Development of Ultra High Performance Composite Impact Panels Using EMAA

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DEVELOPMENT OF ULTRA HIGH PERFORMANCE
COMPOSITE IMPACT PANELS USING EMAA

By

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B.S. University of Maine, 2020

A THESIS
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DEVELOPMENT OF ULTRA HIGH PERFORMANCE COMPOSITE IMPACT PANELS USING EMAA

By Jeffrey Hollstein

Thesis Advisor: Dr. Eric N. Landis

An Abstract of the Thesis Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science (in Civil Engineering)
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UHPC with the addition of fibers is recognized for its increased impact resistance compared to typical strength concrete. To further increase the resilience, recent studies have been conducted to reinforce the UHPC with CFRTP on the front and rear face to create sandwich panels. These studies used PETg/E-glass CFRTP bonded to the UHPC using EMAA (Surlyn) in a stamp thermoforming process. Impact tests conducted on these panels have shown that delamination has been the initial and detrimental failure to the sandwich composite. Increasing the composites resistance to debonding will increase the impact energy required to debond the composite. In this study the bond capability of EMAA (Surlyn) was investigated in an attempt to increase the bond strength and improve the composite sandwich panels impact resilience. Single lap shear and CFRTP reinforced beam bending tests were conducted to investigate the bond of the EMAA to the CFRTP and UHPC respectively. The different glass transition temperatures of EMAA and PETg proved to cause the complication of bubbling in the EMAA between the PETg and UHPC. In an attempt to remove the need for PETg, trials were conducted to create a new CFRTP using CSM E-glass fibers and EMAA matrix. This new CFRTP was created and was able to successfully bond to the UHPC core to create a new Surlyn CSM impact panel. Impact tests of 50 J were
conducted on the two thermoplastic panels and two other panels fabricated using a two-part epoxy and a Urethane adhesive with the PETg CFRTP. The compliance was found before and after impact to measure the damage due to impact. The two-part epoxy and Surlyn CSM panel experienced the lowest amount of damage. However, the Surlyn CSM panel dissipated the least amount of energy due to impact. The original CFRTP/Surlyn Composite panel absorbed the most energy from the impact while presenting the most damage due to major delamination of the panel. The Surlyn CSM panel provided the lowest deflection during impact and the least amount of calculated and visualized damage.
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LIST OF ABBREVIATIONS

Compression After Impact (CAI) .......................................................... 17
Chop Strand Mat (CSM) .......................................................................... 39
Ethylene Methacrylic Acid Copolymer (EMAA)........................................ 11
Continuous Fiber Reinforced Thermoplastic (CFRTP) ................................ 10
Linear Variable Differential Transformer (LVDT)........................................ 30
Polyethylene terephthalate glycol (PETg).................................................. 11
Glass Transition Temperature (Tg).......................................................... 22
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CHAPTER 1
INTRODUCTION

Ultra High Performance Concrete (UHPC) was first used by the United States Army Corps of Engineers in the 1980s and was introduced to the public on a bridge deck in Quebec, Canada in 1997. UHPC is now widely used around the world for various projects from dams to airport runways. This grow in popularity is mainly due to the increased strength of UHPC which has a compressive strength of over 150 MPa as well as a tensile strength of over 8 MPa (Xu 2020). This high strength is due to UHPCs the low water to cement ratio and a clever distribution of fine-grained sand, silica fume, and water reducing admixtures. By using fine materials such as silica fume and a fine grained sand UHCP has a high packing density that presents the higher compressive strength and lower porosity (Wang 2019). With high strength, UHPC has other useful properties such as higher durability, freeze thaw resistance, lower chloride permeability.

With the increase in compressive and tensile strength of UHPC compared to typical concrete, following the principles of fracture mechanics it naturally has lower toughness. This lower toughness causes the UHPC to fail in a brittle manner. To prevent this brittle failure during impact the addition of steel fibers has become standard for impact structures. With the addition of fibers, the ductility and penetration depth can be improved thus increasing the energy absorption capacity (O’Neil 1999, Dancygier 2007). It has been shown that the impact resistance improves greatly with the addition of fibers up to 3% of the mix by mass as well as the deflection during impact (Othman 2016, Yoo 2015). However, even with the addition of fibers the UHPC plates are still subjected to brittle failure due to concentrated loads at high energies (Ranade 2017). Thus, there have been attempts at reinforcing UHPC through externally bonded continuous fiber reinforced thermoplastic (CFRTP) sheets to increase impact resistance. By adding
externally bonded CFRTP to the front and back of UHPC a sandwich panel can be created that has been shown to increase impact strength (Smith-Gillis 2018). Composite sandwich panels have been shown to increase bending strength to weight ratios and increase impact resistance. (Libby 2020, Rajput 2022). The CFRTP sheets can further enhance the safety of an impact structure by protecting from fragmentation and spalling of the concrete from an impact.

An exploratory research program was conducted by Reagan Smith-Gillis (Smith Gillis 2018) to investigate using thermoplastics to bond external reinforcement to UHPC panels to improve impact performance. The advantage of using thermoplastics is that they can be reheated and reused. They investigated external bonding through vacuum infusion using Elium and stamp thermoforming using Polyethylene terephthalate glycol (PETg). Stamp thermoforming is conducted by inducing pressure and heat to a polymer for mold forming. The study concluded that impact panels formed by stamp thermoforming PETg was easier to manufacture and provided higher impact resistance.

The research was continued by Libby, who investigated the use of Surlyn 8940 (EMAA) as an intermediate resin to the CFRTP and UHPC (Libby 2021). The first discovery made during this research showed that 100 psi was enough pressure to adequately bond the impact panel and that a lower pressure would present a weaker bond between the UHPC and Surlyn. This finding was shown through impact testing and beam bending specimens. A bond analysis was conducted comparing the bond ability of Surlyn and PETg neat resin to the PETg/E-glass CFRTP laminate and the UHPC. It was found that the Surlyn had a stronger bond to the UHPC than the PETg neat resin. However, the Surlyn had a weak bond to the PETg. Plates where then fabricated using neat PETg and Surlyn as intermediate resins. The Surlyn/Surlyn Composite panel provided higher impact strength through lower damage after impact. As well lap
shear tests were conducted and found that Surlyn was able to create a stronger bond to the UHPC than PETg neat resin.

The goal of this research was to further increase the impact resistance of the UHPC impact panels by improving the bond between CFRTP and UHPC. To realize this goal, a bond analysis was conducted of the Surlyn Composite panels created by Libby using PETg and Surlyn. The bond analysis investigated the bonding of Surlyn 8940 to PETg fiber reinforced CFRTP and the UHPC core through different tests presented in Chapter 3. From these tests it became clear that the varying forming temperatures between the PETg CFRTP and the intermediate Surlyn resin were causing difficulties in bonding. Thus, to remove the PETg from the composite panels, trials were conducted to create an CFRTP using Surlyn and mesh E-glass. From these trials, described in Chapter 4, a new CFRTP was created and bonded to the UHPC to create a new composite panel. This Surlyn mesh panel was then compared to the previous Surlyn PETg Surlyn Composite panel through impact testing. As well two thermosetting resin panels were created and impact tested to compare the effectiveness of the thermoplastics to typical adhesives for externally reinforced CFRTP. The results of these impact tests are presented in Chapter 5.
CHAPTER 2
BACKGROUND

2.1 Impact Resistance of Materials

Field failures in the early 1800s led researchers to the idea that materials react differently under dynamic loads compared to static loads (Siewert 1999). This led to impact testing of products with impact energies that the material should be able to withstand as a proof test before use. Then testing of materials ability to withstand an impact load became of importance for varying fields of engineering such as aviation, blast structures, and dams. Testing for the strength of a material under an impact load is separated into two different types, high velocity impact and low velocity impact testing. High velocity impact can be considered as an impact from an object with low mass and a high velocity such as a bullet. The high velocity impact is typically conducted using test methods such as Hopkinson pressure bar (Zhang 2008). Whereas low velocity impact testing is typically defined as an impact test that has an impact speed of less than 10m/s and typically has a larger mass than used for a high velocity impact test (Richardson 1996). The low velocity impact drop test is significant for measuring damage done from typical impacts such as flying debris and dropped tools (Baker 1985). One of the reasons for using low velocity impact testing is because provides longer contact time between the impactor and the target leading to more force data during impact.

To be able to produce consistent data on low velocity impact capabilities of a material the pendulum test was created and was able to find the energy that a material can absorb. The pendulum test, which was later improved and standardized, is frequently referred to as the Charpy V-notch test. The Charpy V-notch test works well at finding energy absorption capabilities on isotropic materials such as metals (Cantwell 1991). With the rise in research with composites, troubles arose with pendulum impact testing. It was found that pendulum testing of composite materials induced a complex stress state that
results in varying failure modes. These various failure types can cause problems when comparing the impact performance of different composites (Adams 1989). With the need to find the energy absorption capabilities of composites, the drop weight impact testing of composites became standard.

2.2 Drop Weight Impact Testing

Low velocity impact tests are typically conducted using a drop tower that contains a guided drop weight to impact a specimen. The drop tower impactor, typically called a tup, is connected to the drop frame with a designated mass for impacting the specimen. The specimen is placed at the bottom of the tower and sufficiently secured in the path of the tup. The drop frame is then raised to a specified height and dropped to impact the specimen. An anti-rebound system is typically used to catch the load frame before the tup can make another impact after rebounding.

Prior to conducting a low velocity impact drop test there are multiple considerations to be made, such as the mass and shape of the impactor. During drop weight impact test the area that contacts the specimen is referred to as the tup that the mass acts through. The shape of the tup has been shown to cause different failure types in different plate sizes and types (ASTM D7136, Mitrevski 2005, Borvik 2001). The tup shape should be chosen by the type of failure that is expected of the specimen. For composites one of the most critical damage types is delamination (Safri 2014). Previously UHPC sandwich panels have shown delamination due to low velocity impacts at 50 J (Libby 2021). The typical tup shapes used for drop weight impact testing includes, hemispherical, conical, blunt, and ogive. The hemispherical tup produces delamination and a larger damage area compared to the other typical tup shapes (Mitrevski 2006, Dhakal 2012). The majority of low velocity impacts are conducted using hemispherical impactors. The size of the tup can change the peak force, delamination, and contact time with the specimen (Sevkat 2013). The hemispherical tup will also provide the highest contact force to
the specimen on impact (Safri 2014). Thus the hemispherical 16mm tup was used for this research to cause maximum delamination and be comparative to previous studies.

During a drop weight impact test a specified energy is used calculated from the drop height and impactor mass. The impact velocity is calculated from the drop height due to the acceleration of gravity. Therefore, knowing the drop height and impactor mass the impact energy can be calculated. However, the actual impact energy can be different due to a varying impact velocity. Due to friction between the drop weight and the guide pillars the acceleration of the drop weight will be less than the acceleration of gravity (Habel 2008). This reduction can cause the downward acceleration during the test to be as low as 8.6 m/s² (Banthia 1989). The downward acceleration can be measured through accelerometers attached to the drop weight or a photocell system can measure the velocity before impact (Ranade 2017, Banthia 1989, Ong 1999). Although changing the mass and drop height can keep the impact energy the same, the specimen may still be experiencing different forces. A larger mass with a lower velocity can cause multiple different failures such as delamination, fiber breakage, and matrix cracking. With height adjustments to have the same impact energy but a decrease in mass, the residual deflection was shown to increase (Seyed Yaghoubi 2012). Therefore, the impact energy cannot be the sole parameter used for impact testing and the mass of the impactor must be taken into consideration. The mass of the impactor as well as the specimen is of importance for inertial effects. This extent of damage is also spread out throughout the specimen as compared to similar energies. (Aryal 2019)

An inertial effect during impact testing is an increase of load on the tup that is not experienced by the specimen. This inertial load is due to the mass of the specimens need to accelerate to match the speed of the impactor (Glinicki 1994). The inertial effect can be seen as an initial sharp spike followed by a decaying oscillation on the force over time. This will affect any peak load measurement and the energy
absorbed calculations made using the load displacement curve. Small errors in measuring the force during impact or the initial velocity can lead to significant errors in calculating the energy absorbed (Aymerich 1993). It has been found that if the impactor is at least 3.5 times the mass of the plate then the inertial effects of the impact force recorded can be neglected (Verma 2016; Leissa 1969*). Rather than neglecting the inertial load it can also be calculated. This can be found by using data from accelerometers placed on the specimen and then subtracted from the load ratings measured from the load cells (Banthia 1989).

The thickness of the plates is also an important factor in measuring the impact response (Safri 2014). With an increased panel thickness the energy absorbing capabilities can be increased (Yaghoubi 2012). Cantwell et al. (1989) found that the damage from drop weight impact on a thick beam had a higher local impact stress causing to have a different area where the damage initiated.

The measurements made during a drop weight impact test typically include absorbed energy, penetration depth, and internal damage (Hebert 2008). The results from a drop weight impact test can be found by using just the force during impact with the time and initial velocity. This force can be measured by using a load cell or accelerometer attached to the drop frame (Ranade 2017). The force during impact can be used to create a force time graph. From this graph the peak impact force and duration of impact can be seen. While the load cell will directly measure the force, the acceleration data from the accelerometer will have to be multiplied by the mass of the drop weight to find the force. The accelerometer and load cell are also capable of finding the deflection of the specimen on impact. The data from the load cell can be used to find deformation through a double integration of the force, falling acceleration and mass with respect to time. As well fast frame cameras can be used to capture the deformation on impact (Koziol 2019). The deflection can also be found through a double integration of
the acceleration data with respect to time (Banthia 1989). A typical way of measuring the effectiveness of a specimen against impact is to measure the energy absorbed by the specimen. One way of finding the energy absorbed is by measuring the reaction load of the supports (Cao 2020). Another way is through measuring the rebound height of the tup after initial impact (Opara 2007). The rebound height can be used by subtracting it from the energy that the specimen is impacted at to find the energy absorbed. Special considerations should be made when finding the dissipated energy through the rebound height since the friction from the guide rails will be increasing the deceleration on the rebound. This will be another energy loss that should be accounted as not dissipated by the specimen. However, the energy absorbed is typically found through an integration of the load displacement curve (Hazizan 2002, Hebert 2008, S Elavenil 2012). With this method, inertial effects will have to be considered.

While the parameters found during the drop weight test are important, there is also non-visible damage that can be caused by the impact (Rozylo 2017). From the impact some damage such as matrix cracking and fiber breakage which is non-visible can weaken the specimen’s strength (Taheri-Behrooz 2013). This non-visible impact damage causes a rapid decrease in strength compared to visible damage (Baker 1985). Methods such as the Compression- After-Impact (CAI) test can effectively assess the decrease of strength of a composite under compression after an impact (Rozylo 2017, Prichard 1990). This decrease in strength is due to the nonvisible damage caused to the composite. CAI tests have been used for measuring residual strength of a sandwich composite after low velocity impacts (Gilioli 2014). As well flexural tests after low velocity impact have been used in place of CAI tests (Santiuste 2010, He 2018). By testing under nondestructive flexural tests, the change in compliance from before and after impact can be taken used to understand the damage caused to the impact panel. The change in compliance is the inverse of the materials stiffness and has been used widely as a way of measuring damage of a structure (Choi 2005). The damage sustained by the specimen after impact is related to the absorbed energy. This
has been noticed as visible damage increasing as absorbed energy increases. (Ismail 2019). In metals the energy absorbed is due to the plastic deformation occurring during failure (Cantwell 1991). Whereas the composites have a failure due to varying types such as delamination, matrix cracking, fiber breakage and core crushing in sandwich panels. (Taheri-Behrooz 2013, Rajput 2019). Thus the greater the damage inflicted to the panel the more energy is absorbed by activating more failure mechanisms within the composite (Rajput 2019).

2.3 UHPC Impact Resistance

Many studies have shown that the impact resistance of UHPC can be increased with the addition of fiber content (Othman 2016, Yoo 2016) as well as reducing the total deflection (Yoo 2015). Even with the addition of fibers, thin UHPC plates can experience a shear punching hole and spalling on the back of the panels. (Ranade 2017). Thus with the addition CFRTP to the front and rear face the punching damage can be sustained by the CFRTP on the front face through fiber breakage and the spalling can be contained on the rear face. As well the CFRTP can work together as a composite and the load can be transferred from the concrete to the CFRTP. To achieve composite action, the bond between the CFRTP and concrete must be strong enough to transfer the load. With externally bonded reinforcement to UHPC the bond between the two is typically the weak link in the composite (Karbhari 2009, Yuan 2019).

Testing conducted by Libby investigated the different parameters that could increase this bond strength. In this study Libby investigated the bonding of two thermoplastics, Surlyn 8940 and PETg neat resin. Thermoplastics are polymers that with added heat they can be softened and melted then processed and reshaped through a thermoforming or extrusion process (Mallick 2010). Typically, exterior bonded reinforcement for concrete has been done using thermosetting materials. Thermosetting materials create bonding through chemical reactions (Marques 2011). Urethane based thermosetting epoxy with glass
fibers has been found to be strong under impact loading (Hebert 2008). Thus experiments were conducted using urethane based epoxy to compare the impact resistance of the thermoplastic panels.

In the study by Libby the comparison of a consolidation pressure of 80 psi and 100 psi using PETg neat resin and Surlyn 8940 as intermediate resins. These were compared using beam bending specimens cut from the impact panels fabricated. The failure method of each beam was caused by delamination of the composite from the UHPC core. It was found that from the bending trials the panels consolidated at 100 psi using Surlyn as an intermediate resin would absorb the most energy from loading to failure. Impact trials were then conducted to find the damage sustained by the panels (Libby 2021). The damage sustained from impact was found using the difference in compliance from before and after impact. The result of the study showed that Surlyn as an intermediate resin between the CFRTP and UHPC sustained lower damage due to impact and provided an overall better bond to the UHPC than the PETg neat resin. The increased absorbed energy and lower damage on impact is believed to be caused by the increased bond strength of the Surlyn to UHPC. Thus by increasing the bond between the CFRTP, intermediate resin, and UHPC the panels impact resilience could be improved. In the study treatment of the UHPC by surface roughening was done to enhance the bond between the UHPC and thermoplastics. Yet other parameters and surface preparations were not investigated to improve this bond.

2.4 Characterization of Bond Behavior

When investigating bond strength between two materials the lap shear test is used quite frequently and become standard (Hallonet 2016). The lap shear is exceptional at finding the bond strength of bonding a polymer to an CFRTP and thus was used in this research to optimize the bond between the PETg CFRTP and Surlyn neat resin. The single lap shear test is also the standard method currently used for CFRTP strips bonded to concrete. The current ASTM standard (D8337) for this uses a concrete beam with a
CFRTP strip bonded to one face of it with a frame to hold the concrete block while the CFRTP strip is pulled in tension.

While conducting this test it has proven difficult to perfectly align the CFRTP strip with grips of an Instron machine to pull it in tension (Libby 2021). Therefore, a moment was applied to the CFRTP creating a peeling action on the bond to the concrete beam. This peeling action would affect the final bond strength and prevent the lap shear test from finding an accurate bond strength. By using a three-point beam test the peeling action could be eliminated. The three-point beam bending test consisted of a concrete beam with a saw cut halfway through the bottom at the middle of the beam with an CFRTP strip bonded over the cut. The top half of concrete would carry the compression during bending while the CFRTP strip would carry the tension causing a shear stress between the concrete and CFRTP strip. Then from maximum load the effective shear strength could be calculated (Gartner 2011). During testing of the CFRTP to concrete bond it is important to have the bond to the UHPC be long enough to fully develop the strength of the bond. To fully develop the length of the CFRTP external bond the overlap between the two must be at least 2.5 inches (Hosseini 2014, Chen 2001, Dai 2005).

2.5 Methods to Improve Bond

In an attempt to increase the bond strength, atmospheric plasma treatment was investigated for increasing the bond strength of PETg based CFRTP to Surlyn and to increase fiber wet out between E-glass fibers and Surlyn. CFRTP typically has a smooth surface and a low surface energy from the polymer matrix. This low surface energy can be measured using a method of measuring the water contact angle. By increasing the free surface energy, the water contact angle can decrease therefore increasing the objects wettability. It has been shown that with an increase in wettability the bond strength between two materials can be increased (Liston 1989, Kusano 2007, Cech 2002).
In recent studies atmospheric plasma treatment has been used to considerably increase the bond strength of thermoplastics in lap shear tests (Scarselli 2020, Al-Maliki 2018). The results of treatment can vary for different polymers but it has been found that plasma treatment of PETg can lower the water contact angle of the thermoplastic. (Abernathy 2016) As well plasma treatment has been shown to increase the adhesion of E-glass fibers to thermoplastics (Lopez De Armentia 2019). Thus atmospheric plasma treatment was considered when trying to increase bond ability throughout this project.

During atmospheric plasma treatment considerations should be made to how the treatment is conducted. The distance from the nozzle to the specimen and the nozzle speed used can greatly impact the bond strength after treatment (Moroni 2020). For optimal bonding a nozzle distance of 5-10 mm and a maximum speed of 100 mm/s should be used. It has been shown that the time between treatment and bonding does not have a significant effect on the bond strength up to 24 hours of after treatment.

2.6 Surlyn (EMAA)

Surlyn discovered in the 1960s is the trade name by DuPont for an ionomer made of an ethylene methacrylic acid copolymer (EMAA). This copolymer has shown considerable bond ability to UHPC as compared to other thermoplastics (Libby 2021). EMAA is known for having high impact toughness and is considered a self-healing polymer, that when punctured is able to close the puncture and return to an air tight shape (Kalista 2003, Varley 2011, Gordon 2016, Loh 2021). Throughout the years, different grades of Surlyn have been made to create varying polymers. Surlyn has been found to be amorphous or semi crystalline depending on the grade used (Gordon 2016, Reynolds 2011). When working with Surlyn during forming a high temperature or excess moisture can cause bubbling in the polymer. (Professional Plastics). Surlyn has been used before to create a composite and improve toughening and healing when
introduced (Gao 2019). The glass transition temperature of PETg and Surlyn 8940 is 176 °F and 116°F (Libby 2020). The glass transition temperature (Tg) is a temperature at the center of the range at which a polymer changes from a solid to a liquid state (Tarjus 2011). The Tg is an important criterion for determining the miscibility between two polymers (Painter 1991). Since the Tg of the PETg and Surlyn are quite different it is difficult to reach a temperature in which both are in the transition phase. Thus using one polymer for the external reinforcement resolves this problem. From testing it has been shown that Surlyn provides a stronger bond to UHPC than PETg neat resin (Libby 2020). Surlyn has been used as a matrix for a composite with carbon nanotubes that showed significant performance as a composite (Kalista 2003).
CHAPTER 3
UHPC & PET-G BONDING TO SURLYN

Previous work conducted on this project showed that the impact panels with a Surlyn intermediate resin formed a stronger bond to the UHPC than to the PET-g thermoplastic laminates. This chapter further investigates the bond ability of Surlyn 9840 to PET-g/E-glass thermoplastic laminates and UHPC using lap shear testing and a three point bending of composite beams.

3.1 Lap Shear Testing

A lap shear test was conducted to investigate the adequate temperature and pressure to use when bonding PET-g/E-glass laminates to Surlyn neat resin. As well as temperature and pressure, atmospheric plasma treatment of the PET-g/E-glass laminates was administered to increase the surface energy and wettability. This lap shear test was conducted according to ASTM standard DS868 for lap shear testing of CFRTP bonding.

3.1.1 Lap Shear Specimen Manufacturing

The initial PET-g/E-glass composite was made at the ASCC TPL using 2” unidirectional E-glass tapes pre impregnated with PET-g. These tapes were stacked using a reverse pyramid in the directions [0°,45°,-45°,90°]₃ and then doubled for a total of 16 layers and formed at 335°F. The total thickness of these laminates was 0.106”, approximately twice the thickness of the laminates used for the impact panels. This increase in thickness was done to increase the stiffness of the specimen to prevent a peeling action on the specimens during lap shear testing. The initial laminates were cut into 4” x 12” parts to be bonded with a 1” overlap by a strip of Surlyn. A 1” x 12” laminates strip was used on each end to provide even grips for the specimens. The laminates and Surlyn were put into the monarch press at the ASCC TPL with an aluminum plate to separate the grips and overlap. In the monarch press, the desired pressure
was applied and held as the specimen was heated to forming temperature presented in Table 3.1. The specimen was then held at the forming temperature for a dwell time of 10 min and then actively cooled to room temperature. The formed specimen can be seen in Figure 3.1. Once formed they were cut using a waterjet at the ASCC to 1” wide lap shear specimens show in Figure 3.2. The initial trials started at 175°F to try and bond below the melt temperature of Surlyn at 201°F but above the glass transition temperature of 116°F. Within this range the glass transition temperature of PETg is 175°F so this was chosen as the starting point of the trials. These parts would stick together but would come apart while handling or being cut in the waterjet. Thus it was determined that at a temperature this low the PETg and Surlyn were unable to bond to each other even with 120 psi and plasma treatment of the CFRTP surface. From there the temperature was increased greatly to the typical forming temperature of PETg at 330°F as well as a lower temperature to compare. When the lap shear panels were formed at 330°F it was noticed that there was bubbling in the Surlyn layer outside of the specimen.

Table 3.1 - Lap shear forming parameters and results

<table>
<thead>
<tr>
<th>Forming Parameters</th>
<th>Pressure (psi)</th>
<th>Bonded</th>
</tr>
</thead>
<tbody>
<tr>
<td>330°F Plasma Treated</td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>330°F</td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>265°F Plasma Treated</td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>265°F</td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>175°F Plasma Treated</td>
<td>100</td>
<td>No</td>
</tr>
<tr>
<td>175°F</td>
<td>100</td>
<td>No</td>
</tr>
<tr>
<td>175°F Plasma Treated</td>
<td>120</td>
<td>No</td>
</tr>
<tr>
<td>175°F</td>
<td>120</td>
<td>No</td>
</tr>
</tbody>
</table>
Half of these 4” x 12” thermoplastic plates were treated using atmospheric plasma to increase wettability of the surface before bonding. In a study by Abernathy 2016 PETg had an increased wettability after different types of plasma etching. This plasma treatment was done within an hour prior to forming of the specimens. The treatment followed was based off of a study by Moroni et al. where they found that the bond failure load of a plasma treated thermoplastic would decrease as the treatment diameter got above 10mm or with a treatment speed faster than 100mm/s. The setup for the atmospheric plasma treatment conducted consisted of the plasma treatment nozzle attached to a steel
angle using a clamp as shown in Figure 3.3. The parameters used for this treatment was a maximum distance from the outlet to the laminates of 5mm and a treatment speed of less than 100mm/s. This was achieved by measuring the distance from the nozzle outlet to the PETg while clamping it to ensure a maximum distance of 5mm. Since each specimen was 304.1 mm in length, each had to be treated for more than three seconds to achieve a speed of 100m/s. Each of the laminates was treated on one half of each side that would be bonded. The untreated side was then marked with a sharpie to ensure the correct side was used. The laminate plates where then each individually wrapped in tinfoil and brought to the ASCC to be formed in the monarch press within the hour of treatment.

![Atmospheric plasma treatment](image)

**Figure 3.3 – Atmospheric plasma treatment**

### 3.1.2 Lap Shear Testing

The single lap shear specimens were tested using a 100 kN servo hydraulic Instron and following ASTM standard D5868-01(2014). Prior to testing the bond area width and length was recorded as well as the specimen’s overall thickness using calipers. The specimen was then placed in the grips of the Instron as
shown in Figure 3.4 and a holding pressure was applied. When the gripping pressure was applied a compressive force was recorded by the Instron. This compressive force was less than 100 lbs and was not enough to cause any visible damage to the specimens. According to the ASTM standard the lap shear specimens should be loaded at 13mm/s. However, this loading rate caused the specimens to fail within seconds leading to minimal data. To increase the data, the specimen was then loaded at a rate of 2mm/s until failure. During testing the force vs time was measured and the ultimate force during testing was recorded. A picture of specimen failure was taken to understand bond and failure type. This test was conducted for six lap shear specimens for each bonding case.

Figure 3.4 – Lap shear testing

3.1.3 Lap Shear Results

The main interest for the lap shear test was to investigate the possible ways of strengthening the bond between the Surlyn resin and the CFRTP. In this test the ultimate bond shear strength was used as a
comparison for different bonding techniques. During testing the failure of each was a sudden brittle debonding between the CFRTP and Surlyn resin. The bond strength was found by dividing the ultimate failure force by the bond area. The resulting bond strengths from testing are shown in Figure 3.6. While the specimens formed at 265°F were more consistent with bond strength they showed to have a weaker bond than those formed at 330°F. The specimens showed varying debonding failures which are shown in Figure 3.5. While the specimen that showed the highest overall strength had been plasma treated it can be seen that overall the average and median of the plasma treated specimens were lower than when formed at similar temperatures. Thus it can be concluded that the atmospheric plasma treatment of the PETg CFRTP provides little to no increase in bond strength with Surlyn 8940 resin.
Figure 3.5 Broken lap shear specimens 330°F (Left) and 265°F (Right)

Figure 3.6 – Bond strength of specimens
3.2 Three Point Bending of Thermoplastic Beams

ASTM standard (D8337/D8337M) shows that for testing shear strengths of CFRTP composites applied to concrete, a single lap shear test should be conducted. In this test a concrete beam has approximately half an CFRTP strip bonded to the long face with a Linear Variable Differential Transformer (LVDT) attached. The LVDT is an electromechanical transducer that can measure displacement down to 1000\textsuperscript{th} of a millimeter. The concrete block is then held in a frame while the CFRTP is pulled in tension causing the bond to the concrete to fail in shear. Previous work on this project was conducted following this standard but came across problems during testing. The main problem during testing was the effect of a moment on the CFRTP to concrete bond caused by the Instron grips not being perfectly aligned with the CFRTP strip when closed. (Libby 2020) This moment caused a peeling action that led to the bonds failing earlier and even before loading all together. Thus the three-point beam bending test developed by (Gartner 2011) was used to negate the effect of a moment allowing pure shear to fail the beam specimens.

3.2.1 Thermoplastic Beams Manufacturing

The concrete beams of size 3” x 3” x 11” were manufactured in three different ways. This was done to increase the amount of available specimens for beam testing without obtaining extra materials. The first six beams made were UHPC and cured in a wet room at 95% humidity for 28 days. Two UHPC beams were made and cured in the wet room for one day and then moved to a hot water bath for at 75°C for 7 days. The last two of the beams were made out of the normal concrete mix design shown in Table 3.2. They were cured in the wet room for one day and then in the hot water bath for 7 days. After curing the concrete cubes batched with each of the beams was tested in compression in accordance with ASTM C109. The average compressive strength of the cubes is presented above in Table 3.3. A wet saw was
used to cut the beams in the center halfway through. This was done to prevent the bottom portion of the concrete beam from being in tension during bending. The beam was then surface roughened, on the side with the saw cut, using a wire wheel. A high-powered air compressor was then used to blow all the dust from the surface.

Table 3.2 - Normal Concrete Mix Proportions

<table>
<thead>
<tr>
<th>Mix Constituent</th>
<th>Proportion by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Lime Cement</td>
<td>0.155</td>
</tr>
<tr>
<td>Sand</td>
<td>0.311</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.470</td>
</tr>
<tr>
<td>ADVA 198</td>
<td>0.001</td>
</tr>
<tr>
<td>Water</td>
<td>0.063</td>
</tr>
</tbody>
</table>

Table 3.3 - Cube Compressive Strength For Concrete

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHPC 1</td>
<td>13,975</td>
</tr>
<tr>
<td>UHPC 2</td>
<td>16,433</td>
</tr>
<tr>
<td>UHPC 3</td>
<td>16,723</td>
</tr>
<tr>
<td>Normal</td>
<td>6,006</td>
</tr>
<tr>
<td>Panel 16</td>
<td>17,240</td>
</tr>
</tbody>
</table>

A 16 layer CFRTP was bonded to the concrete beams using Surlyn and PETg neat resin over the saw cut. This consolidation was done in the monarch press at the ASCC. The process involved placing the concrete beam saw cut side up with the resin and CFRTP placed on top. The monarch press then increased pressure to 100 psi and was set to maintain this pressure throughout. The top plate was then heated to 330°F while in contact with the CFRTP and held that temperature for a dwell time listed below in Table 3.4. The specimen was then actively cooled to room temperature. A total of 8 beams were
made with 2 for each of the parameters listed in Table 3.4 using UHPC and normal concrete. An example of one of these beams is shown in Figure 3.7 with the saw cut facing up with the CFRTP bonded over it.

### Table 3.4 - Beam forming parameters

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>Dwell time</th>
<th>Resin type</th>
<th>Pressure</th>
<th>Temperature °F</th>
<th>Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHPC, NC</td>
<td>5</td>
<td>Surlyn</td>
<td>100</td>
<td>330</td>
<td>165</td>
</tr>
<tr>
<td>UHPC, NC</td>
<td>10</td>
<td>Surlyn</td>
<td>100</td>
<td>330</td>
<td>165</td>
</tr>
<tr>
<td>UHPC</td>
<td>15</td>
<td>Surlyn</td>
<td>100</td>
<td>330</td>
<td>165</td>
</tr>
<tr>
<td>UHPC</td>
<td>10</td>
<td>PET-g</td>
<td>100</td>
<td>330</td>
<td>165</td>
</tr>
</tbody>
</table>

![Figure 3.7 - Three point beam specimen](image)

#### 3.2.2 Three Point Beam Testing

The three-point bending beams where loaded using a 100 kN servo hydraulic Instron located at the ASCC. The test was conducted following a study by Gartner et al. with consideration to the ASTM standard (C293M-16) for center loading concrete beams. As shown in Figure 3.8 the beam was placed in the Instron with the saw cut placed directly under the center loading point with the CFRTP strip facing downwards. The loading frame was set up to have a beam span of 9” with a 1” overhang on each side.
To find the bond area of the resin to the concrete, six measurements of the bond width and three for the length were taken using calipers. The beam was loaded at a position rate of 0.01 in/min and the test was stopped after beam failure. Beam failure was evident as the resin debonding could be heard and the force would decrease 90%. During testing the load was recorded using a load cell connected to the load point and the center deflection was recorded by the position of the load point.

![Three point bending fixture](image)

**Figure 3.8 - Three point bending fixture**

### 3.2.3 Three Point Beam Results

The main interest of the three-point bending test was to effectively investigate the bond strength of Surlyn to UHPC. During testing, each of the beams failed by a debonding between the concrete and the Surlyn or PETg neat resin bond. This was known because the Surlyn and CFRTP would still be bonded together but not to the concrete on failure. As well, after failure the UHPC would be cracked at the top of the saw cut showing that the UHPC beams could not carry the load without the CFRTP strips as shown in Figure 3.9. In analyzing the results, Equation 3.1 - Bond Strength of Concrete to Resin proposed by Gartner et al. was used to find the relative bond strength as proposed by Gartner et al. The resulting
bond strength was then plotted with respect to center displacement for each test as shown in Figure 3.10. The area under the curve up to failure was found numerically using the trapezoidal method of integration. This can be taken as the relative energy absorbed from the resin UHPC bond. The energy absorption with a 15-minute dwell time can be seen as higher than the rest in Figure 3.11. The 15-minute dwell time also presented the highest peak load as shown in Figure 3.12.

![Debonded beam cracking after testing](image)

**Figure 3.9 - Debonded beam cracking after testing**

**Equation 3.1 - Bond Strength of Concrete to Resin proposed by Gartner et al.**

\[
\tau_b = \frac{3PL}{5hwS}
\]
Where $\tau_s$ = relative shear capacity of concrete to resin bond (psi), $P$ = average peak center load during testing (lbs), $L$ = span length (in.), $h$ = beam depth (in.), $w$ = bond width (in.), $S$ = bond length (in).

Figure 3.10 - Load vs deflection curve during three point bending
Figure 3.11 - Energy absorbed by beam specimens

Figure 3.12 – Relative shear capacity of concrete to CFRTP bond
3.3 Discussion

The single-lap shear tests showed the different bonding between the CFRTP and the Surlyn with results in Figure 3.6. At a higher forming temperature, the lamina of the CFRTP was able to separate and allow the Surlyn to flow between them. It is possible that the lamina shifting into the Surlyn in the 330°F contributed to their higher bond strength. The separation and shifting of the lamina sheets is undesirable during formal. As well the lamina will not be capable of shifting into the Surlyn resin in the middle portion of an impact panel which will exclude the perimeter when cut for the final specimen. However, the mixing of the two polymers is desirable for a cohesive bond between the two. Therefore a forming temperature of 330°F would be desirable for bonding the Surlyn to PETg. The 330°F specimens created for the lap shear test had bubbles develop in the Surlyn portion. This bubbling is frequently caused by a forming temperature that is too high or moisture during consolidation. (Professional Plastics) Since this was not seen in any consolidations below 330°F it is likely due to the high temperature during consolidation. However, this problem was not seen in the forming of the beam specimens. The beam specimens where heated using only the top heating plate on a 1” x 6” area that was open to the atmosphere which could have led to lower temperatures within the Surlyn during forming. This could be the reason that the beams formed at 266°F failed to bond to the concrete.

From the beam tests it can be seen that Surlyn has the capability to form a stronger bond to the UHPC than the PETg. This coincides with results found from the lap shear beam tests conducted according to ASTM standards (Libby 2020). Thus to achieve a stronger bond to the UHPC Surlyn should be used over PETg neat resin.
CHAPTER 4
DEVELOPMENT OF A SURLYN & E-GLASS CFRTP

4.1 Introduction

From literature review and previous impact tests it is known that during impact, delamination of composites is a typical failure that can be detrimental to the composite. For the impact panels there are two different bonds between the intermediate resin, UHPC, and CFRTP that could delaminate causing failure of the composite. As found from Chapter 3 the Surlyn is capable of creating a stronger bond to UHPC than PETg. By creating an CFRTP using Surlyn as the only polymer, then the intermediate resin can be eliminated. This will allow for the bond between the Surlyn and UHPC to be the critical strength of the composite.

The following section illustrates the trials for creating a Surlyn/E-glass composite laminate. These trials were conducted at the ASCC TPL in the monarch press. The monarch press is able to apply pressure while heating the platens in contact with the specimen. The manufacturing process consisted of three sets of trials to effectively bond the E-glass fibers to the Surlyn skin film to create a lamina. The first two trials used a unidirectional fiber bundles of E-glass. After the first two trials had failed the third trial was conducted using a chop strand mat (CSM) of E-glass. After the third trial the process was reformed to consolidate multiple CSM at a time. Trials were then conducted to bond the lamina to UHPC. In the end a new composite lamina was created that was able to successfully bond to UHPC and create a new composite impact panel.
4.2 Unidirectional Trial

The trials began using Unidirectional bundles of E-glass fibers to be bonded using 0.0075” thick Surlyn skin films. This trial was conducted in an attempt to create a unidirectional lamina that could eventually be bonded to a UHPC to increase impact resistance. In the end the Unidirectional bundles had to be abandoned due to the inability of the Surlyn to penetrate into the bundles of fibers called fiber tows.

4.2.1 Initial Trial

The initial trial was conducted using unidirectional E-glass fibers cut to be 5”x5” between two sheets of Surlyn skin film cut to be 6”x6”. The E-glass fibers were cut using electric shears while the Surlyn was cut using a guillotine at the ASCC. Temperatures of 250°F to 300°F were tested in the monarch press at the ASCC with a pressure of 100 psi throughout consolidation. These temperatures were chosen based on the melt temperature of Surlyn 1601-2 being 208°F and previous Surlyn used showing bubbling at 330°F. After the trial it was clear the temperature was too low as the Surlyn was unable to adequately flow and wet out the fibers. The Surlyn was able to bond to the tows of fibers but not flow into the fibers as shown below in Figure 4.1. The initial shape of the Surlyn was cut to be 6” square and remained the same shape after consolidation. This shows that the Surlyn was not flowing and the temperature or pressure needed to be increased from these original parameters.
4.2.2 Secondary Trial

The second trial also conducted at the ASCC was done using unidirectional fibers at temperatures between $450^\circ F - 525^\circ F$ with varying pressures. These temperatures were taken from the typical processing temperatures on the technical data sheet listed as $330^\circ F$ to $500^\circ F$. The first trial started toward the middle of the range at $450^\circ F$ with a pressure of 100 psi. The resulting laminate had the Surlyn flow between the fibers pushing them apart typically called fiber wash. With this fiber wash the Surlyn was flowing but unable to penetrate and wet the fibers in the tow bundles as shown in Figure 4.2. Thus, in the next attempt the temperature was increased to $475^\circ F$ for fiber wet out and the pressure was
decreased to 25 psi to mitigate fiber wash. The second attempt was unable to adequately wet out the fibers and still showed fiber wash. In an attempt to wet out the fibers a trial was conducted at 525°F at 50psi. In this trial the Surlyn was not able to penetrate the fiber bundles. It was concluded that other measures than applying heat and pressure must be considered to create this unidirectional lamina.

![Figure 4.2 - Fiber washed specimen](image)

To find other ideas for fiber wetting literature was searched and various employees were consulted at the ASCC. Different attempts at consolidation were conducted as they were presented. The first method tried was to increase the amount of Surlyn sheets used in forming. Up to four sheets of Surlyn were used on top and bottom during a consolidation but showed no improvement in fiber wetting. This increase in Surlyn allowed for the Surlyn to flow but when using more than two sheets the Surlyn would flow to the edge of the press. An increase in dwell time up to 25 minutes at forming temperature was attempted to allow time for the Surlyn to penetrate the fiber tows. An attempt to remove the sizing holding the tows
together was made using boiled water and acetone. As well after sizing removal an attempt to knead the resin into the fibers was conducted by ramping pressure from 10 to 75 psi while at forming temperature. None of the attempted methods improved the bond or the penetration of Surlyn into the fiber tows. During these trials it was noticed that the end of the tows, where the fibers spread out, the Surlyn was able to adequately bond to the fibers as seen in Figure 4.3.

![Figure 4.3 - Fiber Wetting at Tow Splitting](image)

From this trial we were unable to find a method to adequately create a composite using unidirectional E-glass fibers and the Surlyn sheets. What we learned during the trials is that isolated fibers could be wetted out and two sheets of Surlyn each side with a temperature of 450°F allowed adequate flow. This led to the idea of using mesh fibers for consolidation with four Surlyn sheets and a temperature of around 450°F.
4.3 Mesh Fibers Trials

The mesh fiber trials were conducted in the order listed in Table 4.1. The result of the first trial was showed the fibers having a yellow discoloration and the Surlyn was unable to bond to the fibers as shown in Figure 4.4. This led to an attempt to decrease temperature to remove discoloration but increase pressure to wet out the fibers. The lower temperatures were unable to effectively adhere the Surlyn to the mesh fibers and the discoloration did not waver. Thus the discoloration was ignored and temperature was increased in search of adequate fiber wetting. After trial five the fibers started to show signs of wetting but with a pressure of 200 psi fiber wash started to occur. During trial six the fibers were effectively wetted out with minimal fiber wash at 100psi and the 200 psi was considered unnecessary as it would likely lead to fiber wash.

Table 4.1 - Mesh Fiber Trials

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Temp (°F)</th>
<th>Pressure (psi)</th>
<th>Dwell (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>425</td>
<td>100</td>
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</tr>
<tr>
<td>5</td>
<td>425</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>450</td>
<td>100</td>
<td>5</td>
</tr>
</tbody>
</table>
After completing these trials, the next step was to create enough lamina to bond to a UHPC core. While creating the UHPC core a few problems arose. The first problem was the time to fabricate one impact panel. The impact panels need 18 layers of the E-glass CSM and with the current process each CSM would take an hour to create in the monarc h press. This with cutting all the CSM and Surlyn and then consolidating into one plate would take 20 hours for the total process. The second problem that arose was at the forming temperature desired the sheets where unable to completely bond to the edges of the concrete core. This debonding using 18 lamina with a concrete core can be seen in Figure 4.7. It was noticed while making one of the plates that when the laminae are stacked they provide further wetting of the fibers. Thus a trial to consolidate three CSM at once was conducted following the stacking shown in Figure 4.5. This CSM stacked lamina fixed the problem adhering to the UHPC core as well as lower the fabrication time to 8 hours. The 3 stacked lamina also showed better fiber wetting after consolidation as shown in Figure 4.6.
In previous fabrications, 8 layers of fibers were used in the orientation [0, 45, -45, 90] and externally bonded to a UHPC core using an intermediate resin. The impact panels in this milestone were fabricated
using 9 layers of mesh Surlyn/E-glass lamina directly bonded to the UHPC core. The number of layers was increased to 9 due to the lower volume of E-glass fibers in the mesh sheets.

The first 20 mesh Surlyn/E-glass laminae were fabricated in the ASCC using the monarch press. These initial laminae were fabricated using a chemical release to prevent the Surlyn from bonding to the heating platens. Using a chemical release can leave a residue on the thermoplastic that weakens the bond ability to other surfaces. Due to this, these laminae were used as a trial consolidation. This consolidation was stacked as follows, 10 E-glass/Surlyn lamina, five Surlyn skin film sheets, UHPC core, five Surlyn skin film sheets, 10 E-glass/Surlyn lamina. The stack was then placed in the monarch and a pressure of 100 psi was applied. The hydraulics was then manually turned off to hold the position and the temperature was increased to 450°F and dwelled for five minutes. At a temperature of 425°F a crack in the core could be seen and bubbling of the Surlyn could be heard. At 450°F the concrete core started to slide out the front of the press. The trial impact panel after consolidation can be seen in Figure 4.7. From visual observation it is seen that for the lamina bonded to the UHPC core, the majority of fibers are completely wetted out giving it a yellow hazy look. However, the lamina was 13” by 13” while the UHPC core and Surlyn skin film sheets were 12” by 12” leaving an overhang of lamina off the UHPC core. Along this overhang the Surlyn from the lamina bubbled left the fibers with resin attached. As well the outside fibers were partially burned.
The UHPC is cast using nylon fibers from Nycon with a melting temperature of 435°F. The melting of the nylon fibers and differential heating of the UHPC core are believed to be the cause of the cracking during consolidation. Thus the next panel was formed at a temperature of 350°F. To find this temperature a few trials were conducted to find the lowest temperature in which two Surlyn sheets would bond and become unrecognizable as two. This is shown in Figure 4.8 and Figure 4.9 where at 325°F the Surlyn is two defined square sheets but at 350°F the sheets are one and starting to round at the edges. The trial panel had shown to be thicker than intended due to excess Surlyn matrix used in forming the lamina. The number of Surlyn sheets between the lamina and UHPC core was decreased to two on each side. This was done to reduce the thickness and prevent having enough Surlyn melted around the UHPC to allow sliding. The time to heat the plate was also changed from 20 minutes to 45 minutes to prevent possible differential heating in the concrete core.
Figure 4.8 – Surlyn formed at 325°F 100psi

Figure 4.9 – Surlyn formed at 350°F 100psi
The second panel was created using 18 individual Surlyn/ E-glass laminas with two Surlyn skin film sheets. The process used was to apply a force of 0.6 tons on the 12” x 12” plate and heat to a temperature of 350°F over 45 minutes. Once at temperature the pressure was increased to 100 psi (7.2 tons) and the monarch press started actively cooling the panel. Once cooled to room temperature the plate had to sit for an additional 30 minutes to dissipate the heat from the concrete core.

The second panel had successfully bonded to the concrete core in the center but failed to bond at the edges of the panel. The fibers were not wetted out as well as the first panel. This panel can be seen in Figure 4.10.
To reduce the fabrication time as well as increase fiber wetting, the Surlyn/E-glass laminas were fabricated using the previous parameters of 450°F at 100 psi, but with a new stacking sequence. The new stacking sequence is illustrated in Figure 4.5. This new stacking sequence proved to wet out the fibers better than previous lamina. These three sheet lamina were used to fabricate the third panel. The third panel was fabricated using the same parameters as the second with 350°F over 45 minutes and 100 psi during cooling. The panel only needed a total of six of the three sheet lamina and four Surlyn sheets split evenly on top and bottom. This panel successfully bonded to the concrete core and successfully wetted out the fibers without the concrete core shifting or cracking. The final consolidation can be seen in Figure 4.11. Some of the problems that are still present include the corners and edges of the panels not entirely bonding to each other and the UHPC. This is believed to be caused from the heating in the monarch press where the specimen is open to the atmosphere so the corners will not
reach the full temperature that the middle reaches. This became less of a problem when the 3 sheet lamina were introduced but still persisted.

![Third Trial panel](image)

**Figure 4.11 - Third Trial panel**

### 4.5 Results

The trials resulted in a process to form impact panels made from UHPC, Surlyn, and E-glass fibers. The complete process is as follows. Consolidation of six of the “3 stacked lamina” sheets using the stacking sequence seen in Figure 4.5 at a temperature of 450°F with 100 psi and a dwell time of five minutes. Each of these lamina is made to be 13” x 13” in the monarch press at the ASCC TPL. Then the final impact panel is formed following the stacking order, three “3 stacked lamina” sheets, two Surlyn sheets, UHPC plate, two Surlyn sheets, three “3 stacked lamina” sheets. This stack is formed by applying a pressure of five psi and heating to a temperature of 350°F and then actively cooling while applying a
pressure of 100psi. The impact panel was then cut in the waterjet to create a smooth sided 5.8” square panel.
CHAPTER 5
IMPACT TESTING

The panels created previously in this project have yet to be compared to any other types of external reinforcement for UHPC. Therefore a few thermoset resins have been chosen to create impact panels for comparison to the thermoplastic panels created in this research. Each of these panels was tested under a single impact and two quasi static tests under the same parameters.

In this chapter the manufacturing process for each panel is listed along with the testing method and results. The thermoplastic panels (CFRTP/Surlyn) made of PETg and Surlyn were cast using a thermoforming process. The thermoset resins used in this were recommended by McMaster-Carr as typical structural epoxies used for bonding to PETg and concrete. These where applied in a simplified process following procedures listed by their technical data sheets.

5.1 Manufacturing Impact Panels

The panels were all manufactured using UHPC as the core with externally bonded CFRTP containing E-glass. E-glass was first used for electrical insulation but is now the most widely used of the glass reinforcements (Zweben 2005). The panels were then each cut using a waterjet to create specimens for impact testing. To cut the UHPC reinforced impact panels using the waterjet, special parameters have to be considered. The panel must be cut as concrete with no steel at a speed of 40% and the cutting must start off the part and pierce it from the outside. This procedure was followed to create a smooth finish on each side and prevent delamination during cutting. When other settings are used a panel can have an uneven cut and even delaminate from the UHPC core as shown in Figure 5.1. Thus, each panel in this section was cut using the same parameters in the waterjet. After each specimen was cut to size, they were left in the ASCC lab together at room temperature. This was done as the temperature can influence the impact resistance of epoxy composites (Suresh Kumar 2015).
The CFRTP laminates used for the CFRTP/Surlyn composite, two-part epoxy, and CFRTP Urethane panels were made using 2” wide unidirectional pre-impregnated PETg/E-glass tapes with a fiber volume of 60%. These CFRTP sheets were fabricated at the ASSC TPL using the FiberForge RELAY 2000 Station that automates tape layup and the monarch press to consolidate the layup. These were made to be a square sheet with a 13” width and 8 layers of unidirectional fibers oriented in the directions [0,45,-45,90]. The final thickness of each of these CFRTP laminates was between 0.05” to 0.07”.

5.1.1 UHPC Panel Core

In order to create comparative impact panels each UHPC core had to be cast and formed using the same process. This process included creating compressive cubes to verify each panels strength. Each panel was formed in the concrete lab located in Boardman Hall at the University of Maine. These panels were fabricating using the mix proportions listed in Table 5.1. This mix proportion was presented by ERDC and has been modified from using steel fibers to ¾” Nycon-RC nylon fibers. This switch to nylon fibers was done to make the panels easier to fabricate since the steel fibers with a diameter of 0.2mm could pierce skin during mixing. However, the addition of the nylon fibers will weaken the mixture since nylon fibers have a tensile strength of 44 ksi and steel fibers 140 ksi.
Table 5.1 – Mix constituents for UHPC

<table>
<thead>
<tr>
<th>Mix Constituent</th>
<th>Percentage by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Lime Cement</td>
<td>37.4%</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>6.6%</td>
</tr>
<tr>
<td>Silica Sand</td>
<td>46.1%</td>
</tr>
<tr>
<td>ADVA 198</td>
<td>1.2%</td>
</tr>
<tr>
<td>Water</td>
<td>8.7%</td>
</tr>
<tr>
<td>Nylon Fibers</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

The process of creating the UHPC panels started with applying form oil to a six sided panel mold sized 12” by 12” by ½” and a form for 3 cubes sized at 2”. Figure 5.2 shows the six sided panel mold with C clips and the 2” compressive cube molds. Then the Portland Lime Cement (PLC), Silica fume, and Silica sand where weighed out and added to the mixer shown in Figure 5.3. The mixer was then run until the
dry ingredients were mixed. The water and superplasticizer were measured and mixed separately. The water and superplasticizer mixture was then added to the dry ingredients in lifts of about 10% of the original mixture and mixed. This was done until the mixture turned into a moldable UHPC. Typically, around 75 to 85% of the water and superplasticizer were used. After the UHPC became moldable the nylon fibers were added and mixed until completely mixed throughout. The complete mixture was then removed from the mixer and placed into the molds by hand. While adding the concrete to the mold the panel mold was placed on the vibration table and vibrated for 45 seconds to remove and air bubbles and to help the UHPC to even out throughout the panel. Then at the top of the six sided mold was placed and C clamps were used to apply pressure, squeezing out excess concrete. By adding excess concrete to the mold and squeezing it out using C clips, a smooth top surface is achieved with minimal surface voids. The UHPC in its mold was then moved to the wet room that has a temperature of 75°F and a humidity of 95%. After 24 hours, the UHPC is removed from the mold and placed back in the wet room for 27 days to fully cure. After 28 days in the wet room, the 2” cubes are tested for their compressive strength to validate the panel strength. These compressive strengths of the 2” cubes for each panel type are listed in Table 5.2. The panels were then moved to the ASCC and where surface roughened on the top and bottom face using a wire wheel. The remaining dust was then blown away with a high powered air compressor and the rinsed with water to remove any excess dust before consolidation. The panels were then hand washed in a sink to remove any dust left from surface roughening. To make sure there was no moisture left in the UHPC the panels were then placed in the oven and heated to a temperature of 250°F. Once cooled the panels were ready to be bonded to the laminates.
Table 5.2 – Average compressive strength of UHPC used for impact panels

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surlyn CSM</td>
<td>93.3</td>
</tr>
<tr>
<td>2 Part Epoxy</td>
<td>113.0</td>
</tr>
<tr>
<td>CFRTP Surlyn</td>
<td>107.0</td>
</tr>
<tr>
<td>CFRTP Urethane</td>
<td>81.9</td>
</tr>
</tbody>
</table>

5.1.2 CFRTP/Surlyn Plate

Previously in this project CFRTP/Surlyn composite panels were created in Boardman Hall using a Baldwin press. The process involved, heating the CFRTP, Surlyn, and UHPC core in an oven over 40 minutes with
a thermocouple to measure temperature. Then removing the parts from the oven and placing it the Baldwin press while still hot. The press then held the panels at a pressure of 100 psi until the panel was cooled to room temperature.

To improve this process, the panels were attempted to be fabricated at the ASCC TPL using the monarch press. The monarch press provides the possibility of applying heat and pressure simultaneously. To create the CSTCFRTP/Surlyn composite panel, the PETg laminates were bonded to the UHPC core using an intermediate Surlyn resin. The Surlyn neat resin was of grade 8940 and had a thickness of 1/8” before consolidation. The other materials used to create this panel includes the PETg CFRTP and UHPC core. The first panel consolidated in the monarch was done using a pressure of 100 psi up to a temperature of 330°F. Then the panel had a dwell time of 15 minutes to follow the findings from Chapter 3 beam specimens. The UHPC core then cracked and spread apart during the dwell, destroying the panel. The panel was then cooled to room temperature while still holding pressure. The panel shown in Figure 5.4 shows the cracked UHPC core panel separated by the Surlyn. The second attempt at forming was done by applying a pressure of 100 psi and then holding the position. Then after reaching forming temperature the press was once again set to 100 psi. After a minute at temperature and pressure the UHPC core cracked and separated once again. The third attempt proved successful was done by applying a low pressure of 20 psi and heating the plate to 330°F. Then once at temperature the press was set to apply the pressure of 100 psi but once this pressure was reached the press was set to hold the position regardless of pressure. Some issues with this plate shown in Figure 5.5 were that the top CFRTP plate shifted one direction approximately one inch. While the plate was forming crackling could be heard and bubbles can be seen in the Surlyn between the CFRTP and UHPC core. This panel was not used for impact testing due to improper water jet settings being used, resulting in a delaminated panel shown in Figure 5.1.
Figure 5.4 - UHPC Panel cracked during forming

Figure 5.5 – CFRTP/Surlyn Composite panel with sliding of PETg CFRTP
The CFRTP/Surlyn impact panel used was consolidated in the monarch press using the process of applying minimal pressure and heating to 335°F. Once at temperature the panel was actively cooled while a pressure of 100psi was applied. The change in parameters was done to follow those used for the Surlyn CSM panel consolidation. As shown during the consolidation of the Surlyn CSM panel the dwell time and initial pressure was causing the sliding and cracking of UHPC core.

![Final CFRTP Surlyn Composite panel](image)

**Figure 5.6** – Final CFRTP Surlyn Composite panel

Once consolidated, the panel had 5.8” squares cut out using the waterjet to make impact panels for testing. Figure 5.6 shows the impact panel after forming prior to being cut in the waterjet. As well bubbling occurred in the intermediate resin between the CFRTP and UHPC. This was solved along with the other problems when the dwell time was removed and the pressure was applied during cooling.
5.1.3 CFRTP Two-part Epoxy Impact Panel

The two-part epoxy impact panel was made using the 8-layer PET-g/E-glass CFRTP laminate sheets with a two-part epoxy as an intermediate resin to the UHPC core. The two-part epoxy used was a urethane based adhesive labeled U-05FL. The panel was fabricated in concrete lab at Boardman Hall at the University of Maine. Before consolidating the UHPC core and panels had any dust blown off them using an air compressor. The two-part epoxy was put into a dual dispensing gun and mixed using a 5.9” long taper tip nozzle. This was applied to the UHPC directly and the PETg laminate was used to evenly distribute the epoxy along the surface. After spreading the PETg laminate was removed and more epoxy was added to any dry spots. After the epoxy was fully applied, a force of 200 lbs was then applied to the top of the CFRTP sheet to squeeze the excess epoxy and create an even layer throughout the panel. After five minutes 50 lbs of steel was left on the plate to hold pressure for the next 24 hours until the epoxy cured to full strength. The 12” by 12” panel was then cut in the water jet and the final specimen is shown in Figure 5.7.
5.1.4 CFRTP Urethane Panel

The CFRTP Urethane Panel was fabricated using the 8 layer PETg/E-glass CFRTP laminates sheets, UHPC core, and the intermediate Polymer adhesive. The intermediate Polymer adhesive used is a structural adhesive labeled Loctite 5570 made from Urethane and a modified silane polymer.

The fabrication process was conducted in Boardman Hall at the University of Maine. The Urethane adhesive was dispensed using a calk gun and smoothened on the UHPC and CFRTP using a trowel with a flat bottom as shown in Figure 5.8. The CFRTP was then placed on the UHPC and the process was repeated for the bottom. The panel was then placed between two flat molds and C clamps were used to apply a pressure squeezing out the Urethane adhesive as shown in Figure 5.9. From the technical data sheet, the Urethane adhesive takes 7 days to reach peak strength. Therefore, the panels were left for 7 days to fully cure.
Figure 5.8 – Materials used for CFRTP Urethane panel fabrication

Figure 5.9 – CFRTP Urethane panel compressed
5.1.5 Surlyn CSM Plate

The fabrication process of the Surlyn CSM plate is listed in detail in section 4.4.

5.2 Impact Testing Method

To investigate the effect of using externally bonded CFRTP to reinforce concrete as an impact structure, the following testing was conducted at the ASCC. The testing was conducted in three parts that included quasi static loading and a drop weight impact. Each panel was run through these three tests before proceeding with the next. From these tests the energy absorbed and the relative damage sustained by the panel could be calculated.

Testing was conducted using a 25kN Instron for quasi static loading and an Instron CEAST 9350 drop tower impact system (Ceast drop tower). The 25kN Instron had a fixture made for these panels as shown in Figure 5.11. The fixture was able to support the panel on all four sides creating a two way bending when loading. A linear variable differential transformer (LVDT) was attached to the frame to measure the deflection of the bottom of the panel. The top of the fixture has a 16 mm hemispherical tip to load the specimen to simulate the tup used for impact. Before starting testing a plate was placed in the Ceast drop tower and a mark was made where the tup would impact the specimen. Then the specimen was placed in the Instron frame to align the loading tip with the impact location. As well the plate was placed upside down to check the LVDT placement. Calipers were then used to take four measurements of the thickness of each specimen. The thicknesses of each of the panels is listed below in Table 5.3.

Table 5.3 – Impact panel thicknesses

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Two-Part CTCFRTP</th>
<th>Surlyn CSM</th>
<th>CFRTP Urethane</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.5</td>
<td>18.4</td>
<td>24.0</td>
<td>18.7</td>
</tr>
</tbody>
</table>
The components of the Ceast drop tower can be seen in Figure 5.12. The loading frame used has a mass of 1.3 kg and the tup with a load cell has a mass of 0.742 kg. The loading frame has two additional 1 kg mass weights added on to obtain the desired mass on impact. Overall the total mass during impact is 4.042 kg. The machine then calculated the drop height required for a 50 J impact to be 1.261m presenting an impact velocity of 4.97 m/s. 50 J was chosen as it was found to incite enough damage to delaminate the Surlyn Composite panels previously and cause near complete delamination (Libby 2020). However due to friction between the loading frame and the guide rails the velocity will be less than calculated. Thus, the initial velocity was found using a photocell that the loading frame passes through before impact as shown in Figure 5.10. The average impact velocity on impact was 4.9 m/s rather than 4.97 m/s. This caused a lower average impact energy on the specimen of 48.54 J with a coefficient of variation of 0.35. Prior to testing, trials were conducted to verify the photocell velocity recordings with the drop height. Using the initial velocity, force during impact and time the velocity during impact is calculated using Equation 5.1. Where $v = \text{velocity}$, $dt = \text{sampling time}$, $F = \text{force}$, $g = \text{acceleration due to gravity}$, and $m = \text{mass of impactor}$. The sampling time used during this testing was 0.001 milliseconds or a sampling time of 1 MHz.

Equation 5.1 – Velocity during impact

$$v_i = v_{i-1} - dt * \frac{\frac{F_i + F_{i-1}}{2} - g * m}{m}$$
Figure 5.10 – Drop tower photocell

Figure 5.11 - Quasi Static Loading Setup
The testing started with placing a plate in the 25 kN Instron frame. The (LVDT) was then put into contact with the bottom of the panel and was reset to show a deflection of 0. Then using the WaveMatrix program on the Instron, the specimen was loaded at a ramp rate of 2500 N/min up to 2500N and was then subsequently unloaded at the same rate. After unloaded the test was paused and the specimen was removed from the frame. The specimen was then placed in the Ceast drop tower with the same orientation as when in the Instron and secured using bolts and washers shown in Figure 5.12.

Some of the panels were smaller than the frame made for the impact tower. Therefore some panels were restrained by placing an extra washer on the panel to allow the bolted washers to contact the specimen as shown in Figure 5.13. After securing the specimen in the drop tower, it was then impacted with a 16-mm hemispherical tup with a weight of 3.5kg from a height of 1.458 m. These testing parameters result in an impact energy of 50 J and a velocity of 5.35 m/s. During testing, the force and time were recorded based off of a load cell in the tup. From the force and time data taken from the load cell, the Ceast drop tower calculated the deflection of the specimen during impact. After impact the specimen was then removed and photos were taken of the broken specimen. The specimen was then returned to the Instron to continue the quasi static testing.
Figure 5.12 - Instron CEAST 9350 Ceast Drop Weight Tower
The continuation of the quasi static loading was conducted following the same parameters as the first part of testing. The specimen was placed in the Instron with the same orientation as in the first two-parts. This orientation was kept consistent by placing the panel labeling in the back left corner during testing. The hemispherical loading tip was able to fit in the indentation of the plate caused by the impact testing. The specimen was then loaded at a rate of 2500N/min. This test was stopped when the load reached 2500N or the maximum deflection of the LVDT was reached at 5 mm.

During testing a complication with the Instron caused the LVDT to lose connection and fail to record the data for the Surlyn CSM panels as well as half of the CFRTP adhesive and two-part epoxy panels. However, the Instron recorded the position of the loading tip and therefore the change in compliance could be found using the position compared to the LVDT. The relationship between the LVDT and position data has been plotted and shown in Figure 5.14. This relationship can be found and quantified.
Using the graph from Figure 5.14. This is believed to be due to the position accounting for the compression of the panel by being measured from the top rather than the LVDT data from the bottom. Using the graph, the relative center deflection was found using the position data for the remaining of the specimens. With the center deflection the compliance before and after impact was found and the percent change in compliance was calculated. As shown in Table 5.3 the different panels presented varying thicknesses which when finding the stiffness, the thickness will affect this at a cubed rate. By taking the percent change relative to the initial then the effect of the thickness on the initial and post stiffness will not be of concern since they will cancel each other out when finding the change.

Figure 5.14 – LVDT and position comparison
5.3 Results

During impact testing data was collected from the Instron during the quasi static loading and the drop tower during impact. From the data collected from the Instron, the compliance can be found for each panel. The drop tower provides the impact energy and force during impact. From this we can calculate the deflection during impact and absorbed energy. In this section the results are broken up by the data collection the first being quasi static presenting compliance and the second section presenting the force data during impact and the results found from that.

5.3.1 Quasi Static Results

The load displacement curves for both quasi static testing was found using a load cell, LVDT, and the position of the Instron during testing. From this data a load displacement curve could be made for before and after impact. An example of these curves can be seen in Figure 5.16 showing one of the two-part epoxy panels and the relative slope during loading. From these graphs, the initial loading slope can be found as the elastic modulus which is the inverse of compliance. Thus by finding the approximate slope of the two loading curves the compliance before and after impact can be calculated. The elastic modulus was found by taking two points along each loading curve between 0.5 and 2.5 kN. The points chosen were done to represent initial compliance. For the CFRTP CFRTP Urethane panels, the composite was breaking during initial loading as shown in Figure 5.15. Therefore, the initial compliance of the original slope was taken before the damage started.
Figure 5.15 – Quasi static loading of CFRTP Urethane panel

Figure 5.16 – Relative slopes used for change in compliance
The center displacement was initially found using the LVDT placed on the bottom of the panel during loading. After testing 12 of the specimens a problem with the Instron arose that led to the LVDT data not being recorded for the remaining tests. Thus the center displacement had to be calculated using the position data found from the Instron. The change in compliance was then found by taking the difference of the two and dividing it by the original compliance. The results of the change in compliance for each panel is shown in Figure 5.17.

![Change In Compliance](image)

Figure 5.17 – Relative change in compliance

### 5.3.2 Drop Tower Results

During impact testing the drop tower recorded the initial data, time, and force during impact. An example of the force recorded can be seen in Figure 5.18. From the graph the maximum load due to impact can be found.
Figure 5.18 – Force and deflection over time

With the mass of the impactor and this data the velocity, displacement, and energy absorbed by the specimen during impact could be calculated. First the acceleration could be found using the force and the mass during impact. Through integration the velocity and displacement during impact during time could be found. The energy absorbed was then found using Equation 5.2 where $E_i$ is the energy absorbed at point $i$, $F$ is the force, $v$ is the velocity, and $t_s$ is the sampling time. Each of these calculations were done by the drop tower. The energy absorbed for each specimen is presented in Figure 5.20.

Equation 5.2 – Energy during impact

$$E_i = \sum_{i=0}^{i-1} E_i + \xi \left( \frac{F_i v_i + F_{i-1} v_{i-1}}{2} \right)$$
Figure 5.19 – Energy absorbed during impact

Figure 5.20 – Energy absorbed by each specimen from 50 Joule impact
The maximum deflection during impact shown in Figure 5.21 shows the Surlyn CSM and two-part epoxy having the lowest deflection during impact. This matches our data of change in compliance for damage other than the Surlyn Composite panel having a lower deflection than damage. This is likely due to the increased delamination that occurred in the Surlyn Composite panel compared to the CFRTP Urethane panel.

After impact, the panels were inspected and photographed to show the varying failure types. The delamination of each panel was found through visual inspection and tapping of the panel with a metal rod hearing the delamination.
The Surlyn Composite panels had clear delamination in the front with an average diameter of 2.4” as well on the back with a diameter of 5” shown in Figure 5.22 and Figure 5.23. For one panel the delamination reached the outside edge and the UHPC cracked. For the other three the delamination was contained to the panel and there was no visible cracking seen on the edges of the panel.

The two-part epoxy panels had a small dent with no front delamination but a circular back delamination as shown in Figure 5.24 and Figure 5.25. There was no cracking shown on the side of the UHPC and the center had a slight deflection.

The Surlyn CSM Panels showed significantly less residual deflection of the center and a smaller dent depth noticeable by visual inspection. Though delamination may be present in the front face it is unseen due to the hazy coloring of the CFRTP seen in Figure 5.26. On the rear face shown in Figure 5.27 the delamination can be seen and has a different sound when the area is tapped with a metal rod.

The White epoxy panels showed visible damage through cracking of the UHPC on the edges and delamination on the rear face which is difficult to see in Figure 5.29 but is approximately 2” in diameter. The cracking shown in Figure 5.30 occurred on all four sides approximately an inch from the corner. The White epoxy panels showed little dent depth similar to that of the Surlyn CSM panels. There was considerably noticeable residual deflection of the center, confirming the increased deflection on impact.
Figure 5.22 – Front impacted Surlyn Composite panel

Figure 5.23 – Rear impacted Surlyn Composite panel
Figure 5.24 – Front impacted two-part epoxy panel

Figure 5.25 – Rear impacted two-part epoxy panel
Figure 5.26 – Front impacted Surlyn CSM panel

Figure 5.27 – Rear impacted Surlyn CSM panel
Figure 5.28 – Front impacted CFRTP Urethane panel

Figure 5.29 – Rear impacted CFRTP Urethane panel
5.4 Discussion

The goal of the impact testing was to adequately compare the impact resistant of the four different types of panels. To realize this goal, the energy absorption due to impact and change in compliance was of importance. As seen the energy absorbed by the Surlyn CSM panels was the lowest. This is likely due to the Surlyn CSM panels sustaining the least amount of damage as shown by the relative change in compliance shown in Figure 5.17. While metals absorb energy through plastic deformation, these composite panels will absorb the energy through delamination, fiber breaking, matrix cracking, and cracking of the UHPC core. The panel made of the CFRTP Urethane shows this through the UHPC cracking from impact. This panel had started to fail from the original quasi static tests showing that the CFRTP Urethane had an inadequate bond that could not keep composite action during loading shown in Figure 5.15. During impact the CFRTP Urethane had not shown to absorb less energy than the two-part
epoxy and Surlyn Composite panel. This is likely due to the UHPC absorbing the impact. Whereas the Surlyn Composite panel was able to remain bonded to the panel during quasi static loading and under impact delaminated and cracked the UHPC. These multiple failures are possibly the cause for the Surlyn Composite panels ability to almost completely absorb the impact energy. The Surlyn CSM panels had shown little to no visible delamination to the front or back of the UHPC but showed fiber breakage on the point of impact. This fiber breakage could be the sole breakage that absorbed the energy of the impact leading to a lower absorbed energy by the specimen. It is possible that this is due to the bond between the Surlyn CSM and UHPC being strong enough to keep composite action and not delaminate during testing. One of the testing Surlyn CSM panels was put through multiple impact tests while setting up and verifying the parameters of the impact test. This specimen shown in Figure 5.31 had shown delamination failure after many impacts of crushing the concrete in the center before delaminating from the specimen. However, it is important to note that this may be due to the CFRTP sustaining more of the load caused by its increased thickness. As seen from Table 5.3 the Surlyn CSM plates are thicker than the others due to the amount of Surlyn skin films used in creating the 3 sheet lamina. It is possible that this thicker CFRTP is capable of withstanding the impact without much help from the UHPC or bottom CFRTP. As well, mesh fibers were used for the Surlyn CSM panels which could present a stronger CFRTP causing the lower dent depth and damage to the composite. Another factor in varying impact resistance is the compressive strength of the UHPC core used to in fabricating the panels. The compressive strengths in Table 5.2 show the variation of the compressive strengths which was not accounted for in any of the calculations.
Figure 5.31 – Surlyn CSM panel rear face after multiple impacts
Overall the work on this thesis provided a new alternative impact panel and a new manufacturing method for the Surlyn Composite panel. These were compared to two panels made using thermosetting resins through a low velocity impact test. Overall the new Surlyn CSM panel manufactured was found to have a lower energy absorption ability to a 50 J impact but showed lower deflection during impact and decreased damage sustained after.

As mentioned in Chapter 1 the goal of this research was to further increase the impact resistance of the UHPC impact panels by improving the bond between CFRTP and UHPC. This goal was achieved by creating a new panel with Surlyn CSM mesh resin that proved to be more resilient to an impact of 50 J. This was shown through a lower change in compliance of the Surlyn CSM panel as well as the visible damage. An alternative to this was to provide an outside comparison to the thermoplastic panels using typical thermosetting resins. The two-part epoxy used proved to provide a panel that was effective of absorbing a similar energy to the Surlyn Composite panel but with less damage. This increased energy absorption with less damage to the composite is shown in the increased dent depth on the impacted face of the panel. Overall the goal of this research was met by fabricating two new impact panels that sustained less damage than the Surlyn Composite panel during impact while absorbing over 90% of the energy on impact.

**2.7 6.1 Future work recommendations**

Future work should be conducted investigating the Surlyn CSM and how it bonds with the E-glass mesh fibers. It may be of importance to understand the yellow haze caused by thermoforming the Surlyn and E-glass together and if this is caused by the chemical composition of the Surlyn reacting with any sizing
that may be attached to the mesh fibers. Better characterization of the Surlyn can be found by conducting further tests on the thermoplastic. Such as a Thermomechanical Analysis (TMA) to evaluate the coefficient of thermal expansion and a Differential Scanning Calorimetry (DSC) test to find the glass transition temperature of the material. With a microscopy test the voids in the composite can be found and with the data from the burn off test to find the mass of matrix the fiber volume fraction can be calculated. With the fiber volume fraction and the known strength of the matrix and fibers, the strength of the composite can be found.

The impact strength of each panel can be further investigated by conducting more impact tests at higher energies. It is possible that the Surlyn CSM and two-part epoxy panels could absorb a similar amount of energy while the others are unable to due to the lesser damage sustained from the initial impact. If this test is conducted at higher energies, it is possible that the panels will reach their maximum energy absorption capabilities and the Surlyn CSM may outperform the others in energy absorption. Inertial effects will need to be considered in the future if these panels are to be used on a larger scale since inertial effects will increase as the specimen size increases (Suaris 1981). These inertial effects can be calculated by attaching an accelerometer to the specimen during impact and interpolating the deflection on impact using the boundary conditions with the accelerometer data. From this deflection the force from the tup can be found and the difference between the calculated load and measured load will give the inertial load that can be subtracted.


DuPont. (n.d.). *DuPont™ Surlyn 1601-2 TDS* (pp. 1–4).


IEMAI. (n.d.). *PETG Technical Data Sheet (TDS).* 2–3.


NYCON. (n.d.). *NYCON-RC ¾” Nylon Fibers TDS*.


APPENDIX A: LOW VELOCITY IMPACT DATA

This appendix contains the data collected for each panel tested in low velocity impact. This data contains the energy absorbed, compliance, thickness, and impact velocity. 4 impact specimens were cut from each 12” x 12” panels and are labeled together by panel. The abbreviations for each panel is as follows, 2pt = two-part epoxy, W= Polymer CFRTP Urethane panel, H= Surlyn Composite panel, S= Surlyn panel.
### Table A.6.1 – Impact Specimen Thickness and Energy Absorbed

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Table A.4 – Compressive strength of UHPC cores used for panels

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BIOGRAPHY OF THE AUTHOR

Jeffrey Hollstein grew up in Pembroke Massachusetts and graduated from Pembroke High school in 2016. After high school he attended the University of Maine and graduated in 2020 with a Bachelor’s degree in Civil Engineering. He then continued his education at the University of Maine in the Civil engineering department with an interest in Structures. After receiving his degree, Jeffrey will be joining Hoyle, Tanner & Associates as a bridge engineer. Jeffrey is a candidate for a Masters of Science degree in Civil Engineering from the University of Maine in August 2022.