effects. The fabric reinforced composite ply is modeled as a homogeneous orthotropic elastic or elastic-plastic damaging material whose properties are degraded on loading by micro cracking prior to ultimate failure.
A continuum damage mechanics formulation is used in which ply degradation parameters are internal state variables which are governed by damage evolution equations. Results reveal that for fabric reinforcements there are two main failure mechanisms: fiber dominated failure in tension or compression in the two fiber directions and matrix dominated failure in in-plane shear.

Paepegem and Degrieck [17] presented a damage model for fiber reinforced composites. To study the dynamic behavior of fiber reinforced composites a series of small scale impact experiments have been performed. During the experiments the displacements, velocities and forces were measured using a contactless optical method. With the use of a high speed camera the onset and growth of damage can be tracked. Moreover the deflection of the specimen during the impact experiment can be calculated with a digital phase-shift shadow Moiré technique. The impact damage model is then implemented in the commercial finite element software ABAQUS/Explicit, and the parameters are determined by comparing numerical simulations with corresponding experimental results. Drop weight tests on full-scale components provide a structural validation for the developed material model.

The effects of laminate thickness on the impact behavior of E-glass polyester laminates were studied by Sutherland and Soares [18]. Laminated panels with different thicknesses were made in order to study the effect of thickness on the impact behavior. These laminated panels were subjected to impact at increasing energy levels, at both the highest and lowest velocities attainable within the falling weight impact test machine.
It was observed that the thinner laminates exhibited failure at low energy impacts than the thicker specimens which exhibited failure at high velocities. Also the thicker plates were observed to be stronger and stiffer than the thinner plates. The impact energy for the damage to occur in thicker plates was indeed higher compared to that in thinner plates. And it was also observed that the thicker laminates gave lower deflections. At higher energies and during high velocity tests the specimens suffered perforation and the reason for this was the effect of the variability of thickness rather than a direct effect of velocity. Hence thickness of the laminate plays a major role when the panels are subjected to impact at high velocities [18, 19].

The choice of a resin system for use depends on a number of characteristics like good adhesion, micro cracking resistance, fatigue resistance and degradation from water ingress. Figure 8 shows the basic mechanical properties of commonly used resin systems which have been cured at 20°C and 80°C for about seven days. Resin system with 20°C has been shown in the figure with light color whereas the resin system with 80°C has been shown with dark color.

![Comparative Tensile Strength and Stiffness of Resins](image)

Figure 8. Comparative Tensile Strength and Stiffness of Resins
It has been observed that the laminate will reach a stress level where the resin will begin to crack away from those fiber reinforcements not aligned with the applied load, and these cracks will spread through the resin matrix. This is known as micro cracking. The strain that a laminate can reach before micro cracking depends strongly on the toughness and adhesive properties of the resin system. For brittle resin systems such as most polyesters this point occurs before laminate failure and so severely limits the strains to which such laminates can be subjected. Also it has been observed that the toughness of a resin influences the impact behavior of any composite. Hence the selection of appropriate resin is very important.

The tensile strengths of polyester laminates have been examined with respect to E-glass fiber unsaturated polyester resin (UPR) interfacial properties by Rota et al. [20]. The tensile strengths of the polyester laminates were determined as a measure of interfacial bond strength. The strength, stiffness and toughness of the interfacial bond, all affect a composite’s ultimate properties and the mechanisms by which it fails. The synthesis of the unsaturated polyester resin was done by varying the composition of styrene. The composition was varied by setting two levels, low and high. The low levels by weight contained 35 % styrene and the high levels contained 45 % styrene. It has been observed that the compositions with low degrees of unsaturation increases the flexibility of unsaturated polymer resins, improves adhesion with E-glass fibers and consequently Increases the tensile strength of polyester laminates. Also it has been observed that lowering the tensile modulus of cured unsaturated polyester resins is followed by reduced tensile strength.
Cartie and Irving [21] studied the effect of resin and fiber properties on impact and compression after impact (CAI). They observed that resin toughness rather than fiber strength and stiffness, is the major parameter influencing CAI performance in quasi-isotropic carbon fiber laminates.

The effect of glass-resin interface strength on the impact strength of fiber reinforced plastics was studied by Lawrence and Broutman [22]. The interface strength was altered by the surface treatment of fabrics by silane coupling agents. The interlaminar shear strength was determined in order to evaluate the interface strength. The total energy for polyester laminates displays a minimum at a critical value of interlaminar shear strength. It was observed that for a polyester laminate the shear strength must be minimized in order to obtain the maximum impact energy.
CHAPTER 2

METHOD OF PREPARATION OF TRANSPARENT POLYMER COMPOSITE LAMINATED GLASS PANELS
This chapter describes the process followed for fabrication of transparent glass fiber reinforced polyester interlayer and their lamination with glass sheets.

In this research E-glass fibers have been used which are low cost general purpose type fibers. E-glass fibers are available in different forms based on different applications. The most common classifications of them are roving, chopped strand, chopped strand mat and woven roving. Woven fabrics are selected for this research as they exhibit good stability along with high impact resistance and toughness. The type of E-glass woven fabric used in this research is shown in Figure 9 below.

![Glass fiber cloth](image)

Figure 9. Glass fiber cloth

For the matrix many composites use thermosetting or thermoplastic polymers also known as resins. The plastics are polymers that bond to the reinforcement and help to determine
the physical properties of the end product. Thermosetting materials or thermosets are formed from a chemical reaction in situ where the resin and catalyst are mixed and then undergo a non reversible chemical reaction to form a hard, infusible product. Thermosetting resins like polyester and epoxy are easy to process as they cure with simple mechanisms. Once cured thermosets will not become liquid again if heated although above a certain temperature their mechanical properties will change significantly. Polyester resins are capable of being cured from a liquid or solid state when subjected to the right conditions. Most polyester resins are viscous, pale colored liquids consisting of a solution of polyester in a monomer, which is usually styrene. The addition of styrene in amounts of up to 50% helps to make the resin easier to handle by reducing its viscosity [23].

The styrene also performs the vital function of enabling the resin to cure from a liquid to a solid by cross linking the molecular chains of the polyester, without the evolution of any by products. These resins can therefore be moulded without the use of pressure and are called contact or low pressure resins. Polyester resins have a limited storage life as they will set or gel on their own over a long period of time. Often small quantities of inhibitor are added during the resin manufacture to slow this gelling action. For use in moulding a polyester resin requires the addition of several ancillary products.

For this research we have used Methyl Ethyl Ketone Peroxide (MEKP) as the initiator and Cobalt Naphthenate as the accelerator to cure the resin. Resins can be formulated to the moulders requirements simply by the addition of an accelerator prior to moulding. This rate of polymerization is too slow for practical purposes and therefore accelerators
are used to achieve the polymerization of the resin within a practical time period. An accelerator is added to the resin to enable the reaction to proceed at room temperature and at a greater rate. With the addition of styrene, the styrene cross links the polymer chains at each of the reactive sites to form a highly complex three dimensional network. The polyester resin is then said to be cured. It is now a chemically resistant hard solid. Great care is needed in the preparation of the resin mix prior to moulding. The resin and any additives must be carefully stirred to disperse all the components evenly. Vacuum degassing is employed to ensure that the resin has no air bubbles after mixing. It is also important to add the accelerator in carefully measured amounts to control the polymerization reaction and to give the best material properties for a given application. Too much of the accelerator will cause too rapid a gelation time, whereas too little will result in under cure.

Apart from polyester resin we have also used Polyurethane resin in this research as an adhesive to bond the composite interlayer to the glass sheets. Polyurethane is the generic term for the cured product which is formed from a chemical reaction between a polyol resin and a polyisocyanate hardener. They are two part resin systems where the base resin and the hardener are combined just prior to the application. When the two components are mixed a three dimensional molecular structure is produced. This forms a solid resin which gives optimal mechanical properties. Polyurethane resins cure faster than epoxies and polyesters. The major advantages of polyurethanes are that they provide good adhesion, they are water resistant, their cure speed is excellent, and they have very good gloss retention and excellent abrasion resistance. Dvorak and Suvorov [24] observed that the polyurethane interlayer better supports the impacted face sheet than epoxy interlayer.
Therefore, where there is a requirement for good adhesion and water resistance as well as high gloss and color stability (i.e. non-yellowing) polyurethane systems can be used in order to obtain the desired properties.

**Fabrication of Composite Interlayer:**

Though there are several techniques that have been developed for the preparation of a fiber reinforced polymer matrix composite the use of the Hand Lay-up technique remains to be the simplest technique till date. In this research we have used the Hand Lay-up technique for simplicity and also since the production volume is very low. The first step involved in composite fabrication is the mold preparation. The outer shell of the mold, i.e. the base and the upper cover, are made of one inch thick acrylic sheets. Mylar sheets were used to cover the surface of the acrylic. The use of Mylar prevents the resin from sticking on to its surface while curing, so the composite can be easily removed from the mold. A frame that would serve as a mold is made out of four 1.0" and 1/8" thick wide Aluminum bars. These bars are machined as per the dimensions required for the frame, as shown in figure 10. A coat of wax is applied to the Aluminum bars which would provide easy release after curing. This frame is assembled on the base of the mold. Care is taken to keep the bars of the frame in place by applying suitable adhesives.
The second step involves preparing the resin. The quantity of resin required to make a composite is taken in a beaker. Suitable proportions of MEKP and Cobalt Naphthenate are added and mixed together. The mixture is set aside in a vacuum degassing chamber so as to allow the air bubbles to escape by creating vacuum inside the chamber. Figure 11 shows the vacuum degassing chamber that has been used.
Then a small amount of the resin mixture is poured into the mold so as to wet the base surface. At this stage a layer of fiber cloth which has been cut to the desired dimensions is placed in the mold and gently some more resin is poured on top of the cloth. Any entrapped air bubbles are removed using a spatula by gently compacting the glass cloth against the mold. This process is repeated to build up the desired thickness and fiber volume fraction in the composite.

Care should be taken to ensure that there must be no air bubbles left in the mold. If there are any air bubbles present then they are being gently removed by using a spatula.
Now at this stage the mold is closed and pressure is applied by clamping the mold with the help of C-clamps as shown in Figure 12. The mold is allowed to cure for 36-48 hours.

![Mold clamped with C-clamps](image)

**Figure 12. Mold clamped with C-clamps**

**Fabrication of Laminated Glass Panel:**

Laminated glass is prepared by sandwiching the composite interlayer between two annealed or heat strengthened glass plies. A two part polyurethane resin mixture is used as an adhesive between the interlayer and glass.

The procedure for laminated glass fabrication is as follows:

1) The glass ply is placed on a table and a thin layer of the polyurethane resin mixture is evenly spread on the upper side of the ply.

2) The interlayer is placed on it. Suitable pressure is applied to evenly spread the urethane and help in removing any entrapped air bubbles.
3) A thin layer of the resin mixture is evenly spread on the upper side of the interlayer and the second glass ply is placed over it. Again suitable pressure is applied to the top of the glass sheet.

4) Guides are placed on all sides in order to prevent the glass plies from moving relative to each other.

5) The setup is left to cure for about 36-48 hours at room temperature.

In order to achieve better bonding between glass and resin, the glass was pre treated with a coupling agent or silane. Glass is typically coated with a silane to improve its bond strength with the resin matrix and thereby increases the service life of the composite. A silane like 3-aminopropyltrimethoxysilane promotes adhesion of polymer resin to cured polymer substrates by first reacting with the OH groups on the substrate with the silane functional group. This forms a strong chemical bond providing the substrate with reactive attached amino groups to form a chemical bond to a polymer. If the silane such as 3-aminopropyltrimethoxysilane has to react with both the cured polymer substrate and the polymer resin that is applied to the substrate through the amino group, the silane can be applied to the surface of the substrate through reaction with water or hydrolyzing in the silane formulation and/or in atmosphere. This forms a thin highly cross linked polyaminopropylsilesquioxane layer which promotes adhesion between the two polymer layers. It is achieved by the reaction of the layers with the aminopropyl group. An additional benefit is the improved dispersability of silanated fillers in matrix monomers. Composites with silanated fillers possess superior mechanical properties and wear resistance and increased resistance to water absorption when compared with composites
containing non-silanated fillers. The procedure for the application of silane coating on glass is as follows: A 95% ethanol-5% water solution is adjusted to pH 4.5-5.5 with acetic acid. Silane is added with stirring to yield a 2% final concentration. Five minutes should be allowed for hydrolysis and silanol formation. The glass plates are dipped into the solution, agitated gently, and removed after 1-2 minutes. They are rinsed free of excess materials by dipping briefly in ethanol. Particles, e.g. fillers and supports, are silylated by stirring them in silane solution for 2-3 minutes and then decanting the solution. The particles are usually rinsed twice briefly with ethanol. The silane coated glass/composite surface is cured for 5-10 minutes at 110 °C or for 24 hours at room temperature.
CHAPTER 3

MECHANICAL TESTING OF REINFORCED COMPOSITE WINDOW PANELS
Introduction

Mechanical characterization of the laminated panel and the bond between the interlayer and glass sheets has been conducted using the 3-point bend tests, lap shear tests and impact tests. 3-point bend tests and impact tests were carried out on laminated glass panels while lap shear tests were carried out to determine the bond strength obtained with polyurethane and polyester as an adhesive. The composite interlayer consists of E-glass cloth reinforced polyester matrix. Bend testing is a quality control test which determines the strength of a material by bending the material.

3-Point Bend Testing:

The bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material. It is often used as a quality control test having the advantage of simplicity of both the test piece and equipment. The bend test uses a coupon that is bent in three point bending. The test is carried out in accordance with ASTM standard D790-03 [25]. The three point bending test is widely used to characterize mechanical behavior of materials. It provides values for the flexural modulus, flexural stress and flexural strain of the material. The main advantage of a three point flexural test is the ease of the specimen preparation and testing. A small beam of rectangular cross section is placed on two supports. A displacement is applied at its center and the resulting force is recorded. This test is performed on an instron testing machine where the three point fixture is attached to the machine as shown in Figure 13.
Fiber reinforced composite panels of thickness 1/8" were prepared for the test. The first type of polyester composite panels tested were cast in-situ between heat strengthened glass sheets which were either silane coated or non-silane coated. Bend testing of these panels resulted in debonding of glass from the interlayer. The second type of panel consists of annealed glass sheets that were silane coated and bonded to cured polyester composite interlayer with a polyurethane adhesive. The cured polyester composite interlayer was either silane coated or non-silane coated. The adhesive that has been used is polyurethane. Laminated glass specimens of 12" x 5" size were prepared for the three point bend testing. For the 12" x 5" samples, the glass fiber reinforced composite interlayer was cut into 12" x 5" sized panels from a bigger sized panel. They were then laminated to 12" x 5" sized panels. The resin of the same composition (1.2% MEKP, 0.03% Cobalt Naphthenate) as that was used to make the composite was used for the fabrication of these laminated glass panels. Figure 14 shows the picture of the cross-sectional view of the laminated glass panel that has been prepared and used for testing.
Test apparatus and Procedure:

The tests were conducted using an Instron 8800 Servo hydraulic testing system. The three point bend fixture attached to the load cell and the specimen placement is shown in Figure 15 below.
Care was taken to align the specimen correctly. During the loading of the specimen we carefully watched the sample for the first cracks to form and monitor the loads and the load vs. displacement graph. The test was stopped after the sample broke completely or before the fractured sample touched the base of the three point bend fixture. Load vs. displacement data was obtained from the data acquisition system connected to the instron machine for analysis.

**Test Results:**

The Load vs. Displacement plots were plotted for the samples that were tested by the three point bend test method. The plots for the samples consisting of silane coated composites bonded to the glass with the application of polyurethane adhesive are shown below in Figure 16.
Figure 16: Plots of load vs. displacement obtained during three-point bend testing of silane treated annealed glass panels made with polyurethane adhesive

The plots for the non silane coated composites bonded to annealed glass with polyurethane adhesive are shown below in Figure 17.
Figure 17: Plots of load vs. displacement obtained during three-point bend testing of non-silane treated annealed glass panels made with polyurethane adhesive

Also testing was done on commercially available laminated glass with the PVB interlayer of about 1.5mm thickness. The plots for those specimens are shown in Figure 18 below.

![Figure 18: Commercial Laminated Glass with PVB interlayer graph](image)
The breakage patterns of all the above panels tested by this method are shown in figure 19 below.
Figure 19: Breakage patterns of glass by Three Point Bend testing shown in the order, Silane coated composite interlayer; Non silane coated composite interlayer and commercially purchased PVB laminate.

From Figure 19 it was observed that the panel with silane coated composite interlayer produced cracks across the surface of the panel whereas the panel with non silane coated composite interlayer and commercially purchased PVB laminate resulted in a uniform breakage pattern in the form of a “V” shape.

The bending strength is calculated using the formula [25]:

\[ \sigma = \frac{3PL}{2bh^2} \]

Where \( P \) = Maximum load for failure (N)
L is the length of the specimen (mm), b is the width of the specimen (mm) and h is the thickness of the specimen (mm). The bending strength is 165.5 MPa for the silane coated composite glass laminate made with polyurethane adhesive, 67.7 MPa for the non silane coated composite glass laminate made with polyurethane adhesive and 16.4 MPa for the commercially purchased laminates for which the interlayer thickness is about half that of the composite laminates.

From the test results it was observed that the 12" X 5" annealed glass panels bonded to the composite interlayer coated with silane using polyurethane adhesive exhibited a higher failure load than the panels with composite interlayer not treated with silane. The average failure load of laminated panels with silane coated composites is 3.33 KN which is higher than the panels with no silane which exhibited an average failure load of 1.54 KN. It has been observed that treating glass and composites with silane resulted in promoting adhesion to the adhesive and also resulted in producing a higher flexural strength for the laminated glass specimens. The bending strength was higher for the silane coated specimens than compared to the non silane coated specimens. The silane coated panels gave a bending strength of 165.5 MPa where as the non silane coated panels gave a bending strength of 67.7 MPa. The commercially purchased laminates with PVB interlayer gave an average failure load of 370 N with a bending strength of 16.4 MPa respectively.

The experimentally obtained plots for the panels with different configurations have been summarized in Table 2.
<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Description of the Interlayer</th>
<th>Adhesive</th>
<th>Failure Load(KN)</th>
<th>Average Failure Load(KN)</th>
<th>Flexural Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Silane Coated Composite</td>
<td>Polyurethane</td>
<td>2.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>Silane Coated Composite</td>
<td>Polyurethane</td>
<td>4.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>Silane Coated Composite</td>
<td>Polyurethane</td>
<td>2.41</td>
<td>3.33</td>
<td>165.5</td>
</tr>
<tr>
<td>A4</td>
<td>Silane Coated Composite</td>
<td>Polyurethane</td>
<td>3.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>Non Silane Coated Composite</td>
<td>Polyurethane</td>
<td>1.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>Non Silane Coated Composite</td>
<td>Polyurethane</td>
<td>1.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>Non Silane Coated Composite</td>
<td>Polyurethane</td>
<td>1.68</td>
<td>1.54</td>
<td>67.7</td>
</tr>
<tr>
<td>B4</td>
<td>Non Silane Coated Composite</td>
<td>Polyurethane</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>PVB</td>
<td>PVB</td>
<td>0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>PVB</td>
<td>PVB</td>
<td>0.36</td>
<td>0.37</td>
<td>16.4</td>
</tr>
</tbody>
</table>
**Lap shear Testing**

Lap Shear tests are a common way to determine the shear strength of adhesives for bonding materials such as plastics and metals. The test method is primarily used for qualitative comparisons. The test is applicable for determining adhesive strength and adhesive environmental durability. Lap shear strength is used to determine the maximum shear force required to fracture a sample. This process is similar to conventional tensile tests. Mating lap shear panels are coated and adhesively bonded to each other. A tensile testing machine is used to apply the required load. Figure 20 shows the lap joints that are bonded together with an adhesive and attached to the grips of a testing machine.

![Figure 20: Lap shear joints bonded with an adhesive](image)

Advanced composite materials are widely used in applications such as aircraft and automotive industry due to their high strength to stiffness ratio and high corrosion resistance. Their use as structural materials often requires that the composite be attached to another structure by means of an adhesive. An adhesive bonded structure generally
consists of three components of different mechanical properties namely the two adherents and the adhesive layer. The strength of an adhesive joint is not a property of the adhesive alone but depends on many factors like the adherents, the adhesive, the joint geometry, preparation of specimens and service conditions. The geometrical parameters that influence the strength of an adhesive are the length of the specimen, the length of the bonded portion of the overlap, crack length and the thickness of the adherends. The single lap joint is quite sensitive to changes in geometrical parameters. Lap shear tests are generally carried out in accordance with ASTM D 1002-05 [26] and ASTM D 5868-01 [27] test standards.

In this research two types of resins, an unsaturated polyester resin and a polyurethane resin were used as adhesives in making the lap joint. The major failure modes of the joints using these resins are cohesive and adhesive failure. Adhesive failure can be reduced by surface preparation of adherends while the cohesive failure depends on the strength of the resins. A possible way of increasing the cohesive failure resistance is to use fiber or particulate reinforced adhesives.

**Specimen Preparation:**

The test specimens were prepared by taking fiber reinforced polyester composite and glass plates of size 4.5" x 1.5", having a thickness of 1/8" and bonded together with two different adhesives; polyester resin and polyurethane resin. The bond length is 3/8". The composite and the glass pieces were cut from a bigger panel.
Four different types of test specimens were prepared for this test. The first category involves bonding the glass to silane coated composites with the help of an unsaturated polyester resin. The second category involves bonding the glass to non silane coated composites with the use of an unsaturated polyester resin. The third category involves bonding the glass to silane coated composites with a polyurethane adhesive. And the last category involves bonding the glass to non silane coated composites with a polyurethane adhesive. In each category a minimum of three samples were tested. The tests were conducted on an Instron 8800 Servo hydraulic testing system. Figure 21 shows the specimen being held firmly in the grips of an Instron testing machine.

![Figure 21: Specimen held in the grips of an Instron Machine](image)

**Test Results:**

Figure 22 shows the plots of load vs. displacement for all the silane coated composites bonded to glass with polyester resin.
Figure 22. Load vs. Displacement curves for silane coated tensile lap-shear samples bonded with polyester

The curves for the non silane coated composites bonded to glass with polyester resin are shown in figure 23 below.

Figure 23. Load vs. Displacement curves for non silane coated tensile lap-shear samples bonded with polyester
From the plots it was observed that the silane coated composites (P1, P2, P3) bonded to glass with polyester required more load than the non silane coated composites (P4, P5, P6). The maximum load at failure for the silane coated composites is 1.07 KN and for the non silane coated composites is 0.905 KN.

The plots for silane coated composites bonded to glass using polyurethane adhesive are shown in Figure 24.

![Figure 24](image)

Figure 24. Load vs. Displacement curves for silane coated tensile lap-shear samples Bonded with polyurethane

The curves for the non silane composites bonded to glass using polyurethane adhesive are shown in Figure 25.
Figure 25. Load vs. Displacement curves for non silane coated tensile lap-shear samples bonded with polyurethane

From the plots it was observed that the silane coated composites (U1,U2,U3,U4) bonded to glass with polyurethane required more load for shearing than the non silane coated composites (U5,U6,U7,U8). The average maximum load at failure for the silane coated composites is 1.62 KN while for the non silane coated composites it is 1.14 KN.

Lap Shear Strength was calculated using the following equation,

Lap Shear Strength = Maximum load / Area of the overlap [27]

Where,

Area of the overlap = specimen width (b) x overlap (d)

The specimen width is 38.1mm (1.5") and overlap is 3.17mm (0.125").
Firstly the lap shear strength for all the samples is calculated separately and then the average value is tabulated for each category of samples. The results of the lap shear strengths of the specimens tested are tabulated in Table 3.

Table 3. Average Lap Shear Strength of various specimens

<table>
<thead>
<tr>
<th>Specimen Description</th>
<th>Adhesive</th>
<th>Lap Shear Strength (MPa)</th>
<th>Average Lap Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silane Coated</td>
<td>Polyester</td>
<td>P1=9.3, P2=8.78, P3=8.65</td>
<td>8.91</td>
</tr>
<tr>
<td>Composites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non Silane Coated</td>
<td>Polyester</td>
<td>P4=7.58, P5=7.61, P6=7.43</td>
<td>7.54</td>
</tr>
<tr>
<td>Composites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silane Coated</td>
<td>Polyurethane</td>
<td>U1=13.2, U2=13.9, U3=15.3, U4=14.0</td>
<td>14.1</td>
</tr>
<tr>
<td>Composites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non Silane Coated</td>
<td>Polyurethane</td>
<td>U5=9.3, U6=8.9, U7=11.0, U8=8.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Composites</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the lap shear test results it was observed that the silane coated lap shear samples bonded with polyurethane exhibited a higher failure load than the non silane coated samples and the lap shear samples bonded with polyester. As a result the average lap shear strength of the silane coated samples bonded with polyurethane was the highest among all the other specimens that were tested. Hence it was concluded that the lap shear strength of a polyurethane adhesive was more than the lap shear strength of a polyester adhesive.
Impact Testing

Composite sandwich structures are widely used in aerospace, marine, automobile and recreational industries because of their high stiffness, corrosion resistance, light weight and stability. They generally behave in a brittle manner when subjected to a wide spectrum of impact loads. This sensitivity to impact damage is due to the brittle behavior of the fibers used to reinforce such composites, and the resins used for the matrix phase.

The main purpose of this work is to integrate the known principles of impact testing to fiber reinforced polymer composite laminated panels. This testing plays a major role in understanding the damage propagation inside composites. Generally when a sandwich structure is subjected to impact, part of the energy associated with the impact is used for the elastic deformation on the material. The remaining energy in excess is dissipated through several mechanisms like fiber breakage, fiber-matrix debonding and delamination in the face sheets [28]. Under impact loading the composite face sheet loading spreads over a large region inside the plate. Damage mechanisms may vary with changes in material parameters such as fiber/resin type, interface and laminate production method. Since these damage mechanisms are highly dependent on the exact nature of the impact event, the impact response of a composite material has proved very difficult to standardize [29].

Impact tests are designed to measure the resistance to failure of a material to a suddenly applied force. The tests should be carried out in accordance with the Florida Building Code protocol TAS 202 [30]. To satisfy the requirements of the code the glazing must
resist the penetration of a large missile which is a 9 lb wood 2"x 4" traveling at 50 ft/sec or 33 mph. The test measures the impact energy or the energy absorbed prior to fracture. Impact energy is a measure of the work done to fracture a test specimen. When the striker impacts the specimen the specimen absorbs energy until it yields. At this point the specimen begins to undergo plastic deformation and continues to absorb energy. When the specimen can absorb no more energy then fracture occurs. This test is most commonly used to evaluate the impact toughness of materials. The falling weight impact test involves dropping a weight in the vertical direction. With the height and weight known the impact energy could be calculated. This type of testing has many advantages. It is applicable for molded parts and samples. It is unidirectional with no preferential direction of failure. Failures originate at the weakest point in the sample and propagate from there. Samples don't have to shatter to be considered failures. Failure can be defined by deformation, crack initiation, or complete fracture. Failure occurs generally as cleavage failure or failure due to micro voids. These factors make falling weight testing a better simulation of functional impact exposures, and therefore closer to real life conditions. The method of using the drop weight impact includes the use of a falling Weight that impacts the specimen. This impact striker is known as a tup which falls vertically on the center of a specimen. As the striker strikes the specimen it absorbs energy and starts deforming. When the specimen can absorb no more energy then failure occurs.

Since cracks usually appear at the surface opposite the one that is struck, the results can be greatly influenced by the quality of the surface of test specimens [31].
Therefore, the compositions of this surface layer, its texture, type of texture are very important variables. Flaws in this surface will also affect results. Impact properties of plastic materials can be very sensitive to temperature. This test can be carried out at any reasonable temperature and humidity. The test samples are exposed to impact with a piece of lumber which is the striker used in this work. The lumber weighs approximately 5.7 lbs and is 2'' x 4'' x 4' in size. It is allowed to fall on the specimen through a PVC pipe from a height of about 25 feet traveling at a speed of 12m/s (27 mph). The test specimens subjected to impact testing are laminated glass specimens sized 18'' x 12'', 15'' x 27'' and 18'' x 27'' respectively. The total thickness of the panel is 3/8''. The laminates are held in a frame that is manufactured to hold them firmly while being impacted with the striker. The framework consists of two rectangular brackets held together with a number of equally spaced screws. The screws are thereby tightened after the panel has been fixed in the frame. In order to fix the panel into the frame a coat of silicone sealant is being applied to the edges of the frame. This gel acts as a cladding material for the composite laminate when it is clamped in the frame. As the silicone gets hardened the specimen is clamped in the frame. The frame that holds the laminated glass panel subjected to impact is shown in Figure 26. The frame was placed on the ground during the test. The striker was dropped from the prescribed height in such a way that it hits the test specimen. When the striker was dropped, it hit the specimen and bounced back again to rehit the specimen producing cracks on the surface of the glass.
However the composite interlayer in the laminated glass panel did not break. Also the striker did not make a hole in the laminated glass panel that was subjected to testing and only produced cracks which spread across the panel as observed from Figure 26.

Figure 26. Laminated glass panel after being subjected to impact testing with a 2”x4”x4’ striker
When testing was done with a 2" x 4" x 8' striker the striker hit the specimen in such a way that it made a hole on the laminated glass panel. The composite interlayer also broke. Since annealed glass was used for testing the striker penetrated through the laminated panel. Better results are expected by using heat-strengthened glass for the large missile impact testing as it is twice as strong as annealed glass of the same size and thickness. Figure 27 shows the laminated glass panel that was subjected to testing.

Figure 27. Laminated glass panel after being subjected to impact testing with a 2"x 4"x8' striker
CHAPTER-4

CONCLUSIONS AND FUTURE WORK
The primary objective of this research work was to fabricate highly damage resistant laminated glass panels and study the failure of these panels under impact loading generated by flying debris during a windstorm such as a hurricane. Panels sized 18" x 12", 12" x 5" and 18" x 27" were fabricated in this work. These panels could be used as window panels for buildings in hurricane prone areas. Transparent glass fiber reinforced polyester resin composite panels were fabricated and used as the interlayer in the laminated glass. The laminate was created by adhesive bonding of the interlayer to the glass sheets. The adhesive used was a two-part polyurethane resin. The average interlayer thickness used was 1/8" resulting in the total thickness of the laminate being 3/8" (10mm).

Good transparency was achieved by matching the refractive indices of the glass fibers and the polymer matrix to light. The greater the match between the refractive indices the better will be the transparency. Figure 27 shows a view of a hallway as seen through the transparent composite glass panel that has been fabricated in this research.
Different tests have been used for the panels fabricated to determine their mechanical properties and impact behavior. Three point bend tests have been done to determine the strength of the panel under bending loads. Lap shear tests have been done using a polyurethane and polyester as the adhesive to determine the interfacial bond strength of the adhesive. Falling weight impact tests have been conducted on the panels to qualitatively measure their resistance to failure under impact loading.

It was observed from the three point bend test results that the laminated glass panels bonded to the composite interlayer coated with silane using a polyurethane adhesive exhibited a higher failure load than other panels that were tested. The average failure load of the silane coated laminated panels using a polyurethane adhesive was 46% higher than the non silane coated laminated glass panels. Also the flexural strength of these silane coated laminated glass panels was 40% higher than that of the non silane coated laminated glass panels. Hence it was concluded that coating of glass and composite with silane increased the flexural strength of the laminated glass panels.

From the lap shear test results it was observed that the silane coated lap shear specimens bonded with a polyurethane adhesive exhibited a higher load than other specimens that were tested. The average lap shear strength of the silane coated specimens bonded with a polyurethane adhesive was 63% higher than the average lap shear strength of the silane coated specimens bonded with polyester. Also the average lap shear strength of the non silane coated specimens bonded with a polyurethane adhesive was 79% higher than the
non silane coated specimens bonded with polyester. Hence it was concluded that the
interfacial bond strength of a polyurethane adhesive was more than that of polyester.

From the large missile impact test it was observed that the composite interlayer in the
laminated glass panel did not break. The striker that was dropped on the specimen from a
height of 25 feet through a PVC pipe traveling at a speed of 12m/s (27mph) did not make
a hole in the laminated glass panel. It only produced cracks across the surface of the
laminated glass panel that was used for testing.

In this work new fiber reinforced laminated glass window panels have been developed.
There is a lot of scope for further research and analysis of these panels fabricated and
tested. Some of the areas that we intend to work in the near future are:

1) Develop new ways to reduce distortion during viewing of distant objects through
the glass panels.

2) Perform finite element analysis of the response of the laminated glass panels
using LS DYNA. This would help us further analyze the behavior of the panels
under impact and also predict the damage characteristics. A non linear dynamic,
finite element code, LY DYNA, has been used by a number of researchers so as
to study the response of composite laminates subjected to impact loads.

3) Develop a more efficient method to fabricate the composite interlayer for
automated production. The current technique developed in the lab is the Hand lay
up technique.

4) Study the mechanical behavior of the laminated panels during an explosion.
1) http://www.alumaxbath.com/tech/tgp.htm

2) http://www.glassdesignconcepts.com/gallery/gallery.html


5) www.delong.typepad.com


10) www.shelterboxschools.org


17) Abeele, F.V., Paepegem, W.V., and Degrieck, J., “Impact Damage Model for Fiber-Reinforced Composite Materials”, presented at Ghent University, Laboratory Soete, Department of Mechanical Construction and Production, Sint-Pietersnieuwstraat, Belgium, 2002.


