Characterization of Polyethylene Structure Membrane

Master-Thesis

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Statement

I hereby declare that the work presented in this Master thesis, entitled Characterization of Polyethylene Structure Membrane, is entirely my own and that I did not use any sources or auxiliary means other than those referenced.

Truro, NS, Canada, February 26, 2021

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1.0 ABSTRACT:

Polyethylene structure membrane has been used for many years to cover steel framed buildings. These membranes are able to withstand high loads of wind, snow, and rain yet they are a relatively unknown material in the world of tensile structures. In order to raise the awareness of polyethylene membranes they need to be characterized for their physical attributes, durability, recyclability, and other qualities. This characterization has to be done according to some standards that only exist for PVC coated polyester fabrics. These standards have classes based on weight and strength. The results of the characterization and comparison to the PVC standards show polyethylene structure membranes that can meet or exceed the strength of material that is significantly heavier. The density of polyethylene is 35% less than PVC resulting in a lightweight material, but the manufacturing process used in the formation of the slit tapes for the scrim gives the material its high strength. From a physical strength perspective this study shows that polyethylene membranes can be a participant in the tensile structure arena. The classification system of structure membranes should not be limited to materials of specific weight but rather to strength and performance.

2.0 INTRODUCTION:

Polymers of many types are used extensively in our lives today. A few of the applications that come to mind range from carpets to blankets; from clothing to short-term lumber covers; from polymer lumber to permanent structure membranes. These applications can include a wide variety of polymers, but polyolefins are the group used in the manufacturing processes at Intertape Polymer Group (IPG) in Truro, Nova Scotia. Polyolefins include polypropylene and polyethylene; they are non-polar, non-porous, and inert in nature (Whittington, 1978). Polyolefins are used because they are low cost in processing but have an excellent performance record due to their high modulus, high tensile strength, and high chemical resistance (Miyagawa et al., 2007). Mendes et al. (2003) stated that polyolefins are both economically and commercially important. Of particular interest in this report is the group known as polyethylene having the chemical formula of CH_3-$(CH_2)_n$-CH_3 (Wypych, 2008). This group is divided into two main categories, low density polyethylene (LDPE) and high density polyethylene (HDPE), by a benchmark density of 0.94 g/cm^3 (Wypych, 2008). Polyethylene has particularly good strength properties and is easily stabilized for outdoor exposure (Mendes et al., 2003). Stabilization of the polyethylene limits degradation which occurs during exposure to ultraviolet radiation and heat (Andrady et al., 1998).

The focus of this report is the polyethylene membrane manufactured by IPG that is used as a structure membrane. The structure membrane is used primarily in temporary or permanent steel framed structures. Permanent structures are intended to last more than 10 years but probably less than 25 years. This report will characterize the polyethylene structure membrane for its use in tensile structures.

2.1 Introduction to Manufacturing Process:

High density polyethylene (HDPE) resin pellets are brought in by railcars for the first stage of the process, making the tapes for the woven scrim substrate. The plastic pellets are melted in an extruder and extruded in a cast, or thin sheet. This is quench cooled in a water bath then slit into flat narrow strips called slit tape. At this point the molecules in the polymer are somewhat like a plate of spaghetti noodles. They are long but very randomly aligned. Because of this randomness the slit tapes are very stretchy and low strength. The tapes are put through a process involving orientation and annealing which heats and stretches them in a very controlled manner. The molecules are aligned, and the tape becomes narrower and very strong. The tapes are wound on spools and some are sent to the beaming department while others are sent to the weaving department.

In the beaming department the tapes are wound onto a large metal spool called a beam. The tapes are kept flat and straight; this is the machine, or warp, direction of the fabric. The length of the beam depends on the material being made but is generally 4000 metres long. These beams are moved to the weaving department where they are fitted onto the looms. At the looms, the tapes are woven through the warp tapes in a plain weave, with a one up, one down pattern. This is inserting the transverse, or weft, direction of the fabric. The structure membrane is made using a patented process where the tapes are double stacked. This means that instead of single tapes in each direction there are two tapes; one on top of the other.

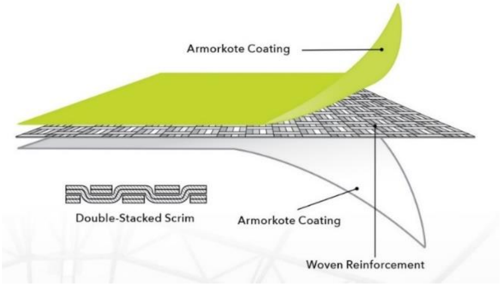

Figure 1: Diagrammatic representation of patented double stacked plain weave, courtesy of IPG.

The rolls from the looms are approximately 950 m long and 373 cm wide. These rolls are moved to the coating department where molten plastic is applied to both sides of the substrates. The molten polyolefin, approximately 280°C, is extruded from a slot die onto the top surface of the scrim. The scrim and coating are nipped between a Teflon coated nip roller and a chill roller. The chill roll is cooled with water and after this nip point the polyolefin is 40°C or less.

The coating weight and profile are monitored by an on-line beta ray gauging system that monitors basis weight of the scrim before and after coating. This provides real time evaluation of the coating thickness. The same process is used to coat the second side of the scrim. Low density polyethylene (LDPE) resin pellets are mixed with a UV inhibitor and colour concentrate then melted at 280ºC and extruded onto the scrim.

NovaShield™ 400 non-FR has clear high density polyethylene (HDPE) slit tapes containing UV inhibitors that protect the plastic from the damaging UV radiation of the sun. The coating is made of low-density polyethylene (LDPE) resin pellets with UV inhibitors and colour concentrates. The colours available for this product are white/white, beige/white, blue/white, green/white, and red/white.

NovaShield™ 400 FR Plus has off-white high-density polyethylene (HDPE) slit tapes containing UV inhibitors and a Flame Retardant additive. The coating is made of low-density polyethylene (LDPE) resin pellets with UV inhibitors and pigmented flame retardant additives. The colours available for this product are white/white, sandstone/white, blue/white, green/white, and grey/white, the grey is sometimes referred to as silver.

NovaShield™ FRU ELITE has the same scrim and coating as is described in the NovaShield™ FR Plus above; however, it has the addition of a white film on one side. The blown film is made of polyethylene resin pellets with UV inhibitors and colour concentrate. In FRU

ELITE, the film also contains flame retardants. The colour available for the ELITE products at this point in time is white/white.

The polyethylene structure membrane is a balanced weave. That is the warp and weft tapes have the same properties in denier and breaking strength; however, the resulting membrane is anisotropic because in the weaving process the warp tapes are held in tension while the weft tape travels further to go over and under the warp tapes. Also, the warp direction is held in tension during the coating process while the weft direction is not. This results in a membrane that is usually stronger in the warp direction than it is in the weft direction.

2.2 Introduction to Steel Framed Buildings:

Briefly, the two main types of steel framed buildings are mono cover and Keder style. The one piece mono cover can be a smaller structure like the hoop frame shown in figure 2. This has the cover constructed as a single unit and pulled over the frame in the lengthwise direction of the building.

Figure 2: Example of a single cover steel framed building, photo courtesy of HiQual Alberta.

This style of building is very inexpensive and of a more temporary nature, especially if it does not have a more permanent foundation.

The Keder style of building is constructed by pulling panels from one side of the building to the other through Keder extrusions then covering the Keder extrusion with a flap to make them completely waterproof. The Keder extrusion is on every truss. These buildings generally have a permanent foundation and are much larger with a clear span interior easily 100 metres wide.

Figure 3: Examples of Keder style membrane buildings, photo courtesy of Norseman Group Ltd.

There is also the building cover that I would consider a mix of the two and it will use two or three mono covers in one building. The mono covers are pulled through Keder extrusions that could be 30 metres apart. Figure 4 shows two mono cover joined by the Keder extrusion which can be seen in the darker line following one of the trusses. This building will have a more extensive foundation than the hoop building and is a more permanent structure.

Figure 4: Mono covers joined by Keder extrusion, photo courtesy of Les Industries Harnois.

There are four basic designs of the steel framed membrane structure commonly in use today:

- Single Truss
- Double Truss
- I-Beam Sidewall
- Plate Girder

The Single truss building has trusses supporting the covering membrane that are only constructed of a single pipe following the curvature of the structure. See Figure 5 for an example of the single truss building style.

Figure 5: Single Truss building style, , photo courtesy of Norseman Group Ltd.

The double truss has two arches joined by steel webbing that follow the curvature of the membrane structure. The depth of the truss can change depending on the width and height of the structure. The trusses, whether they are single or double trusses are joined together with purlins. See figure 6 for an example of the double truss style of structure.

Figure 6: The double truss building style, photo courtesy of Pembina Valley Canvas.

The truss structure, such as these examples, has been used for many years. With our membrane they have been in use for approximately 20 years. Newer styles have evolved and the next two are examples of those newer styles.

The I-beam sidewall has a double truss roof structure, but I-beams are the supporting sidewalls, see figure 7. The I-beams are so named because the beam is in the shape of an upper case I. This style gives a straight sidewall instead of a curvature that starts are the ground. It can still use membrane on the sidewall, rather than having wood or concrete sidewalls.

Figure 7: I-beam Sidewall style, photo courtesy of Norseman Group Ltd.

Similar to the I-beam sidewall is the Plate Girder style, see figure 8. The plate girder is an I-beam with web plates, flanges, and stiffeners. According to www.structuralguide.com (2021) the plate girder can be used when high loads are anticipated, and they have a high degree of stability. The appearance of the plate girder is not the typical light membrane structure but more closely resembles a conventional metal building. The cover in figure 8 is also a Keder cover with Keders on every plate girder steel member.

Figure 8: Plate Girder structure style, photo courtesy of Accu-Steel.

The structures described above are the structures Polyethylene membranes have been used in for over 20 years. The largest structures currently being constructed in these styles are 108 m wide and 220 m long. These are clear span structures.

3.0 CHARACTERIZATION OF POLYETHYLENE MEMBRANE

Polyethylene is considered a thermoplastic because it can be melted with heat and once cooled and crystallized into solid form can be re-melted and re-processed. Polyethylene can be processed by melting with heat in an extruder and further melted by the shearing action between the wall of the barrel and the flights of the screw which melts, mixes, and pushes the polymer through the extruder into the die. The die can be several shapes, but the best known by this author are the coat hanger dies. The coat hanger die has a single pipe at the top where the molten polymer mixture flows into the die and it flows straight down and along the sloping shoulders of the die, so the mixture fills the entire width of the die. Once the mixture leaves the die it is frozen in its crystallized state by chilling. The resulting material is tested using a variety of methods to characterize the physical state and strength of the material. The methods described in this section are those specific to polyethylene structure membrane.

3.1 Description of Methods Used:

3.1.1 Physical Strength – Tensile Tests:

Polymers are viscoelastic, that is to say they exhibit the behaviour of both viscous materials and elastic materials. Panpanicolaou and Zaoutsos (2011) state that the viscous material forgets its original form when the load is removed in a constant stress experiment. Conversely the elastic material remembers its original form when the same load is removed in a constant stress experiment and returns to its original shape. The Viscoelastic material; however, will remember its original form but, when subjected to multiple load/relaxation cycles, the memory will fade over time and it will never return to its original form. Also, if the load is not constant but increases at a constant rate the material will leave the elastic state and enter its plastic state from which it never will return to the original state. If the load is great enough the material will rupture. The rupture point is determined by tensile tests using a Universal Testing Machine capable of constant rate of extension (CRE).

There are two types of tensile testing performed on the fabric; one is Grab Tensile, and the other is Strip Tensile (commonly called Breaking Strength). Both tensile strength tests measure the level of force required to rupture the base fabric. Grab tensile and strip tensile deviate by the width of the material tested and the size of the jaws used. In strip tensile the full width of the fabric is gripped by the jaws of the testing machine and is pulled apart at a steady rate until the fabric ruptures.

Strip tensile tests are used by engineers to determine the allowable pre-stress and stress during installation and tensioning. The North American test used is American Society for Testing and Materials (ASTM) D4851 "Standard Test Methods for Coated and Laminated Fabrics for Architectural Use" and the European test used is EN ISO 1421 Method 1 "Rubber- or plastics-coated fabrics — Determination of tensile strength and elongation at break". The strain rate used during the test is important to note as polymers exhibit strain rate sensitivity. A low strain rate will show higher elongation and lower load at break than a higher strain rate will. Sepe, 2020 states that the yield strength and modulus will increase as the strain rate increases and because of the unique behaviour of polymers the ductility will decrease. The ductility is illustrated as the elongation in tensile tests.

The standard ASTM D4851 requires the universal testing machine with the constant rate of extension to be set at 50 mm/min. The sample is cut 25.4 mm wide. In EN ISO 1421 Method 1 the sample is cut 50 mm wide and the constant rate of extension is set at 100 mm/min. Each specimen is tested, and the average is reported for both test methods.

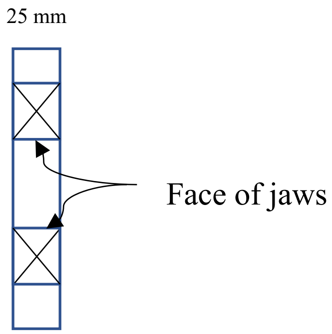

Figure 9: Strip Tensile Test schematic diagram.

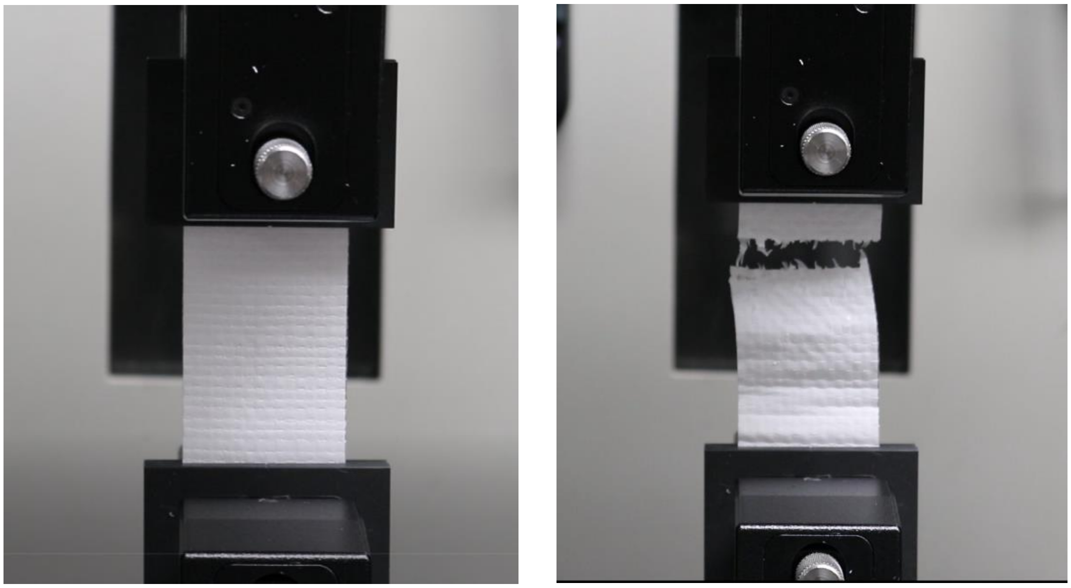

Figure 10: Strip tensile test by EN ISO 1421 at start and finish of test.

In grab tensile the front jaws measure 25 mm x 25 mm, and they grip the centre of a 100 mm wide specimen. The grab tensile test is a measure of the material's ability to redistribute high local stresses and is usually approximately 25% higher than the strip tensile values. The same methods are used for grab tensile, except EN ISO 1421 Method 2 is the grab tensile.

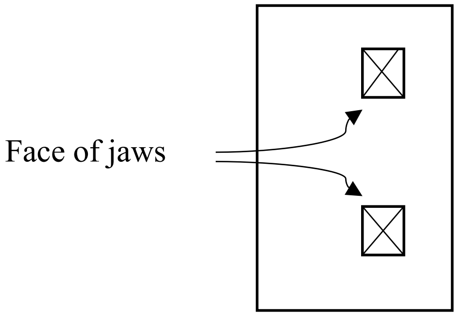

Figure 11: Grab Tensile Test schematic diagram.

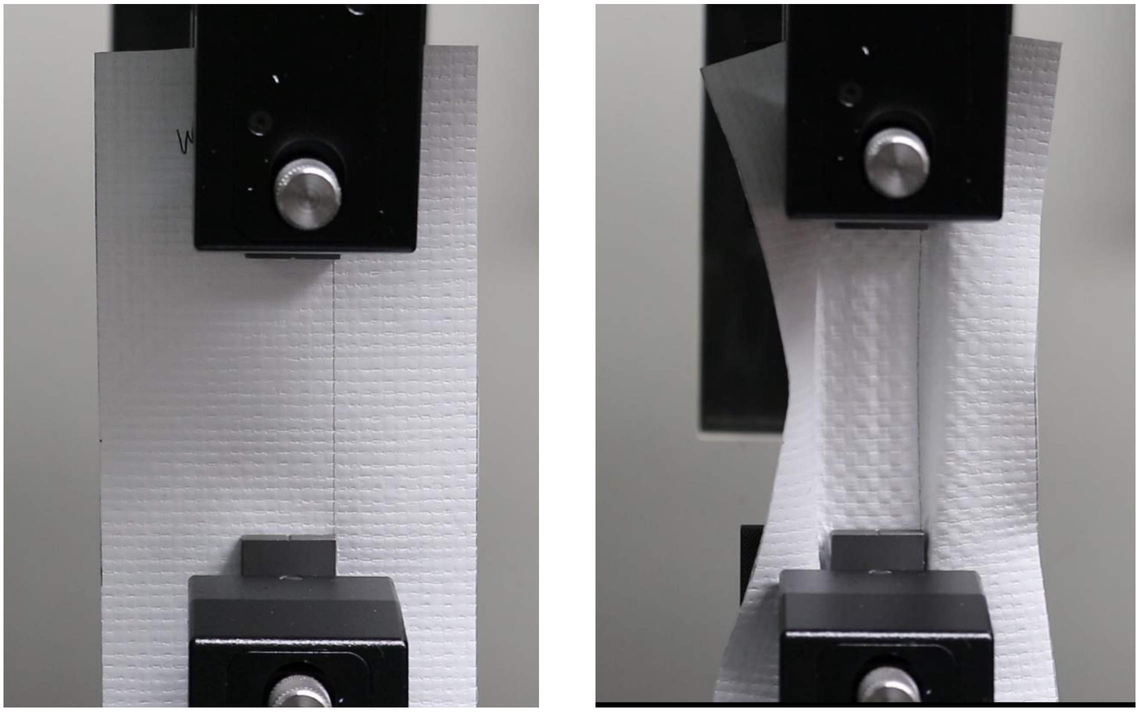

Figure 12: Sample in Grab tensile test at start of test and just before rupture at end of test.

3.1.2 Physical Strength – Tear Tests:

Tear strength gives a measure of the resistance to propagation of tear when the membrane has been slit or cut. The force it takes to tear the membrane can show its ability to prevent localized overstresses or damage that can result in larger tears. The tear strength provides a measure of the resistance to a cut or slit in the fabric. Two types of tear tests are performed; Tongue Tear, also called the Trouser Tear, and Trapezoidal Tear.

The trapezoidal tear tests the resistance to “in-plane” tearing. Of the two tests this is most applicable to the kind of tearing forces applied to membrane structure fabrics. A short slit is made in the edge of the fabric and pulled evenly from the slit. It ruptures one tape at a time as the trapezoidal shaped sample is pulled apart by the testing machine. The North American test method is ASTM D4533 “Standard Test Method for Trapezoid Tearing Strength of Geotextiles” and the European test method is DIN 1875-3 “Rubber- or plastics-coated fabrics - Determination of tear strength - Part 3: Trapezoidal method”.

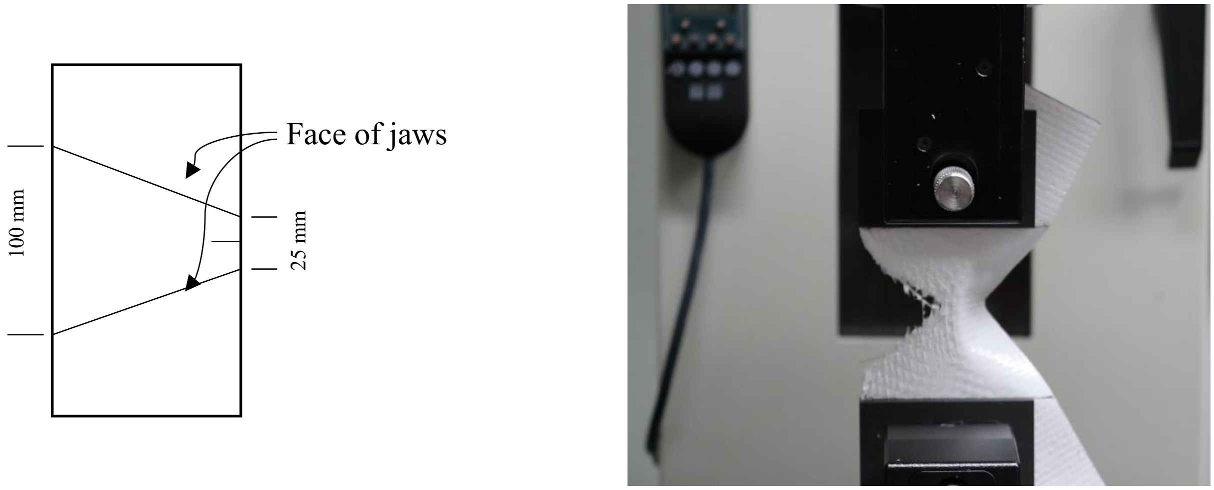

Figure 13: Trapezoid Tear Test schematic diagram and actual test.

The tongue tear is an “out-of-plane” test where the two tongues, or trouser legs, of fabric are pulled in the opposite direction as per ASTM D2261 “Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure (Constant-Rate-of-Extension Tensile Testing Machine)”. This allows the tapes of the base fabric to bunch together as it is being torn. Because of the bunching of tapes two or three tapes will break together as opposed to the single tapes that are broken in the trapezoidal tear test. The European test method for this test is EN 53363 “Determining the Tear Resistance of Plastic Film and Sheeting by the Trouser Tear Method”.

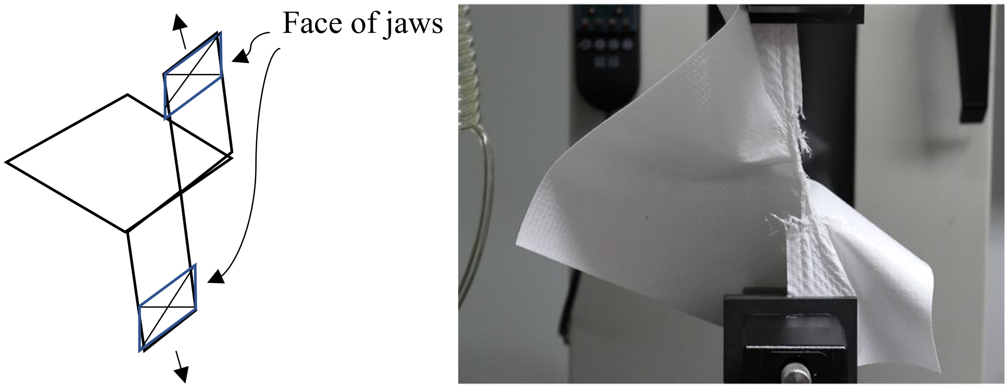

Figure 14: Tongue Tear Test schematic diagram and actual test.

3.1.3 Physical Strength – Burst Test:

The Mullen Burst is a test that measures the force required to rupture the fabric in a one inch diameter circular area using a rubber diaphragm under pressure. It shows the fabric’s ability to withstand a foreign object being pressed against it. The North American test used is ASTM D751 “Standard Test Method for Coated Fabric” sections 18-31 and uses a Mullen burst tester. The material is clamped in the test area and a rubber diaphragm is inflated with hydraulic fluid to the point that the test material is burst by the diaphragm. The gauge of the Mullen burst tester records the force required to burst the material.

Figure 15: Mullen Burst tester.

3.1.4 Hydrostatic Resistance:

Hydrostatic Resistance is tested by ASTM D751 "Standard Test Methods for Coated Fabrics" Sections 36-40 using a Mullen tester, in this case water is used to create pressure on the sample. The sample is clamped in the test area of 1 inch diameter. Water is pressurized below the sample until the first droplet of water comes through the material. This test illustrates the barrier property of the membrane and its ability to withstand ponding water and even the forces behind wind-driven rain.

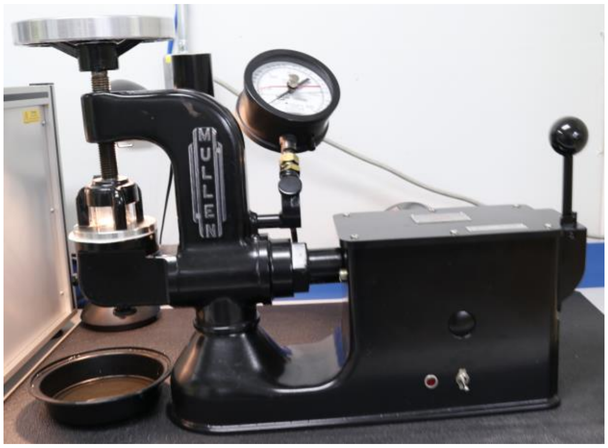

Figure 16: Hydrostatic resistance tester, also by Mullen Testers.

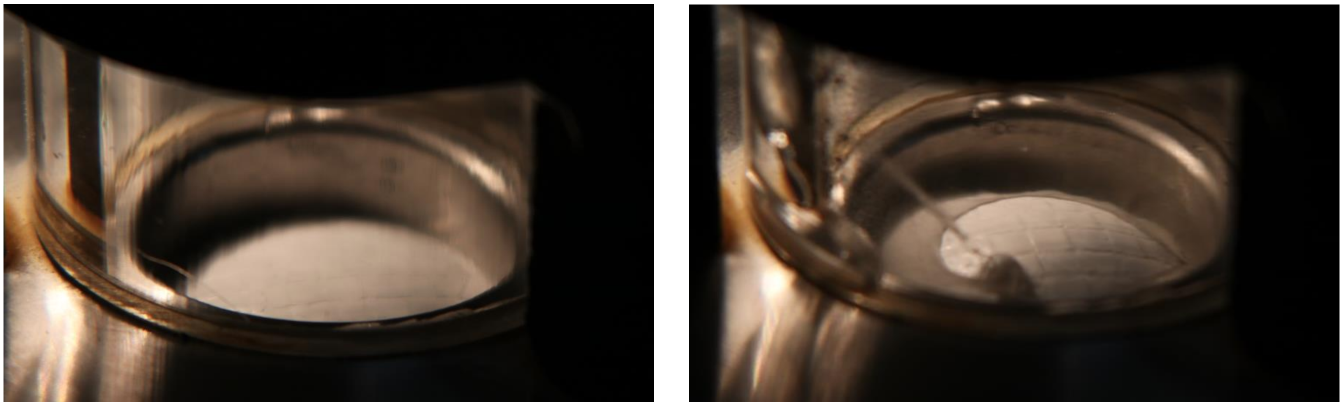

Figure 17: The sample in the Hydrostatic resistance tester, at the start of test and at point of failure

3.1.5 Abrasion Resistance:

The abrasion is measured using a Taber Abraser, following ASTM D3889 “Standard Test Method for Coated Fabrics Abrasion Resistance (Rotary Platform Abrader)”. The abrasive wheels are grade H-10 and the maximum weight of 1000 g is applied to each wheel on the Taber Abraser. The sample is clamped to the rotating platform which causes the abrasive wheels to rotate on the surface of the sample. This test is used to evaluate the number of cycles to scrim and the weight loss after 500 cycles and 1000 cycles. The number of cycles to scrim is important as it shows the toughness of the coating and its ability to withstand abrasion. The abrasion occurs mainly at the time of installation, but it could also occur by wear against the interior frame if tensioning has not been adequate.

Figure 18: Taber Abraser used to measure the abrasion resistance.

3.1.6 Biaxial Strength:

The previously discussed tensile testing, in section 2.1.1, was based on uniaxial elongation. This information shows the ultimate strength of the membrane; however, in practice the membrane is tensioned in the warp and weft directions at the same time. The polyethylene membrane is anisotropic with different properties in the warp direction than it has in the weft direction. In biaxial testing the membrane is held in tension in the warp and the weft direction at the same time with differing ratios of pretension. Using the test method EIN EN 17117-1, "Rubber- or plastics-coated fabrics – Mechanical test methods under biaxial stress states", the force applied is cycled and from the data the elastic modulus, or stiffness, of the membrane is determined in each direction as well as the stiffness interaction between the two directions (Bögner-Balz, 2019).

Poisson's Ratio is the ratio for the interaction between the warp and weft. For an anisotropic material, the relationship is inverse. When pulled in the warp direction the material becomes narrower in the other direction:

Poisson’s Ratio for the interaction between the warp and weft can be expressed as:

$$\upsilon_{12} = E_{1122}/E_{1111}$$

where E_{1122} is the stiffness interaction between the warp and weft

and E_{1111} is the stiffness in the warp direction

Poisson’s Ratio for the interaction between the weft and warp can be expressed as:

$$\upsilon_{21} = E_{1122}/E_{2222}$$

where E_{2222} is the stiffness in the weft direction

Elastic moduli and Poisson’s Ratio are key performance indicators used in structural analysis and load modelling.

3.1.7 Fire Resistance

The polyethylene structure membrane can be classified as fire resistant or non-fire resistant. There are many instances, especially in agricultural applications where non-fire resistant is acceptable. However, when human occupancy occurs most building codes will require fire resistance. There are many tests for fire resistance and up until recent years they were all based on conventional building materials. In North America there are three main fire tests that are required for membrane structures. They are described below.

The first test, NFPA 701 “Standard Methods of Fire Tests for Flame Propagation of Textiles and Films”, is a vertical burn test and it is comprised of Method 1 and Method 2. Method

1 is a small scale burn test with test specimens measuring 15.0 cm x 40.0 cm. The specimen is weighed before the test begins then is hung by a pin bar at the back of a test chamber. A specified gas flame is applied to the specimen for 45 seconds, then removed. If the specimen is burning it is allowed to burn until it becomes extinguished. The specimens are weighed, and percent weight loss is determined. The performance criteria for NFPA 701 Method 1 are <40% average weight loss and <2.0 seconds maximum flaming drip time.

NFPA 701 Method 2 is a large scale burn test, and the test specimens measure 12.5 cm x 120 cm. The test specimens are clamped at the top of the specimen but in the middle of the vertical chimney. Two more clamps hold the specimen in place on the sides 7.62 cm from the bottom and the rest of the specimen hangs freely. The burner is lit with a gas flow sufficient to produce a flame that is 28.0 cm high. This flame burns at the bottom of the specimen for 120 seconds. The acceptance criteria for this test are <2.0 seconds after flame time, <2.0 seconds burning of flaming drips on the floor of the tester, and <43.5 cm damaged length or char length. The weight of the material does not matter with this test.

Figure 19: NFPA 701 Method 2 burn test chamber and sample in holder.

Canada has a similar vertical fire test called CAN/ULC S109 “Flame Tests of Flame Resistant Fabrics and Films”, the specimens being tested in the “as received” condition in small scale and large scale specimen sizes.

A horizontal fire test required in the United States is ASTM E84 “Standard Test Method for Surface Burning Characteristics of Building Materials”. This is a Steiner tunnel test where the specimens are suspended at the top of the tunnel. In the case of membranes, they are pliable and therefore are suspended on chicken wire at the top of the tunnel. The specimens are cut 61 cm x 762 cm. A large Bunsen burner at one end of the tunnel is lit with a horizontal flame that is 61 cm long and the specimen is monitored for burn time and the smoke developed. An index is developed based on the relation of the specimen to two other materials. Cement board is considered the zero of the scale and red oak is the 100 end of the scale. According to the method Class 1 or Class A material have a flame spread index < 25 and smoke developed index < 450. Some jurisdictions require a smoke developed index < 50.

In Canada, the horizontal fire test is CAN/ULC S102 “Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies”. The tunnel is preheated to 85°C then cooled to 40°C before the sample is placed in the top of the lidded tunnel. The flame spread is observed and recorded every second and the flame spread distance is plotted versus time. The area under the curve is used to determine the Flame Spread Value. The Smoke Developed Value is determined by comparing to cement board and red oak, being 0 and 100, as in ASTM E84.

The last fire test that is very important in the structure industry in North America is the California Fire Marshal certification. This certification is based on Title 19, section 1237 for exterior material and is a small scale vertical burn. The material is held in a sample holder suspended from a metal rod over a burner. The flame burns for 12 seconds and the sample is evaluated on the damaged length, afterflame time, and burning drips. The material is tested in its "as received" condition, after water leaching for 72 hours, and after weathering for 100 hours in accelerated UV testing machines.

In Europe, as in North America, each country has its own fire tests. In recent years; however, the standard EN ISO 13501 "Fire classification of construction products and building elements-Part 1: Classification using data from reaction to fire tests" has become the classification for the reaction to fire accepted in the EU. This standard not only classifies the reaction to fire it also tests to determine the ignitability, flame spread, heat release, smoke production, and its production of flaming droplets and/or particles. There are seven classes for construction products:

Non-combustible/limited combustible materials:	A1, A2
Combustible materials with very limited contribution to fire:	B
Combustible materials with limited contribution to fire:	C
Combustible materials with medium contribution to fire:	D
Combustible materials with high contribution to fire:	E
Combustible materials with easily flammable:	F

Additionally, there is a classification of smoke emission levels:

s1: quantity or speed of smoke development is absent or weak.
s2: quantity or speed of smoke development is of average intensity.
s3: quantity or speed of smoke development is of high intensity.

and classification of flaming droplets and/or particles:

d0: no droplets.
d1: slow dripping.
d2: high dripping.

Several test methods are included in this standard depending on the type of material and how it is used. The polyethylene membrane has been tested using the ignitability test EN ISO 11925 as it is relevant for all classes of material except those that are non-combustible or of limited combustibility.

3.1.8 Durability

The durability of structure membranes is very important to understand. Many membrane structures are erected with the intention of many years of service; however, during those years of service the polymer membrane is exposed to natural weathering such as heat and ultraviolet (UV) radiation. If polymer degradation can be understood, it may be possible to predict the life-time of the building components made from polymeric resins and replacement protocol can be established (Khan and Hamid, 1995). The study of the "aging" process of polymers was considered to be important by Tavares et al. (2003) because it can assist with the forecasting of the life span of the polymer.

The degradation noted by Andrady et al. (1998) ranges from surface discolouration, which affects the aesthetic appeal, to the loss of mechanical properties, which can seriously limit the performance. Mendes et al. (2003) concluded degradation can be on the molecular level affecting the crystallinity of the polymer chain leading to embrittlement and consequent loss of the property of elongation or ductility. Incorporating additives such as antioxidants and UV inhibitors during the manufacturing process can give heat and light stability to the polymers.

It has been suggested previously that understanding the degradation of polymers, and the rate of degradation, is beneficial in order to predict life-times and therefore replacement times of structure membranes. Intuitively the best way to study this would be in situ; however, this could mean waiting years to get results. To save time tests have been designed which accelerates the effects of weathering and most degradation studies are done in this manner.

A machine produced by Q-Panel Lab Products, known as a QUV machine, can be used for accelerated laboratory exposure. The QUV machine has two banks of fluorescent tubes that emit ultraviolet radiation at wavelength 340 nm and at a specified irradiance set point. The temperature and moisture levels are also controlled in this machine. See Figure 20 for the sample configuration and fluorescent tube location in a QUV machine.

Figure 20: QUV machine with samples in place.

The machine operation and sample exposure are carried out following ASTM G154, "Standard practice for operating fluorescent light apparatus for UV exposure of nonmetallic materials", and G151, "Standard practice for exposing nonmetallic materials in accelerated test devices that use laboratory light sources". The exposure conditions are eight hours of UV at 60°C; four hours condensation at 50°C. The irradiance level of UV light setpoint is 1.35 W/m²/nm. The samples are rotated through the machine regularly during the exposure to ensure that each specimen receives an equal amount of radiation and that replicates are treated equally.

Specimens are pulled from the QUV machine every 1000 hours. The exposed areas are examined for microscopic evidence of surface changes from degradation, mainly crazing or cracking in the coating. The specimens are tested for colour and gloss at the 1000 hour intervals as well. Finally, the specimens are tested for physical strength by the strip tensile method ASTM D4851. According to the Canadian Building Code which adopted CAN/ULC S367 “Air-, Cable- and Frame-supported Membrane Structures” in 2009, this test is completed at 1000 hours and 4000 hours. Additionally, trapezoidal testing according to ASTM D4533 is conducted at the same exposure intervals. The exposed tests are compared to the strength of the retained samples to determine the percent retained strength.

Retained strength can be expressed as:

$$\text{Retained Strength (\%)} = ((\text{Force}_O - \text{Force}_S) / \text{Force}_O) * 100$$

Where Force_O is the strip tensile strength (or trapezoidal tear strength) of the base fabric

And Force_S is the strip tensile strength (or trapezoidal tear strength) of the exposed specimen.

3.1.9 Light Transmission/Translucency

Polyethylene structure membrane is a translucent material allowing a certain amount of light to pass through. Three interactions can take place; the light can be absorbed, transmitted, or reflected. The sun’s light, or solar radiation, is most often represented as a bell curve such as in Figure 21.

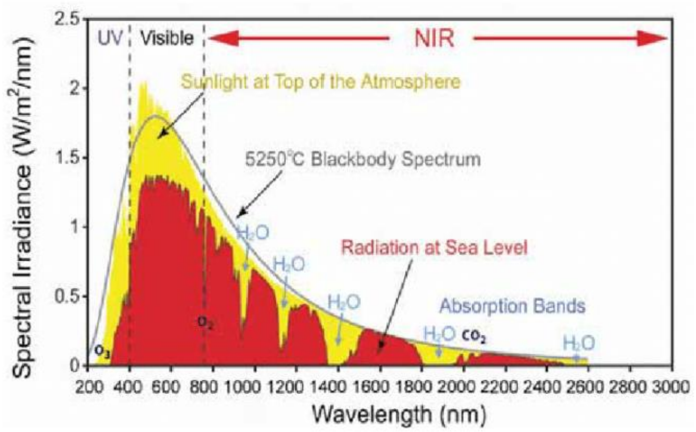

Figure 21: Solar Radiation graph (Tanaka and Matsuo, 2011).

There are three main types of light in solar radiation; ultraviolet (UV) from 200 to 400 nm, Visible from 400 to 740 nm, and near infrared (NIR) from 740 nm and higher. Instrumentation can measure the spectral reflectance and transmission and the absorptance is calculated from Kirchhoff's Relationship where:

$$\rho + \alpha + \tau = 1$$

The method used for this is ASTM E903 "Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres". In this way we can determine the UV light, visible light and NIR light that is either transmitted, reflected, or absorbed by the structure membrane. Because the polyethylene structure membrane is coated white on at least one side, if not both, no UV radiation passes through. It is blocked by the titanium dioxide (TiO_2) in the white coating.

The typical values of outdoor light levels in a moderate climate are given by Bögner-Balz (2019):

Illuminance - Sunny summer day 100,000 Lux
Cloudy summer day 20,000 Lux
Cloudy winter day 3,000 – 5,000 Lux

These values are measured without any object or material between the sun and the measuring device. The values from ASTM E903 can be used to calculate the illuminance inside a single layer membrane building with the following calculation:

$$T_m = \frac{T_1}{1-r_1}$$

Where T_m is the illuminance in the structure, T_1 is the transmittance of the membrane and r_1 is the reflectance of the membrane. The calculated T_m is the transmittance as it would be on a sunny day. In general, on a cloudy summer day the illuminance would be reduced by five times and a cloudy winter day it would be reduced by 20 times (Bögner-Balz, 2019). Table 1 lists the recommended light levels in various work areas according to Engineering Tool Box, 2004.

Table 1: Recommended light levels for various work areas (www.engineeringtoolbox.com, 2004).

ACTIVITY	ILLUMINANCE (Lux)
Warehouses, homes, theaters	150
Coffee break room, waiting rooms	200
Normal office work, auditoriums	500
Normal drawing work	1000
Detailed drawing work	1500-2000
Performance of very prolonged and exacting visual tasks	5000-20000

4.0 WELDING

Polyethylene membranes can be heat welded using hot air or hot wedge welding equipment. Due to its inert nature, it cannot be welded using high frequency or RF welding. Most panel welding is done with hot air floor crawling machines such as the one in Figures 22, 23, and 24. Generally, a panel weld is formed by overlapping two layers of membrane and inserting the nozzle, blowing hot air, between the layers. The typical weld width is 38mm to 44mm. The proper setpoint of temperature and speed is determined through experimenting with these variables and testing the resulting welds according to the test methods described in section 4.1, seam peel and seam shear. The setpoints in one machine can be a starting point; however, every machine is different depending on manufacturer and age. Other machine settings that can sometimes be adjusted are the nip pressure and/or the air velocity. The hot air floor crawlers are operated by nipping the membrane at the point the hot air is applied between a nip roller and the floor, so weights are applied to the top of the machine. Wedge welders are nipped at the point the hot wedge is applied between two nip rollers. The pressure can be adjusted between the two nip rollers on these types of welding machines. The air flow cannot always be adjusted on hot air welders. For instance, the Eagle Cadillac hot air welder cannot be adjusted, and the Leister hot air welders can be. The Leister hot air welders are usually operated at 85% air flow.

In the process of finding ideal welding conditions, it is better to slow the machine down over increasing the temperature of the hot air. The dwell time is increased when the speed is reduced, and the coating of the membrane is given time to melt. When the temperature is simply increased the reinforcing base fabric is more likely to shrink or deform. If the reinforcing base fabric shrinks it can form puckers or distortion in the end product. Distortions should be kept to a minimum. The more distorted the fabric becomes the less likely those distortions will be pulled out in the tensioning process during installation. A more serious concern is the reduction of strength of the base fabric if it is damaged by excessive heat during the welding process. This will be discussed in section 4.1, Weld Testing.

A second type of weld usually needed in structure membranes are the rope hems or Keders. Most manufacturers of polyethylene covers make the Keders in the edges of the panels rather than welding a separate single flap Keder. A larger standing hot air welder is used for this type of welding. The Keder rope is fed through a nozzle with the fabric rolled over the rope and a weld is produced right up against the rope holding it tightly in place. The Miller Weldmaster is very popular for this type of welding and many metres of Keder can be produced very quickly.

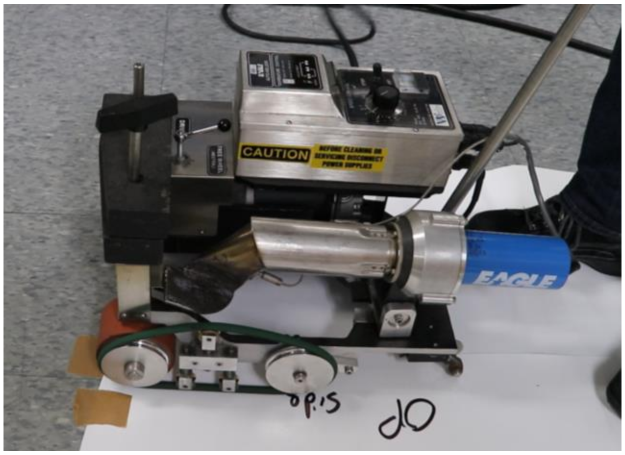

Figure 22: Side view of hot air floor crawler welder.

Figure 23: Top view of hot air floor crawler welder.

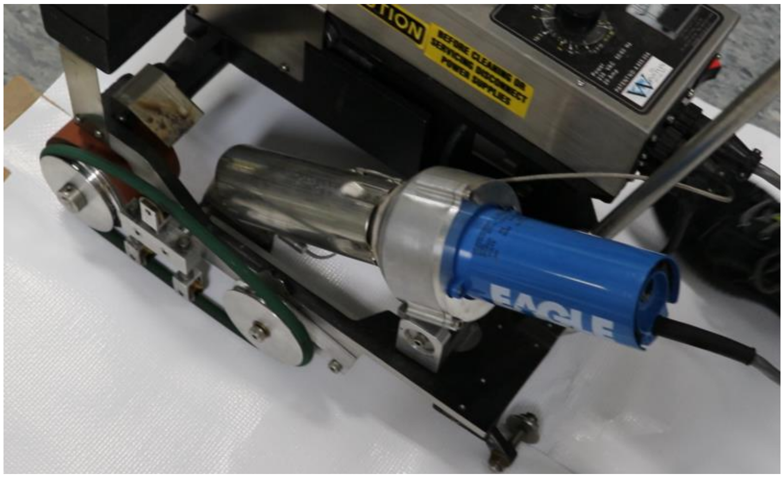

Figure 24: Top view of hot air floor crawler welder with nozzle between the overlapped fabric.

The polyethylene membrane typically is manufactured at a width of 366 cm which means few seams are required to make large panels. As described above, these seams are made with hot air, and sometimes hot wedge, both of which are used at relatively high production speeds if compared to bar welding, or high frequency welding. However, because the polyethylene membrane cannot be welded with high frequency welding it is difficult to produce seams that come together in a corner such as pie shaped wedges.

4.1 Weld Testing

Welds can only be tested in a destructive manner to determine if they are strong enough, yet not damaging the base fabric. Because of this it is important to test welds in a systematic and controlled manner. In Canada, the building code has adopted the method CAN/ULC S367 “Air-, cable-, and frame-supported membrane structures” for the design, fabrication, installation, and maintenance of membrane covered structures. In the fabrication section of the method the requirements for the testing of welds are described. The frequency of testing is at least once for every 1000 linear metres per welding machine, or once per shift, whichever is more frequent

(CAN/ULC S367, 2012). I recommend at the beginning of every shift as well. The tests are weld adhesion, or seam peel, seam shear strength, and static load testing.

4.1.1 Weld Adhesion

I shall refer to this test throughout this paper as seam peel. The test specimen is 24.5 mm wide and is cut from the centre of the seam. If the seam is not cut from the centre of the weld there are extra forces required to break the coating bond at the edges of the weld. By removing these the seam peel is a true picture of the strength of the adhesion between the coating and the base fabric. The operator will also see if the weld itself is sufficient. This will guide the operator in choosing their temperature and speed. Ideally when the weld is pulled apart there will be coating peeling from both sides of the weld.

Figure 25: Test specimen drawn on the welded membrane.

Figure 26: Beginning of seam peel on universal testing machine.

4.1.2 Seam Shear Strength

The seam shear is a uniaxial tensile test perpendicular to the seam. This tests the strength of the base fabric after a seam has been produced. The tensile strength of the seam is compared to the strength of the original base fabric to determine the retained strength. The tensile test used for this segment is the same as described in section 3.1.1, ASTM D4851.

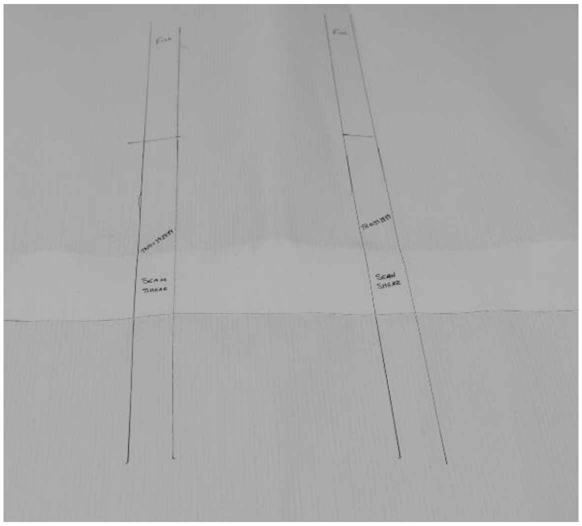

Figure 27: Test specimens drawn on the welded membrane.

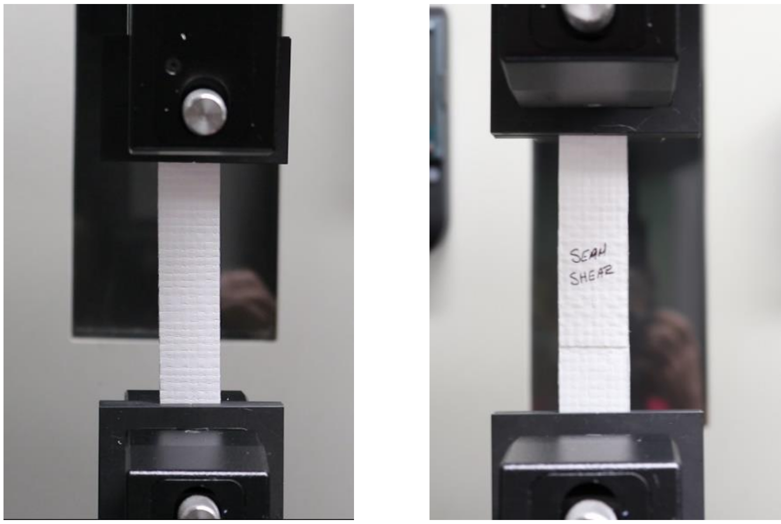

Figure 28: Base fabric in strip tensile and seam sample in same.

Retained strength can be expressed as:

Retained Strength (%) = $((\text{Force}_O - \text{Force}_S) / \text{Force}_O) * 100$

Where Force_O is the strip tensile strength of the base fabric

And Force_S is the strip tensile strength of the welded fabric.

4.1.3 Seam Static Load Testing

The static loading is performed on a sample of the welded membrane. This will show the creep performance of a seam and is done at room temperature. The seam is welded as normal and a sample is cut from the membrane with the seam perpendicular to the length of the specimen. The specimen is clamped in such way that it hangs freely. A weight is attached to the bottom of the specimen that is equal to either 200% of the maximum design service load or the load that is 25% of the breaking strength as determined by the strip tensile test, as described in section 3.1.1, by ASTM D4851. The duration of the test is four hours without visible deterioration of the seam.

Alternatively, the creep test can be performed using a universal testing machine capable of holding a load for four hours. Elongation of the specimen is recorded in percent.

5.0 WEIGHT – TRANSPORTATION AND INSTALLATION

The strength to weight ratio of polyethylene structure membrane is one of its most striking characteristics. The basis weight of the NovaShield™ non-FR and FR Plus membranes is 407 gsm and yet the tensile strength of the membrane is approximately 45 kN/m. This weight has a huge consideration in the cost of transportation and the ease of installation. Large panels can be manipulated by manpower in many cases. Not only is the weight to tensile strength ratio high the polyethylene membranes also have very high tear strengths, exceeding 0.44 kN force much of the time.

6.0 ENVIRONMENTAL CONSIDERATIONS

The environment is such an important consideration. Sustainability is a huge focus of manufacturing companies in these recent years and in particular manufacturers of plastic which polyethylene structure membrane is. There have been many bans on plastics, especially single use plastics. Structure membranes are not single use plastics and indeed are stabilized to last 15 to 20 years, at least. But they are still plastic and as such under scrutiny in the manufacturing process, converting process, and end of life disposal. This type of examination is studying the circularity of a product, the entire life of a product from the birth to the grave. There are many study groups around the world and the one I will describe here is Cradle to Cradle Products Innovation Institute. This institute is a global entity with science based methods for evaluating products for their safety, circularity, and responsible manufacture. This institute has a Cradle to Cradle certification.

6.1 Cradle to Cradle Certification

Cradle to Cradle certification, also called C2C certification, can be obtained after a product has been evaluated based on five categories. These five categories are: material health, material reuse, renewable energy and carbon management, water stewardship, and social fairness. Once assessed a product is assigned an achievement level for each of the categories. The lowest level achieved in any one of the categories is the level assigned to that product. The achievement levels are Basic, Bronze, Silver, Gold, and Platinum. A product requires certification renewal every two years. A description of the five categories (Cradle to Cradle Certified™ Products Program, 2021) follows:

The first of the five categories is Material Health. The chemicals used to manufacture a product are examined by a team of scientists to rate them on their safety for human and environmental contact. Assessment bodies accredited by the program will contact the suppliers as a confidential third party and evaluate at all the raw materials that go into the constituent parts.

The second category is Material Reutilization. This is the rating on recyclability and is concerned with post-consumer recycled content (PCR) and post-industrial recycled content (PIR). How can waste be eliminated from the manufacturing process? Only by the manufacturer reclaiming their waste in the industrial process and finding ways for the material to be incorporated once the consumer is finished with it, the end of its life cycle. It may not go back into the structure membrane where strength and durability are of the utmost concern, but they can go into other products with less rigorous requirements.

Thirdly the products are evaluated on Renewable Energy and Carbon Management. The assessment bodies look at the energy required to manufacture the product. The effort is to focus the manufacturer on using renewable energy rather than fossil fuels to reduce, or even eliminate, the production of greenhouse gases.

The fourth category is Water Stewardship. Water is a valuable resource. Treating it in a wasteful manner reduces the watershed and reduces the clean water available for people and really all living organisms. Water is required in many manufacturing processes but through upgraded equipment and state of the art chillers and reclaimers the amount needed can be significantly reduced.

Lastly, Social Fairness is considered. Products are not produced in a vacuum; it takes the effort of many people along the way and those people must be considered. A safe working environment is required, and a living wage is necessary.

Not only are products rated on these five categories, but they must also be re-evaluated every two years as the Cradle to Cradle Products Innovation Institute, which administers this program, wants manufacturers to be always improving and striving for a higher level of achievement, reducing the impact on the environment, and thereby reducing climate change.

The NovaShield™ polyethylene structure membrane has a **Bronze** overall achievement level.

7.0 MEMBRANE PERFORMACE

The following tables contain the data for polyethylene structure membrane according to all the performance criteria as described in sections 3 and 4.

Table 2: Physical Strength characteristics of polyethylene structure membrane

Parameter	***Standard***	***NovaShield™ non-FR***	***NovaShield™ FR Plus***	***NovaShield™ FRU Elite***
Mass, g/m²	DIN EN ISO 2286	407	407	466
Strip Tensile Strength, kN/5cm Warp/Weft	DIN EN ISO 1421-1, Method 1	2.2/2.1	2.3/2.2	2.5/2.2
Elongation at break, % Warp/Weft		19/16	22/18	22/18
Strip Tensile Strength, lbs/in Warp/Weft	ASTM D4851	245/235	262/248	265/250
Elongation at break, % Warp/Weft		20/17	22/17	22/18
Grab Tensile Strength, kN Warp/Weft	DIN EN ISO 1421-1, Method 2	1.6/1.5	1.6/1.5	1.9/1.8
Grab Tensile Strength, lbs Warp/Weft	ASTM D5034	370/345	360/350	425/400
Trapezoidal Tear Strength, kN Warp/Weft	DIN 1875-3	0.42/0.40	0.49/0.40	0.38/0.35
Trapezoidal Tear Strength, lbs Warp/Weft	ASTM D4533	95/90	110/90	85/80
Tongue Tear Strength, kN Warp/Weft	DIN 53363	0.49/0.44	0.53/0.49	100/90
Tongue Tear Strength, lbs Warp/Weft	ASTM D2261	110/100	120/110	100/90
Mullen Burst Strength, kPa Warp, Weft	ASTM D751	4512	4650	4500
Mullen Burst Strength, psi Warp, Weft	ASTM D751	655	675	650
Hydrostatic Resistance, kN	ASTM D751	1199	1110	2997
Hydrostatic Resistance, lbs	ASTM D751	270	250	675

7.2 Abrasion Resistance:

Table 3: Abrasion resistance data from ASTM D3889 testing.

	Average
1) NovaShield™ non-FR (white/white)	
<u>First side</u>	
Cycles to scrim:	**30**
Weight loss after 500 cycles (%):	**0.88**
Weight loss after 1000 cycles (%):	**1.66**
<u>Second side</u>	
Cycles to scrim:	**40**
Weight loss after 500 cycles (%):	**1.02**
Weight loss after 1000 cycles (%):	**1.91**
2) NovaShield™ FR Plus (white/white)	
<u>First side</u>	
Cycles to scrim:	**110**
Weight loss after 500 cycles (%):	**0.92**
Weight loss after 1000 cycles (%):	**1.57**
<u>Second side</u>	
Cycles to scrim:	**175**
Weight loss after 500 cycles (%):	**0.96**
Weight loss after 1000 cycles (%):	**1.63**
3) NovaShield™ FRU ELITE (white/white)	
<u>First side</u>	
Cycles to scrim:	**110**
Weight loss after 500 cycles (%):	**0.92**
Weight loss after 1000 cycles (%):	**1.57**
<u>Second side</u>	
Cycles to scrim:	**1100**
Weight loss after 500 cycles (%):	**0.64**
Weight loss after 1000 cycles (%):	**1.14**

7.3 Biaxial Test Data:

NovaShield™ non-FR

Table 4: Elastic Moduli independent of stress ratio combination, courtesy of DEKRA, Stuttgart,DE

Elastic Moduli		Warp to weft stress ratio combination					
		1:1 2:1	1:1 1:2	1:1 1:0	1:1 0:1	2:1 1:0	1:2 0:1
Warp	kN/m	257	252	274	256	269	260
Fill	kN/m	250	287	273	284	245	284
Poisson Ratio warp and fill		0.14	0.09	0.14	0.09	0.08	0.09
Poisson Ratio fill and warp		0.14	0.08	0.14	0.08	0.09	0.08

NovaShield™ FR Plus

Table 5: Elastic Moduli independent of stress ratio combination, courtesy of DEKRA, Stuttgart,DE

Elastic Moduli		Warp to weft stress ratio combination					
		1:1 2:1	1:1 1:2	1:1 1:0	1:1 0:1	2:1 1:0	1:2 0:1
Warp	kN/m	268	267	288	267	285	267
Fill	kN/m	282	315	273	312	262	313
Poisson Ratio warp and fill		0.15	0.10	0.12	0.10	0.08	0.11
Poisson Ratio fill and warp		0.15	0.09	0.12	0.09	0.09	0.10

NovaShield™ FRU Elite

Table 6: Elastic Moduli independent of stress ratio combination, courtesy of DEKRA, Stuttgart,DE

Elastic Moduli		Warp to weft stress ratio combination					
		1:1 2:1	1:1 1:2	1:1 1:0	1:1 0:1	2:1 1:0	1:2 0:1
Warp	kN/m	263	257	274	251	270	242
Fill	kN/m	250	312	273	313	266	313
Poisson Ratio warp and fill		0.16	0.12	0.14	0.14	0.11	0.13
Poisson Ratio fill and warp		0.15	0.10	0.14	0.11	0.11	0.10

7.4 Fire Resistance:

Table 7: NFPA 701 Method 1

	NovaShield™ non-FR	NovaShield™ FR Plus	NovaShield™ FRU Elite
Mean Mass Loss (%)	N/A	1.7	13.6
Average Flaming Dripping Time (s)	N/A	0.0	0.0
Overall Result	N/A	Pass	Pass

Table 8: NFPA 701 Method 2

	NovaShield™ non-FR	NovaShield™ FR Plus	NovaShield™ FRU Elite
Length of char (cm)	N/A	13.8	21.1
After flame time (s)	N/A	0.0	0.0
Average Flaming Dripping Time (s)	N/A	0.0	0.0
Overall Result	N/A	Pass	Pass

Table 9: CAN/ULC S109

Small Scale Burn Test	NovaShield™ non-FR	NovaShield™ FR Plus	NovaShield™ FRU Elite
Damaged Length (mm)	N/A	116	94
After flame time (s)	N/A	0.0	3.1
Average Flaming Dripping Time (s)	N/A	0.0	0.0
Overall Result	N/A	Pass	Pass
Large Scale Burn Test	**NovaShield™ non-FR**	**NovaShield™ FR Plus**	**NovaShield™ FRU Elite**
Maximum Individual Damaged Length (mm)	N/A	125	67
After flame time (s)	N/A	0.0	0.0
Average Flaming Dripping Time (s)	N/A	0.0	0.0
Overall Result	N/A	Pass	Pass

Table 10: ASTM E84

	NovaShield™ non-FR	NovaShield™ FR Plus	NovaShield™ FRU Elite
Flame Spread Index	5	0	0
Smoke Developed Index	55	75	175

Table 11: CAN/ULC S102

	NovaShield™ non-FR	NovaShield™ FR Plus	NovaShield™ FRU Elite
Flame Spread Index	15	0	5
Smoke Developed Index	100	47	130

Table 12: Fire Classification DIN EN 13501

	NovaShield™ non-FR	NovaShield™ FR Plus	NovaShield™ FRU Elite
Fire Behaviour	NA	B	TBD
Smoke Production	NA	s1	TBD
Flaming Droplets	NA	d0	TBD

TBD: To be determined.

7.5 Durability:

Table 13: QUV testing

Specimen Code	FRU88X-6 4mil (Various Colour Combinations)			
	Warp		Weft	
	Average	Standard Deviation	Average	Standard Deviation
Retained Tensile Strength (%) 1000 hours	97	4.0	98	3.7
Retained Tensile Strength (%) 4000 hours	100	6.6	102	5.4
Retained Trapezoidal Tear (%) 1000 hours	104	9.3	104	11.4
Retained Trapezoidal Tear (%) 4000 hours	109	9.0	112	10.8

Real-life exposure of membrane cover:

A building owner decided to re-cover their membrane covered warehouse as the material had been installed in 2000. They had no issues with the cover at this point, just decided to put new membrane on the building. When the old cover was removed several pieces of white/white fabric and blue/white fabric were sent for evaluation. This is non-flame retardant NovaShield™ 400. The white fabric that had been exposed was very yellowed, dull, and cracking. The blue fabric that had been exposed was still blue but dull and cracking to the point that scrim could be seen through the cracks. The white coating that was on the interior of the building (in both white/white and blue/white) was still shiny and supple.

The data from the 17-year-old cover are compared to the average NovaShield™ non-FR 400 data from the year 2004 which is as far back as our electronic data base goes. The product NovaShield™ non-FR 400 had been changed to ArmorKote™, which included a long-life white, and chemically resistant UV inhibitor by 2004. The cover is the same structure but not long-life white or chemically resistant UV.

Table 14: Tensile Test results of 17 year old membrane cover.

Property	Test Method	NovaShield™ non-FR 400 2004 Avg.	17 year old NovaShield™ non-FR 400, white/white **White exposed**		17 year old NovaShield™ non-FR 400, blue/white **Blue exposed**	
				Δ (%)		Δ (%)
Strip Tensile, lb/in Warp	ASTM D5035 2" wide	268	243	-9.3	234	-12.7
Strip Tensile, lb/in Fill	ASTM D5035 2" wide	246	233	-5.3	196	-20.3
Strip Tensile, lb/in Warp	ASTM D4851 1" wide	-	230	-	240	-
Strip Tensile, lb/in Fill	ASTM D4851 1" wide	-	220	-	182	-
Grab Tensile, lbs Warp	ASTM D751	368	356	-3.3	347	-5.7
Grab Tensile, lbs Fill	ASTM D751	340	347	2.1	299	-12.1

Table 15: Tear Test results of 17 year old membrane cover.

Property	Test Method	NovaShield™ non-FR 400 2004 Avg.	17 year old NovaShield™ non-FR 400, white/white **White exposed**		17 year old NovaShield™ non-FR 400, blue/white **Blue exposed**	
				Δ (%)		Δ (%)
Tongue Tear, lbs Warp	ASTM D2261	117	115	-1.7	116	-0.9
Tongue Tear, lbs Fill	ASTM D2261	116	110	-5.2	110	-5.2
Trap Tear, lbs Warp	ASTM D4533	98	89	-9.2	85	-13.3
Trap Tear, lbs Fill	ASTM D4533	92	90	-2.2	75	-18.5

Table 16: Seam Shear values of 17 year old membrane cover.

Property	Test Method	17 year old NovaShield™ non-FR 400, white/white **White exposed**	17 year old NovaShield™ non-FR 400, blue/white **Blue exposed**
Seam Shear % Retained Strength	ASTM D4851	77	90

7.6 Light Transmission/Translucency:

NovaShield™ FR Plus

Table 17: Hemispherical Spectral Reflectance and Near-Normal/Hemispherical Spectral Transmittance as tested by ASTM E903.

	% Reflectance			% Transmittance		
	UV	VIS	NIR	UV	VIS	NIR
White/white	12.2	90.7	80.2	0.0	6.4	11.5
Sandstone/white	10.6	64.8	75.3	0.0	2.7	9.3

.

Illuminance Inside a single layer of membrane		
	White/White	69,000 Lux
	Sandstone/White	7,000 Lux

NovaShield™ non-FR

Table 18: Hemispherical Spectral Reflectance and Near-Normal/Hemispherical Spectral Transmittance as tested by ASTM E903.

	% Reflectance			% Transmittance		
	UV	VIS	NIR	UV	VIS	NIR
Clear/clear	18.2	35.0	31.2	26.0	61.8	61.8
White/white	11.0	86.4	74.5	0.0	10.7	16.4
Beige/white	10.2	62.2	66.6	0.0	8.2	18.7
Green/white	5.3	7.1	41.7	0.0	0.7	19.0
Blue/white	7.9	16.6	58.7	0.0	1.4	20.4

Illuminance Inside a single layer of membrane		
	Clear/Clear	95,000 Lux
	White/White	78,000 Lux
	Beige/White	21,000 Lux
	Green/White	750 Lux
	Blue/White	1,700 Lux

7.7 Characterization to DIN 18204-1 “Components for enclosures made of textile fabrics and plastic films – Part 1: Structures and tents

Table 19: Requirements and performance classes and NovaShield™ non-FR:

Row	Parameter		Standard	Textile Fabrics			
				Class Z 1	Class Z 2	Class Z 3	**NovaShield™ Non-FR**
1	Carrier fabric		DIN EN ISO 2076	Polyester (PES)			**HDPE**
2	Coating		-	Soft polyvinyl chloride (soft PVC)			**LDPE**
3	Total area-related mass; g/m^2		DIN EN ISO 2286-2	≥ 450	≥ 580	≥ 650	**407**
4	Tensile strength; kN/5 cm; Warp/Weft		DIN EN ISO 1421, procedure 1	2.0 / 1.6	2.5 / 2.5	3.0 / 3.0	**2.2/2.1**
5a	Elongation at break,%			≥ 15 / ≥ 15			**19/16**
5b	maximum elongation at 10% of the tensile force according to line 4; %; Warp/Weft			≤ 2 / ≤ 6			**1.5/0.95**
6	Tear propagation resistance; kN; Warp/Weft		DIN EN 1875-3	0.1 / 0.1	0.13 / 0.13	0.2 / 0.2	**0.4/0.4**
7	Adhesive strength[a] N/5 cm		DIN EN 15619: 2014-07, Appendix B	100	100	100	**70**
8a	Weld strength[a]; b[b] 15 mm - <40 mm; kN/5 cm; Warp/Weft		DIN EN ISO 1421, procedure 1	at 23 ° C: min. 70% of the tensile strength according to line 4 at 70 ° C: min. 40% of the tensile strength according to line 4			**23°C: 85%** **70°C: 70%**
8b	Weld strength[a]; b[b] ≥ 40 mm; kN/5 cm; Warp/Weft			at 23 ° C: min. 80% of the tensile strength according to line 4 at 70 ° C: min. 60% of the tensile strength according to line 4			**23°C: 85%** **70°C: 70%**
9a	Strength[a] f_{Ku} of the Keder connections; kN/5 cm	⌀ 8 mm	DIN EN ISO 1421, procedure 1	at 23 ° C: 0.8 at 70 ° C: 0.30			**TBD**
9b		⌀ 10 mm		at 23 ° C: 1.0 at 70 ° C: 0.60			**TBD**
9c		⌀ 12 mm		at 23 ° C: 1.2 at 70 ° C: 0.80			**TBD**

a each individual value, at least
b weld width

The limit deviations of the test temperatures are ± 2 K.

Table 20: Requirements and performance classes and NovaShield™ FR Plus:

Row	Parameter		Standard	Textile Fabrics			
				Class Z 1	Class Z 2	Class Z 3	**NovaShield™ FR Plus**
1	Carrier fabric		DIN EN ISO 2076	Polyester (PES)			**HDPE**
2	Coating		-	Soft polyvinyl chloride (soft PVC)			**LDPE**
3	Total area-related mass; g/m²		DIN EN ISO 2286-2	≥ 450	≥ 580	≥ 650	**407**
4	Tensile strength; kN/5 cm; Warp/Weft		DIN EN ISO 1421, procedure 1	2.0 / 1.6	2.5 / 2.5	3.0 / 3.0	**2.3/2.2**
5a	Elongation at break,%			≥ 15 / ≥ 15			**22/18**
5b	maximum elongation at 10% of the tensile force according to line 4; %; Warp/Weft			≤ 2 / ≤ 6			**1.5/1.2**
6	Tear propagation resistance; kN; Warp/Weft		DIN EN 1875-3	0.1 / 0.1	0.13 / 0.13	0.2 / 0.2	**0.5/0.4**
7	Adhesive strength[a] N/5 cm		DIN EN 15619: 2014-07, Appendix B	100	100	100	**80**
8a	Weld strength[a]; b[b] 15 mm - <40 mm; kN/5 cm; Warp/Weft		DIN EN ISO 1421, procedure 1	at 23 ° C: min. 70% of the tensile strength according to line 4 at 70 ° C: min. 40% of the tensile strength according to line 4			**23°C: 85%** **70°C: 70%**
8b	Weld strength[a]; b[b] ≥ 40 mm; kN/5 cm; Warp/Weft			at 23 ° C: min. 80% of the tensile strength according to line 4 at 70 ° C: min. 60% of the tensile strength according to line 4			**23°C: 85%** **70°C: 70%**
9a	Strength[a] f_{Ku} of the Keder connections; kN/5 cm	⌀ 8 mm	DIN EN ISO 1421, procedure 1	at 23 ° C: 0.8 at 70 ° C: 0.30			**TBD**
9b		⌀ 10 mm		at 23 ° C: 1.0 at 70 ° C: 0.60			**TBD**
9c		⌀ 12 mm		at 23 ° C: 1.2 at 70 ° C: 0.80			**TBD**

a each individual value, at least
b weld width

The limit deviations of the test temperatures are ± 2 K.

Table 21: Requirements and performance classes and NovaShield™ FR ELITE:

Row	Parameter		Standard	Textile Fabrics			
				Class Z 1	Class Z 2	Class Z 3	**NovaShield™ FR ELITE**
1	Carrier fabric		DIN EN ISO 2076	Polyester (PES)			**HDPE**
2	Coating		-	Soft polyvinyl chloride (soft PVC)			**LDPE/LLDPE**
3	Total area-related mass; g/m²		DIN EN ISO 2286-2	≥ 450	≥ 580	≥ 650	**466**
4	Tensile strength; kN/5 cm; Warp/Weft		DIN EN ISO 1421, procedure 1	2.0 / 1.6	2.5 / 2.5	3.0 / 3.0	**2.5/2.2**
5a	Elongation at break,%			≥ 15 / ≥ 15			**22/18**
5b	maximum elongation at 10% of the tensile force according to line 4; %; Warp/Weft			≤ 2 / ≤ 6			**1.4/1.1**
6	Tear propagation resistance; kN; Warp/Weft		DIN EN 1875-3	0.1 / 0.1	0.13 / 0.13	0.2 / 0.2	**0.4/0.4**
7	Adhesive strength[a] N/5 cm		DIN EN 15619: 2014-07, Appendix B	100	100	100	**80**
8a	Weld strength[a]; b[b] 15 mm - <40 mm; kN/5 cm; Warp/Weft		DIN EN ISO 1421, procedure 1	at 23 ° C: min. 70% of the tensile strength according to line 4 at 70 ° C: min. 40% of the tensile strength according to line 4			**23°C: 85%** **70°C: 70%**
8b	Weld strength[a]; b[b] ≥ 40 mm; kN/5 cm; Warp/Weft			at 23 ° C: min. 80% of the tensile strength according to line 4 at 70 ° C: min. 60% of the tensile strength according to line 4			**23°C: 85%** **70°C: 70%**
9a	Strength[a] f_{Ku} of the Keder connections; kN/5 cm	⌀ 8 mm	DIN EN ISO 1421, procedure 1	at 23 ° C: 0.8 at 70 ° C: 0.30			**TBD**
9b		⌀ 10 mm		at 23 ° C: 1.0 at 70 ° C: 0.60			**TBD**
9c		⌀ 12 mm		at 23 ° C: 1.2 at 70 ° C: 0.80			**TBD**
a each individual value, at least b weld width							
The limit deviations of the test temperatures are ± 2 K.							

8.0 DISCUSSION:

The purpose of this thesis was to characterize the inherent nature and physical attributes of polyethylene membranes, show the history of their use in steel framed structures, and provide information for their use in tensile structures. This material has been used in covers for over 20 years, primarily in steel framed structures. The history is strong and world-wide having been used in Canada, United States, Mexico, Europe, Russia, China, Australia, and Israel, to name a few of the countries with polyethylene covered structures.

Structures covered with white coated polyethylene membranes are a very comfortable environment. The translucency of the material provides a well-lit interior. The membrane diffuses the light which means there are no shadows, nor are there bright and/or dim areas.

This polyethylene membrane has UV inhibitors added to the base fabric and coating to protect it from the degradative effects of the sun's radiation. Extensive testing has been performed on this membrane using accelerated weathering equipment. Real life data have been collected from structure covers that have been returned when new covers have been installed. Because of these data the life expectancy of the NovaShield™ non-FR and FR Plus is more than 15 years and the NovaShield™ FRU ELITE is more than 20 years.

The polyethylene membrane has been tested for its resistance to cold crack. The coating does not crack at -60°C when folded over a 6.35 mm diameter rod. Therefore, it can be utilized in very cold environments without fear of cracking. The membrane does contract at cold temperatures, for instance at -20°C it will contract 0.3% in the machine direction and 0.8% in the fill direction. The contraction is not permanent, and the membrane will return to its original length in both directions when it returns to 20°C. This is important to know when designing for compensation of covers being installed during winter months or in very cold climates.

Higher temperatures will cause shrinkage to occur in the polyethylene membranes and shrinkage is a permanent condition. Shrinkage does not occur until the membrane reaches 50°C and at that point the membrane will shrink 0.08% in the warp direction and 0.16% in the fill direction. As opposed to the contraction at cold temperatures that is not permanent shrinkage is permanent and the membrane does not return to its original length or width. This is important to take into consideration during compensation calculations. However, if the membrane is white in colour it stays cool as it reflects so much of the near infrared wavelength of the sun. The white membrane will only become the temperature of the air surrounding it. If the membrane is a dark colour, such as green, it can become quite hot. The green absorbs a significant amount of the near infrared wavelength so it can reach temperatures in the sun that could cause shrinkage of the membrane.

Polyethylene is inert in nature and does not require the use of plasticizers for processing. Therefore, dirt and debris to not stick to membranes made of polyethylene and they are easily cleaned. Plasticizers used in some materials can bloom to the surface and result in a surface that dirt will adhere to. Polyethylene does not provide a surface upon which micro-organisms will grow because there is no food source for them. However, if water and dirt is allowed to wick into the scrim, or base fabric, algae can grow between the coating layers feeding on that dirt and water and this can be an aesthetic problem in covers that are coated white/white.

Because of the tightly woven HDPE scrim the hand of polyethylene membranes is not very drapey. It has been used in some retractable applications, usually as a roll-up rather than a fold-up. Polyethylene membrane is ideally suited for a fixed cover application.

Polyethylene is combustible but can be made fire retardant. The fire retardancy properties allow for the material to self-extinguish as it remains in contact with fire. This ability is to allow anyone in the building time to escape from the building. It is important to note that it is not fire-*proof* but fire-*retardant*. However, in real-life fire situations even the non-flame retardant covers have shown excellent performance. Anecdotally, we have heard of many fire situations where the heat from the fire melted the cover and never came into contact with the fire allowing the smoke to escape.

Polyethylene is easily recycled, and recycled polyethylene is used in many products. Polyethylene membranes are mixed with HDPE scrim covered with LDPE extrusion coating on both sides. This does limit the uses for the recycled material, but it is still in demand for many processes such as composite building materials and other industrial type products. IPG recycles the material by grinding the membrane material, re-processing it into pellet form and using in the scrim or coating of material with less stringent property requirements and also plastic cores on which we wind finished and in-process material.

Polyethylene structure membranes are certified as being manufactured in a safe, circular, and responsible way, both considering the environment health and human health. This is an important factor to consider as people are becoming more and more aware of the need for sustainable manufacturing processes. The material health category, as described in section 6.1, of sustainability programs are separating materials into two groups; those that are safe for humans and the environment and those that are not safe for humans and the environment. Certain structure membranes currently being used would not meet the material health category due to the chemicals used in their manufacturing processes. This is yet another reason why polyethylene should be considered as a viable alternative when planning for membrane covered structures.

Polyethylene membranes are half the weight of many structural membranes being approximately 400 gsm yet comparable in strength to membranes that weigh 700 to 900 gsm. This is a great benefit when thinking about the entire process of covering a structure. The membrane is lighter to handle in the converting process and bundling panels for transport. The transportation costs are lower than for heavier materials. Lifting the panels into place can use lighter equipment, this does depend on the size of the panel or cover, of course.

The coating on either side of the scrim is 4 mil thick (0.10 mm) and care must be taken during handling. Particularly during installation, the cover should not be dragged over the ground where it can be scuffed. If the extrusion coating is damaged to the point the scrim is exposed the barrier to water and dirt is broken and wicking at these sites can occur. Aesthetically this can be a problem, but it also exposes the scrim to the damaging effects of the sun prematurely.

Polyethylene membrane is very easily welded using either hot air or hot wedge. This makes the welding process very speedy compared to high frequency welding or bar welding. In addition, there are no fumes or odours released during the welding, regardless of whether the material is flame retardant or non-flame retardant. Because of the high speed and the floor crawling welders that can be used the membrane is very well suited to long straight seams. Complex shapes, such as tight curves, can be more difficult to produce. Hot air hand welders can be used on the polyethylene membranes. This will require some practice to become proficient. The melting point of the HDPE scrim is approximately 130°C. This is a relatively low melting point, and the hot air will be well above this requiring the welding to be accomplished very quickly. The hand welders are used for repairs in the field. Care must be taken not to damage the material during this type of work.

Polyethylene membranes have been used for many years withstanding storms of high winds, heavy rains, and snow loads. They are a lightweight, cost-effective solution for membrane structures with their high tensile strength and excellent resistance to tearing. The tables 19, 20, and 21 show the three polyethylene membranes highlighted in this paper compared to classes of PVC coated polyester scrim. The tensile and tear strength meets or exceeds Class Z1 but the weight is less. A lighter weight is an advantage in handling, shipping, and installing, not a disadvantage. The density of polyethylene is approximately 35% lower than that of PVC coated polyester, with polyethylene density 0.94 g/cm^3 and PVC density 1.4 g/cm^3. It is time for the classification of structure membranes to be based on performance and strength, not weight.

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