Influence of a Steel Strike Face on an Ultra High Molecular Weight Polyethylene Hybrid Composite

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A locally developed procedure was used for the manufacture of thick UHMWPE compliant laminates. Fibre metal hybrids were constructed from the locally manufactured laminatea and Dyneema® HB2 rigid ballistic laminates with bonding between the laminate and strike face achieved using an acrylic adhesive. The FML's will be subjected to high velocity ballistic loading with 12mm hemispherical impactors, both with and without a metal strike face. High speed video will be used to evaluate the energy dissipation of the FML, with the influence of the strike face identified, and characterised using optical microscopy. The final influence of the strike face in this study has not been fully characterised yet as the testing is not complete. Presented below in this report is a review of published data from similar work with FML's suggesting a positive influence is likely.

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Nomenclature

Terms:

UHMWPE	=	Ultra-High Molecular Weight Polyethylene
LLDPE	=	Linear Low Density Polyethylene
LDPE	=	Low Density Polyethylene
PE	=	Polyethylene
PPE	=	Polypropylene
FML	=	Fibre Metal Laminate
FSP	=	Fragment Simulating Projectile

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[1] PLTOFF, School of Engineering & Information Technology. ZEIT4500.

ARL	=	Army Research Laboratory
BFD	=	Back Face Deflection
UD	=	Uni-directional *(typically fibre orientation descriptor)*
CA3	=	BlueScope® Steel material designator
PUR	=	Poly-Urethane Resin
HB2	=	Dyneema® uni-directional UHMWPE composite with Kraton rubber matrix
DSC	=	Differential Scanning Calorimetry
AHSS	=	Advanced High Strength Steels

Variables:

V_0	=	Initial projectile velocity	[ms^{-1}]
V_{50}	=	Ballistic limit	[ms^{-1}]
c_L	=	Longitudinal wave speed	[ms^{-1}]
E	=	Modulus of Elasticity	[GPa]
ρ	=	Density	[kgm^{-3}]
ϵ	=	Failure Strain	
R	=	Projectile radius	[m]
h_{Fe}	=	Thickness of plate	[m]
σ_0	=	Tensile Yield limit	[MPa]
n_p	=	Number of petaling layers	
E_p	=	Energy of petaling	[Nm]
m_p	=	Projectile mass	[kg]

I. Introduction

Since its initial use in the 1950's as a biomedical prosthetic, ultra-high molecular weight polyethylene (UHMWPE) has evolved into an industry leading, light weight polymer, with applications in aerospace, marine, medical, and sports. The discovery of a gel spinning process in the late 1970's initiated the commercial production of the high strength, high modulus fibres that we know today as Dyneema® and Spectra® (Werff & Heisser, 2013). The high draw ratio's achievable through the gel spinning process which result in an extremely high molecular orientation, leading to exceptional specific strengths have fuelled continuing advancements in the development of UHMWPE. These continued advancements are subsequently inspiring research into the application of UHMWPE for high performance light weight armour grade composite systems[2]. The considerable open source scientific research available into this application includes most high performance fibres[3], across a variety of configurations[4], but UHMWPE still dominates the field (Lee, et al., 2000).

The identifiable consistency covering the evaluated open source literature, has been the use of thermoset resin matrices. Although limited, some research has been conducted into thermoplastic matrices and compliant laminates, with (Morye, et al., 2000) specifically studying a comparison between the two matrices in ballistic rigid laminates (Morye, et al., 2000). The Aberdeen Army Research Laboratory (ARL) also examined thermoplastic matrices, and the relationship between thermoplastic ratio and structural properties in armour grade composites, focussing specifically on combat helmets. Unfortunately, the ARL found thermoplastic matrices deficient in this application due to excessive back face deformation (BFD) and penetration compromise (Zhang, et al., 2015). Alternatively, the experimental results obtained by (Morye, et al., 2000) reported a promising 15% increase in V_0 results when comparing thermoplastic ballistic rigid laminates to epoxy aramids of equivalent areal density. The specific matrix used by (Morye, et al., 2000) is not stated, but does indicate promise for a pure thermoplastic compliant laminate.

Complementing monolithic composite research, is the significant research into fibre metal laminate (FML) hybrid composites. The performance of E-glass polypropylene and aluminium hybrid FML's was reported by (Compston, et al., 2001) which found the performance of polypropylene based FML's superior in contrast to their thermoset counterpart. This work was furthered by (Wambua, et al., 2007) who examined the ballistic behaviour of natural fibre polypropylene FML's, diverging from the stacked layer FML to a hybrid with variations in strike and backing face. Despite the matrix, metal, and stacking sequence variations of all these works, all found a performance increase through metal hybridisation.

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[2] Armour grade composites are also regularly known as compliant laminates.
[3] Common high performance fibres are aramid, carbon, glass, flax, hemp and jute.
[4] Compliant laminate hybrid configurations; Fibre metal laminates, UHMWPE and carbon composites, fibre wrapped metals, and quasi tropic UD laminates.

I.A. Project Aim

The aim of this project is to identify the influence of a steel strike face on an UHMWPE compliant laminate exposed to ballistic loading. Considerable research has identified shear plugging and interlaminar delamination as the primary energy absorption modes for compliant laminates, with friction as a secondary mode. In purely thermoplastic ballistic laminates temperature dependence is a significant factor restricting use to lower velocities, or requiring significantly thicker panels than if a thermoset matrix were used. To limit the depth of melt penetration, and subsequently force the laminate into its primary failure modes, a strike face is included creating a fibre metal laminate hybrid. The application of a strike face lends itself naturally to ballistic applications for equipment and vehicles as the strike face is already a component of the larger system. Historically, this has resulted in research with lightweight materials such as aluminium, as this was the preferential material for vehicular weight reduction. The evolving development of advanced high strength steels (AHSS) has seen a decline in the use of aluminium to save weight, with AHSS skins providing greater weight savings at equivalent strengths (Unit, 2011) (Mohrbacher, 2005) (Alpine Armouring Inc., 2017). Therefore, this study plans to bridge the works of (Compston, et al., 2001) and (Wambua, et al., 2007) by evaluating the influence of an automotive grade steel and polyethylene composite FML. Commensurate to the study of (Wambua, et al., 2007), this study will utilise a steel strike face on an UHMWPE composite with a low-density polyethylene (LDPE) matrix. To achieve this aim, a manufacturing procedure will be developed, a successful bonding technique evaluated, and the final product tested and evaluated.

I.B. Project Scope

This study will use a kinetic energy (KE) balance to evaluate the influence of a C3A[5] steel strike-face on an UHMWPE compliant laminate. A series of compliant laminates constructed with Dyneema® uni-directional fibre will be used, with some of the compliant laminates having a C3A strike face adhered using acrylic adhesive DP8005 to construct a FML. The targets[6] will be secured in a semi evacuated chamber, on the top and bottom edges as per the method used by (Lee, et al., 2000). During his study of armour grade composites, (Lee, et al., 2000) identified a clamping technique which negated edge effect for high velocity ballistic impacts. The targets will be impacted with 12mm hemispherical non-deformable steel balls at high velocity[7], with the projectile velocity measured before and after impact via laser chronograph and high speed video respectively.

The penetration mechanics of the impacted panels will be inspected post mortem via amplified microscopy to analyse the modes of failure, focussing on the anomalies between the FML's, and their non-adhered composite counterpart of the same construction. A study into the fragment impacts on nylon composites by (Iremonger & Went, 1996) used a similar approach to great success. He optically identified different failure mechanisms, and correlated performance with failure and energy observations. Energy was also used successfully by (Werff & Heisser, 2013) and (Morye, et al., 2000).

II. Project Approach

II.A. Fabric Geometry – *and ballistic impact*

Fabric selection is a trade-off between protection and burden, with fabric geometry playing a significant role in the effectiveness of ballistic protection. Cheeseman and Bogetti described the response of a material and its geometry as a "structural response" (Cheeseman & Bogetti, 2003), with the weave and weft density having considerable influence. Traditionally, basic 2D woven[8] fabrics have been used for protection against grenades, stabbing, blunt-force attacks, and impact velocities below $V_{critical}$[9], as the weave inhibits projectile wedge through. Weaves are typically composed from two yarns, warp and weft, interlaced to create the fabric surface. The primary energy dissipation method observed for woven fabrics is the deformation pyramid as shown in Fig. 1. This pyramid forms as tension in the weave is drawn toward the point of impact (Cheeseman & Bogetti, 2003). Subsequently due to fabric geometry and wave reflection at the weave nodes, these fabrics exhibit amplified stress in the principal yarns during impact, as illustrated in figure 1 by the red sections of the fibres. This local stress amplification is the cause of highly localised shear failure, or plugging of weaves during high velocity impacts, and subsequently the reason for UD preference at higher velocities.

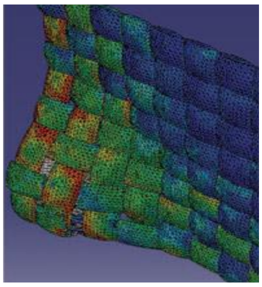

Figure 1. Stress distribution of woven fabric at t=8.12 μs after impact at 494.217m/s
(Sun, et al., 2013)

[5] C3A is the BlueScope™ material designator for cold rolled, annealed 260MPa mild steel.

[6] Targets will be both the FML and non-adhered compliant laminates.

[7] The term 'high velocity' refers to velocities between 100 and 1000 ms^{-1} (Bhatnagar, 2016)

[8] A brief description and graphical representation of woven fabric geometries is included in appendix A.

[9] Velocity at which strain develops in the fibre equivalent to failure strain, resulting in an almost instantaneous rupture.

Uni-directional (UD) fabrics are typically supplied in a [0/90] cross-plied construct, Fig. 2, either bonded by a partially cured thermoset matrix, or self-reinforced by molecular bonding which is achieved through application of elevated temperature and pressure (Thomas, 2008). They avoid the reflected stress amplification effects of weaves illustrated above, distributing the tensile stress across a greater area of yarn (Jacobs & Van Dingenen, 2001). Subsequently, due to their geometric construction, UD fabric exhibits significant sensitivity to wedge through. This filament movement coupled with the relatively low friction co-efficient between fibres means UD fabrics are rarely used for ballistic mitigation as a fabric alone, but typically in the form of a compliant laminate (Werff & Heisser, 2013). By consolidating into a compliant laminate, through the addition of a matrix, UD fabrics distribute most of their energy dissipation into tensile fibre failure, a mode the fibre is strongest[11], unlike shear plugging in weaves.

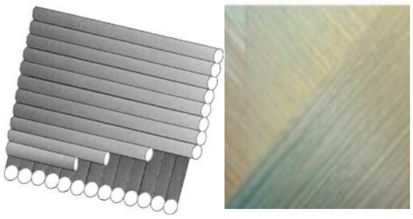

Figure 2[10]. Uni-directional fabric in 0/90° orientation

II.B. Ballistic Regime

The way composite materials respond to impact loading and dissipate the incident kinetic energy is very different from that of metals. Unlike metals, which absorb the energy through elastic and plastic deformation, composites have very limited ability deform plastically, subsequently resulting in large areas of fracture and delamination. The impact response of the fibre-reinforced composite is dependent upon its constituents (Alagirusamy, et al., 2006), and is commonly simplified using classical yarn impact theory (Nguyen, 2015).

Ballistic loading can be classified into three velocity regimes: low, high and hypervelocity. The energy dissipation and failure mechanics of each regime is significantly different and requires due attention. The focus of this study will be for events in the high velocity regime, which can be considered *"... the point that the contact period of the projectile is less than the period of the lowest vibrational mode of the composite"* as quoted by (Naik & Shrirao, 2004). High velocity structural response is typically governed by local strike area behaviour, with yarns typically failing before significant transverse deflection occurs.

Single yarn theory[12] has been explored and used by many researchers to emulate the response of compliant laminates, and is typically the building block of numerical modelling. During ballistic loading a wave is induced in the fibre travelling out from the impact at a velocity. Concurrent to this wave is the motion of the fibre transversely and the inward flow toward the impact region as illustrated in figure 3. To evaluate the critical velocity in a dynamic loading event such as figure 3 (Werff & Heisser, 2013) used equation 1, finding a significant over match on behalf of the fibre. Their calculated result was almost 80% greater than the experimental velocity achieved. They suggested this was a result of fibre property deterioration through induced heating.

$$V_{critical} = \sqrt{\epsilon \, \frac{E}{\rho} \left\{ 2\sqrt{\epsilon(1+E)} - \epsilon \right\}} \tag{1}$$

Shock induced heating during ballistic impacts has been observed and described by (Hazell, et al., 2011) during fly plate experiments where the fibre decomposed[13] and all anisotropic behaviour ceased. Similarly, fibre crystallinity changes were observed by (Cheeseman & Bogetti, 2003) following ballistic impact as a function of shock induce heating.

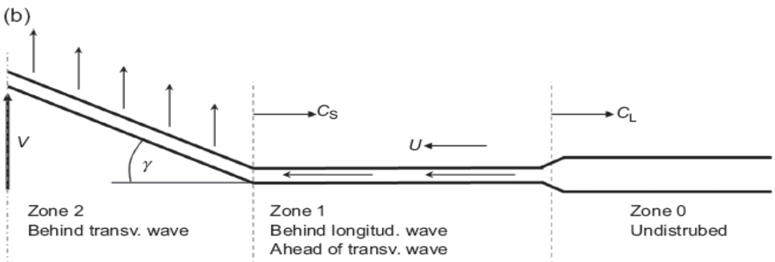

Figure 3. Illustration of transversely impact yarn and subsequent wave, flow and displacement vectors (Werff & Heisser, 2013)

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[10] (Jacobs & Van Dingenen, 2001) (Zhang, Satapathy, Vargas-Gonzalez, & Walsh, 2015)

[11] Dyneema® has a tensile strength of 3500 MPa (Department of Materials Science and Engineering, UNK).

[12] (Russell, et al., 2013), (Nguyen, 2015)

[13] Decomposition is the material melting temperature where the matrix and fibre became non-discernible. In this instance the material was Dyneema®.

II.C. Matrix Selection

Advanced fibre compliant laminates include the use of polymeric matrices to form rigid geometries, with both thermoset and thermoplastic matrices used. The typical matrix selection criteria for ballistic composites is consolidated panel rigidity, and fibre deterioration temperature. Where the finished application is personal body armour, the composite must comply with specific BFD restrictions as stipulated in NIJ and European standards.

Growing environmental concern surrounding the use of solvents and fumes associated with thermosets has seen recent research focus change to thermoplastics. Thermoplastic matrices offer considerable improvement over thermosets in both cost and environmental footprint, as well as having the ability for field repair and manipulation after consolidation (Song & Lee, 2016).

(Zhang, et al., 2015) suggested using PE matrices in compliant laminates failed to achieve the required panel stiffness for personal applications. This is contradictory to (Nguyen, 2015) who reported significant flexure results using PE laminates through controlling areal density. Complementary to this are the findings of (Carillo, et al., 2012) and (Alagirusamy, et al., 2006) who both reported significant increases in ballistic performance from thermoplastic.

It has been suggested the ballistic response of UHMWPE fibre is a function of the wave speeds through the fibre dissipating the energy across more area. Suggested by (Nguyen, 2015) in his work with ballistic PE is matrix addition showed no considerable influence on wave speed. He accredits this to the weak Van der Waals bonding, and the virtually instant separation of matrix and fibre. (Cheeseman & Bogetti, 2003) argue against this, suggesting if just fibre properties were the deciding factor, nylon would outperform Kevlar, and that the total response is collectively *" …(a) relationship between mechanical properties"*.

A significant consideration with the selection of thermoplastics is temperature stability as previously discussed in fabric geometry, with PE having a relatively low glass transition point. When impacts are expected to be at higher velocities[14], matrix and fibre melting has been observed by (Bhatnagar, 2016) and (Hazell, et al., 2011). The use of hybrid systems aids to improve the temperature stability through providing an initial high temperature surface, but still retaining the elastic properties of a compliant laminate. Opposite to higher density matrix laminates, PE composites have the ability for molecular motion during impact as the temperature resilient surface deteriorates, suggesting for applications where BFD is not critical, such as vehicle and equipment protection, the use of malleable thermoplastic matrices is warranted.

II.D. Composite manufacture

The manufacture of compliant laminates is still subject to considerable propriety limited processing, especially where matrix selection diverges from the typical commercial thermosets. Typically, composite manufacture is achieved through a compression moulding process at elevated temperature, either with a hot press or autoclave. A typical layup is alternating layers of fabric and matrix, with an approximate fibre fraction $\leq$ 20%. The lack of functional groups, and chemical inertness of UHMWPE's has resulted in most commercially available compliant laminates being consolidated with thermosetting matrices[15].

The HB composite range offered by Dyneema® is a good example of the typical commercial compliant laminate. They are constructed from multiple layers of UD-UHMWPE fibre in a thermoset matrix[16]. The Dyneema® recommended manufacturing recipe limits maximum temperature (T_{max}) to 130°C, with a pressure of 165 - 300 bar, over a 50-minute cycle (Dyneema, 2014). The exact pressure is dependent on the ammunition to be defeated, with greater pressure equalling greater performance. This pressure dependence signifies the pressure sensitivity of compliant laminates during manufacture. Bonding between fibre and matrix is achieved through a chemical reaction under which molecular cross-linking is achieved. Once cured, the thermoset goes hard and cross linking is permanent. Curing temperature is determined solely for sustaining the cross-linking reaction, and is typically restrained below the degradation point of UHMWPE preserving the fibre material properties.

With thermoplastic matrices, cross-linking does not occur, instead, intermolecular bonding is achieved through a partial crystallisation of fibre and matrix. Dyneema fibre is reported to start melting at temperatures above 140°C, with full melt occurring at 152°C (Hazell, et al., 2011). Elimination of the cross-linking process means thermoplastics can be produced in significantly shorter time frames, and are distinguishable by their ability to be reshaped with the addition of heat post formation (Alagirusamy, et al., 2006). Literature regarding the manufacture of PE matrix composites is far more limited. (Marais & Feillard, 1992) conducted possibly the most significant study into the manufacture of PE/PE composites, developing a well-informed procedure. Using differential scanning calorimetry, (Marais & Feillard, 1992) identified LDPE matrices transition to melt at 93°C, high density PE (HDPE) at 123°C, and Dyneema® at 141°C. They used this information to develop a processing recipe for the manufacture PE/PE "prepregs" which were later used in compression moulding for compliant laminates. For further detail the reader is referred to (Marais & Feillard, 1992).

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[14] High velocity is regarded between 100 to 1000 m/s (Bhatnagar, 2016)

[15] Dyneema® HB series *(Tote systems Australia)* and Spectra Shield® *(Bulldog protective systems)*.

[16] Polyurethane resin or Kraton rubber matrix as published in DSM's *'Hard Ballistic solutions'* infographic flyer.

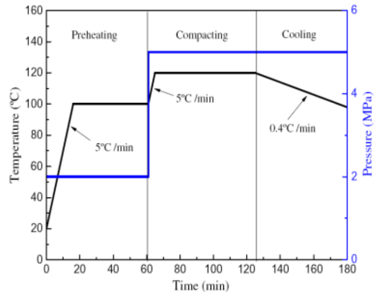


Figure 4 - Manufacture parameters of UHMWPE/ LLDPE compliant laminate. *(Zhang, et al., 2014)*

The DSC results obtained by (Marais & Feillard, 1992) are complementary to the work of (Zhang, et al., 2015), who developed the UHMWPE/ LLDPE manufacturing procedure in Fig. 4 during his study in to the ballistic impact behaviour of PE. Clearly visible in Fig. 4 is the manufacturing temperature limitation to ~140°C, the melt transition temperature of Dyneema®. These findings are contradictory to the those of (Xu & Farris, 2005) who suggested the optimum processing temperature range should be 150°C – 152°C. Using DSC and wide angle X-ray diffraction, Xu and Farris determined that 95% of the original crystallinity was retained in this range. Due to the material similarities between this project and that of (Zhang, et al., 2014), Fig. 4 was taken as a starting point for local composite manufacture.

A recipe was constructed from figure 4 and is detailed below in table 1. A note to recognise in the derived recipe is the reduced pressure of 2.8MPa. This is the limit of the equipment being used for this project. It is worth mentioning here that consolidation at lower pressures has the potential to not only reduce the effectiveness of the panel via reduced fibre wetting, but to also introduce a higher number of interlaminar voids from insufficient degassing, which reduces overall fibre volume fraction. Typical fibre volume fractions should be greater than 60% with preference closer to 80% for compliant laminates (Zhang, et al., 2015). This suggestion from Zhang is disputed by (Greenhalgh, et al., 2013) who suggested increased processing pressures increased interlaminar voidage through insufficient interply resin build.

Table 1. Test Panel Processing Recipe

Segment	Temperature			Time [minutes]	Pressure [MPa]
	initial	final	Ramp rate [°/min]		
0	21	21	0	0	2.8
1	21	100	7.2	11	2.8
2	100	100	0	20	2.8
3	100	140	4	10	2.8
4	140	140	0	10	2.8
5	140	148	1.6	5	2.8
6	148	148	0	20	2.8
7	148	ambient	environmental	----	2.8

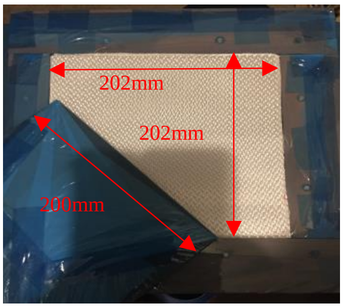


Figure 5. Composite mold tooling.

A composite layup was constructed from Dyneema® 4H satin weave and LDPE builders film[17]. An average thickness of fabric and matrix was measured as 0.319mm and 0.05mm respectively. The total composite layup consisted of 32 fabric plies, and 31 LDPE plies stacked alternately. By weight this was a matrix weight fraction of ~25%, so chosen to simplify the layer stacking sequence.

To facilitate uniform heat diffusion through the panel, a picture frame mould was constructed from steel and timber. A base made from 3mm mild steel sheet had four iron bark timber panels affixed. The timber panels varied in width and length, but a uniform thickness of 15mm was maintained. The timber sections were fixed to the base creating a female section of 202 x 202 mm square. A male insert section was constructed from two 3 x 200 x 200mm mild steel plates and one 5 x 200 x 200mm plate. The three plates were secured together with screws to form a single insert measuring 11 x 200 x 200mm. The mould assembly with the composite layup inserted is pictured in figure 5.

To evaluate the temperature distribution through the composite, a thermocouple was placed in the centre of the panel at layers 0, 7, 15, 23 and 32. Each thermocouple was placed side by side through the subsequent layers, limiting damage and panel deformation during processing. To record the thermocouple temperatures a Heatcon Temperature controller, model HCS9000B was used. A sequence of images illustrating the insertion of the thermocouples and temperature controller is included at Appendix B.

[17] Pictures of how the plies were prepared is included at Appendix D, along with the tools used for fabrication.

Temperature readings were recorded every 60 seconds for the duration of the program and the results plotted below in figure 6. For clarity, only readings from three of the thermocouples are presented[18]. What can be clearly identified from this plot is the tendency of the press to over shoot the programmed temperature, and the time lag for the centre of the panel. The temperature overshoot is proportional to the ramping temperature differential, and the time lag for the centre of the panel to reach the set temperature is relatively consistent. During the final heat stage, segment six of table 1, The outer layer of the panel reached a temperature of 150°C for approximately 2 minutes. Although this has not exceeded the optimum value suggested by (Xu & Farris, 2005), works submitted by (Nguyen, 2015) identified a correlation between consolidation temperature and performance, with little significance for time and pressure therefore this will need to be considered during final panel fabrication.

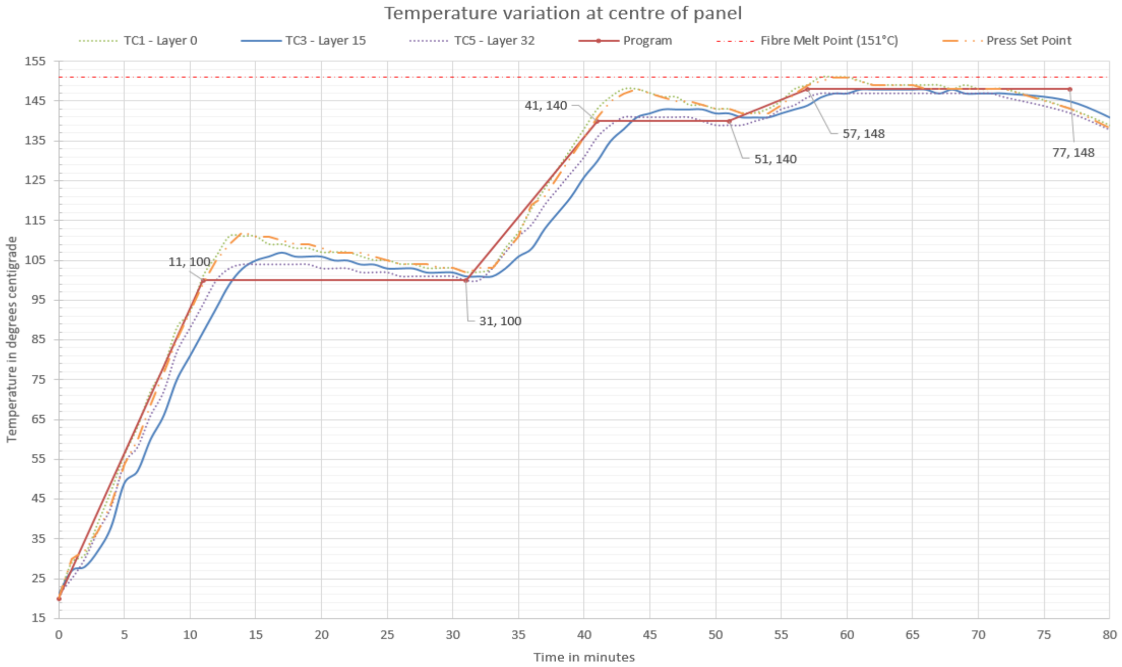


Figure 6. Temperature readings from experimental UHMWPE/LDPE panel manufactured per table 1.

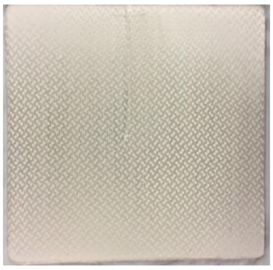


Figure 7. Consolidated test panel constructed of 32/31 ply 4H Dyneema/ LDPE respectively.

Figure 7 is the consolidated laminate removed from the mould. The thermocouple depression is visible on the upper surface. A final panel average thickness of 8.23mm was measured. This is 80% of the anticipated thickness calculated from the fabric dimensions, and can be accredited to the movement of the fabric crimp during compression. No distortion was visible through the fabric, nor were there signs of excessive matrix expulsion about the edges. An unpolished sample was optically assessed under magnification for fibre matrix saturation. The level of fibre matrix cohesion was not obviously apparent optically for the unpolished sample, nor was a lack of cohesion. An optical microscopy image is included at Appendix C. Further testing is yet to be conducted on this panel in the form of composite wave speed, but initial visual inspection suggests the manufacturing method is a satisfactory program for this study.

II.E. Thick Composite

For threats involving higher velocities thick composites are used. They are characterised by increased stiffness and significantly more plies than their thin counterpart, exhibiting more than one stage of perforation (Lee, et al., 2000). The earliest studies on the penetration mechanisms of thick UHMW-PE composite were performed via post-failure analysis of UHMWPE compliant laminates up to 25mm, impacted by both hemispherical spheres and deformable projectiles. This study observed complete delamination in 25mm targets between 50% and 70% of the thickness (Nguyen, 2015). Work by (Iremonger, 1999) and (Morye, et al., 2000) furthered these findings, identifying the front and rear sections of the laminate to behave independently with three key failure modes: shear, delamination, and bulging (Nguyen, 2015).

[18] Only layers 0, 15 and 32 are plotted for clarity in the plot. The symmetric thermocouples, 7 and 23 recorded significantly similar readings, therefore negating their need to be represented here.

In a study using carbon and aramid fibre composites, (Lee, et al., 2000) identified a significant difference in exponent fitting for laminates above 3mm thick. He found a linear relationship below this, similar to the response of monolithic metals, and a power variation above. (Lee, et al., 2000) suggested this was a function of increasing laminate stiffness with thickness, defining two classes of compliant laminate, as suggested above with thick laminates exceeding 3mm.

II.F. Projectile Geometry

Projectile geometry has been shown to play a significant role in the failure mechanisms of ballistic laminates. Blunt nose projectiles have been observed to shear plug *(Fig. 8e)* from the point of impact leading to significant delamination. Alternatively, during conical projectile impacts significant fibre motion occurs resulting in deeper penetration, and reduced delamination and performance (Lee, et al., 2000). This is suported by the observations of (Cheeseman & Bogetti, 2003) who identified V50 reductions of ~25% between blunt and conical projectiles impacting woven laminates.

Fragment simulating projectiles and spheres are readily used as simulants for high velocity particle impacts, reaching a medium between blunt and conical projectiles. A significant point these projectiles do not replicate is the energy absorption through projectile deformation. Considerable energy is dissipated through projectile deformation, influencing subsequent failure modes. A soft ogival projectile will transition from pierce to plug as it deforms and deteriorates during penetration altering failure mode.

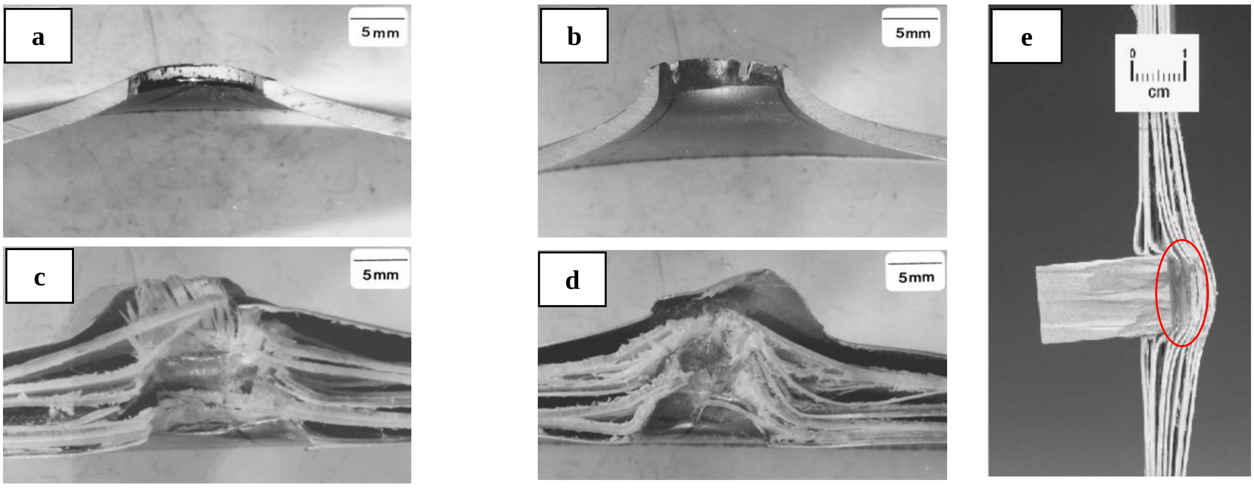


Figure 8. Specimens perforated by (a,c) blunt nose, (b,d) hemispherical impactor, and (e) blunt nose impactor illustrating shear plug formation on nose.

Clearly obvious from figures 8a and b is the variation of penetration mechanics as a function of impactor geometry. As described by (Compston, et al., 2001) this deformation contributes significantly to the energy absorption capacity of the laminate. Figures 8c and d illustrate the signifcant difference in engagement area as a rersult of delamination. The preceeding shear plug in Figs. 8c and e engage signifcantly more area, signifying increased ballisitic resistance. Equation 2 from the (Hoo Fatt, et al., 2003) who modelled the penetration of GLARE fibre metal laminates can be used to estimate the energy absorbed through petaling. For a CA3 steel plate[19] impacted at 700 ms^{-1}, the petaling energy is 5.54 Nm[20]. This is considerably insignificant when an average projectile KE[21] upto 900 Nm[22] can be reasonibly expected using equation 3. This supports the observations of (Compston, et al., 2001) and (Cheeseman & Bogetti, 2003) who suggest the significant proportion of energy dissipated is from delamination and tensile failure. This observation and the graphics illustrated in figures 12a-e illustrate the importance of projectile geometry.

$$E_p = n_p \frac{\sigma_0 \pi^2 R h_{Fe}^2}{4} \tag{2}$$

where n_p is the number of petaling layers, R is projectile radius, h_{fe} is ply thickness and σ_0 yield strength

$$KE = \frac{1}{2} m_p {v_0}^2 \tag{3}$$

[19] Indicative of the strike face material being used for this study

[20] σ_0 = 260MPa, R = 6mm, h_{fe} = 1.2mm, n_p = 1

[21] This system can be considered isolated due to the nature of firing into an evacuated chamber, as with high velocity gas gun experiments.

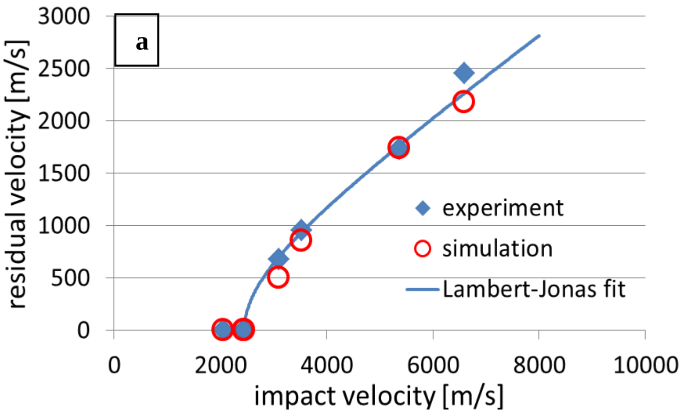
[22] v = 700ms^{-1}, m = 7.36g

II.G. Testing

There are three testing methodologies commonly accepted for the evaluation of ballistic laminates; ballistic limit (V_{50}), back face deflection, and energy consideration. Back face deflection and V_{50} are performance based, pass fail evaluations with respect to known requirements, and provide little determination of success margin. The method of testing is best determined by the application of the laminate, for example deflection signature has limited relevance for equipment protection (Dunn, 2016). Where delineation between differing designs is desired, a qualitative method is better suited.

Typically, energy methods are considered misleading. Projectile velocity and mass can be adjusted to achieve similar energies, but resulting in significantly different ballistic results. Therfore, where energy is the desired methodology the system must be normalised with specific mass and velocity values.

Energy method is often the avenue of choice where numerical modelling is desired. Energy analysis allows a complex ballisitic event to be quantified, and replicated through a series of simplified occurences in the model. (Morye, et al., 2000) was able to simplify a ballistic event to three key components; tensile failure, elastic deformation, and kinetic energy imparted composite deformation. This model produced good correlation with experimental data across a variety of materials, although post mortem data was a required parameter.
Figure 9 below is an experimental plot produced by (Werff & Heisser, 2013) in his development of a hydrocode from energy modelling. He normalised his results with non dimensional parameters formulated by (Cunniff, 1999) in his work to produce a a textile based armour optimisation system. As can be seen there is significant correlation between experimental and modelling results, therefore qualifying the use of energy criteria for analysis, which is supported by (Nguyen, 2015) who observed a linear energy relationship with penetration depth, similar to Fig 9b. What (Werff & Heisser, 2013) identified in their study, is the significance of kinetic energy anallysis. Although the exact modes of energy absorption can not be derived from this method, a comparison can be elucidated illustrating the qualitative performance difference between compliant laminates. For increased fidelity of failure mechanisms, optical microscopy with specimen casting and polishing can be used to obtain intrinisic information on failure modes.



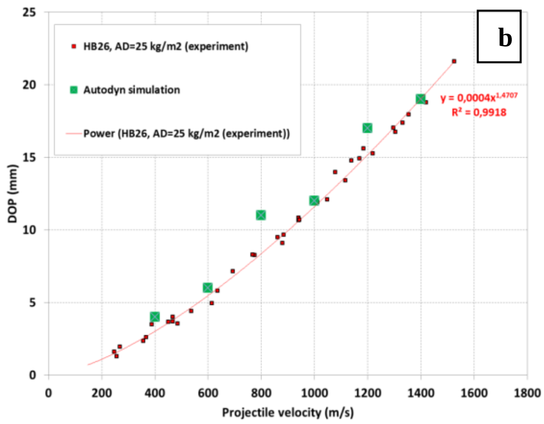


Figure 9. Correlation of experimental and numerical results from ballistic event on compliant laminates illustrating (a) residual velocity and (b) penetration depth against initial projectile velocity. (Werff & Heisser, 2013)

II.H. Strike Face and the Fibre Metal Laminate Hybrid

With the relatively low temperature stability of UHMWPE laminates, and the significance of BFD to their application for personal protection, much research has been conducted into hybrid composites. Hybridisation is achieved through the inclusion of a second, uniquely individual material to the laminate in efforts to improve ballistic performance. Any number of 'unique' materials may be included into the composite, though, typical studies have included only one, with aluminium and steel being the most widely studied.

Glass fibre metal laminates were observed by (Vlot & Krull, 1997) to exhibit minor performance increases at low velocity over monolithic metals, with significant performance increases at higher velocities[23]. This was evaluated using specific energies normalised for target areal density, and was attributed to the metal distributing deformation across an increased volume of fibre content. This work was further investigated by (Compston, et al., 2001) who extended the study to include a polymeric matrix in a 3/2[24] construction. He found a greater specific perforation energy was accommodated through subsequent buckling of the metal layers.

(Wambua, et al., 2007) investigated an alternative avenue of FML, using a combination of FML configurations with mild steel and natural fibre PPE composites, epoxy bonded. They tested hybrids with a metal strike face,

[23] A 15% performance increase was noted for a velocity of 10ms^{-1}, and 5 times performance at a velocity of 100ms^{-1}.
[24] 3 layers of Al with 2 layers of $[90/0]_2$

metal rear face, and metal front and rear up to velocities greater than $300ms^{-1}$. They identified a strike face alone increased performance by up to 50%, with more significant improvements achieved by facing both the front and rear. They observed no significant influence from the adhesive bonding the laminates.

The influence of adhesive in ballistically loaded FML's has not been the focus of significant research itself, and subsequently there is no specific standard. Several standards[25] are published for lap and peel strength of adhesives with composites, but none of note for impact testing. A study by (Teixeira & Sinke, 2015) suggests the use of a modified composite peel test based on the standard float roller peel tests, ASTM D3167. This modified system is still more for interlaminar testing of the composite than to evaluate adhesion impact resilience. A standard that does evaluate impact performance of adhesion is ASTM D950 *'Impact Strength of Adhesive Bonds'*. This standard is not specifically designed for testing composite bonding, but is extended to wood metal bonding, and suggests other bonds can be evaluated with the caveat of the result being comparative instead of determinant. ASTM D950 allows a comparative evaluation of adhesive sensitivity to sudden loading, as in the ballistic event.

As suggested earlier by (Wambua, et al., 2007) no significant influence is incurred as a function of FML epoxy bonding, but (Greenhalgh, et al., 2013) did observe through fractographic analysis delamination influences from the use of tapes.

[25] ASTM D897-08 *Tensile Test Method,* ASTM D3165-00 *Single Lap Shear by Tension,* and ASTM D1876-08 *T-Peel Test*

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Appendix A – 2D Woven fabric structure and description

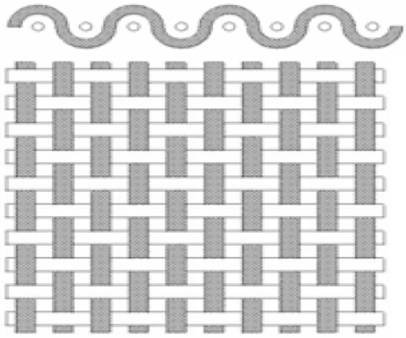


Figure A-1. Plain Weave

Plain weave *(fig. A-1)*: is the under and over interlacing of wefts and warps each time they meet. These fabrics are balanced, and provide good stability. The one for one interlacing of this fabric restricts the ability to distort and conform where complex shape manufacturing is required, like ballistic helmets.

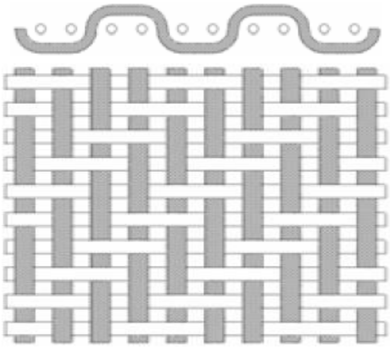


Figure A-2. Twill Weave

Twill weave *(fig. A-2)*: is an open style, with a two for two "herring bone" type weave. This provides greater formability through fibre movement when forming. The fabric is balanced in this pattern and no layer inversion is required when manufacturing multi-layer laminates.

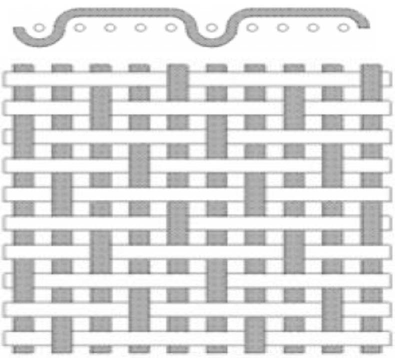


Figure A-3. Satin Weave

Satin Weave *(fig. A-3)*: provide superior drapability in complex forming, and are significantly flatter than other weaves. A weft is passed over a number *(up to 12)* of warps on each weave, with the exact number determining the 'harness' of the satin weave itself. A fabric passing 3 warps would be known as a four harness *(4H)* satin. Each pick repeats the weave, but across a different set of warps. Due to the unbalanced distribution of warp and weft fibres between the sides of the fabric, satin weaves tend to distort during manufacture, typically requiring the inversion of half plies to produce a symmetric laminate.

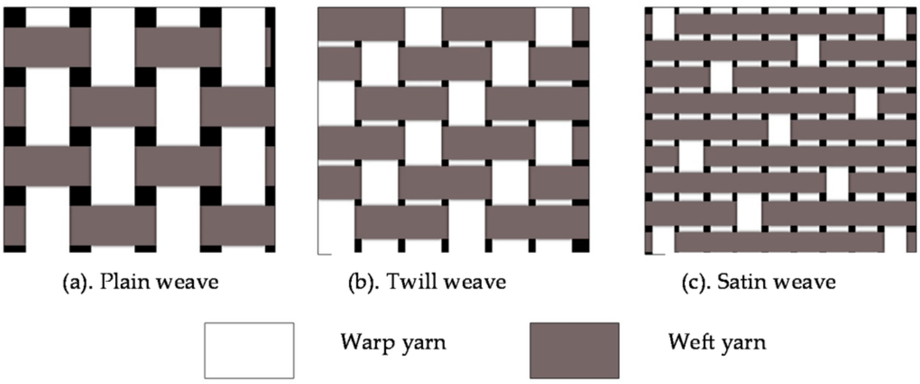


Figure 2 - Identification of warp and weft in 2D woven fabrics
https://www.google.com.au/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwiP15W26PPTAhWDNJQKHUeeB_AQjhwIBQ&url=http%3A%2F%2Fwww.mdpi.com%2F1996-1944%2F9%2F6%2F435%2Fhtm&psig=AFQjCNFoEULio14wrEAgOjtn7_0J9KW-tQ&ust=1495003534618578

Appendix B – Thermocouple placement and through composite temperature analysis setup

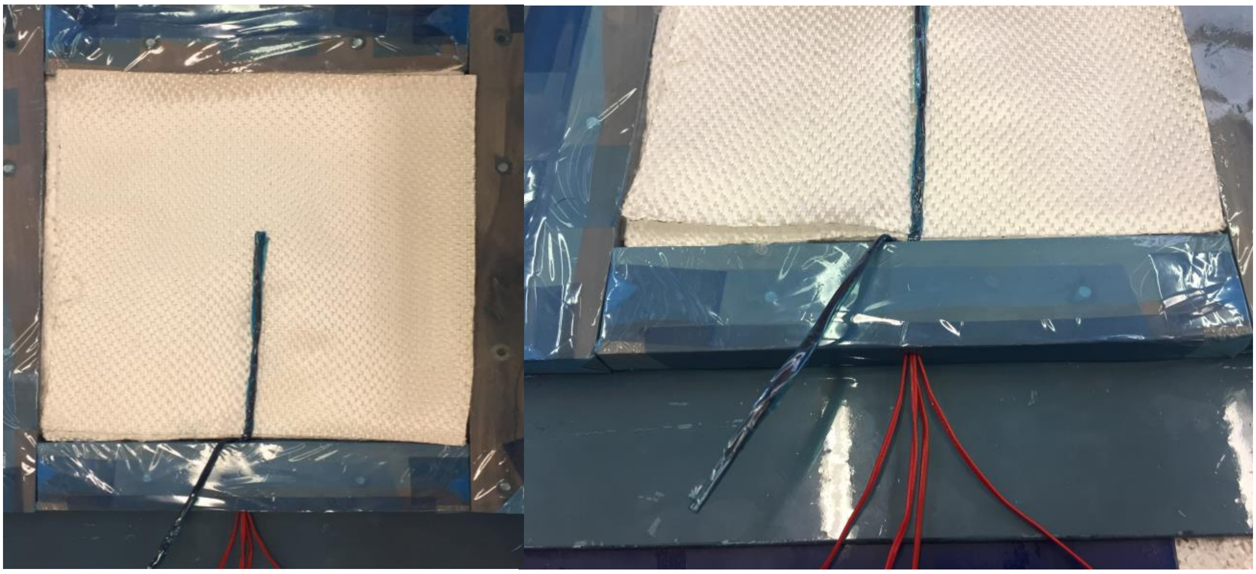


Figure B1. Thermocouple placement on layer 23 of test panel. It can clearly be seen the next thermocouple will lay to the left of this one.

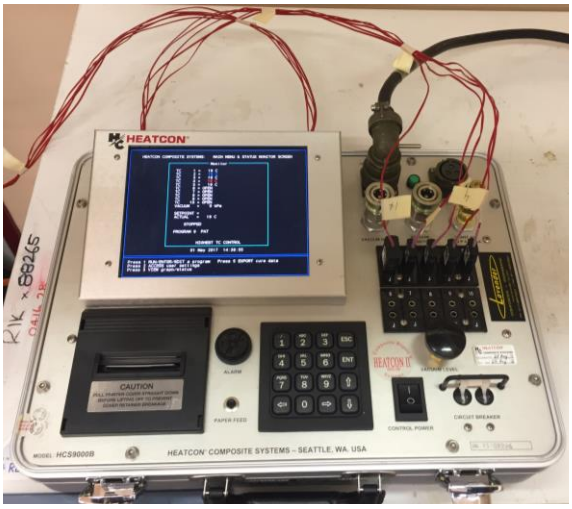


Figure B2. Heatcon Temperature Controller, model HCS9000B.

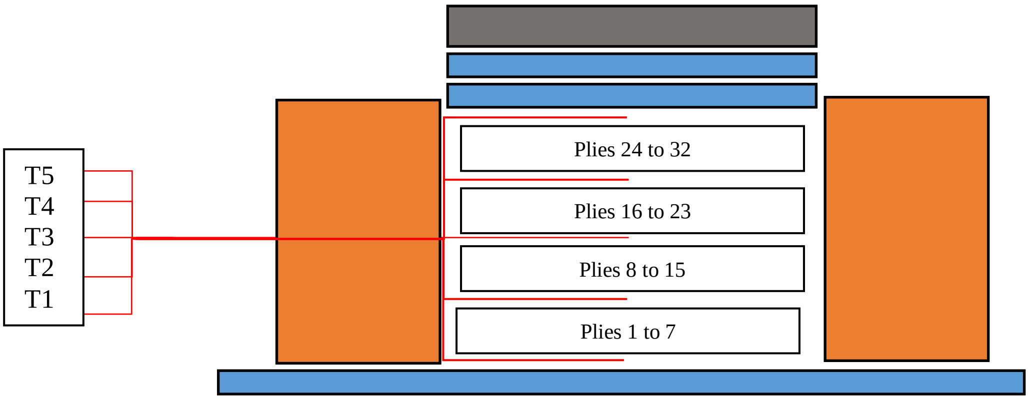


Figure B3. Thermocouple placement in with composite layup inside mold.

Appendix C – Optical Microscopy of Unpolished Composite Sample

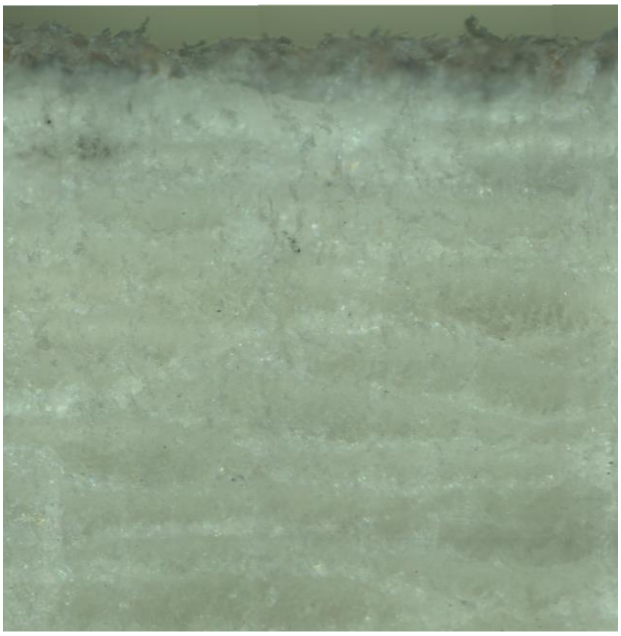


Figure C1. Optical microscopy of unpolished composite

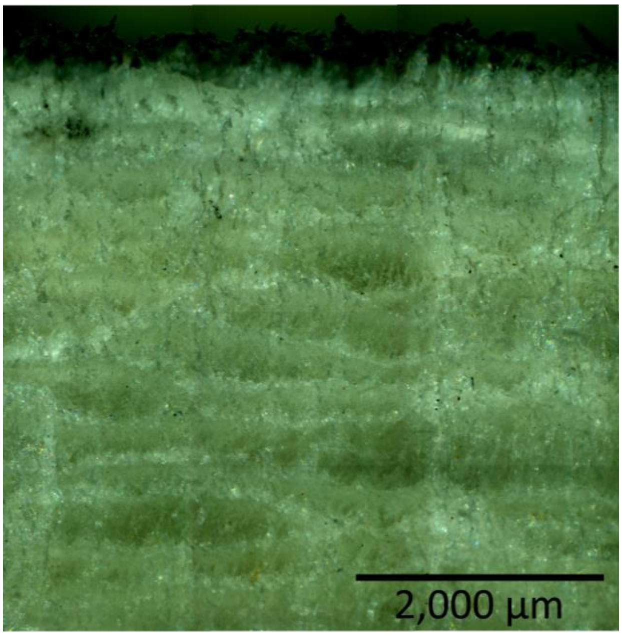


Figure C2. Optical microscopy of unpolished composite – High Contrast

Appendix D – Composite test panel layup preparation and tools.

For the test panel Dyneema® 4H satin weave fabric was used with an areal density of 180gsm, supplied from Advanced Composites Group (ACG) part number of 351-1/SK75/1000. From the part number, we can identify the fibre is SK75 with the material properties included at Appendix E.

Several methods were sampled to cut the fabric, scissors, electric knife, scalpel and hot knife. Ultimately it was the HSGM HSG-0 hot knife, Fig. c1, that proved the most efficient and successful.

The fabric was unrolled to approximately 400mm. A 200mm length of the fabric was measured from fibre to fibre, and marked with a fine marker. A steel 1 metre ruler was placed across the fabric, and the fibre aligned to the edge of the ruler.

The fabric was cut along the ruler with the hot knife by repeatedly cycling the hot knife trigger in a 15/5 second on of cycle. Figure D2 is of the cut edge of the fabric. It can be clearly seen this cycling of the trigger prevented excessive fibre melting away from the cut edge This produced a section of fabric 1100 x 200 mm.

The same process was used to make the 200 x 200mm plies. The section of fabric was laid out flat on a bench, and the edge prepared by trimming with the hot knife. A 300mm ruler used to measure the fibre 200mm from the prepared edge and marked as above. The section was then cut with the hot knife using the 300mm steel rule as a guide.

Figure D1. HSGM hand operated hot knife cutting tool.
Type: HSG-0 with Type: R blade

Figure D2. Dyneema® 4H satin weave fabric cut with HSG-0 in 15/5 second on/off heating cycle.

For matrix preparation, the LDPE film was rolled out and marked across the width into 200 x 200 mm squares. The film is folded in half from OEM, and was prepared this way to save time. The Film was cut with relative simplicity by a pair of scissors.

The layup was placed into the mould, figure D3, in an alternating stacking sequence of fibre, film fibre, to a total of 32/31 fibre/film respectively. The first and last ply were fabric.

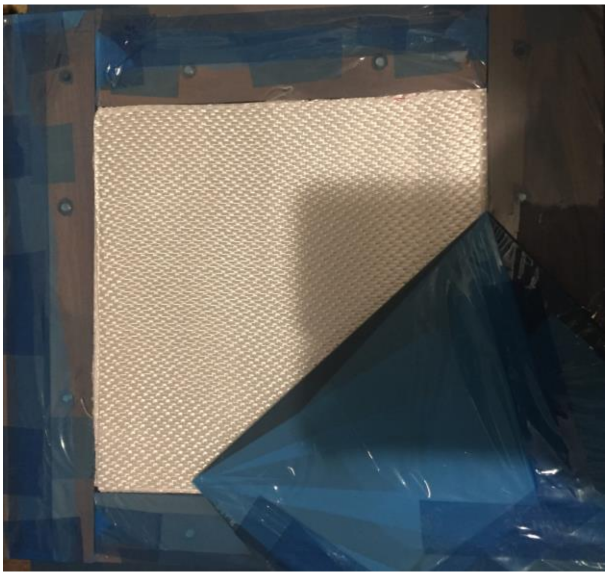


Figure D3. Fibre and matrix layup placed into tooling. Tooling has been wrapped in PTFE release film as per standard composite manufacturing procedures.

Appendix E – Dyneema® Material Properties

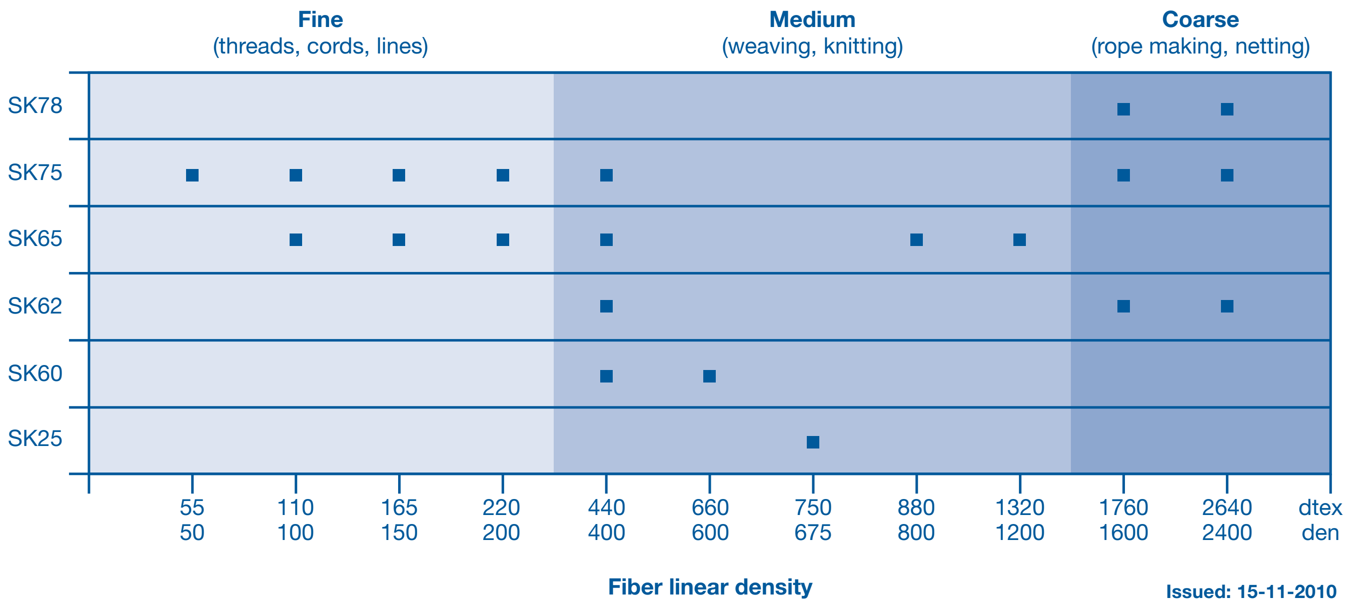
Ultra High Molecular Weight Polyethylene fiber from DSM Dyneema

UHMWPE fiber combines excellent mechanical properties with low density, resulting in high performance-on-weight basis.

The UHMWPE fiber from DSM Dyneema is a gel-spun, multi-filament fiber produced from ultra high molecular weight polyethylene, with main characteristics: high strength, low weight, low elongation at break, and resistance to most chemicals. To stimulate developments, this sheet provides an overview of properties measured on UHMWPE fibers from DSM Dyneema. The disclosed data is not valid for any other source of UHMWPE fibers.

Fiber range.
UHMWPE fibers from DSM Dyneema are produced in three strength ranges and several linear densities with a characteristic very low filament diameter. The tensile properties are correlated with the fiber linear density. Detailed information per fiber type is available on request, as Product Data Sheets, Product Specification Sheets, Material Safety Data Sheets and Fact Sheets.

UHMWPE	Tensile strength			Tensile modulus			Elongation to break %
Fiber type	N/tex	g/den	GPa	N/tex	g/den	GPa	
SK78 SK75	3.4 – 4.0	38 – 45	3.3 – 3.9	112 – 137	1267 – 1552	109 – 132	
SK65 SK62 SK60	2.5 – 3.4	28 – 38	2.4 – 3.3	67 – 102	759 – 1158	65 – 100	3-4
SK25	2.2	25	2.2	54	608	52	



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Appendix E – Dyneema® Material Properties

Mechanical properties.
UHMWPE fibers have a high strength and a high modulus (resistance against deformation) in the fiber direction. In combination with the low density this results in an extremely high strength on weight basis, making it one of the strongest man-made fibers. The elongation at break is relatively low, but owing to the high strength, the energy to break is high. In contrast to other synthetic fibers, the mechanical properties are not influenced by the presence of water. Due to the anisotropic nature of high modulus polyethylene fibers, the modulus and strength in transverse direction are lower than in fiber direction.
Subjecting UHMWPE fiber to long-term static loads leads to a permanent elongation called creep. The UHMWPE fiber types from DSM Dyneema have a higher creep resistance than other UHMWPE fibers enabling their use in various static loading conditions.

MECHANICAL		
Free breaking length	378	km
Axial tensile strength	3.6*	GPa
Axial tensile modulus	116*	GPa
Axial compressive strength	0.1	GPa
Axial compressive modulus	116	GPa
Transverse tensile strength	0.03	GPa
Transverse modulus	3	GPa
Transverse compressive strength	0.1	GPa
Elongation at break	3 – 4 %	
Work to break	45 – 70	MJ/m^3
Creep at 30°C, 300 MPa (Dyneema® SK75)	0.02*	%/day
Creep at 30°C, 300 MPa (Dyneema® SK78)	0.006*	%/day

Thermal properties.
Like other synthetic fibers, the mechanical properties of UHMWPE fibers are influenced by temperature. The strength and modulus increase at sub-ambient temperatures and decrease at higher temperatures. For long duration exposure UHMWPE fiber from DSM Dyneema can be used from cryogenic conditions up to a temperature of 70°C.

Chemical resistance.

Relative to 23°C	-60°C	+23°C	+60°C	+100°C
Tensile strength	110%	100%	80%	55%
Tensile modulus	110%	100%	85%	60%
Elongation at break	90%	100%	100%	105%

THERMAL		
Melting range	144 – 152	°C
Decomposition temperature	> 300	°C
Advised lowest temperature	No limit	
Advised long duration temperature limit	70	°C
Advised short duration temperature limit (non-constrained fiber)	130	°C
Advised short duration temperature limit (constrained fiber)	145	°C
Coefficient of linear thermal expansion	-12×10^{-6}	1/K
Specific heat capacity	1850	J/kg.K
Thermal conductivity (axial)	20	W/m.K
Thermal conductivity (transverse)	0.2	W/m.K

Chemical resistance.
UHMWPE fiber is very resistant against chemicals. Because it is produced from ultra high molecular weight polyethylene, it does not contain any aromatic rings or any amide, hydroxylic or other chemical groups that are susceptible to attack by aggressive agents.

CHEMICAL RESISTANCE		
Resistance to acids		Excellent*
Resistance to alkali		Excellent*
Resistance to most chemicals		Excellent*
Resistance to water		Excellent*
Aviation Jet A fuel (ISO 1817 test liquid F)	RTCA DO160	Excellent
Hydraulic fluid (ISO 1817 test liquid 103)	RTCA DO160	Excellent
Lubricating oil (ISO 1817 test liquid 101)	RTCA DO160	Excellent
Solvents and cleaning fluid (Isopropyl alcohol)	RTCA DO160	Excellent
De-icing fluid (Ethylene glycol)	RTCA DO160	Excellent
Insecticide (Pyrethroid pesticide)	RTCA DO160	Excellent
Fire extinguishant (Protein, Fluroprotein)	RTCA DO160	Excellent

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Appendix E – Dyneema® Material Properties

Physical properties.
UHMWPE fibers feel smooth due to their low friction coefficient. Its low density enables it to float on water. The water absorption in the fiber is negligible.

PHYSICAL		
Natural color	Opaque white	
Density	970 – 980	kg/m³
Crystallinity	< 85 %	
Filament linear density	1 – 3	dpf
Filament diameter	12 – 21	µm
Filament cross section (other types)	Round	
Filament cross section (SK60, SK65)	Bone shape	
Equilibrium moisture regain	None	
Water pick-up (soaked)	None	
Boiling water shrinkage	< 1%	
Hysteresis loss factor (23°C, 5 Hz)	0.02	
Friction coefficient (yarn-on-yarn)	0.05 – 0.07	

Electrical properties.
Polyethylene is an insulator and has no groups with dipole character. After scouring, the UHMWPE fiber is characterized by a high electrical resistance, low dielectric constant and a very low dielectric loss factor.

ELECTRICAL		
Resistance	$>10^{14}$	Ohm
Dielectric strength	900	kV/cm
Dielectric constant (22 °C, 10 GHz)	2.25	
Dielectric loss factor	0.0002	

Acoustic properties.
UHMWPE fiber has a high sonic velocity. In the fiber direction, the sonic velocity is higher than in the transverse direction.
The acoustic impedance, the product of density and transverse sonic velocity, is near that of water.

ACOUSTIC		
Sonic velocity (axial)	10000 - 12000	m/s
Sonic velocity (transverse)	2000	m/s

Optical properties.
UHMWPE fibers are visually opaque.
The fiber is invisible to an UV-light source due to the low UV absorption coefficient in combination with no fluorescence or phosphorescence. It is also invisible for thermal imaging devices because of its low IR absorption coefficient and high thermal conductivity. The low reflectivity of radar waves results in a reduced visibility for radar sources. The refractive index axial to the fiber axis differs from the transverse direction making the fiber perform birefringence.

OPTICAL	
Ultraviolet visibility (UV)	Transparent
Eye visibility (VIS)	Translucent
Near Infrared visibility (NIR)	Highly transparent
Infrared visibility (IR)	Highly transparent
Radar visibility	Highly transparent
Refractive Index (axial)	1.59
Refractive Index (transverse)	1.53
Birefringence	0.06

Flammability.
Fabrics and panels produced from UHMWPE fiber from DSM Dyneema have passed various standards on flammability. Like any other synthetic fiber, it will burn slowly if ignited in atmospheric conditions and is qualified as being self-extinguishing upon removal of the flame.

FLAMMABILITY		
Limited oxygen index	< 20%	
Fabric, horizontal	FMVSS 302	Passed
Fabric, vertical	FAR 25.853b	Passed
Ballistic panel, vertical	DIN 4102	Passed

Appendix E – Dyneema® Material Properties

Fatigue resistance.
Applications with UHMWPE fiber from DSM Dyneema have a higher resistance to repeated axial loading than other fiber types. The fibers combine high strength with high fatigue resistance, even if the loading is partly in compression as in repeated bending of rope applications. Despite its high modulus, the fibers are flexible and have a long flexural fatigue life. Because of the low friction coefficient and good abrasion resistance, internal abrasion of ropes is usually negligible.

FATIGUE RESISTANCE		
Abrasion resistance (yarn-on-yarn)	ASTM D6611	Excellent*
Abrasion resistance (covered rope)		Excellent*
Cutting resistance (covered rope)		Excellent
Flexural fatigue (fiber)		Excellent
Bending fatigue (rope)		Excellent
Tension fatigue (rope)		Excellent*

Environmental properties.
UHMWPE fiber is used in various outdoor applications under harsh weather conditions. In air the fiber is stable for many years. No special precautions are necessary during processing or storage.
Only strong oxidizing media are able to attack the mechanical properties. Compared to other high tenacity fibers, long term exposure to UV shows the lowest decrease in strength and elongation at break.

ENVIRONMENTAL PROPERTIES		
Visible light exposure		Excellent*
UV-exposure	ISO 4892	Very good*
Weathering	ISO 12224	Excellent
Oxidation (28 days, 80°C, 50 bar)	ISO 13438	Passed

Fungal resistance.
UHMWPE fiber from DSM Dyneema has excellent biological resistance. The fiber neither stimulates undesired growth nor is sensitive to any attack by micro-organisms.

FUNGAL RESISTANCE		
Aspergillus niger	RTCA DO160	Excellent
Aspergillus flavus	RTCA DO160	Excellent
Aspergillus versicolor	RTCA DO160	Excellent
Penicillium funiculosum	RTCA DO160	Excellent
Chaetomium globosum	RTCA DO160	Excellent

Toxicity.
Polyethylene is regarded as biologically inert. The UHMWPE fibers from DSM Dyneema are IARC classified 3 (not classifiable carcinogenic to human) based upon its length weighted geometric mean diameter. This diameter is too large to produce respirable fibers, meaning they will never reach the deeper part of the respiratory tract and fibrogenic or carcinogenic effects on the lung will not occur.

* Detailed information per fiber type, as Product Data Sheet, Product Specification Sheet, Material Safety Data Sheet and Fact Sheet, is available on request.

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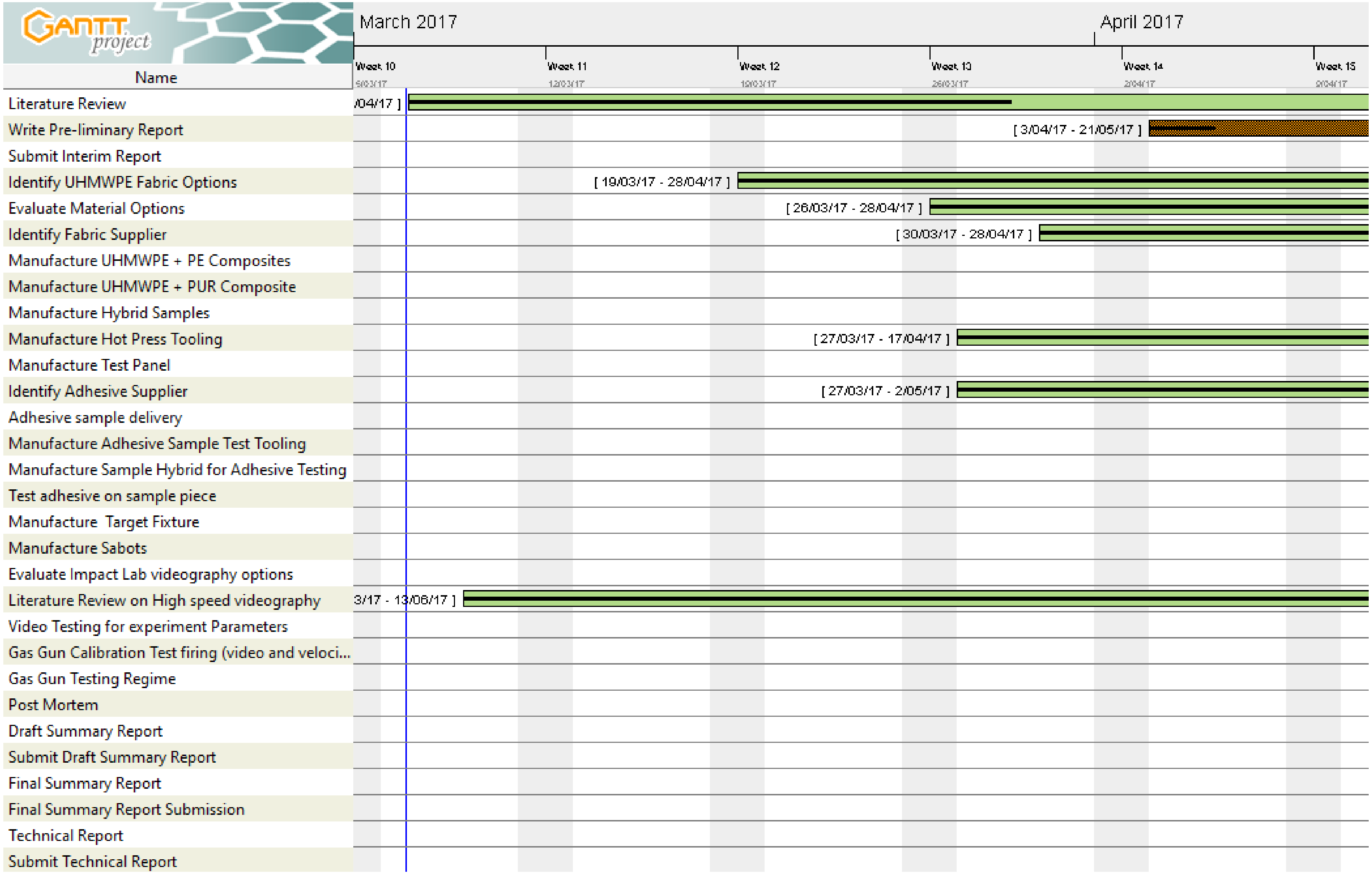
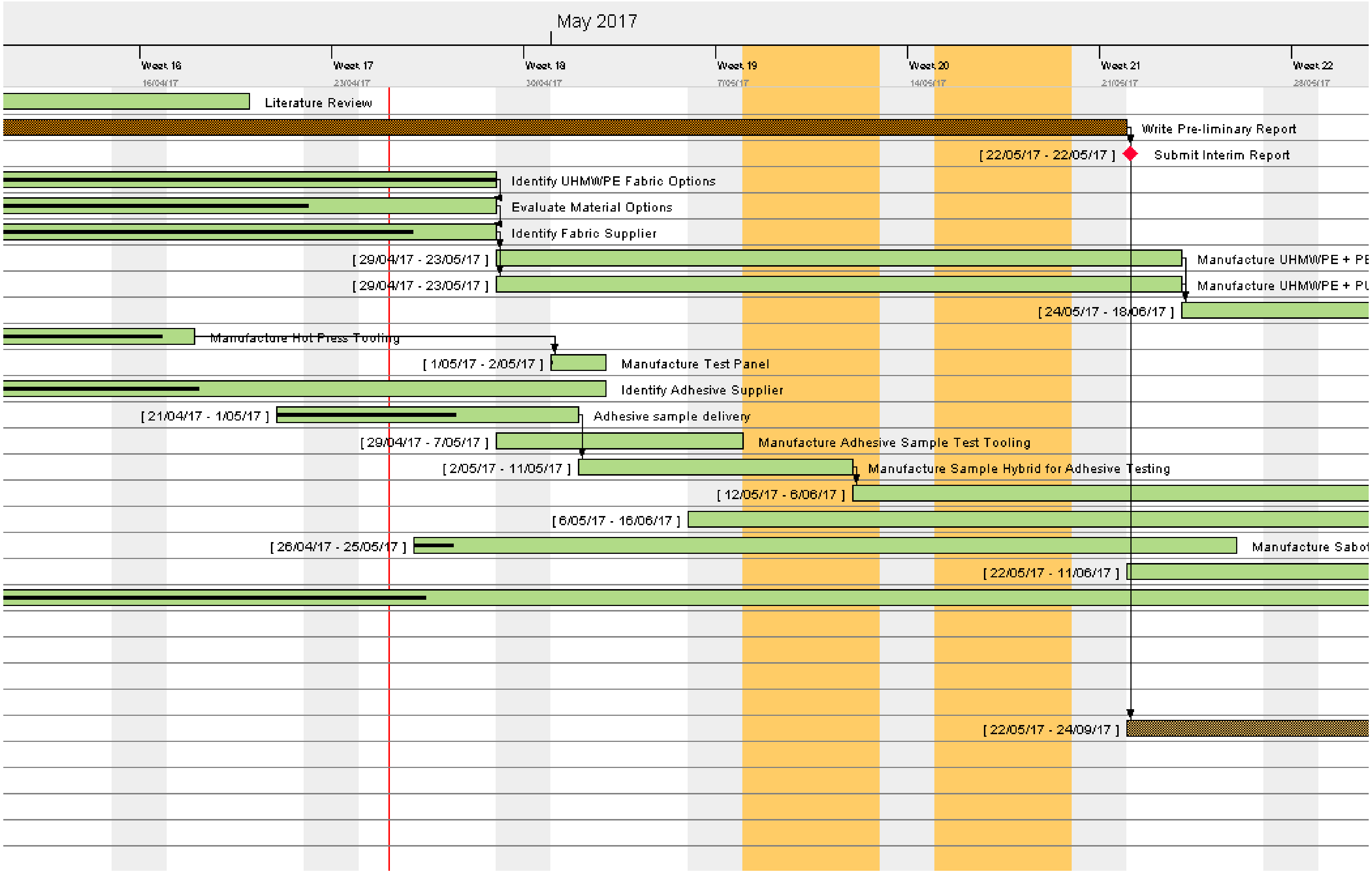
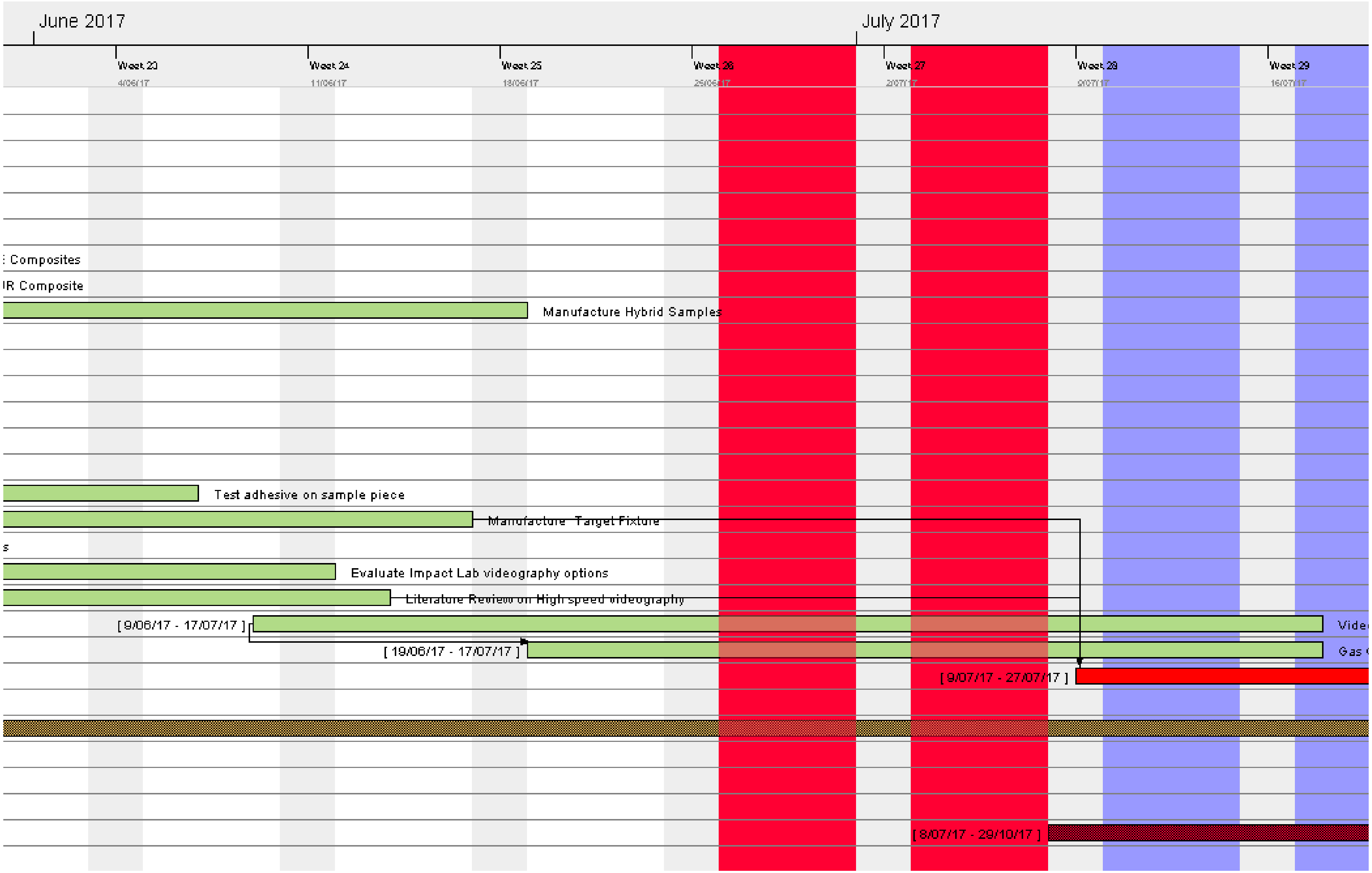
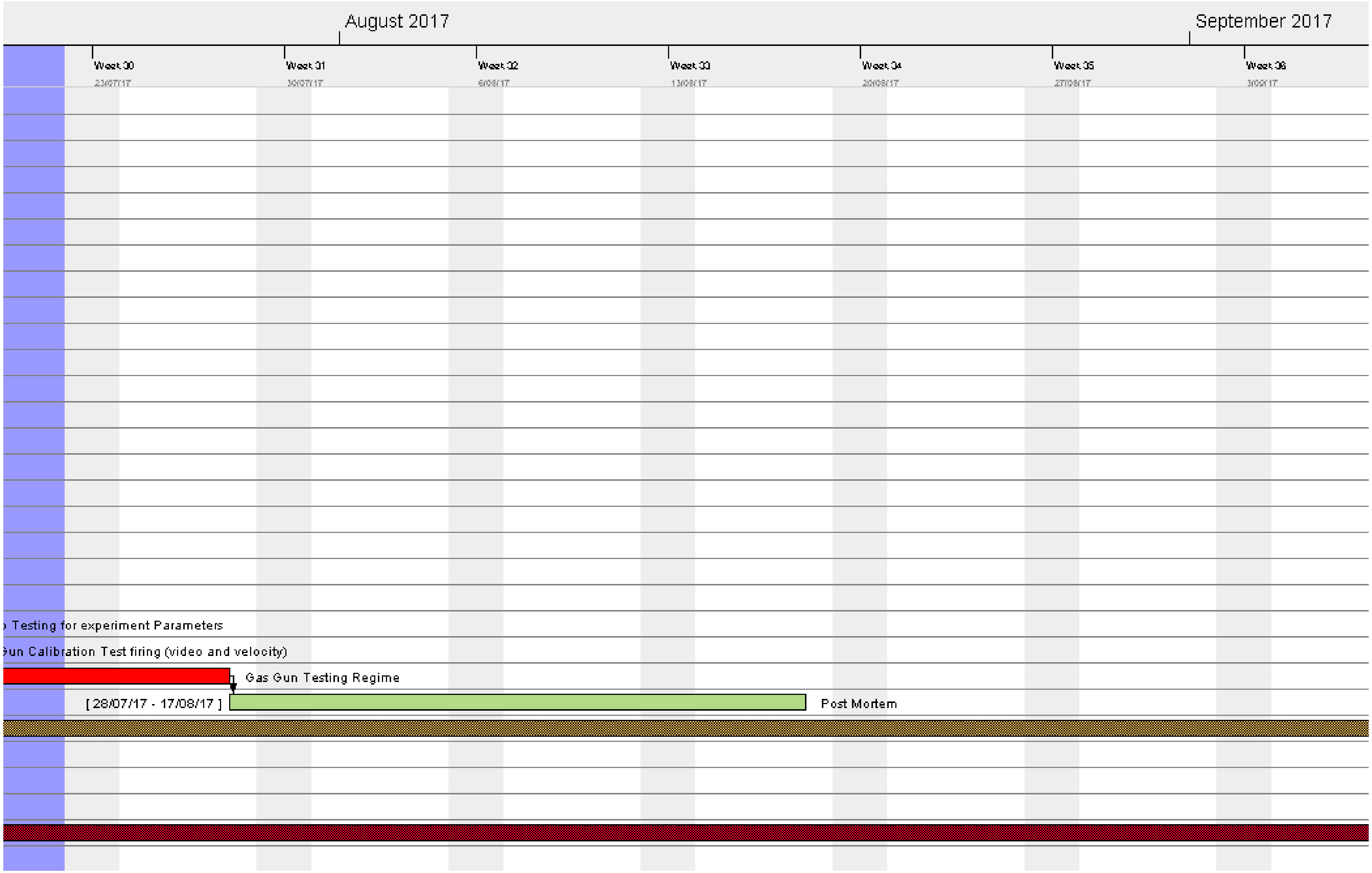
Ref.: CIS YA100

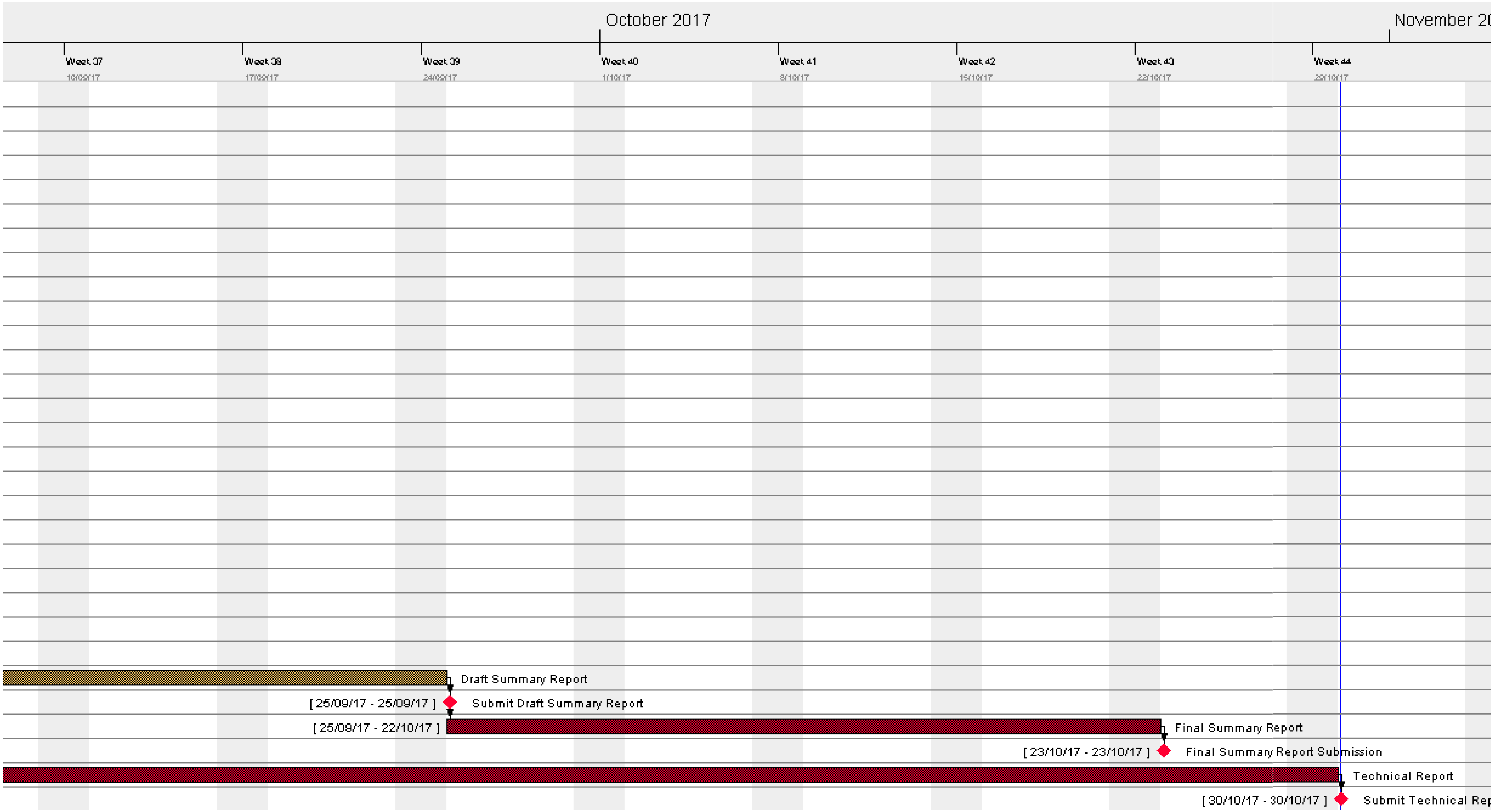
Appendix F to
Final Project Preliminary Report 2017, UNSW


GANTT project
Name
March 2017
April 2017
Week 10
Week 11
Week 12
Week 13
Week 14
Week 15
Literature Review
Write Pre-liminary Report
Submit Interim Report
Identify UHMWPE Fabric Options
Evaluate Material Options
Identify Fabric Supplier
Manufacture UHMWPE + PE Composites
Manufacture UHMWPE + PUR Composite
Manufacture Hybrid Samples
Manufacture Hot Press Tooling
Manufacture Test Panel
Identify Adhesive Supplier
Adhesive sample delivery
Manufacture Adhesive Sample Test Tooling
Manufacture Sample Hybrid for Adhesive Testing
Test adhesive on sample piece
Manufacture Target Fixture
Manufacture Sabots
Evaluate Impact Lab videography options
Literature Review on High speed videography
Video Testing for experiment Parameters
Gas Gun Calibration Test firing (video and veloci...
Gas Gun Testing Regime
Post Mortem
Draft Summary Report
Submit Draft Summary Report
Final Summary Report
Final Summary Report Submission
Technical Report
Submit Technical Report
/04/17]
[3/04/17 - 21/05/17]
[19/03/17 - 28/04/17]
[26/03/17 - 28/04/17]
[30/03/17 - 28/04/17]
[27/03/17 - 17/04/17]
[27/03/17 - 2/05/17]
3/17 - 13/06/17]


May 2017
Week 16
16/04/17
Week 17
23/04/17
Week 18
30/04/17
Week 19
7/05/17
Week 20
14/05/17
Week 21
21/05/17
Week 22
28/05/17
Literature Review
Write Pre-liminary Report
[22/05/17 - 22/05/17]
Submit Interim Report
Identify UHMWPE Fabric Options
Evaluate Material Options
Identify Fabric Supplier
[29/04/17 - 23/05/17]
Manufacture UHMWPE + PE
[29/04/17 - 23/05/17]
Manufacture UHMWPE + PU
[24/05/17 - 18/06/17]
Manufacture Hot Press Tooling
[1/05/17 - 2/05/17]
Manufacture Test Panel
Identify Adhesive Supplier
[21/04/17 - 1/05/17]
Adhesive sample delivery
[29/04/17 - 7/05/17]
Manufacture Adhesive Sample Test Tooling
[2/05/17 - 11/05/17]
Manufacture Sample Hybrid for Adhesive Testing
[12/05/17 - 6/06/17]
[6/05/17 - 16/06/17]
[26/04/17 - 25/05/17]
Manufacture Sabot
[22/05/17 - 11/06/17]
[22/05/17 - 24/09/17]


June 2017
July 2017
Week 23
4/06/17
Week 24
11/06/17
Week 25
18/06/17
Week 26
25/06/17
Week 27
2/07/17
Week 28
9/07/17
Week 29
16/07/17
Composites
IR Composite
Manufacture Hybrid Samples
Test adhesive on sample piece
Manufacture Target Fixture
Evaluate Impact Lab videography options
Literature Review on High speed videography
[9/06/17 - 17/07/17]
[19/06/17 - 17/07/17]
[9/07/17 - 27/07/17]
[8/07/17 - 29/10/17]


August 2017
September 2017
Week 30
Week 31
Week 32
Week 33
Week 34
Week 35
Week 36
Testing for experiment Parameters
Calibration Test firing (video and velocity)
Gas Gun Testing Regime
[28/07/17 - 17/08/17]
Post Mortem


October 2017
November 20
Week 37
Week 38
Week 39
Week 40
Week 41
Week 42
Week 43
Week 44
Draft Summary Report
[25/09/17 - 25/09/17]
Submit Draft Summary Report
[25/09/17 - 22/10/17]
Final Summary Report
[23/10/17 - 23/10/17]
Final Summary Report Submission
Technical Report
[30/10/17 - 30/10/17]
Submit Technical Rep