# Carbon Fibre and Aluminium Foam Composites

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**Abstract**

The occurrence of delamination between the core and laminate of a composite sandwich structure is a major problem that can lead to premature failure of such a material. One way of improving the delamination toughness of a composite sandwich structure is through interlaminar short fibre reinforcement. Positive results have been attained in recent studies at UWA with the use of this technique applied to a sandwich structure of aluminium foam and carbon fibre – a material that shows great potential as a lightweight alternative to materials currently used in automotive, aeronautical and marine applications. This study attempts to further improve the fabrication of such a material with short fibre reinforcement.

Fibre bridging has been identified as a key mechanism in the success of the technique. As such, this study aims to maximise the occurrence of fibre bridging by varying quantities such as the mass and length of reinforcement fibres and the amount of epoxy resin used. Some improvements were made to the fabrication methods and although results for the compressive strength of samples were somewhat inconclusive, it was observed that the delamination toughness had nonetheless been improved. This was verified through the use of scanning electron microscopy. The results of the study also highlighted the need for further investigation into optimising the bonding between carbon fibre and aluminium foam in a sandwich structure.

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# 1. Introduction

The desire to turn to sustainable, renewable sources of energy rather than fossil fuels is currently prevalent in society. This desire is driven by environmental concerns as well as concerns about the price and uncertain availability of oil in the future - demand for oil is expected to exceed supply soon if it has not already. As such, consideration of new lightweight materials to maximise efficiency in automotive, aeronautical and marine applications is of great importance. As well as improving efficiency of existing systems, the use of suitable lightweight alternatives to common materials currently in use also presents the possibility of employing alternative energy sources that may not otherwise be feasible.

Great interest has therefore been taken in the use of composite materials in the past few decades (Ashcroft et al. 2000). Carbon Fibre Reinforced Plastic (CFRP) is one composite material that has received significant attention and is currently in widespread use. Whilst it is commonly acknowledged that carbon fibre exhibits better fatigue strength than steel, its brittle nature and tendency to weaken from exposure to extreme temperatures and impact make it unpredictable in failure and therefore a great concern in terms of safety, especially as damage is very difficult to detect. Various catastrophic incidents such as the crash of Air France 447 and American Airlines Flight 587, for which material failure has been seen as the likely cause, serve as evidence that there exists a lack of understanding of the failure of composite materials.

A major failure mechanism in laminated composite structures is delamination, which can lead to premature failure of such a material. It is therefore beneficial to improve delamination toughness of laminated composites. Several different methods currently employed to do this include nanostitching, “2.5D” fabrics, translaminar Z-pinning, interleaving polymer films and short fibre reinforcement – each with different advantages and disadvantages (Bond et al. 2011, Sohn & Hu 1994, 1998, 2002 Walker, Sohn et al. 2000). Of these, interlaminar short fibre reinforcement which was originally developed by Sohn and Hu (1994) at UWA has proven to be a simple and cost effective method. A contract was in place between UWA, British Aerospace and CSIRO to optimise the technique and develop commercial technology for large scale manufacture; this work did however not go ahead. Research has been completed recently at the University of Bristol to test the effectiveness of some different reinforcement methods.

The short fibre reinforcement technique was validated in this study and shown to be more effective than some interleaving polymer films (Bond et al. 2011).

This project is a continuation of research undertaken at UWA into carbon fibre and aluminium foam sandwich composites (Sohn & Hu 1995, Walker 2001, Ross 2009, Jeyaraman 2010, Massey 2010). The purpose of this experimental study was to improve on existing techniques used to fabricate a carbon fibre and aluminium foam composite sandwich structure with interlaminar short fibre reinforcement. An increase in the occurrence of fibre bridging was desired and expected to lead to positive experimental results associated with the compressive strength and delamination toughness of the fibre reinforced sandwich structure. Compression testing was chosen to test the samples it is fast and simple to carry out and compressive strength is widely recognised as a limiting attribute for layered composite structures. Compressive strength is usually more sensitive to any interlaminar modifications than tensile strength as microbuckling and misalignment of continuous fibres have a much greater influence on compressive strength (Sohn & Hu 1998). A number of samples were prepared both with and without SFR. Quantities such as the mass and length of reinforcement fibres and the amount of epoxy resin used were varied between different batches of samples such that comparisons could be drawn from the testing results.

Successful results from the experimentation would serve as evidence that with the use of a relatively simple technique, the carbon fibre and aluminium foam composite sandwich structure is of increased potential as a lightweight material for use in applications where high specific strength and stiffness are desired.

# 2. Literature Review

## 2.1 Carbon Fibre Reinforced Plastic (CFRP)

Laminated composites have excellent in-plane mechanical properties, however their through-thickness strength and toughness is less impressive as is evident in their tendency to delaminate (Bond et al. 2011). Reliability is closely related to delamination toughness which in turn is related to material strength under tension, compression and impact conditions (Sohn & Hu 1998). In aircraft composites, approximately 70% of structural failures have been found to initiate from the joints (Abdul Razak & Othman 2011). The use of composites has therefore been limited in safety critical applications, most notably in aircraft, where any kind of failure mid-flight is likely catastrophic and fatal (Bond et al 2011). The solutions to technical and economic challenges that would allow composite materials to achieve maximum weight saving potential are beyond the current state of the art (Aero Index Ltd 2011).

Carbon fibre reinforced plastic (CFRP), more commonly referred to simply as carbon fibre, is a composite material produced by impregnating carbon fibre fabric with a polymer resin. Epoxy resins are also excellent adhesives, and are therefore commonly used both to cure the fibre matrix as well as bond multiple composite parts together; this is called co-curing (Cognard 2006). Carbon fibre has achieved widespread acceptance as a lightweight alternative to materials such as steel and aluminium as it provides much greater strength and stiffness for the same mass of material as well as having good chemical resistance (Sohn & Hu 1998, Sohn et al. 2000). It is however more expensive and is therefore generally reserved for applications where the greater cost is acceptable in exchange for an increase in performance and efficiency.

Whilst it exhibits very high specific strength and stiffness, carbon fibre is a brittle material that, like all laminated composites, is susceptible to damage caused by various loadings. These include static loading, low energy impact and environmental factors such as moisture and extreme temperatures which can have a considerable effect on mechanical performance, fatigue behaviour and the nature of failure in composite joints (Ashcroft et al. 2000, Aero Index Ltd 2011, Sohn et al. 2000). Low energy impact in particular can cause sub-surface damage that may not be visible on the laminate surface (Sohn et al. 2000). Bond et al. (2011) suggests that a 10J low velocity impact on a composite panel can reduce its compressive strength by up to 35%.

In this study, carbon fibre reinforced plastic was chosen to be used for the face sheets of the sandwich structure for its favourable properties in this role and for consistency with previous work completed at UWA. The face sheets were fabricated from a roll of twill weave 2x2 carbon fibre fabric measuring 5m by 1.27m, supplied by MarineWare NSW. To keep consistent with that which was used in previous study by Jeyaraman (2010), an order was made for RC200P plain weave carbon fibre fabric. The incorrect material was however received and due to time and budget constraints it was decided to continue work with the twill weave carbon fibre.

*Epoxy Resin*

The epoxy resin used both to co-cure and the carbon fibre face sheets to adhere them to the aluminium foam core was R2514 Multipurpose Tooling Resin. This was mixed with H2428 Multipurpose Tooling Hardener as specified, in the ratio 5 parts resin to 1 part hardener. This epoxy resin was used because it is commonly known to be capable of effectively co-curing carbon fibre and adhering it to other materials such as aluminium, it is the same epoxy resin that has been used in previous work and also because it was already available in the composites laboratory.

## 2.2 Alporas Aluminium Foam

The aluminium foam chosen for use in this study is called Alporas, an ultra-light, closed cell material. Alporas is a heat resistant, corrosion resistant, recyclable, non-toxic material with high energy absorption, acoustic absorption and specific stiffness (Ashby et al. 2000). It has a Young's modulus of around 1GPa and an average density of approximately 250kg/m$^3$; this is less than 10% of the density of solid aluminium. Alporas has similar fatigue strength and lower creep ductility to that of solid aluminium as well as exhibiting better mechanical damping with higher natural flexural vibration frequencies than a solid sheet of the same mass (Ashby et al. 2000). It is best suited to applications where several of these unique properties are utilised. Current applications of Alporas include baffles to absorb traffic noise on underpasses, claddings on buildings and crash absorbers at the front of trains and Formula 1 cars (Ashby et al. 2000, Akiyama et al. 2000).

The properties of Alporas and compatibility with adhesives such as epoxy resins make it ideal as a core material in a composite sandwich structure (Ashby et al. 2000). Jeyaraman (2010) investigated the use of Alporas as well as Alulight, another closed cell aluminium foam, as the core material of a sandwich structure. The lighter, more homogeneous and less expensive Alporas was shown to yield more consistent results so it was chosen to be the only core material used in this study.

Alporas is produced by adding calcium and titanium hydride to a classical metallurgical aluminium melt. The addition of calcium results in formation of calcium oxide (CaO) and calcium aluminium oxide ($CaAl_2O_4$) which, when stirred, causes a remarkable increase in viscosity. Titanium hydride ($TiH_2$) is then added as a blowing agent, releasing hydrogen and causing the melt to expand and foam (Akiyama et al. 2000, Ashby et al. 2000, Banhart 2000). The process is shown in Figure 1 below. This method is seen to produce the most homogeneous of aluminium foams with an average pore size of 4-6mm (Banhart 2000).

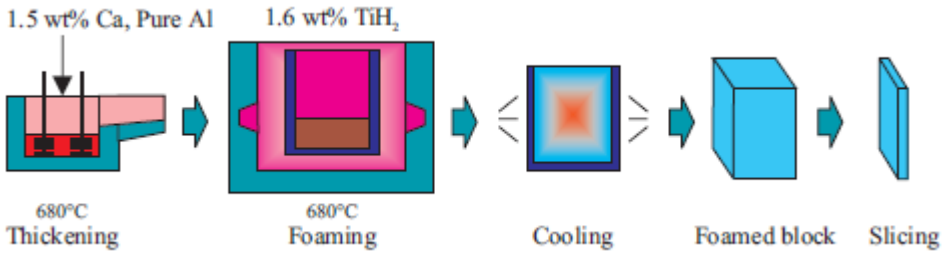


**Figure 1:** Manufacturing Process of Alporas (Akiyama et al. 2000)

Whilst it is currently relatively expensive and not in widespread use, Alporas is a material that is potentially cheap to produce once a significant demand exists to produce it in large quantities (Ashby et al. 2000).

A 1200x700x15mm sheet Supplied by GLEICH Aluminiumwerk, Germany, was taken to the mechanical engineering workshop and cut into 36 pieces of dimensions 190x100x15mm using a band saw. These were then cleaned with acetone using a large paintbrush to remove any aluminium dust/debris and other impurities. Although the average pore size is specified as 4-6mm, it can be seen in **Figure 2** below that pores of much greater size were present on many of the pieces – some of them up to 20mm across.

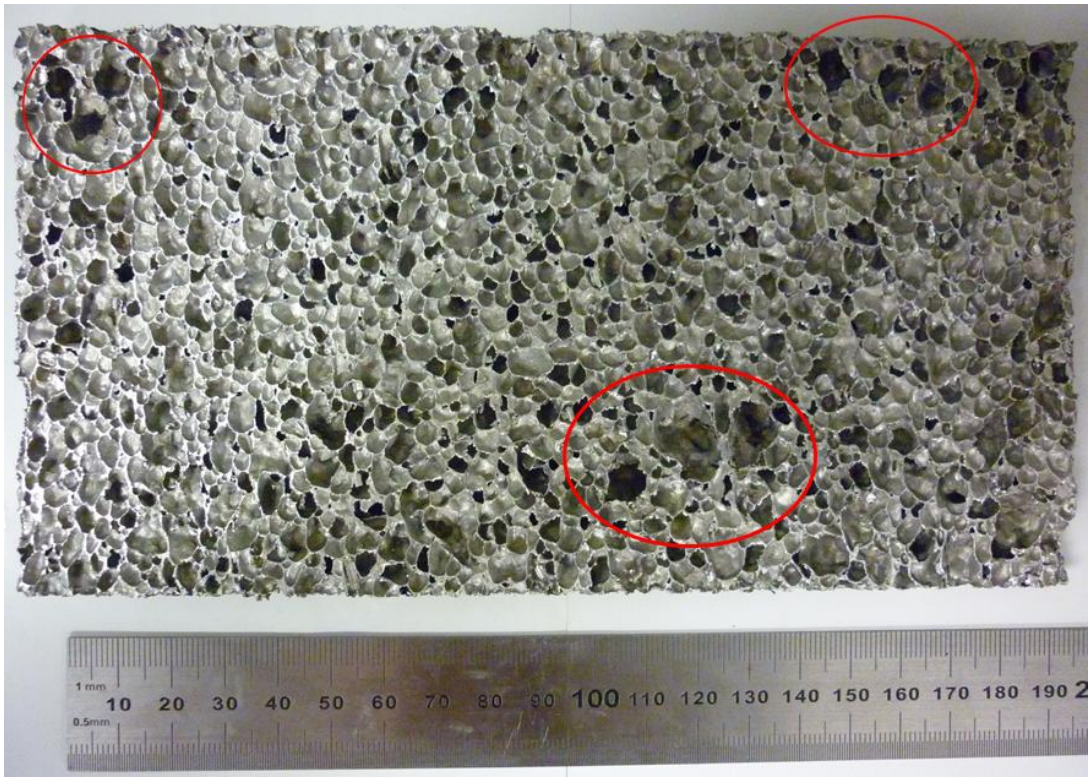


**Figure 2:** Alporas Aluminium Foam

## 2.3 Composite Sandwich Structures

A sandwich structure consists of two thin face sheets bonded to either side of a relatively thick inner core. The face sheets are generally made from high performance materials with high strength and stiffness whereas the core is a very lightweight material. The face sheets provide strength and stiffness whilst the core resists shear and supports the face sheets against wrinkling or buckling (Mladensky & Rizov 2007). This results in an overall lightweight material with high specific strength and specific stiffness that also generally provides good thermal and acoustic insulation, high energy absorption and buoyancy (Mladensky & Rizov 2007).

Composite sandwich structures present great potential in automotive, aircraft and marine applications, where minimising weight is of great importance to maximise performance and efficiency. Aluminium foams such as Alporas are suitable for use as the core material in a sandwich structure and a carbon fibre/aluminium foam composite sandwich structure shows potential as a lightweight alternative to other common materials (Chirwa et al. 2003). The occurrence of delamination of face sheet from the core is a major drawback that limits its widespread acceptance as this effect can lead to premature failure of the material (Sohn & Hu 1998, Abdul Razak & Othman 2011).

A carbon fibre/aluminium foam composite sandwich structure is somewhat comparable to a waffle stiffened or honeycomb core sandwich panel but possibly with lower manufacturing cost and improved durability. Honeycomb structures are also very complex to repair (Ashby et al. 2000, Aero Index Ltd 2011). Some material properties of the different components used to fabricate the carbon fibre/aluminium foam composite sandwich structure are shown below in **Table 1** (Steel and Aluminium are included for the purpose of comparison).

| Material | Density (kg/m$^3$) | Tensile Strength (MPa) | Youngs Modulus (GPa) |
|---|---|---|---|
| **Steel** | 7800 | 1000 | 207 |
| **Aluminium** | 2700 | 462 | 70 |
| **Alporas** | 250 | 1.6 | 1 |
| **Carbon Fibre** | 1900 | 1572 | 380 |
| **Kevlar Fibre** | 1440 | 3000 | 112 |

**Table 1:** Relevant Material Properties (DuPont 2001, GLEICH 2009, Idris 2010)

## 2.4 Adhesive Bonding

The advantages of adhesive bonding over mechanical bonding are well known and include greater strength, less weight, lower cost and can join together complex shapes and dissimilar material substrates (Beckwith & Strong 1999, Ashcroft et al. 2000, Wilson 2010). Adhesives provide higher stiffness and joint efficiency, allow for more uniform and smoother load transfer and do not require drilling operations when compared with mechanical joining with bolts or fasteners and after all, reducing the number of required components is a major goal of composite design in order to minimise the number of secondary joining operations (Brosius et al. 2005, Correia, Keller & Vallée 2009).

Adhesives can however vary in compatibility with different materials. Bonding is strongest when the compatibility between the adhesive and both joining surfaces is good. The closer the chemical nature of the adhesive is to that of a composite structure, the stronger the bonding (Beckwith & Strong 1999). The strength of the adhesive bond requires that the adhesive completely spreads over the surface of the substrates to be joined - this is called wetting the surface. Wetting is improved by chemical compatibility between the surfaces and the adhesive as well as cleanliness of the surfaces (Beckwith & Strong 1999). Compatibility can be improved through the use of surface treatments that include chemical etching, sand blasting, plasma treatment, or

applying a primer to achieve good chemical compatibility with the adhesive (Beckwith & Strong 1999).

Adhesive is generally lower in strength than the composite it is joining, therefore normal procedure is to use only enough adhesive to just completely cover the bonded surfaces (Beckwith & Strong 1999). It follows that strength will decrease with increasing bondline thickness; this is known from experimental results (Gleich et al. 2001). Despite this, in automotive and civil industries, bondline thicknesses can be up to 20mm due possibly to the subsequent ease of manufacture or for gap filling and sealing roles (Gleich et al. 2001). Little is known about the influence of adhesive layer thickness on the properties such as strength, fatigue, creep etc. of adhesively bonded structures. More specifically, in regard to the existence of an optimum bondline thickness, few results have yet been published (Gleich et al. 2001, Correia, Keller & Vallée 2009). Based on the results of some finite element analysis, Gleich et al. (2001) suggested that the maximum strength of adhesively bonded joints does occur at an optimum adhesive layer thickness, depending on both geometry and the materials used. In research undertaken by Correia, Keller & Vallée (2009), it was found that there was indeed an optimum adhesive thickness when experimentally investigating double-lap joints of a glass fibre reinforced plastic bonded with polyurethane adhesive and subjected to quasi-static axial tensile loading. This may be particularly important when dealing with a material such as Alporas aluminium foam which has a rough, uneven surface covered in pores into which epoxy could be lost.

## 2.5 Delamination

Delamination, or debonding, is characterised by the propagation of one or more cracks along the interface of the core and skin resulting in separation (Mahfuz et al. 2005). Laminated composites with adhesive bonding are prone to delamination, particularly at the edges. Delamination is a fundamental problem for both composite and sandwich materials that can lead to a substantial reduction in stiffness and strength and premature failure (Abdul Razak & Othman 2011, Sohn & Hu 1994, 1998). Delamination can occur as a result of not only excessive loads, but cyclic stresses or impact and it also facilitates other failure modes (Sohn & Hu 1998, Sohn et al. 2000). Owing to inherent structural weaknesses of carbon fibre composite laminates, delamination is one of the main issues in this type of material (Sohn & Hu 1994, 1998).

Low energy impact loading can cause sub-surface damage not visible on the laminate surface, which can result in delamination. The occurrence of delamination can therefore be difficult to detect and limits the widespread acceptance of many laminated composite materials (Sohn et al. 2000). Three different modes of fracture (Modes I, II and III) are typically used to characterise delamination failure, as can be seen in **Figure 3** below. Mode III is rare and therefore often ignored (Bond et al. 2011). The compression testing used in this study facilitates Mode II fracture.

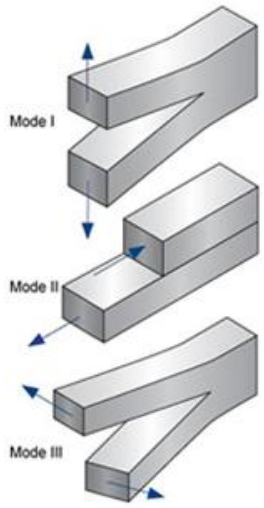


**Figure 3:** The 3 modes of fracture (NDT Resource Centre, 2011)

## 2.6 Interlaminar Reinforcement

Development of interlaminar reinforcement methods to improve delamination toughness of composites has long been a strong focus in the aerospace industry, with particular attention payed to high temperature/humidity environments due to their effects on material properties (Walker & Hu 1999, 2003). In general, an increase in delamination toughness comes at the cost of compressive strength and can alter the bulk composite properties (Sohn & Hu 1994, 1998). The most recognised reinforcement techniques currently include Z-pinning, 2.5D fabrics, interleaving polymer films and short fibre reinforcement (SFR).

Z-pinning involves the insertion of discontinuous short fibres in the z-direction (out of the laminate plane). It is known to be the most effective against delamination, but carries high cost, involves complex operation requiring specialised equipment and leads to degradation of other composite properties such as strength and stiffness. Z-pinning has been shown to increase interlaminar shear strength by 50%, compression-after-

impact strength by 50%, compressive strength by 35% and resistance to impact damage with varying decreases to in-plane stiffness and tensile strength (Walker, Sohn & Hu 2002).

3D woven fabrics have enhanced delamination toughness and are less susceptible to impact damage however normal compressive strength and in plane specific stiffness and strength are reduced by a reduction in fibre alignment and carbon fibre/composite volume ratio. They also suffer from high production cost (Sohn & Hu 1998). 2.5D fabrics can improve delamination toughness without severe detrimental effects on other composite properties. It is made from a 3D fabric by cutting through the "through the thickness" (TTT) fibres that bridge the gap between the two 2D fabrics as is shown in **Figure 4** below. This method is however not very practical considering 3D fabrics are expensive to begin with and additional operation cost is added to obtain the 2.5D fabric. The type of 2.5D fabric is also limited to that of available 3D fabrics (Sohn & Hu 1998).

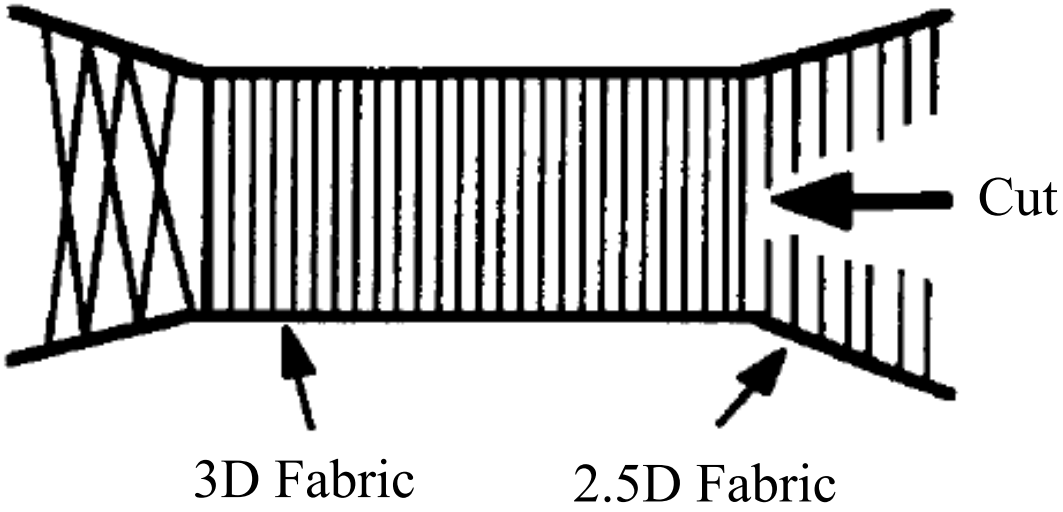


**Figure 4:** Fabrication of 2.5D fabric (Sohn & Hu 1998)

The use of interleaving polymer films provides considerable improvements in both impact resistance and delamination toughness. The technique involves a process of fusing tough polymeric films, in selected toughening areas where premature composite failure may occur, during composite manufacture. Therefore, different failure mechanisms ensue and interleaving has noticeable detrimental effects on other composite properties such as strength and stiffness (Sohn et al. 2000, Bond et al. 2011).

*Short Fibre Reinforcement (SFR)*

The short fibre reinforcement technique was originally developed by Sohn and Hu (1994) at UWA to reinforce layers of carbon fibre with chopped kevlar fibres. It is simple, low cost and flexible as the length and distribution of short fibres can be easily manipulated as well as having little effect on an existing laminating process (Sohn & Hu 1998, Walker & Hu 1999, 2003). The short fibres are desired to be in a woollen form to ensure a thin, even distribution that ensures each individual fibre is properly wet with epoxy. There will then be no areas of clumped up fibres; some of which could remain dry and therefore not be useful as reinforcement.

SFR improves impact resistance and reduces visible impact damage as well as delamination toughness whilst not significantly affecting system properties (Walker & Hu 1999, 2003 Walker, Sohn & Hu 2002). As such, SFR leads to improved compression-after-impact strength (Sohn & Hu 1998). To some extent, compression-after-impact strength is more important than normal compressive strength because premature failure such as delamination always precede catastrophic failure during compression and therefore should be considered for structural designs. Delamination toughness may therefore be a greater design concern than compressive strength. Whilst expensive fibre treatment and coating can improve compressive strength, it does not significantly improve delamination toughness (Sohn & Hu 1998). Results from testing of composites with kevlar reinforcement by Sohn & Hu (1998) saw at most 15% strength reduction whilst delamination toughness increased by 100 to 200%.

The short fibre reinforcement technique has been validated by research undertaken recently at the University of Bristol. Electrical grade glass fibre reinforced plastic (GFRP) was used to test the effectiveness of short fibre reinforcement and some interleaving films in improving mode II fracture toughness. The results showed SFR with kevlar aramid fibres to be the most consistent and effective method as is shown in **Figure 5** below, where the critical mode II strain energy release rate, $G_{IIC}$, is directly related to mode II fracture toughness (Bond et al. 2011). As well as the advantages of SFR described previously, it is worth noting that, interleaving films create two additional interfacial zones and can result in reduced flexural properties whereas short fibre reinforcement produces a randomly orientated layer that creates the potential for a random and disturbed crack path (Walker, Sohn & Hu 2002).

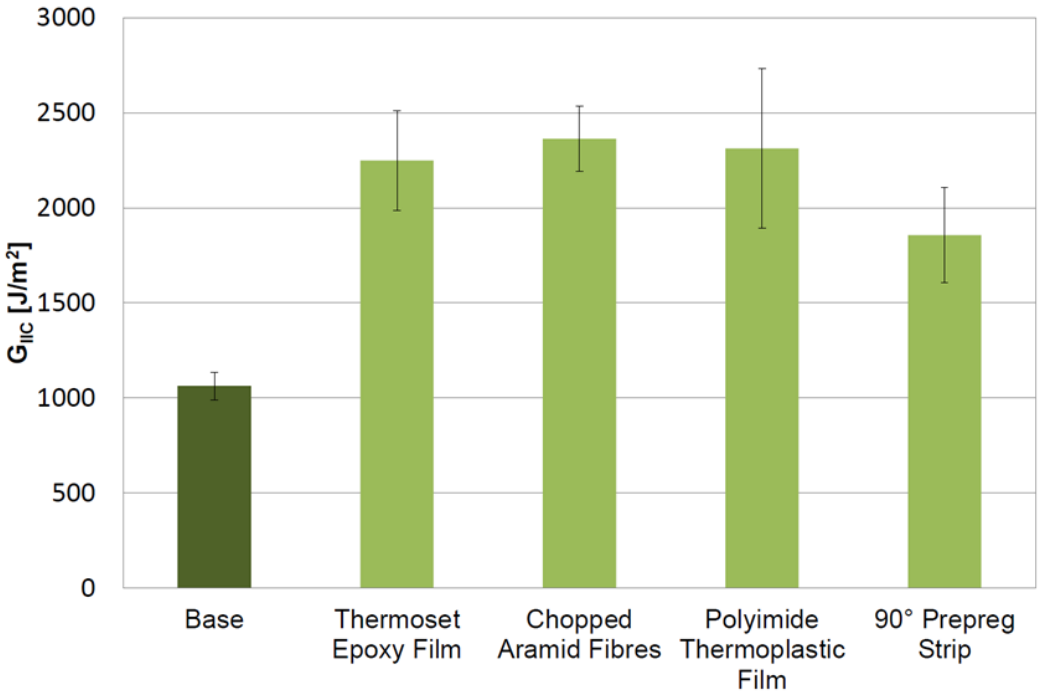


**Figure 5:** Comparison of reinforcement techniques (Bond et al. 2011)

*Fibre Bridging*

Fibre bridging has been identified as a key mechanism in the effectiveness of short fibre reinforcement (Sohn & Hu 1994, Walker 2001). When the reinforcement fibres are strongly bonded to both interlaminar fracture surfaces, they form a bridge between the two and experience a tensile load that resists separation of the materials.

Work has been completed previously at UWA using interlaminar SFR in between the core and laminate of carbon fibre/aluminium foam sandwich composite with positive results; a 28% increase in compressive failure loads sustained with the inclusion of interlaminar kevlar fibre reinforcement. There were however still issues in the application of such reinforcement and evidence via scanning electron microscopy (SEM) that fibre bridging, which has been identified as a key mechanism in the success of the technique, was achieved by only a small proportion of the fibres used (Jeyaraman 2010).

Reducing the length of reinforcement fibres increases the number of fibre ends and therefore may show improvement in the fibre bridging effect. The pores on the surface of the aluminium foam however require that the fibres be long enough to bridge the gap between the inner surface of the pores and the face sheet. Reinforcement fibres of different lengths will therefore be tested in this study to try and maximise the amount of fibre bridging.

*Kevlar Fibre*

Kevlar is an organic fibre in the aromatic polyamide family developed by DuPont in the 60's. It has a unique combination of high strength, modulus, toughness and thermal stability (DuPont 2001). Kevlar is ideal for interlaminar short fibre reinforcement due to its high tensile strength, multiple fracture behaviour and flexibility (Sohn & Hu 1994). In this study, plain weave of Kevlar 49 supplied by E.I. DuPont, USA was used.

*Zylon Fibre*

Stronger and stiffer short fibres such as zylon may also serve as interlaminar reinforcement and may be superior under impact conditions (Sohn et al. 2000). Zylon is however weak in compression and less ductile than kevlar (Bunsell 2005). Jeyaraman (2010) investigated the use of zylon as well as kevlar as interlaminar short fibre reinforcement in a carbon fibre/aluminium foam sandwich composite; kevlar was shown to yield better results so the focus of this study is in the use of kevlar. One sample was however prepared with a combination of kevlar and zylon fibres. A comparison of the properties of the two short fibres is shown below in **Table 2.**

| | **Kevlar 49** | **Zylon** |
|---|---|---|
| **Diameter (μm)** | 12 | 12 |
| **Density (kg/m$^3$)** | 1440 | 1560 |
| **Young's Modulus (GPa)** | 112 | 280 |
| **Tensile Strength (MPa)** | 3000 | 5800 |
| **Elongation at Break (%)** | 4.5 | 2.5 |

**Table 2:** Properties of Kevlar and Zylon Short Fibres (Bunsell 2005, DuPont 2001)

# 3. Experimental Method

## 3.1 Method Summary

The composite sandwich structure consists of an Aluminium foam core in between two carbon fibre face sheets and interlaminar short fibre reinforcement in between the core and skin. Each batch of 8 samples were obtained from a piece that was initially fabricated to a size of 190mm by 100mm, as determined by the size of the purpose built mould in which it would be placed to cure.

Six pieces of plain weave carbon fibre fabric measuring 190mm by 100mm were used to prepare a 3 ply pre-impregnated (prepreg) face sheet for each side of the Al foam core. The prepreg layups were placed in the fridge to delay the curing of epoxy resin whilst the surface of one side of the Aluminium foam was prepared.

Epoxy resin was applied evenly across the Aluminium foam surface. A folded strip of Aluminium foil was then placed centrally along the length of the foam to initiate a "starter crack" and encourage samples to fail in this location during compression testing, therefore allowing comparisons to be made between the different samples. The desired quantity of woollen kevlar fibre was then evenly distributed over the surface of the Aluminium foam and more epoxy was dripped over the top of the kevlar before a toothbrush was used to push the fibres into the pores of the foam. One of the pre-preg layups of carbon fibre was then retrieved from the fridge and placed over the kevlar covered surface of the Aluminium foam and the process of applying epoxy, starter crack and fibre reinforcement was repeated for the opposite surface of the Al foam.

Once the carbon-fibre face sheets had been applied to both sides of the Al foam core, it was placed in a mould to allow the sandwich structure to cure under heat and pressure with the use of a hot platen air press. After curing was complete, the mould was disassembled and the sandwich structure removed and taken to the Mechanical Engineering Workshop to be cut into eight 90mm by 20mm samples, each of which would also have the ends milled to ensure they were square.

The samples were then compression tested with an Instron 8501 testing machine. They were compressed to a displacement change of -5mm, at a rate of -2.5mm/min with load, displacement and time recorded over the course of the test. The data from testing was then compiled in Microsoft Excel where it could be displayed in a graphical format and

values for the failure load of each sample as well as observations of any visible effects during the testing were noted. Refer to Appendix A for photographs of the equipment used.

Some Samples were then chosen for SEM (Scanning Electron Microscope) analysis, for which they had to be cut into smaller sized pieces with the carbon fibre skin separated from the Al foam core. The interlaminar surface of skin and core could then be examined to see how effective the short fibre reinforcement had been.

## 3.2 Mould Assembly

A 6 piece steel mould assembly was used to cure the composite sandwich structure in a hot platen air press. This mould is a prototype that was purpose built sometime in the past at UWA for use in conjunction with the hot platen air press and is suitable to hold samples of dimensions 190mm by 100mm. It is therefore for this reason that these dimensions were used in the fabrication of the composite sandwich structure. Each piece of the mould was thoroughly cleaned before being used as remnants of cured epoxy would be present on the surface from the previous fabrication. This was done using a paint scraper and some poly-vinyl alcohol (PVA) release agent which helped to lift the epoxy from the surface of the steel mould. The paint scraper was not used on the upper and lower surfaces of the mould; it was desired to have a smooth surface finish on the carbon fibre face sheets so in order to avoid scratching the surface, very fine sandpaper was instead used if necessary. The mould was then partially assembled, with two of the cornering sides fixed in place as shown below in **Figures 6 & 7**.

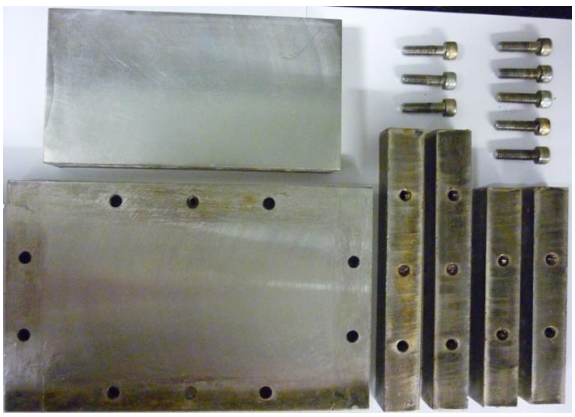

**Figure 6:** Parts of the Mould Assembly

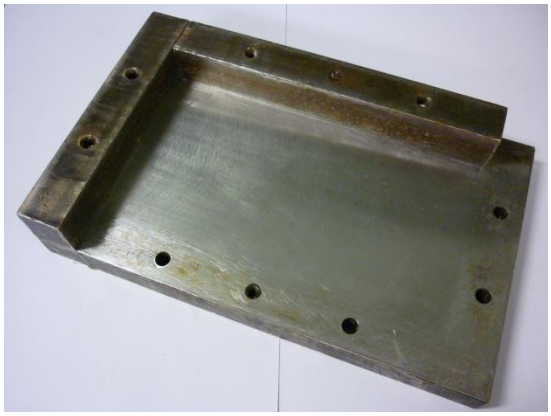

**Figure 7:** Partially Assembled Mould

*Peel Ply*

A porous nylon fabric peel ply, supplied by Boating Hardware Prosail WA, which allows epoxy to be spread evenly over a flat surface using a roller and peeled away without adhering to the surface. It also allows for absorption of some excess epoxy if it is applied a little too thick.

## 3.3 Preparation of Short Fibre Reinforcement

Of the samples that included interlaminar short fibre reinforcement and were prepared and tested, all but one batch contained kevlar fibre to provide this reinforcement. The final batch contained a combination of both kevlar and zylon fibres in equal mass proportions. The kevlar fibre was available as a 1m wide roll of plain weave fabric. In previous work undertaken at UWA (Jeyaraman 2010), a portion of the fabric was cut using some heavy duty fabric scissors and the threads of the plain weave were pulled apart such that they were unidirectional. A group of the fibre threads were then held next to a ruler and cut to the desired length using the heavy duty fabric scissors. In the current study, this method was found to be both inefficient and inaccurate to cut kevlar to lengths in the order of 10mm. An attempt was therefore made to find a better method of procuring chopped kevlar fibres.

*Kevlar Fibre Preparation: Method Refinement Attempt (Unsuccessful)*

The first attempt entailed separating the threads of the plain weave fibre and laying down the now unidirectional fibre threads in parallel on a textile cutting mat which has a measuring grid marked out on the surface. A steel rule would then be used to hold down the ends of the kevlar fibre threads at the desired length as measured by the cutting mat and a cut would be made along the edge of the steel rule with a hand held rotary blade or heavy duty straight edged blade. This would enable much larger quantities of kevlar fibre to be cut quickly, repeatedly and with superior accuracy than the previously employed method. Due to kevlar's incredibly high toughness, both of these hand tools were however found to be inadequate to cut through practical quantities of the kevlar fibre without dragging some of them along and causing the rest to become misaligned. The method was therefore unsuccessful, but could be refined to have fibres somehow held from both ends in tension and/or cut with a guillotine of some sort.

*Kevlar Fibre Preparation: Method Refinement Attempt (Successful)*

The second attempt to improve the preparation of chopped kevlar fibre was to cut the plain weave fabric first into strips, and then into squares using the heavy duty fabric scissors. The plain was not separated into unidirectional threads. The width of the thread which made up the fabric's plain weave was found to be 2mm so the initial cut was measured by counting the appropriate number of 2mm wide threads to meet the desired chopped fibre length (only lengths that were a multiple of 2mm were used). The cut was made to follow the line of the thread along the width of the roll of fabric. The resulting strip of kevlar fibre fabric, still maintaining its plain weave form, was then cut perpendicularly into squares, which could then be pulled apart as equal length chopped fibres. Although the length of chopped fibres was not found to be ideally accurate using this method, it was no worse than the original method whilst efficiency was found to be significantly better. Accuracy of the 6, 10 and 16mm chopped fibre lengths used in this study is thus assumed to be correct to ±1mm. Refer to **Figure 8** below for a diagrammatical representation of the process.

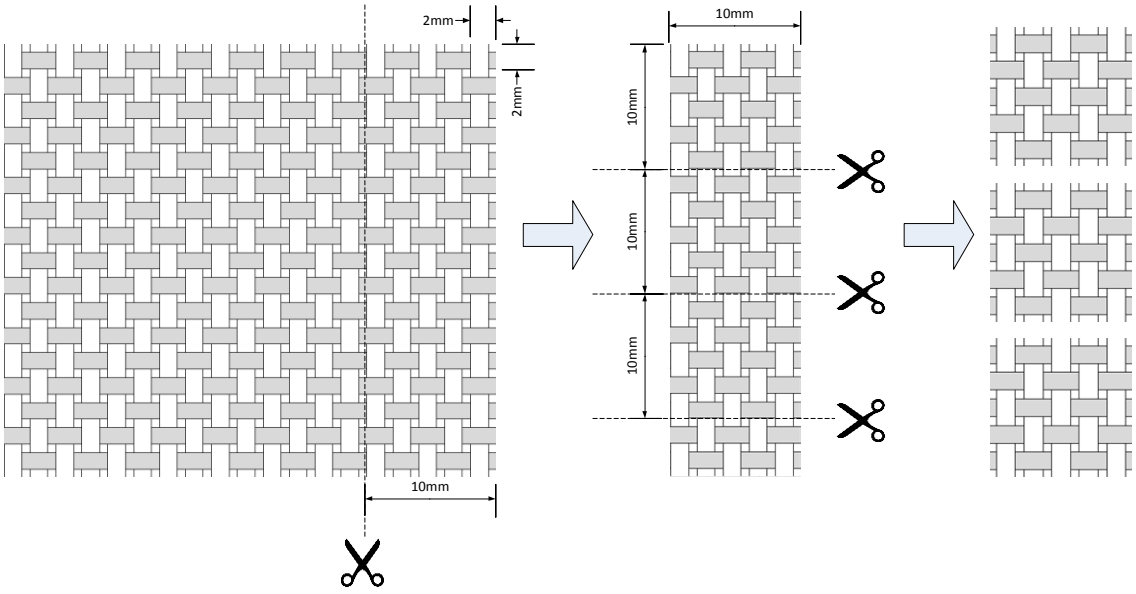


**Figure 8:** Kevlar Cutting Technique

*Conversion to Woollen Form*

The chopped kevlar fibre was required to be converted into a woollen form for optimal performance as short fibre reinforcement. For this, a prototype device that was constructed from a household blender was used (Walker 2001). The modified blender has a large cylindrical Perspex chamber that contains 4 wooden turbules. Chopped

kevlar fibres of the same length were placed inside the chamber, the lid was closed and the blender pulsed for a few seconds at a time until all the kevlar had been converted into a woollen form. The modified blender is shown in **Figure 9** below.

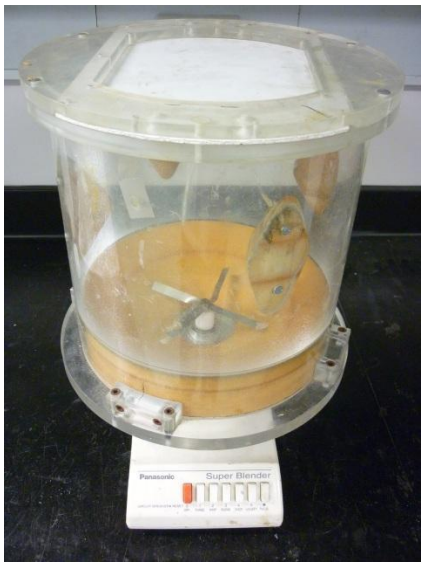


**Figure 9:** Modified Blender

## 3.4 Carbon Fibre Face Sheet Preparation

Before fabrication of the carbon fibre/aluminium foam sandwich composite structure could begin, all relevant bench top work areas would be cleared and wiped down. A sheet of peel ply would be cut to an approximate size of 600mm by 400mm and laid down on the fume extraction bench top surface to prevent any epoxy resin from going onto the bench top surface. Four sheets of peel ply were cut to a size of approximately 210mm by 120mm (slightly larger than the size of the sheets of carbon fibre fabric) and set aside.

The carbon fibre was available as a 1.27m wide roll of plain weave fabric that was placed on the bench top and partially unrolled over a textile cutting mat. A piece of card, measuring 190mm by 100mm, was used as a template and 6 pieces were cut to this size using an OLFA rotary cutter along the edge of a steel rule. These were set aside while the epoxy resin was readied for use.

The epoxy and hardener were each transferred from their large containers into 2 separate, smaller sauce bottles that were labelled accordingly. The sauce bottles made it much quicker and easier to dispense the correct quantities of epoxy and hardener. Two disposable plastic cups were used to mix the epoxy and hardener, half of the total

quantity in each cup to keep the amount used on each side of the sandwich structure equal. The epoxy being used was mixed with hardener in the ratio of 5:1 (epoxy to hardener) as specified for this type of epoxy. Having been placed on the digital scale, the first cup was therefore filled with $5/12^{th}$ of the total desired amount of epoxy before hardener was added until half of the total desired amount was read on the scale. The cup of epoxy and hardener was mixed together with a wooden skewer.

One of the 6 190mm by 100mm sheets of carbon fibre fabric would then be laid on top of one of the 4 slightly larger pieces of peel ply. A thin, even layer of the epoxy resin mixture was carefully applied over the surface of the carbon fibre using a flexible metal scraper before another piece of peel ply was placed on top and an steel roller used to ensure a complete and even distribution of epoxy. This peel ply was carefully peeled away and another sheet of carbon fibre fabric was laid on top of the first. The process described above was repeated until a 3-ply layup was achieved. The peel ply was left on top of the prepreg face sheet and it was placed in the fridge to delay the curing of epoxy resin. The amount of epoxy remaining in the cup was measured to check that it was roughly 10g less than it was originally, as this was found to be approximately the correct amount necessary to sufficiently wet the carbon fibre layup. The second cup of epoxy resin was measured and mixed and another prepreg face sheet was prepared by exactly the same method described above, this was also placed in the fridge.

### 3.5 Application of Short Fibre Reinforcement

From the first cup of epoxy, most of that which remained after preparation of the face sheet was applied evenly across one surface of the aluminium foam with the metal scraper, leaving a small amount of epoxy in the cup. The starter crack was then added centrally along the 190mm length of the aluminium foam surface, checking that it was 40mm from each side with a steel rule. The strip used to create the starter crack was simply cut from a roll of aluminium foil with the OLFA rotary cutter on the textile cutting mat to a size of 120mm by 40mm, then folded in half lengthways to make it 120mm by 20mm. The 120mm length was so it could be folded over the edge of the aluminium foam to keep it from moving out of position.

Interlaminar short fibre reinforcement could now be applied over the surface of the aluminium foam core. Having been already converted to woollen form of a specified length as described in section 3.3, the desired amount of kevlar fibre was measured on the digital scale and manually distributed evenly across the epoxy covered surface of the

aluminium foam. Once an even distribution had been achieved, the last remaining quantity of epoxy from the first cup was dripped over the top of the woollen kevlar fibre, making sure to cover any areas that did not look sufficiently wet from the epoxy that had already been applied to the aluminium foam surface.

*Kevlar Fibre Application: Method Refinement Attempt (Unsuccessful)*

The first investigation into improving contact and bonding between the short fibre reinforcement and the porous surface of the aluminium foam involved the use of a thin and flexible plastic release film. The release film would be laid over the top of the aluminium foam with woollen kevlar fibre distribution and a pressure nozzle used to blow the fibres into the pores of the aluminium foam (without the presence of the release film, fibres surrounding the targeted area would be blown away from the surface). It was however found that the fibres did not sink into the pores as well as desired using this method. The arrangement did not allow the fibres enough freedom to move, nor provide enough force to make them stick to the walls of the pores. Many fibres bridged the gap of pores on the aluminium foam surface and would simply bend into the gap without sticking to an inside wall surface. Peeling away the release film was also found to reverse the desired effect to an extent.

*Kevlar Fibre Application: Method Refinement Attempt (Successful)*

A soft bristled toothbrush was used to push the kevlar fibre into the pores of the aluminium foam to try and maximise contact between the fibres and the inside walls of the pores. It also assisted in wetting the fibres properly as it helped to distribute epoxy evenly throughout all the fibres without leaving any of them clumped up and dry. This technique was employed previously using a small paintbrush with great success; failure loads were improved by about 20% compared to those attained without the use of the technique (Jeyaraman 2010, Massey 2010). A toothbrush was chosen over a paintbrush to be used due to having less tightly packed bristles that were found less likely to grasp the fibres and pull them away from the aluminium foam. Toothbrush's with hard, medium and soft bristles were tested and it was found that the soft bristle toothbrush was the most effective at pushing the fibres into the foam pores without pulling fibres away from the surface of the foam. Bristles were also found to be less resistant to being stuck together with epoxy than those of the paintbrush.

## 3.6 Assembly and Curing of the Composite Sandwich Structure

Once the short fibre reinforcement had been applied to one side of the aluminium foam surface by the method described in section 3.5 above, the first prepreg carbon fibre face sheet that was prepared could be retrieved from the fridge and laid on the bench. The top sheet of peel ply was peeled off and the kevlar covered piece of aluminium foam was carefully placed over the top of the prepreg face sheet (with the kevlar fibre reinforcement face down). The process of applying epoxy resin, starter crack and interlaminar short fibre reinforcement could then be repeated for the second surface of the aluminium foam (as described in section 3.5). See **Figure 10** below for an overview of the layers in the composite sandwich structure.

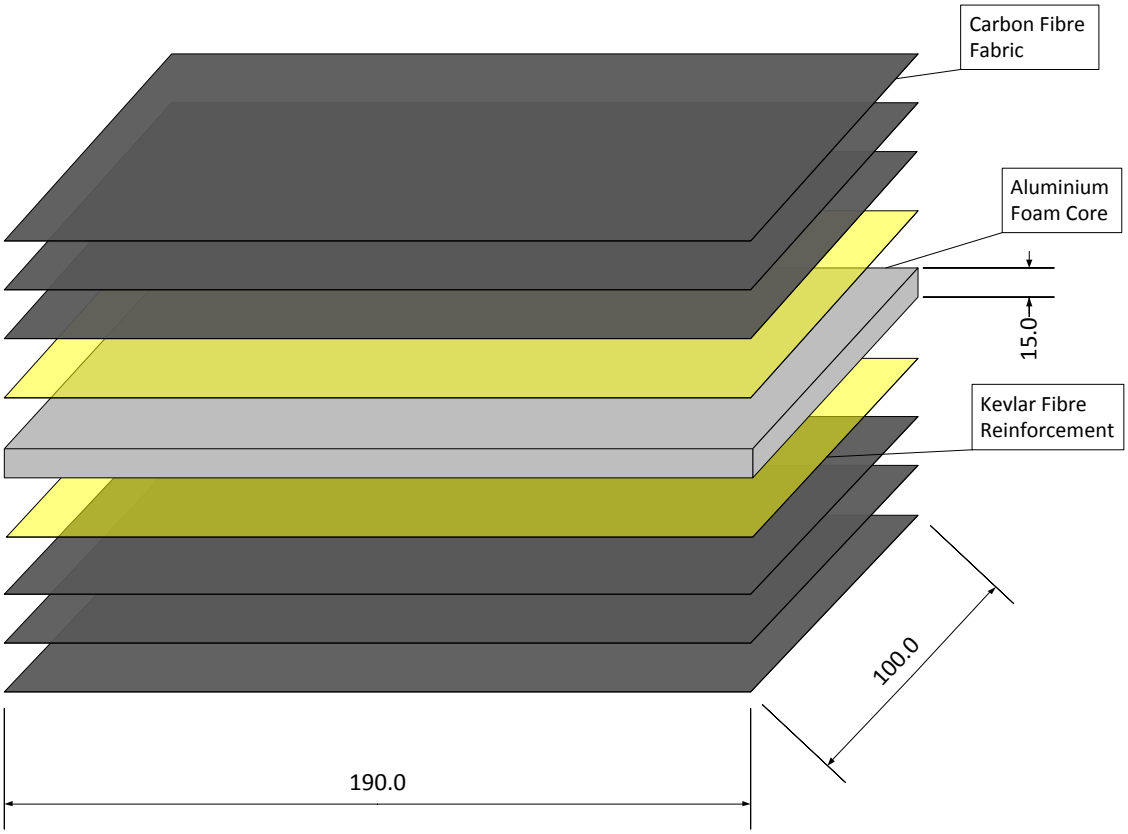


**Figure 10:** Composite Sandwich Structure Assembly

Once the composite sandwich structure was ready to be cured, the peel ply was removed from one side and it was placed in the partially assembled mould, with care taken not to cause any shearing of the laminate skin. The 2 remaining sides of the mould were secured and the final piece of peel ply removed, before sitting the roof of the mould on top of the composite. The mould was then placed in the hot platen air press to cure the epoxy under heat and pressure. The pressure of the air press was set at 300kPa and

heating element rods were inserted into the openings above and below the location of the mould to run it through a heating cycle that was programmed using an HP Eurotherm 2416 controller. A thermostat, connected to the controller, was clamped underneath the upper platen of the press to monitor the temperature of the system. This arrangement is displayed in **Figure 11** below.

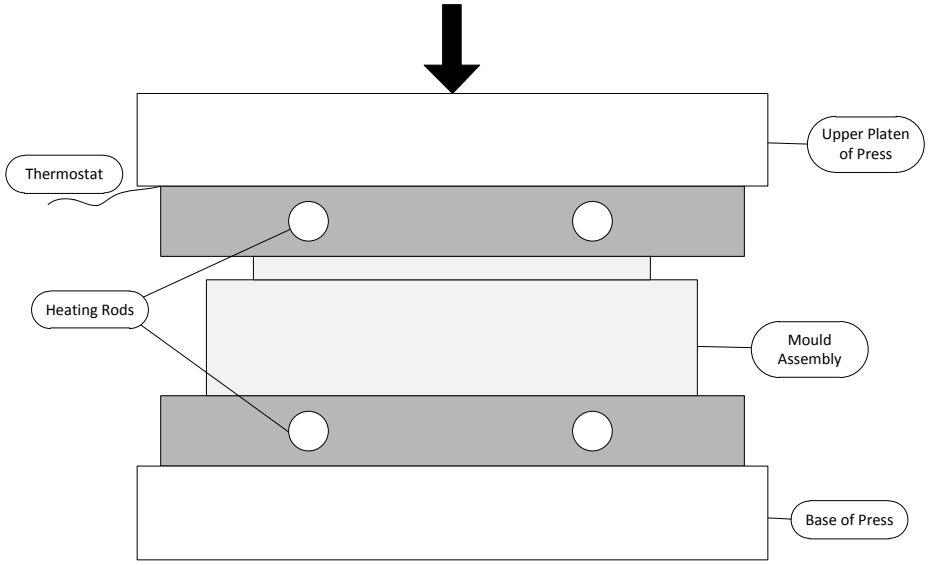


**Figure 11:** Arrangement of Hot Platen Air Press (Figure adapted from Jeyaraman 2010)

*Curing Cycle*

A curing cycle proposed by Walker (2001) was adopted to cure the sandwich panels. The curing cycle is shown in **Figure 12** below, with room temperature assumed to be 20°C. The controller had to be switched off after the second dwell period had finished or else the program would repeat the cycle continuously in a loop.

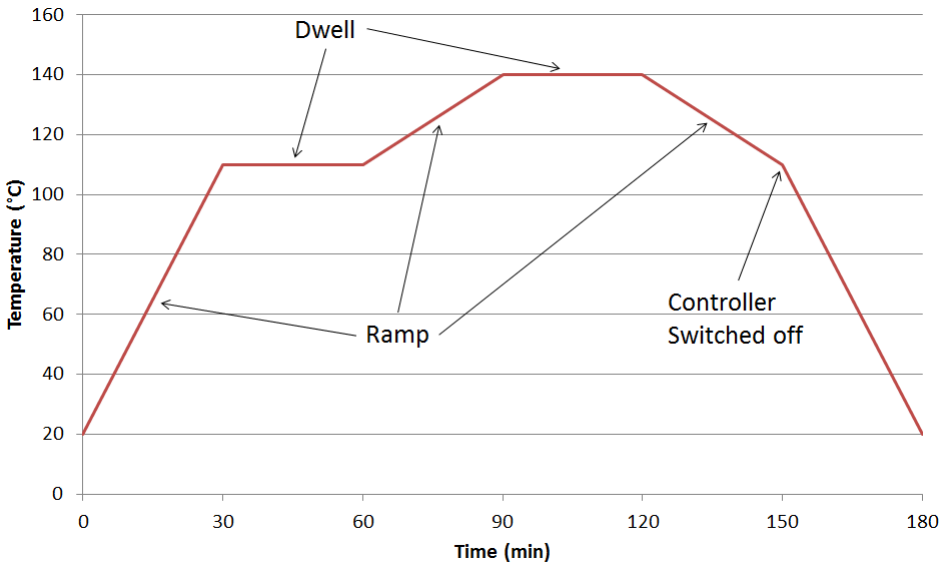


**Figure 12:** Curing Cycle

## 3.7 Machining

A completed composite sandwich panel, having been allowed to cool to room temperature and removed from the mould, was taken to the Mechanical Engineering Workshop to be cut into 8 equal sized samples measuring 90mm by 20mm with a band saw as shown below in **Figure 13**. Although the band saw is not the ideal means for cutting this type of material, it was used due to being the only suitable instrument available. Ends of the samples were milled to achieve a superior surface finish and ensure they were square such that any potential stress concentration during compression testing would be avoided.

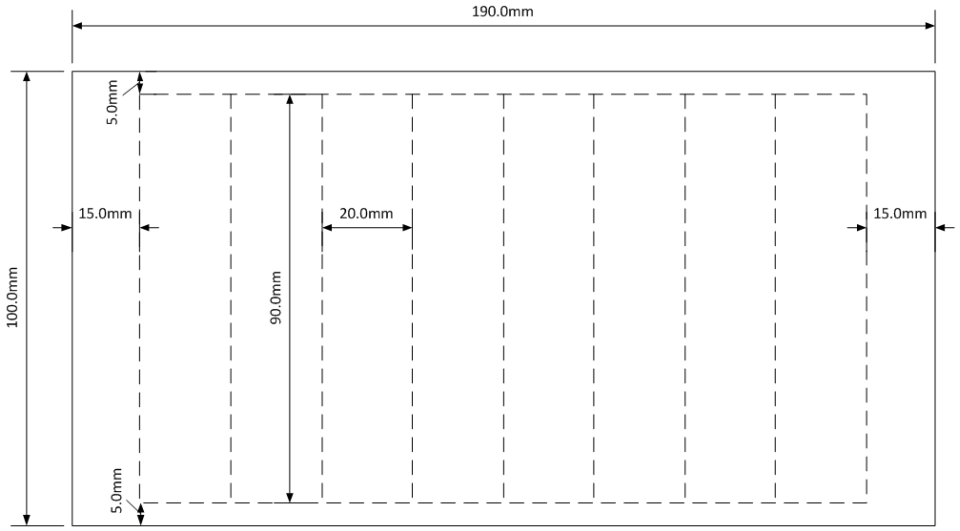


**Figure 13:** Sample Dimensions

## 3.8 Compression Testing

Uniaxial compression testing of the samples was carried out using an Instron 8501 testing machine. As a precaution to avoid any stress concentration in localised areas of the top or bottom surface of the samples, they were positioned on top of a hemispherical steel bearing whilst being compressed. The bearing was lubricated with a thin film of oil. If the loading was not evenly distributed over the surface area of the 2 ends of the sample, the bearing would rotate slightly to balance the distribution of load. Care had to be taken to ensure samples were standing in the very centre of the bearing's top surface in order for it to be of benefit.

Samples were compressed at a displacement rate of -2.5mm/min over 2 minutes with a preload of approximately 0.05kN. Values for displacement, load and time for each test were recorded on a computer so they could later be imported into an Excel spread sheet for analysis.

## 3.9 Scanning Electron Microscopy (SEM)

In order to observe the behaviour of the short fibre reinforcement at the microscopic level, scanning electron microscopy (SEM) was employed. The interlaminar fracture surface of both the aluminium foam core and the carbon fibre skin could be investigated in order to observe signs that the short fibre reinforcement had participated in fibre bridging, which has been identified as a key mechanism in its role of improving delamination toughness (Sohn & Hu 1995, Walker 2001).

In order to be suitable to examine with SEM, samples had to have the carbon fibre skin separated from the Al foam core so the interlaminar fracture surface was exposed and cut into smaller pieces. The chosen samples were clamped in a vice and cut lengthways in half through aluminium foam core, then if the centre had not already fractured during compression testing, another cut was made halfway along the length through the foam but not through the carbon fibre. Each half of the sample could then be bent by hand about the centre to promote delamination, and completely separate the aluminium foam core and carbon fibre skin. This process is shown below in **Figure 14**. The interlaminar surface of each was then exposed and capable of being analysed by SEM imaging.

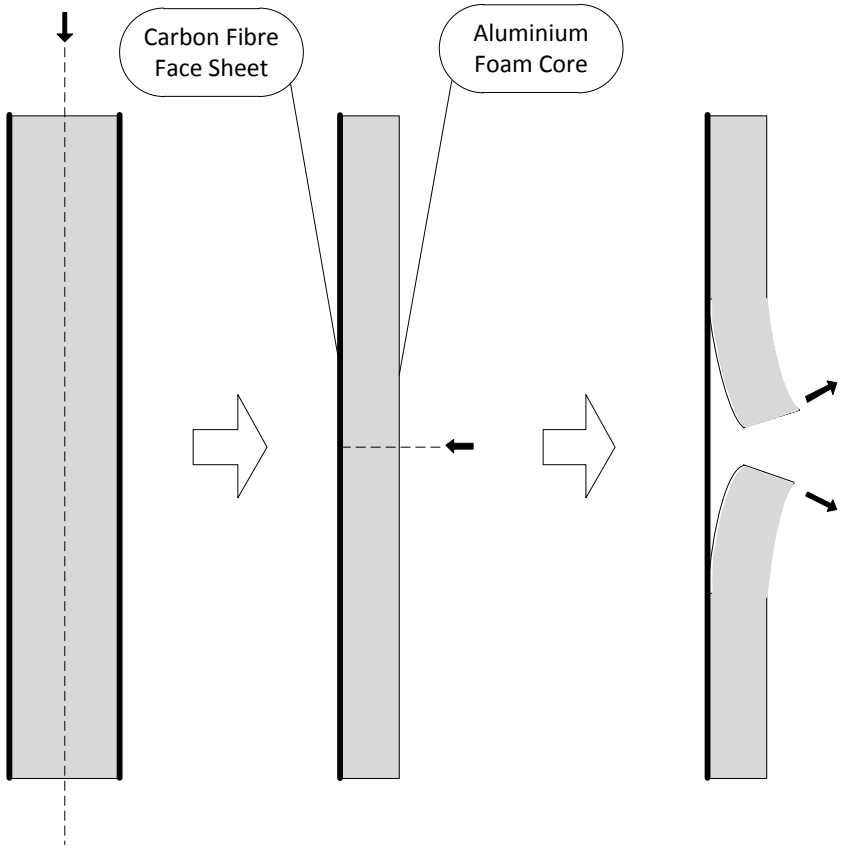


**Figure 14:** Method for Separating Core and Face Sheet

# 4. Safety

## 4.1 Hazard Identification

Most of the work experimental work carried out through the course of this study was conducted in the School of Mechanical Engineering Composites Laboratory G52A. A number of safety hazards were identified as being relevant to this experimental work, including:

- Manual Handling
- Competency with hand tools
- Chemical substances (Acetone, Epoxy Resin, PVA)
- Inhalation of dust from cutting or sanding, chopped woollen short fibres
- Housekeeping
- Fire and Emergency evacuation
- Use of hot platen air press and Instron testing machine

## 4.2 Training and Safety Requirements

### *Lab Safety Induction*

A safety induction was conducted by the area supervisor, as required, prior to use of Lab G52A. This was to highlight the risks involved with use of the lab and equipment as well as emergency procedures. Closed footwear and safety glasses must be worn at all times in the lab. Any operations that could produce fumes or dust must be carried out on the fume extraction bench top with the fume hood turned on, whilst wearing respiratory protection. Users of any chemical substances must first be familiar with the relevant Material Safety Data Sheet (MSDS). The MSDS's for materials used in this study are available at the entrance of the lab G52A and are also included in Appendix C. Gloves were also worn for all operations in the lab to avoid lacerations, irritation or chemical burns to the skin.

Emergency showers, eyewashes, first aid boxes and fire extinguishers are located along the passageway directly outside of lab G52A. Any accidents and injuries that occur must be reported to the officer and a confidential accident report form submitted. In the event of an emergency, a telephone is available in lab G52A to dial 2222 for assistance (or 6488 2222 from any phone). In the event of a fire anywhere in the building, the fire alarm will sound; all personnel must immediately evacuate the building and assemble on James Oval or Car Park 14 until further instructions are given.

*Hot Platen Air Press*

Training for the use of the hot platen air press was provided by the area supervisor during the lab safety induction. Care must be taken to ensure hands are kept away from the platens as they are pressed closed. The press should be left closed and the air pressure turned off when not in use. As the press is operated at temperatures up to 140°C, caution must be exercised to avoid touching the hot equipment whilst in use or until it has had adequate time to cool after use. Appropriate signage should also be displayed to warn other lab users of this hazard. The PID controller must also be switched off at the end of the cycle to avoid overheating the sample as well as to prevent any electrical fire hazard.

*Instron Testing Machine*

Training for the use of the Instron 8501 testing machine was not undertaken for this study as all testing was carried out by Senior Technician, Malcolm Stafford, who is also the area supervisor for lab G50J, where the machine is located. Safety glasses and steel capped footwear were nonetheless required to be worn in lab G50J whilst the testing was carried out.

## 4.3 Risk Matrix

The UWA Risk Management Matrix will be used to assess safety hazards involved in the experimental work of this project. The measures of consequences, likelihood and level of risk are described in Tables 3, 4 and 5 below. Table 6 contains the risk assessment of all identified hazards.

| Descriptor | Example Detail Description |
|---|---|
| Fatality | Death |
| Major injury | Extensive injuries, lost time injury >5 days , permanent disability (eg broken bones, major strains) |
| Minor injury | Medical treatment required, lost time injury from 1 – 5 days (eg minor strains) |
| First aid | First aid treatment where medical treatment not required (e.g minor cuts and burns) |
| Negligible | Incident does not require medical treatment, property damage may have occurred |

**Table 3:** Measure of Consequence for Personal Injury

| Descriptor | Description |
|---|---|
| Very likely | It is expected to occur at some time in the near future |
| Likely | Will probably occur in most circumstances |
| Occasionally | Might occur at some time |
| Unlikely | Could occur at some time |
| Highly unlikely | May occur in exceptional circumstances |

**Table 4:** Measure of Likelihood

| Likelihood (L) | Consequences (C) | | | | |
|---|---|---|---|---|---|
| | Negligible | First aid | Minor | Major | Fatality |
| Very likely | H | H | E | E | E |
| Likely | M | H | H | E | E |
| Occasionally | L | M | H | E | E |
| Unlikely | L | L | M | H | E |
| Highly unlikely | L | L | M | H | H |

**E: extreme risk:** Notify supervisor, Head of Department and Safety and Health Office as required. Immediate action required.
**H: high risk**: Notify supervisor and Safety and Health Representative immediately. Action identified within 1 week.
**M: moderate risk:** Notify supervisor and Safety and Health Representative. Take immediate action to minimise injury with remedial action identified within 2 weeks.
**L: low risk:** Supervisor attention required. Remedial action identified within 1 month.

**Table 5:** Measure of Risk

| Identified Hazards | Risk Assessment | | Risk Measure | Recommended Controls | Follow up (by whom, by when) |
|---|---|---|---|---|---|
| Laceration from rotary cutter/scissors | Minor Injury | Likely | High | Wear gloves, fingers kept as far as possible from the blades cutting path | Area Supervisor, Immediate |
| Burn injury from hot platen air press | Minor Injury | Occasionally | High | Appropriate signage used as warning, ensure PID controller is promptly turned off at end of cycle | Area Supervisor, Immediate |
| Fingers crushed by air press | Major Injury | Occasionally | Extreme | No leaning on any part of the press, free hand kept far away from press during operation | Head of School, Immediate |
| Inhalation of fumes/dust | Minor Injury | Likely | High | Wear respirator, work carried out under operational fume hood | Area Supervisor, Immediate |
| Eyes hit with debris from mould cleaning/instron testing | Major Injury | Likely | Extreme | Safety glasses worn | Head of School, Immediate |
| Chemical injury to skin/eyes | Minor Injury | Likely | High | Wear gloves and safety glasses | Area Supervisor, Immediate |
| Injury to feet by dropping mould | Minor Injury | Likely | High | Wear enclosed footwear, mould always handled carefully with both hands and placed on a stable surface | Area Supervisor, Immediate |
| Electrocution | Fatality | Highly Unlikely | High | All cables checked for damage, kept tidy and unplugged after use | Head of School, Immediate |
| Skin irritation from handling of synthetic fibres | Negligible | Likely | Moderate | Wear gloves | Area Supervisor, Remedial action within 1 month |

**Table 6:** Risk Management Summary

# 5. Results and Discussion

## 5.1 Compression Testing Results

The average failure loads for the 8 samples in each batch of are shown below in **Table 7**. A few samples (no more than two in any one batch) were taken as outliers and therefore were not included in the calculation of average failure load. Plots of load vs. displacement for each batch of samples can be seen in Appendix B. Note that batch no. 15 contained a combination of both kevlar and zylon fibres, in equal mass ratio. Zylon fibres were already available cut into 6mm lengths from previous work, which is why this length was used.

| Batch no. | Mass of Epoxy (g) | Kevlar Fibre Length (mm) | Kevlar Density (g/m2) | Failure Load (kN) | Standard Deviation (kN) |
|---|---|---|---|---|---|
| 2 | 100 | - | - | 1.65 | 0.25 |
| 3 | 40 | - | - | 3.33 | 0.66 |
| 4 | 40 | - | - | 3.98 | 0.45 |
| 13 | 50 | - | - | 4.03 | 0.25 |
| 15 | 50 | 16(K)/6(Z) | 32 | 3.26 | 0.37 |
| 14 | 50 | 16 | 32 | 3.48 | 0.70 |
| 11 | 40 | 16 | 53 | 3.96 | 0.65 |
| 9 | 40 | 16 | 32 | 3.94 | 0.60 |
| 12 | 40 | 16 | 16 | 3.66 | 0.70 |
| 7 | 40 | 10 | 53 | 3.56 | 0.43 |
| 8 | 40 | 10 | 32 | 2.84 | 0.40 |
| 6 | 40 | 10 | 16 | 3.67 | 0.50 |
| 1 | 40 | 10 | 8 | 4.18 | 0.50 |
| 5 | 40 | 6 | 16 | 3.56 | 0.32 |
| 10 | 40 | 6 | 32 | 3.22 | 0.86 |

**Table 7:** Average failure loads (8 samples in each batch, batch no. 15 includes a combination of kevlar and zylon fibres)

The typical behaviour of load vs. displacement is shown below in **Figure 15**. The load increases until it peaks when the sandwich composite reaches its failure load at which time the carbon fibre face sheets fracture and the material suffers a great loss in stiffness. The load supported by the material then decreases gradually, with the area under the graph representing the total amount of energy absorbed by the sandwich composite.

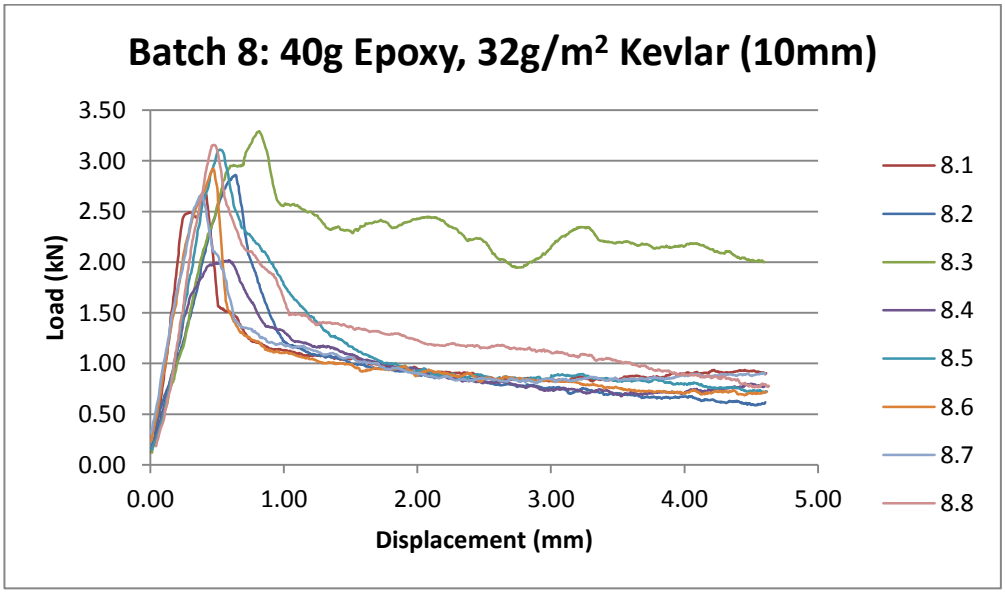


**Figure 15:** Typical Load vs. Displacement Curves

Some samples, as shown in **Figure 16** below, experienced multiple peak loads after the initial failure. This suggests the presence of a sizable pore in the aluminium foam core which is quickly filled after the initial failure, resulting in the sandwich composite regaining some stiffness.

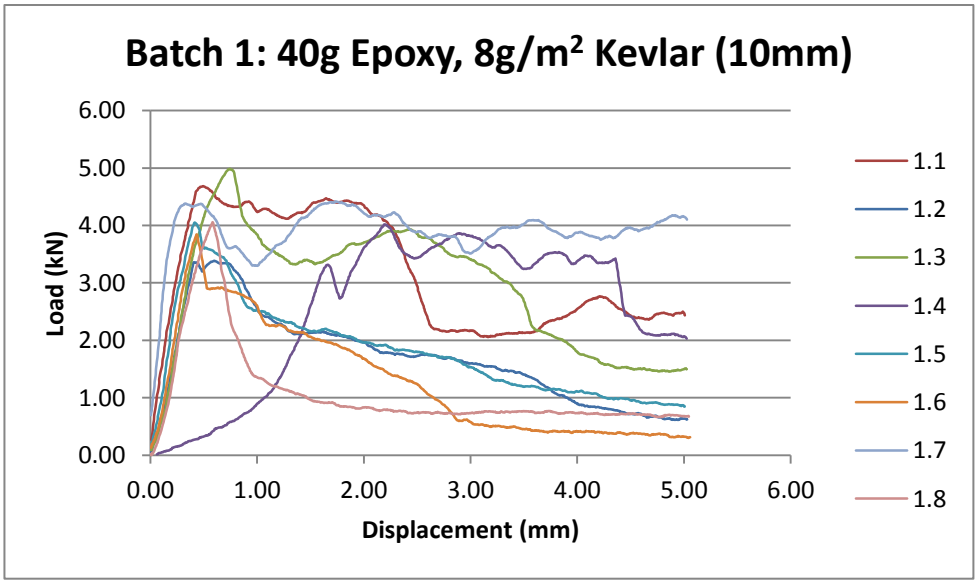


**Figure 16:** Load vs. Displacement with Multiple Peaks

Batch no. 2 was prepared with as much epoxy as possible to show the effect of excessive epoxy on the properties of the material. As expected, failure loads were very low for this case though it is worth noting that delamination did not occur. The load vs. displacement plot for this batch displayed noticeably different behaviour than the rest of the samples tested as can be seen below in **Figure 17**. In this case the stiffness of the

composite sandwich, whilst very low, remains fairly steady. Rather than a single brittle fracture propagating from the location of the starter crack, the carbon fibre skin was heavily wrinkled suggesting that the core material in this case has failed to properly support the thin skin and prevent it from buckling (Mladensky & Rizov 2007). The adhesive bondline thickness is therefore believed to be too thick with the use of this excessive quantity of epoxy, resulting in an ineffective sandwich structure.

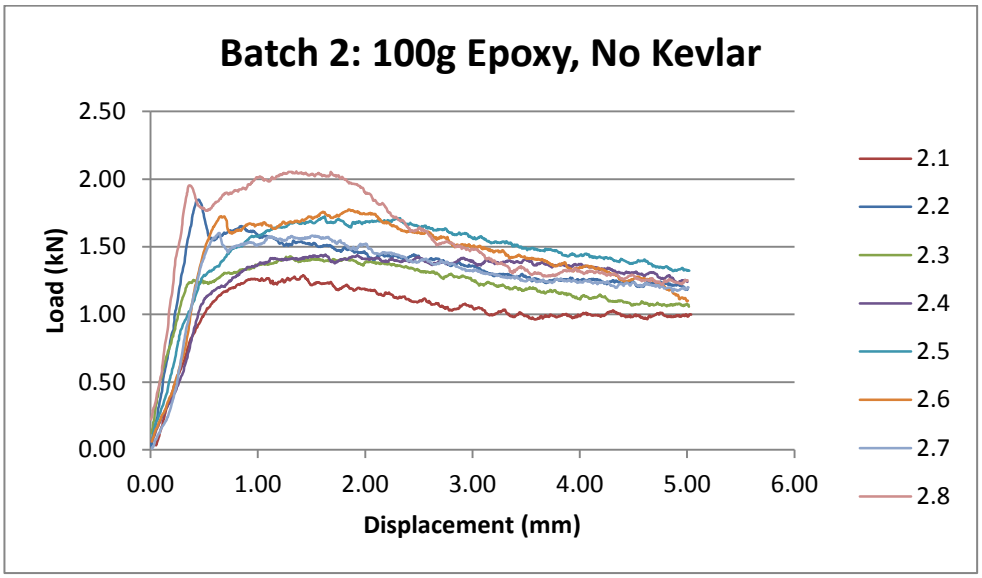


**Figure 17:** Load vs. Displacement for Samples in Batch no. 2

The control samples prepared with a total of 40g and 50g epoxy and no reinforcement showed much greater strength with an average failure load of 3.66kN across the samples from batches 3 and 4, 4.03kN average failure load for batch 13. This is at least a 19% increase from the 3.07kN result achieved by the control samples from previous work using 30g epoxy (Jeyaraman 2010). Going by the theory that adhesive joints exhibit a maximum strength which corresponds to an optimum bondline thickness (Correia, Keller and Vallee 2009), these results suggests that the adhesive layer between skin and core is excessively thick when 100g epoxy is used, too thin when 30g epoxy is used and somewhere around 40 or 50g of epoxy is closer to the optimum amount.

The failure load results for the samples with kevlar short fibre reinforcement showed little deviation and there was no significant correlation found between the length or quantity of kevlar and the strength of the composite structure. Several effects were observed during compression testing to do with the manner in which samples failed. The expected failure mechanism was for samples to fail in the centre with a brittle fracture of the carbon fibre skin on each side of the sample initiated by the presence of

the starter crack. Around 28% of samples did however only show this kind of brittle fracture of the skin on one side before the whole sample proceeded to bend about the centre towards the fractured side. This will be referred to as the "bend effect". Around 24% of samples failed at either the top or bottom of the sample with no brittle fracture of the skin near the starter crack. This effect has been observed often in previous work by UWA students and has been referred to as the "end effect". Only around 6% of samples displayed delamination of the skin during testing. Each of these cases is shown in **Figure 18** below.

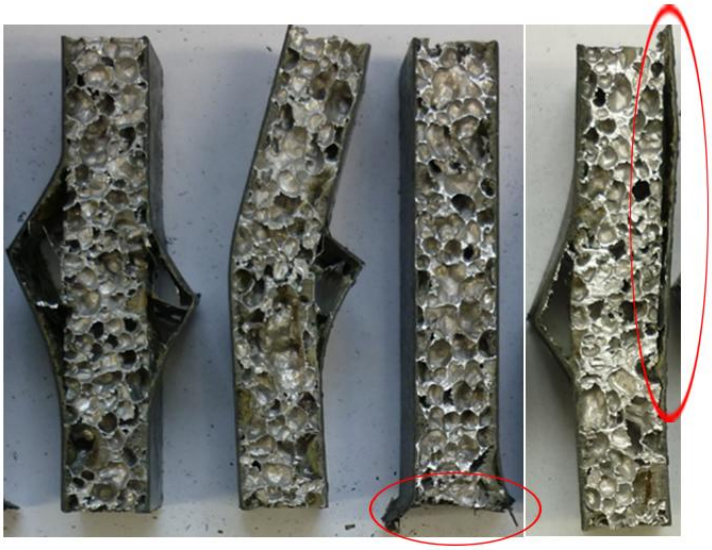

**Figure 18:** Failure mechanisms (From left to right: expected failure at starter crack, "bend effect", "end effect" and delamination of skin)

Previous work completed at UWA in which the "end effect" was often encountered suggested that it was caused by uneven ends of the sample that were not completely flush with the surface of the Instron testing machine, leading to unwanted stress concentration. In the current study, precautions were taken to ensure a good and even surface finish at both ends of all samples. Samples that displayed the "end effect" were also found to consistently have the highest failure loads from their respective batch of samples. Laminated composites are also known to be prone to failing at edges when under compressive loads. As such, it is now believed that these samples simply had a stronger adhesive bond between the skin and core such that the starter crack was not enough to induce failure at the centre of the sample. This is also supported by the fact that the skin and core of such samples were noticeably more difficult to manually separate after testing in preparation for SEM analysis.

Of the small number of samples which displayed delamination, the delaminated skin still remained bonded to part of the core after testing whereas previous UWA studies produced many samples where the skin became completely separated from the core. The samples that partially delaminated also consistently had the lowest failure loads from their respective batch of samples. The very minor presence of delamination shows that the delamination toughness of the material has indeed been improved overall.

## 5.2 Scanning Electron Microscopy (SEM) Results

The samples that were chosen for SEM analysis and their respective failure loads are displayed below in **Table 8**. During the process of separating these samples to expose the interlaminar fracture surface, it was observed that samples 1.3 and 11.2, the only samples chosen which displayed the end effect, were significantly more difficult to separate than the other samples. The carbon fibre skin simply fractured instead of delaminating when it was attempted to manually separate these samples as per the method described in section 3.9. More cuts were simply made with the hacksaw and the process repeated until the fracture surface was exposed, but much fewer usable pieces were obtained from these two samples. Samples 6.3 and 12.6, the weakest of the chosen samples, on the other hand were separated with ease. The carbon fibre skin remained intact and the entire fracture surface was visible on both the core and skin.

| **Sample no.** | **1.3** | **6.3** | **9.2** | **9.8** | **11.2** | **12.6** |
|---|---|---|---|---|---|---|
| **Failure Load (kN)** | 4.99 | 4.27 | 4.81 | 4.67 | 4.87 | 4.17 |
| **Effects During Failure** | E | B | BD | - | E | B |

**Table 8:** Samples Chosen for SEM Analysis (E = end effect, B = bend effect, D = delamination)

When the skin and core of the sandwich structure had been separated in order to be examined with SEM, it was observed that significant amounts of kevlar fibre remained bonded to the core surface of several samples. Previously it was observed that almost all of the fibre reinforcement remained bonded only to the surface of the carbon fibre skin. This shows that whilst bonding of fibres to the core has been improved, the epoxy resin forms a stronger bond with the carbon fibre than with the aluminium foam. It may therefore be worthwhile investigating the use of surface treatments or even different adhesives as discussed in section 2.4 to maximise the compatibility of the adhesive with the aluminium foam.

SEM images of the interlaminar surface of samples, after having been compression tested, gives more information about the behavior of the kevlar SFR and the presence of fibre bridging. Kevlar fibre is seen to experience multiple split break in **Figure 19** below. Fibrillation of the kevlar fibres visible in **Figure 20** below is further evidence that they are failing under tension and therefore participating in fibre bridging (Elices & Llorca 2002, Sohn & Hu 1998). Fibre pullout marks are also visible in **Figure 20**, serving as evidence that the fibres were bonded to both the skin and core surfaces prior to being separated.


**Figure 19:** Multiple Split Break of Kevlar Fibres

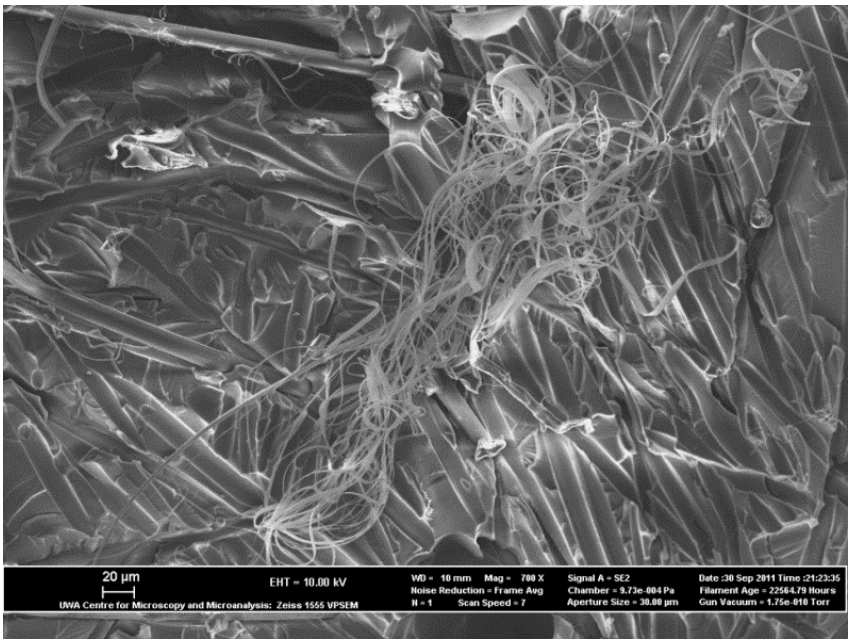


**Figure 20:** Fibrillation and Fibre Pullout Marks

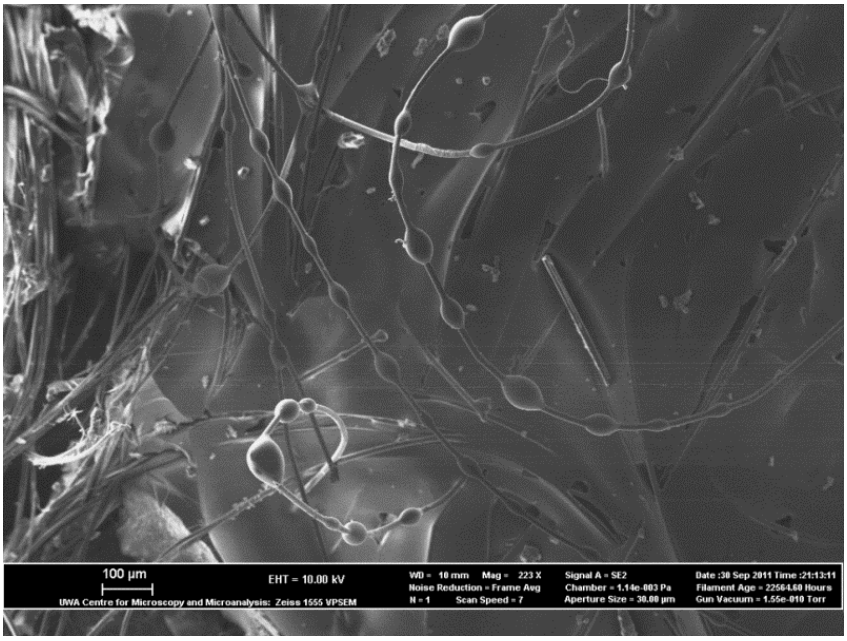


**Figure 21:** Kevlar Fibres Wet with Epoxy

**Figure 21** shows some kevlar fibres on the carbon fibre face sheet fracture surface. The image is taken in an area where the cluster of fibres is ballooned out from the carbon fibre surface as the corresponding surface of the aluminium foam core contained a sizable pore. It can be seen from the many large bubbles around the fibres that they are all properly wet with epoxy, to a higher degree than was observed in images from the previous study (Jeyaraman 2010). This is further evidence that the subsequent increase in amount of epoxy used was necessary.

The many small flakes visible in **Figures 19 & 21** are impurities, most likely introduced during the manual application of the short fibre reinforcement. Their vast presence, which likely has a detrimental effect on the properties of the structure, highlights the need for adaption of the method described in section 3.5 that can be used effectively in large scale manufacture. This should not be a difficult task to accomplish.

## 6. Conclusions

Although the results for failure loads of the samples tested were somewhat inconclusive in relating the length and density of reinforcement fibres to delamination toughness, there were many visual observations that suggest an improvement in delamination toughness when compared to previous work completed at UWA. SEM analysis also showed evidence of a strong presence of fibre bridging.

There are many factors that affect the behaviour of this composite sandwich structure and there is still much refinement to be done to optimize the fabrication and effectiveness of this material as well as the short fibre reinforcement technique applied to it. Although bonding between the carbon fibre face sheet and kevlar reinforcement fibres with the aluminium core was seen to be improved with an increased quantity of epoxy and some refinements to fabrication methods, it is believed that more can be done to maximise the effectiveness of this bonding and improve the reliability of the structure.

Compression testing is a fast and simple method of testing but results are affected by many different factors. It may not be the ideal testing method for the samples prepared in this study; the porous and somewhat inhomogeneous nature of the aluminium foam is seen to be a major source of inconsistencies with some pores measuring up to 20mm in diameter, which is the width of the samples. Laminated composites under compression are also prone to failure at the edge and this was shown to happen around 20% of the time even with the presence of a central starter crack. Alternate test methods should be employed to eliminate as many of these variables as possible.

## 7. Recommendations for Future Work

The fabrication of a carbon fibre/aluminium foam composite sandwich structure with interlaminar short fibre reinforcement needs further refinement in order to enhance the suitability of this material in a broader context.

### *Improve Bonding*

In order to maximise the compatibility of the aluminium foam core with the adhesive, the use of a more vigorous method of cleaning or other surface treatments should be considered, as well as the possibility of using a different adhesive that may be more compatible with aluminium surfaces. More investigation should be made into the potential optimum adhesive bondline thickness and how this can be achieved when using a rough surfaced material such as Alporas aluminium foam.

### *Short Fibre Reinforcement*

Although very little benefit was observed in using short fibre reinforcement at very short 6mm lengths, it may be worth investigating the effect of using of even longer fibres than the 16mm ones tested in this study. There are possibly also benefits in using a combination of shorter and longer fibres together, or even a combination of different types of fibres (e.g. kevlar and zylon), which have different properties and may each contribute different benefits to the sandwich structure.

### *Testing of Samples*

The use of a larger sample size may provide more consistent and useful results from compression testing as this would likely lessen the effect of the many pores of above average size present in the Alporas aluminium foam. It would also be worth implementing different and possibly more reliable methods of testing such as a "wedge" test that facilitates mode I fracture of the laminate from the core to assess delamination toughness. It would also be beneficial to employ impact testing to further assess the effectiveness of short fibre reinforcement applied to a carbon fibre/aluminium foam composite sandwich structure.

### *Finite Element Analysis*

The use of finite element analysis should be employed to further understand the behaviour of short fibre reinforcement applied to a carbon fibre/aluminium foam composite sandwich structure and to draw comparisons with experimental results.

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Bond, IP, Greenhalgh, ES, Trask, RS, Yasaee, M 2011, 'Mode II interfacial toughening through discontinuous interleaves for damage suppression and control', Composites: Part A (2011), doi: 10.1016/j.compositesa.2011.09.026

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## Appendix A: Experimental Equipment


**Figure 22:** Experimental Equipment (From left to right: Robuso scissors, OLFA rotary cutter, flexible applicator, steel roller, scraper, toothbrush, steel rule)


**Figure 23:** Epoxy Resin, Hardener and Mixing Cup

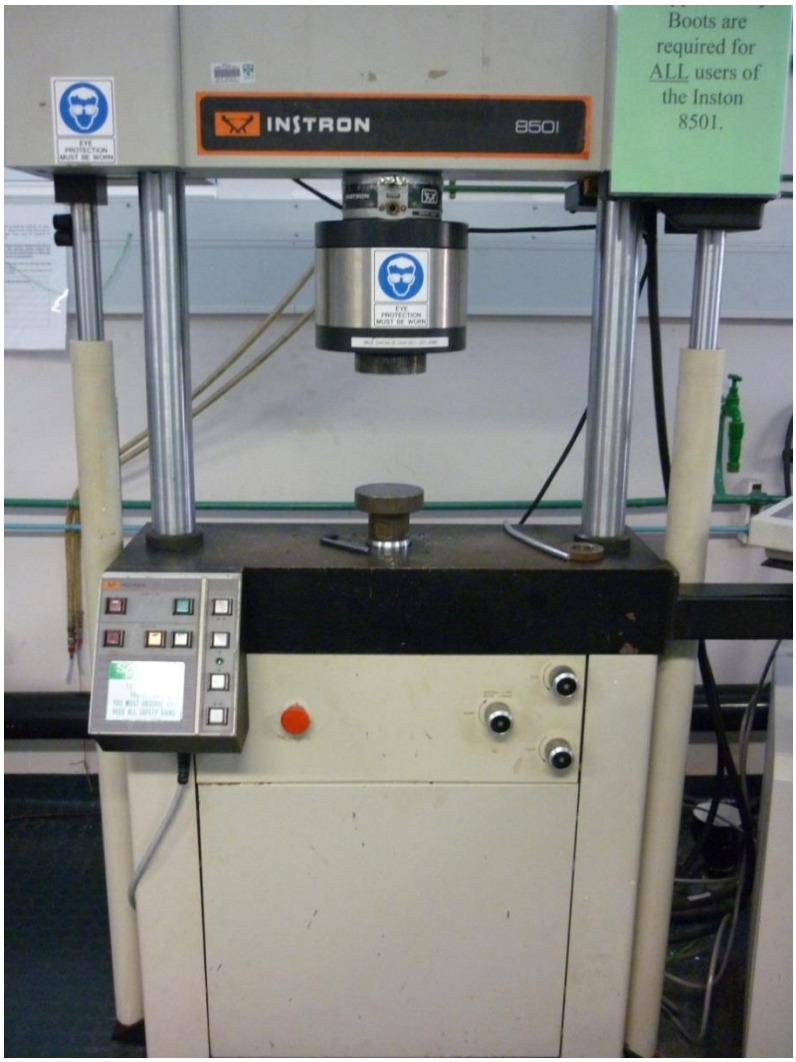



**Figure 24:** Instron 8501 Testing Machine

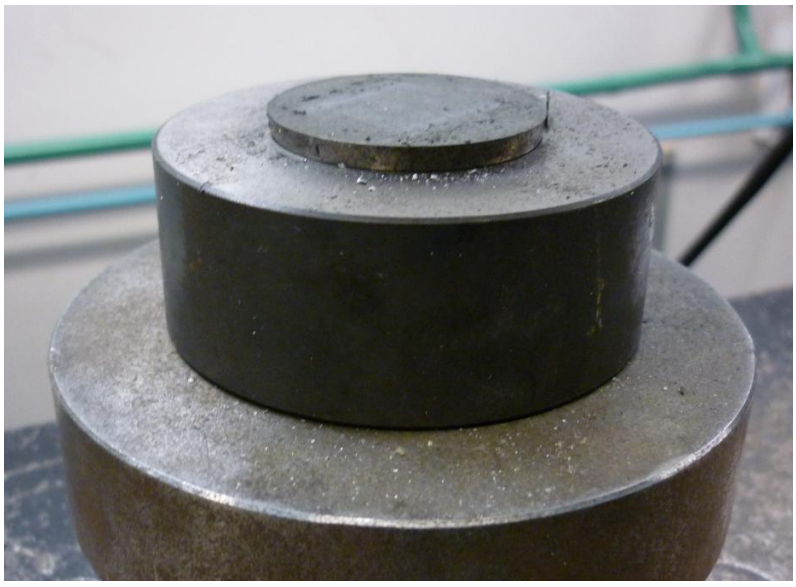


**Figure 25:** Hemispherical bearing used in compression testing

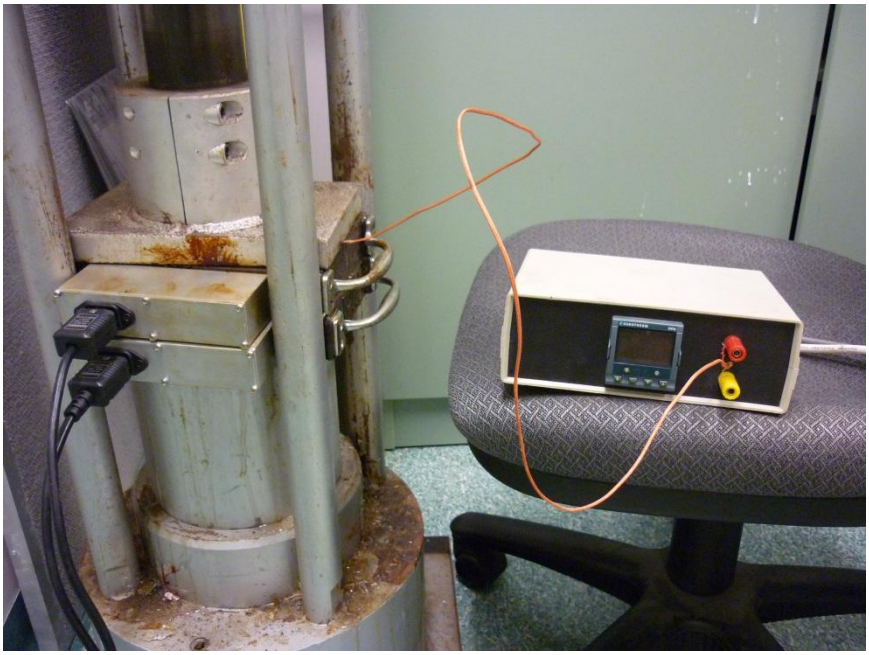
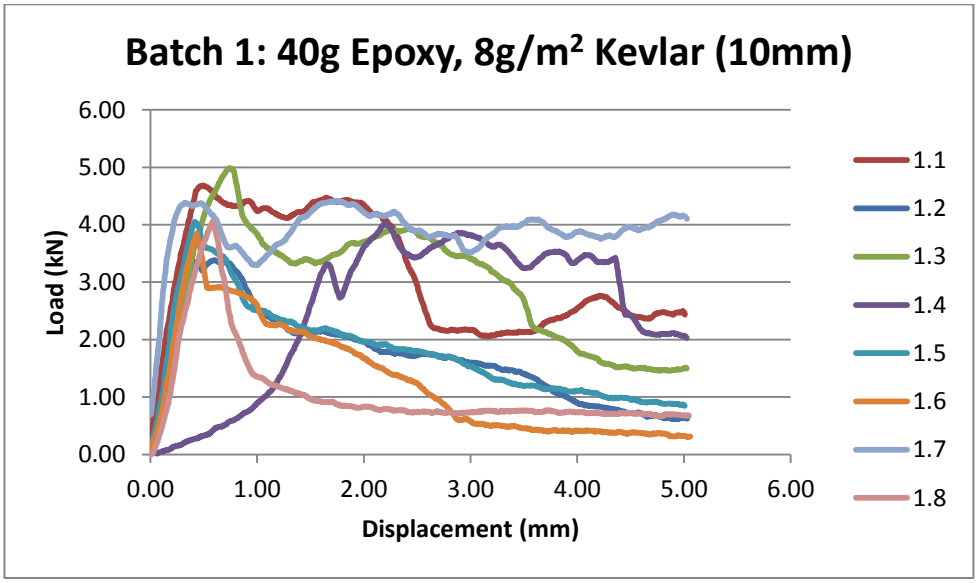
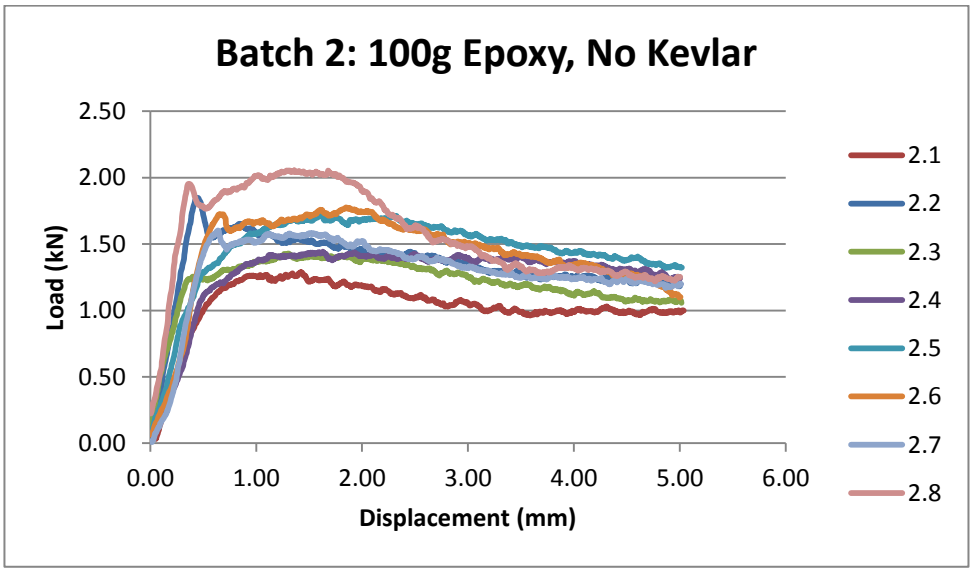


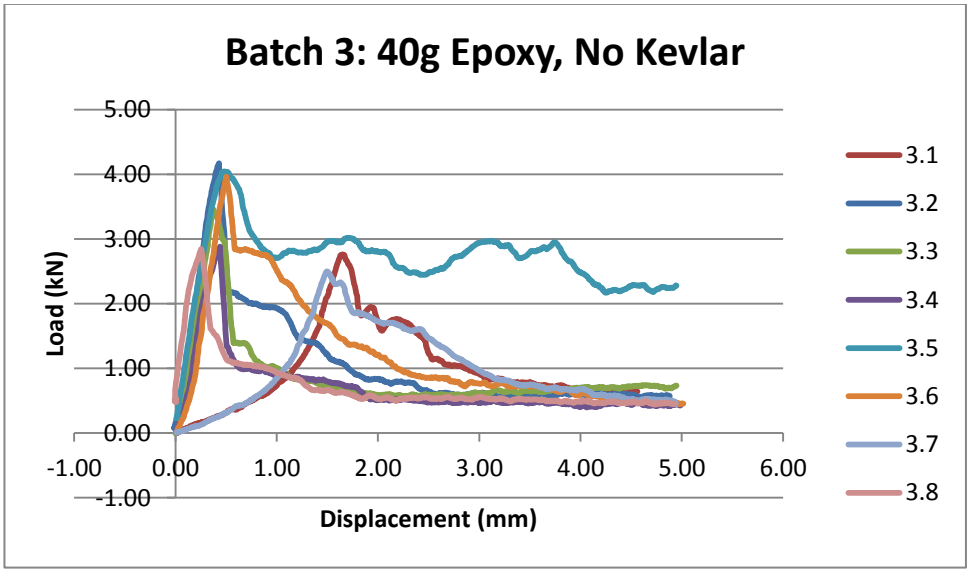
**Figure 26:** Hot Platen Air Press and Eurotherm 2416 PID Controller

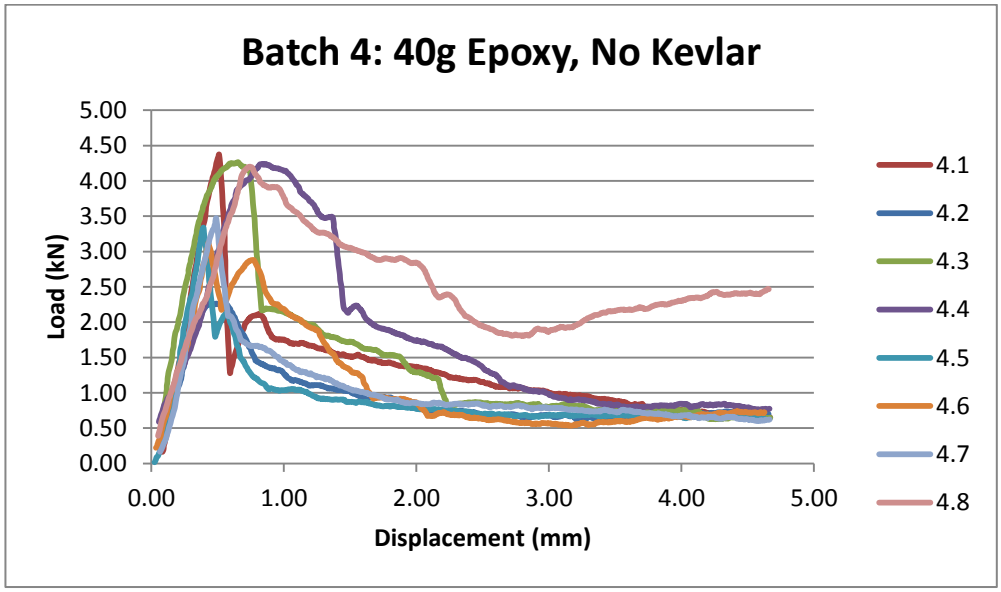
**Figure 27:** Heating Rods

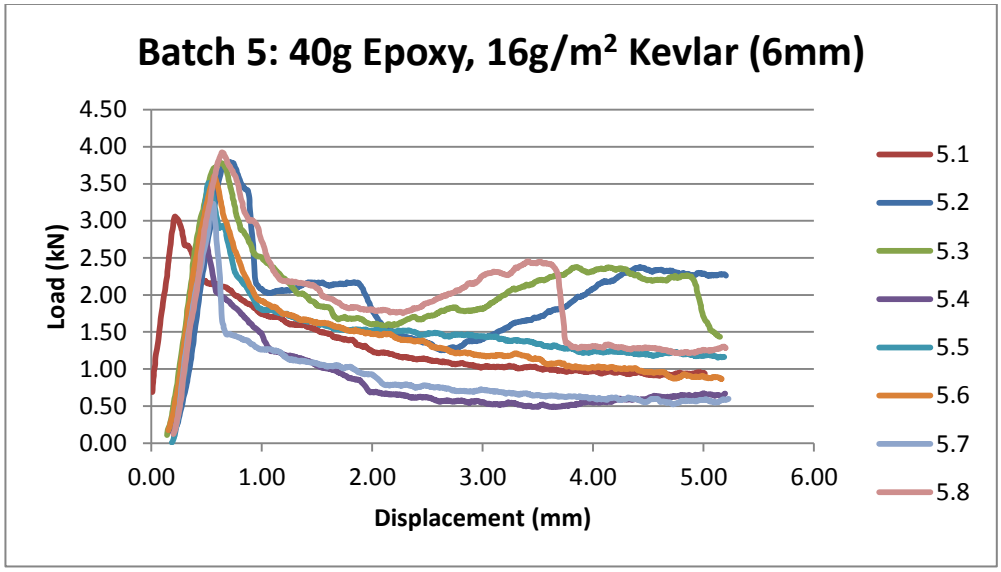
## Appendix B: Load vs. Displacement Plots for Each Batch of Samples Tested

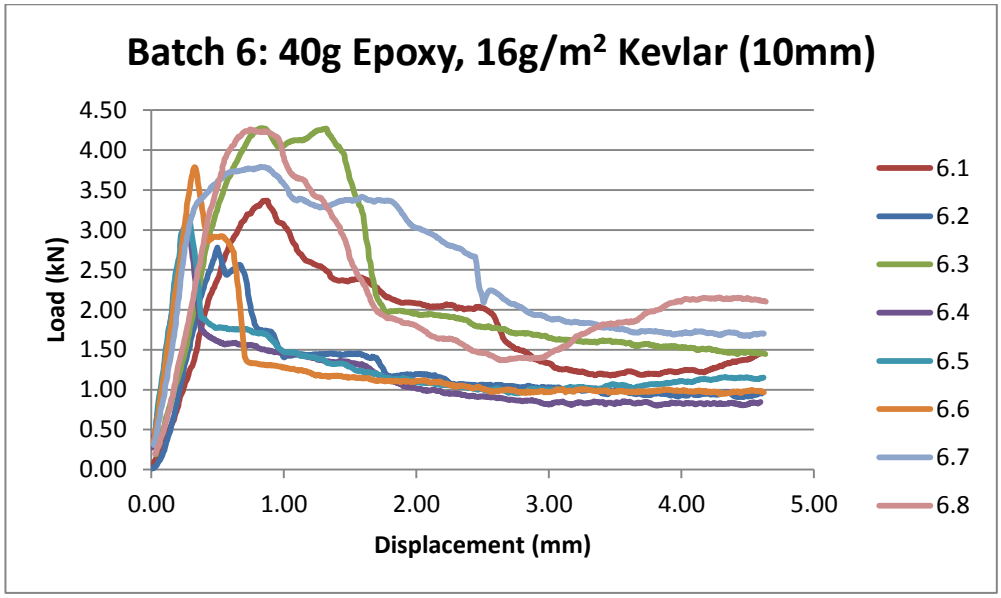


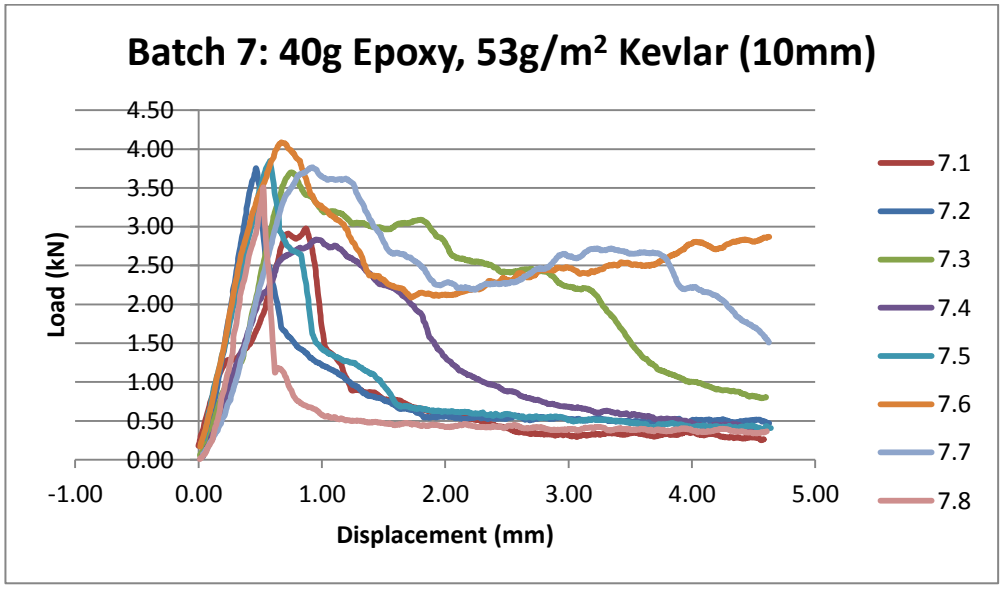



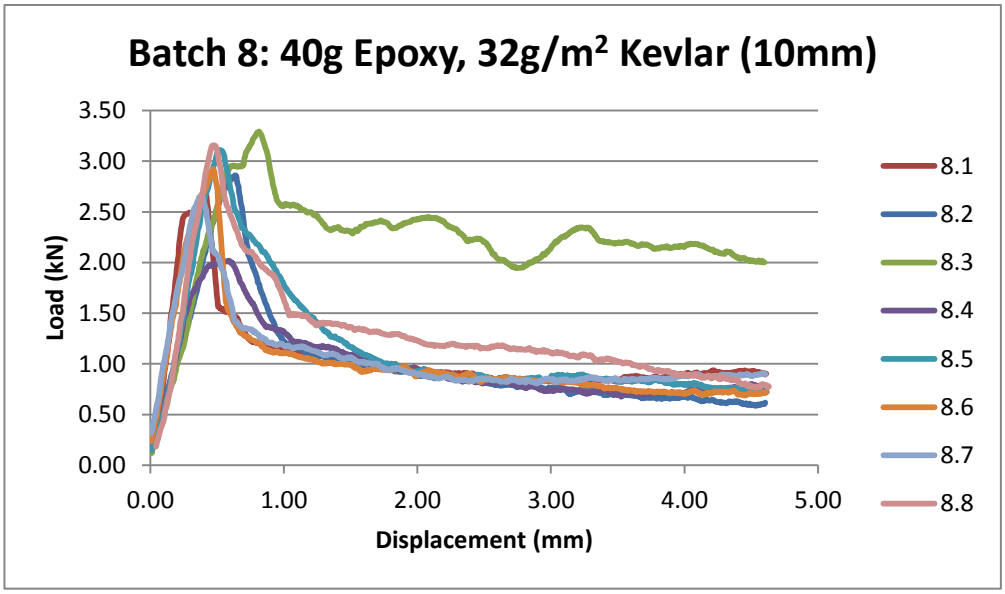



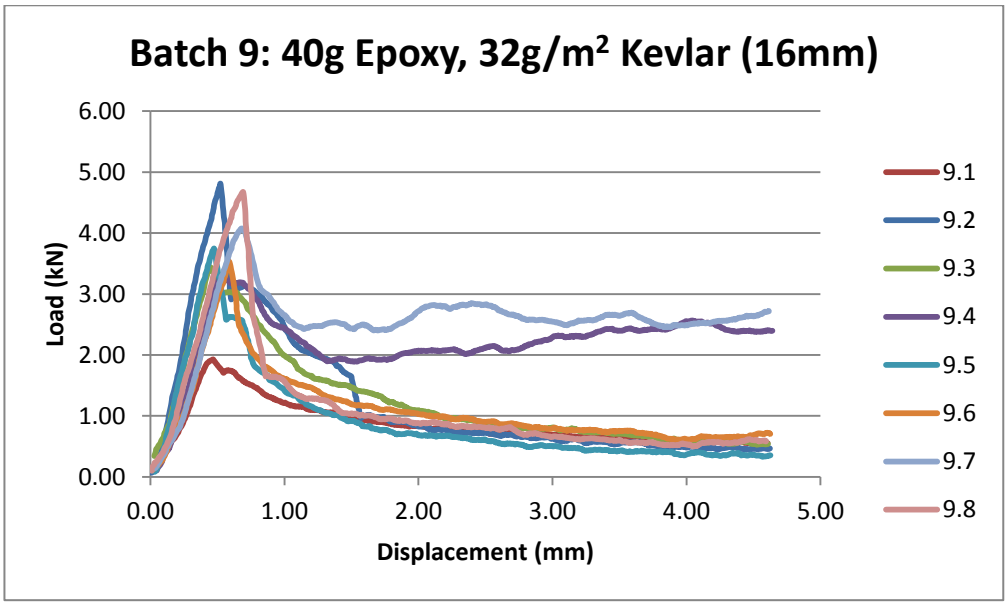

Batch 4: 40g Epoxy, No Kevlar
Load (kN)
Displacement (mm)
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8

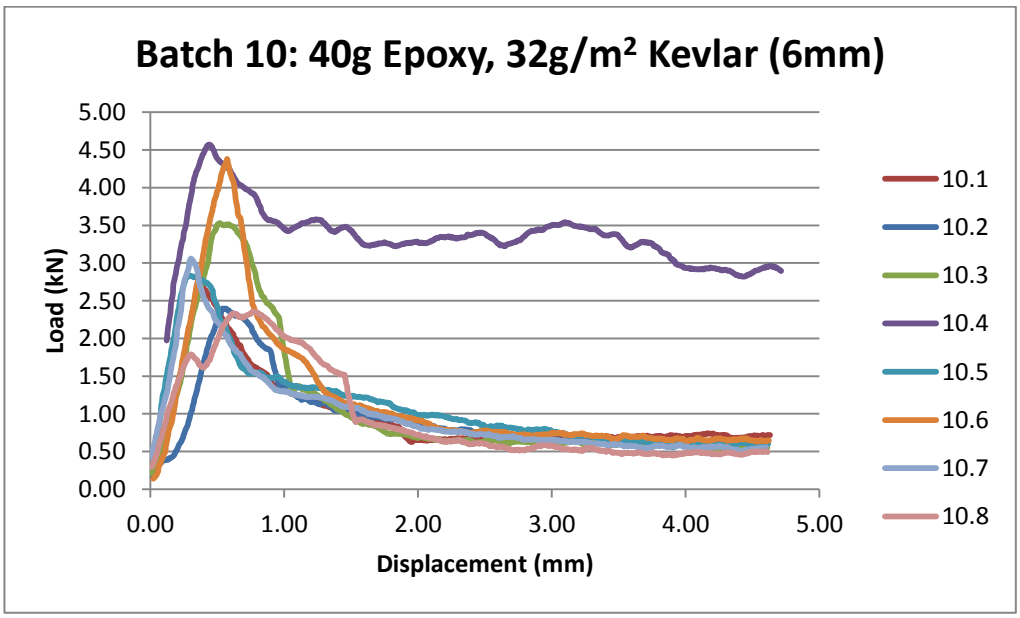

Batch 5: 40g Epoxy, 16g/m² Kevlar (6mm)
Load (kN)
Displacement (mm)
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8

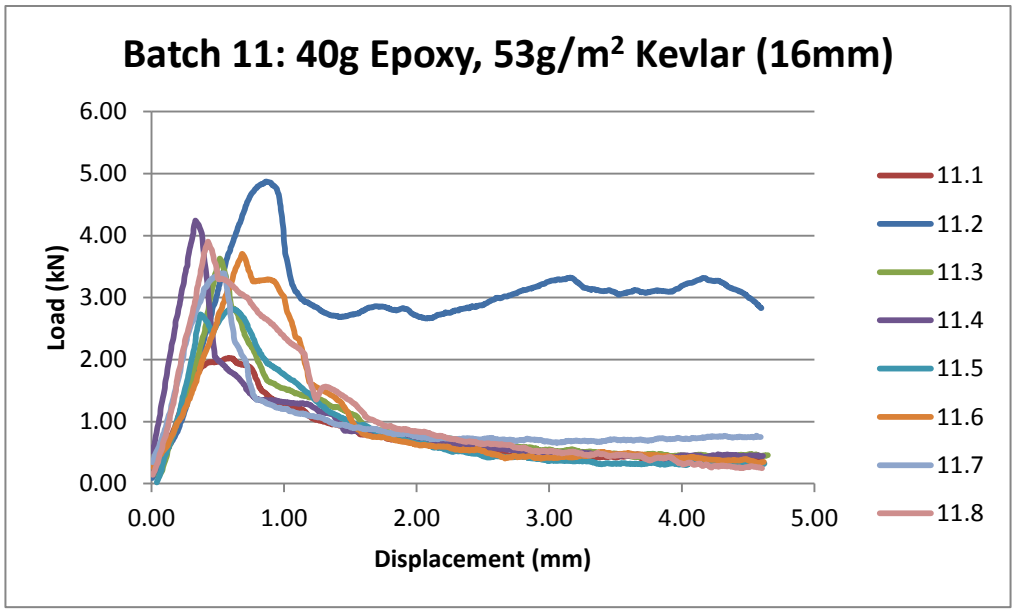

Batch 6: 40g Epoxy, 16g/m² Kevlar (10mm)
Load (kN)
Displacement (mm)
6.1
6.2
6.3
6.4
6.5
6.6
6.7
6.8

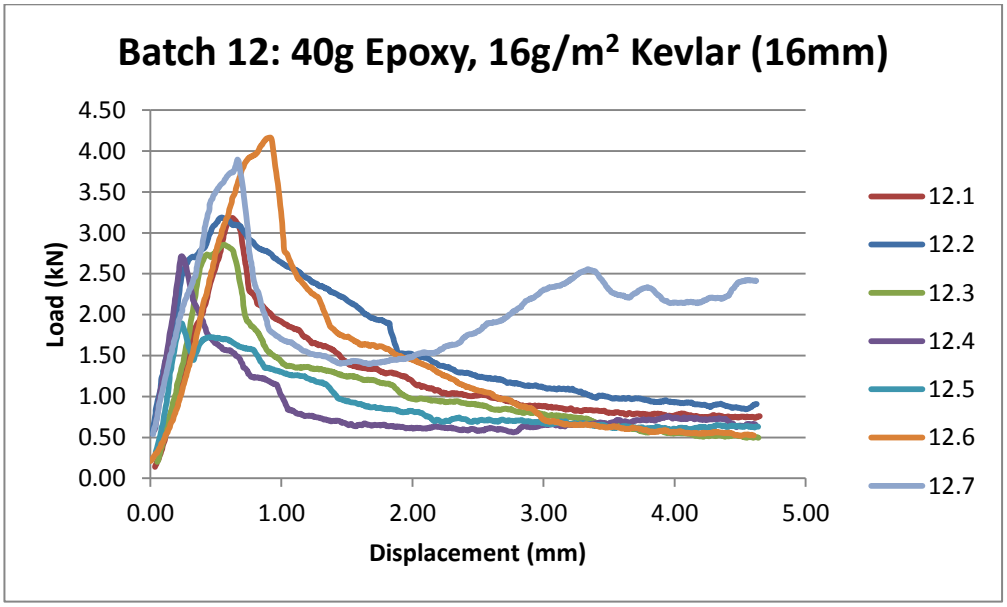

Batch 7: 40g Epoxy, 53g/m² Kevlar (10mm)
Load (kN)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-1.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
7.1
7.2
7.3
7.4
7.5
7.6
7.7
7.8


Batch 8: 40g Epoxy, 32g/m² Kevlar (10mm)
Load (kN)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
8.1
8.2
8.3
8.4
8.5
8.6
8.7
8.8


Batch 9: 40g Epoxy, 32g/m² Kevlar (16mm)
Load (kN)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
9.1
9.2
9.3
9.4
9.5
9.6
9.7
9.8


Batch 10: 40g Epoxy, 32g/m² Kevlar (6mm)
Load (kN)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
10.1
10.2
10.3
10.4
10.5
10.6
10.7
10.8


Batch 11: 40g Epoxy, 53g/m² Kevlar (16mm)
Load (kN)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
11.1
11.2
11.3
11.4
11.5
11.6
11.7
11.8


Batch 12: 40g Epoxy, 16g/m² Kevlar (16mm)
Load (kN)
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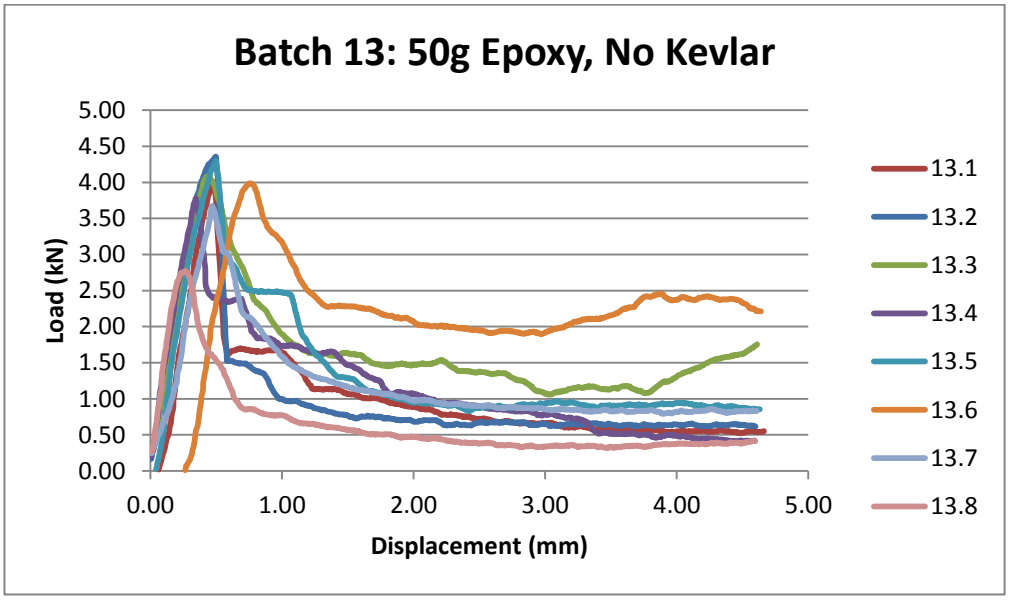
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
12.1
12.2
12.3
12.4
12.5
12.6
12.7


Batch 13: 50g Epoxy, No Kevlar
Load (kN)
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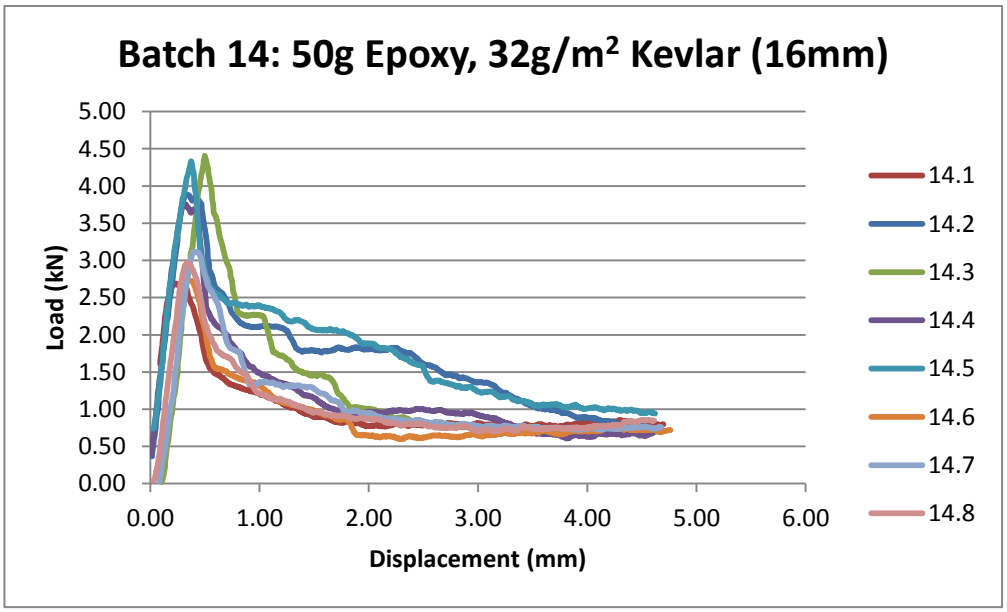
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
13.1
13.2
13.3
13.4
13.5
13.6
13.7
13.8


Batch 14: 50g Epoxy, 32g/m² Kevlar (16mm)
Load (kN)
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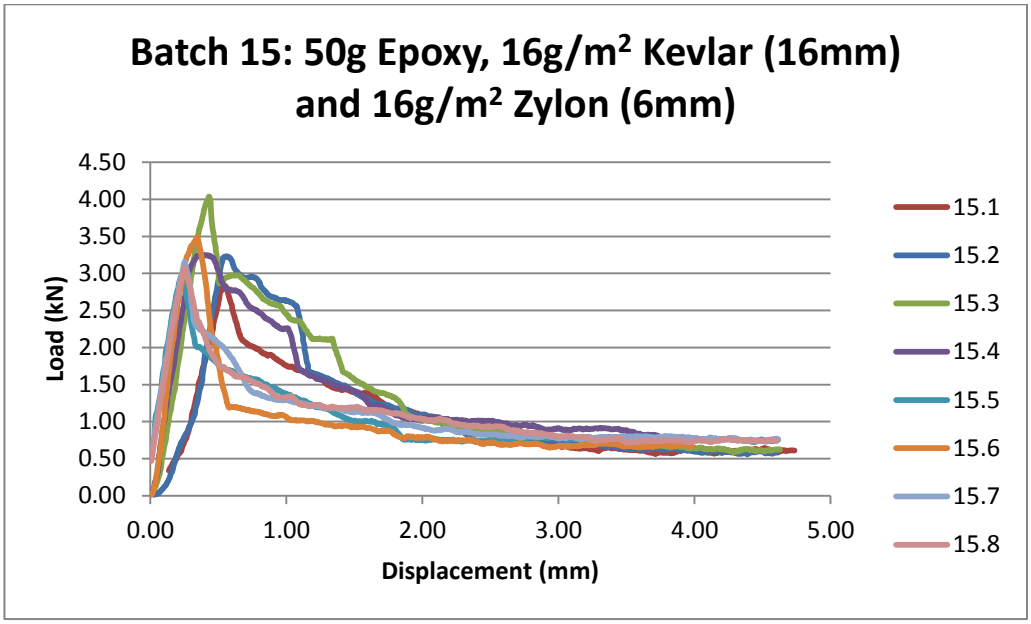
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Displacement (mm)
14.1
14.2
14.3
14.4
14.5
14.6
14.7
14.8


Batch 15: 50g Epoxy, 16g/m² Kevlar (16mm) and 16g/m² Zylon (6mm)
Load (kN)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
1.00
2.00
3.00
4.00
5.00
Displacement (mm)
15.1
15.2
15.3
15.4
15.5
15.6
15.7
15.8

**SIGMA-ALDRICH**

# SAFETY DATA SHEET

according to EC directive 2001/58/EC
Version 3.0 Revision Date 02.04.2007
Print Date 29.05.2010

## 1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

Product name : **Acetone**

Product Number : 443638
Brand : Sigma-Aldrich

Company : Sigma-Aldrich Pty. Ltd.
12 Anella Avenue
CASTLE HILL NSW 2154
AUSTRALIA
Telephone : +61298410555180080097
Fax : +612984105001800800096
Emergency Phone # : +44 (0)8701 906777 (1800 448 465)

## 2. HAZARDS IDENTIFICATION

Classified as hazardous according to criteria of NOHSC. - HAZARDOUS SUBSTANCE.
DANGEROUS GOODS.

**Risk advice to man and the environment**
Highly flammable. Irritating to eyes. Repeated exposure may cause skin dryness or cracking. Vapours may cause drowsiness and dizziness.

## 3. COMPOSITION/INFORMATION ON INGREDIENTS

Formula : C3H6O
Molecular Weight : 58.08 g/mol

| CAS-No. | EC-No. | Index-No. | Classification | Concentration [%] |
|---|---|---|---|---|
| **Acetone** | | | | |
| 67-64-1 | 200-662-2 | 606-001-00-8 | F, Xi, R11- R36- R66- R67 | - |

## 4. FIRST AID MEASURES

**General advice**
Consult a physician. Show this safety data sheet to the doctor in attendance.

**If inhaled**
If breathed in, move person into fresh air. If not breathing give artificial respiration. Consult a physician.

**In case of skin contact**
Wash off with soap and plenty of water. Consult a physician.

**In case of eye contact**
Rinse thoroughly with plenty of water for at least 15 minutes and consult a physician.

**If swallowed**
Do NOT induce vomiting. Never give anything by mouth to an unconscious person. Rinse mouth with water. Consult a physician.



## 5. FIRE-FIGHTING MEASURES

**Suitable extinguishing media**
Carbon dioxide (CO2) For small (incipient) fires, use media such as "alcohol" foam, dry chemical, or carbon dioxide. For large fires, apply water from as far as possible. Use very large quantities (flooding) of water applied as a mist or spray; solid streams of water may be ineffective. Cool all affected containers with flooding quantities of water.

**Special protective equipment for fire-fighters**
Wear self contained breathing apparatus for fire fighting if necessary.

**Further information**
Use water spray to cool unopened containers.

## 6. ACCIDENTAL RELEASE MEASURES

**Personal precautions**
Use personal protective equipment. Avoid breathing vapors, mist or gas. Ensure adequate ventilation. Remove all sources of ignition. Evacuate personnel to safe areas. Beware of vapours accumulating to form explosive concentrations. Vapours can accumulate in low areas.

**Environmental precautions**
Prevent further leakage or spillage if safe to do so. Do not let product enter drains.

**Methods for cleaning up**
Contain spillage, and then collect with non-combustible absorbent material, (e.g. sand, earth, diatomaceous earth, vermiculite) and place in container for disposal according to local / national regulations (see section 13).

## 7. HANDLING AND STORAGE

**Handling**
Avoid contact with skin and eyes. Avoid inhalation of vapour or mist.
Keep away from sources of ignition - No smoking. Take measures to prevent the build up of electrostatic charge.

**Storage**
Keep container tightly closed in a dry and well-ventilated place. Containers which are opened must be carefully resealed and kept upright to prevent leakage.

## 8. EXPOSURE CONTROLS / PERSONAL PROTECTION

**Personal protective equipment**

**Respiratory protection**
Where risk assessment shows air-purifying respirators are appropriate use a full-face respirator with multi-purpose combination (US) or type AXBEK (EN 14387) respirator cartridges as a backup to engineering controls. If the respirator is the sole means of protection, use a full-face supplied air respirator. Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU).

**Hand protection**
Handle with gloves.

**Eye protection**
Safety glasses

**Skin and body protection**
Choose body protection according to the amount and concentration of the dangerous substance at the work place.

**Hygiene measures**
Handle in accordance with good industrial hygiene and safety practice. Wash hands before breaks and at the end of workday.

## 9. PHYSICAL AND CHEMICAL PROPERTIES

**Appearance**

| | |
|---|---|
| Form | liquid, clear |
| Colour | colourless |

**Safety data**

| | |
|---|---|
| pH | no data available |
| Melting point | -94.0 °C (-137.2 °F) |
| Boiling point | 56.0 °C (132.8 °F) |
| Flash point | -17.0 °C (1.4 °F) - closed cup |
| Ignition temperature | 465 °C (869 °F) |
| Lower explosion limit | 2 %(V) |
| Upper explosion limit | 13 %(V) |
| Vapour pressure | 533.3 hPa (400.0 mmHg) at 39.5 °C (103.1 °F)<br>245.3 hPa (184.0 mmHg) at 20.0 °C (68.0 °F) |
| Density | 0.79 g/cm3 |
| Water solubility | completely miscible |
| Partition coefficient (n-octanol/water) | log Pow: -0.24 |

## 10. STABILITY AND REACTIVITY

**Storage stability**
Stable under recommended storage conditions.

**Conditions to avoid**
Heat, flames and sparks.

**Materials to avoid**
Bases, Oxidizing agents, Reducing agents, Acetone reacts violently with phosphorous oxychloride.

**Hazardous decomposition products**

**Hazardous decomposition products formed under fire conditions.**
Carbon oxides

## 11. TOXICOLOGICAL INFORMATION

**Acute toxicity**

LD50 Oral - rat - 5,800 mg/kg
Remarks: Behavioral:Altered sleep time (including change in righting reflex). Behavioral:Tremor.

LC50 Inhalation - rat - 8 h - 50,100 mg/m3

LD50 Dermal - guinea pig - 7,426 mg/kg

**Irritation and corrosion**

Skin - rabbit - Mild skin irritation - 24 h

Eyes - rabbit - Eye irritation - 24 h

**Sensitization**

Chronic exposure may cause dermatitis.

**Chronic exposure**



This product is or contains a component that is not classifiable as to its carcinogenicity based on its IARC, ACGIH, NTP, or EPA classification.

**Potential Health Effects**

| | |
|---|---|
| **Inhalation** | May be harmful if inhaled. May cause respiratory tract irritation. Vapours may cause drowsiness and dizziness. |
| **Skin** | May be harmful if absorbed through skin. May cause skin irritation. Repeated exposure may cause skin dryness or cracking. |
| **Eyes** | Causes eye irritation. |
| **Ingestion** | May be harmful if swallowed. |
| **Target Organs** | Liver, Kidney, |

## 12. ECOLOGICAL INFORMATION

**Elimination information (persistence and degradability)**

no data available

**Ecotoxicity effects**

| | |
|---|---|
| Toxicity to fish | LC50 - Oncorhynchus mykiss (rainbow trout) - 5,540.00 mg/l - 96 h |
| Toxicity to daphnia and other aquatic invertebrates. | EC50 - Daphnia magna (Water flea) - 13,500.00 mg/l - 48 h |

**Further information on ecology**

no data available

## 13. DISPOSAL CONSIDERATIONS

**Product**
Contact a licensed professional waste disposal service to dispose of this material. Burn in a chemical incinerator equipped with an afterburner and scrubber but exert extra care in igniting as this material is highly flammable. Observe all federal, state, and local environmental regulations.

**Contaminated packaging**
Dispose of as unused product.

## 14. TRANSPORT INFORMATION

**ADR/RID**
UN-No.: 1090 Class: 3 Packing group: II
Proper shipping name: ACETONE

**IMDG**
UN-No.: 1090 Class: 3 Packing group: II EMS-No: F-E, S-D
Proper shipping name: ACETONE
Marine pollutant: No

**IATA**
UN-No.: 1090 Class: 3 Packing group: II
Proper shipping name: Acetone

## 15. REGULATORY INFORMATION

**Labelling according to EC Directives**

EC Label

| | |
|---|---|
| Hazard symbols | |
| F | Highly flammable |
| Xi | Irritant |
| R-phrase(s) | |
| R11 | Highly flammable. |
| R36 | Irritating to eyes. |
| R66 | Repeated exposure may cause skin dryness or cracking. |
| R67 | Vapours may cause drowsiness and dizziness. |
| S-phrase(s) | |
| S 9 | Keep container in a well-ventilated place. |
| S16 | Keep away from sources of ignition - No smoking. |
| S26 | In case of contact with eyes, rinse immediately with plenty of water and seek medical advice. |

**16. OTHER INFORMATION**

**Further information**


The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of the product. Sigma-Aldrich Co. shall not be held liable for any damage resulting from handling or from contact with the above product. See reverse side of invoice or packing slip for additional terms and conditions of sale.

**SIGMA-ALDRICH**

# SAFETY DATA SHEET

according to Regulation (EC) No. 1907/2006
Version 3.2 Revision Date 28.09.2009
Print Date 29.05.2010

## 1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

Product name : Poly(vinyl alcohol)

Product Number : 341584
Brand : Aldrich

Company : Sigma-Aldrich Pty. Ltd.
12 Anella Avenue
CASTLE HILL NSW 2154
AUSTRALIA
Telephone : +61298410555180080097
Fax : +61298410500180080096
Emergency Phone # : +44 (0)8701 906777 (1800 448 465)

## 2. HAZARDS IDENTIFICATION

Not classified as hazardous according to criteria of NOHSC.

This substance is not classified as dangerous according to Directive 67/548/EEC.

## 3. COMPOSITION/INFORMATION ON INGREDIENTS

| CAS-No. | EC-No. | Index-No. | Classification | Concentration |
|---|---|---|---|---|
| **Ethenol, homopolymer** | | | | |
| 9002-89-5 | - | - | - | - |

## 4. FIRST AID MEASURES

**If inhaled**
If breathed in, move person into fresh air. If not breathing give artificial respiration

**In case of skin contact**
Wash off with soap and plenty of water.

**In case of eye contact**
Flush eyes with water as a precaution.

**If swallowed**
Never give anything by mouth to an unconscious person. Rinse mouth with water.

## 5. FIRE-FIGHTING MEASURES

**Suitable extinguishing media**
Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.

**Special protective equipment for fire-fighters**
Wear self contained breathing apparatus for fire fighting if necessary.

**Further information**
Under fire conditions, material may decompose to form flammable and/or explosive mixtures in air.



## 6. ACCIDENTAL RELEASE MEASURES

**Personal precautions**
Avoid dust formation.

**Environmental precautions**
Do not let product enter drains.

**Methods for cleaning up**
Sweep up and shovel. Keep in suitable, closed containers for disposal.

## 7. HANDLING AND STORAGE

**Handling**
Provide appropriate exhaust ventilation at places where dust is formed. Normal measures for preventive fire protection.

**Storage**
Store in cool place. Keep container tightly closed in a dry and well-ventilated place.

## 8. EXPOSURE CONTROLS/PERSONAL PROTECTION

We are not aware of any national exposure limit.

**Personal protective equipment**

**Respiratory protection**
Respiratory protection is not required. Where protection from nuisance levels of dusts are desired, use type N95 (US) or type P1 (EN 143) dust masks. Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU).

**Hand protection**
For prolonged or repeated contact use protective gloves.

**Eye protection**
Safety glasses

**Hygiene measures**
General industrial hygiene practice.

## 9. PHYSICAL AND CHEMICAL PROPERTIES

**Appearance**

| | |
|---|---|
| Form | crystalline |
| Colour | colourless |

**Safety data**

| | |
|---|---|
| pH | no data available |
| Melting point | 200 °C |
| Boiling point | no data available |
| Flash point | > 113 °C - closed cup |
| Ignition temperature | no data available |
| Lower explosion limit | no data available |
| Upper explosion limit | no data available |
| Density | 1.269 g/cm3 |
| Water solubility | no data available |

## 10. STABILITY AND REACTIVITY

**Storage stability**
Stable under recommended storage conditions.

**Conditions to avoid**
Exposure to light may affect product quality.

**Materials to avoid**
Strong oxidizing agents

**Hazardous decomposition products**
Hazardous decomposition products formed under fire conditions. - Carbon oxides
Hazardous decomposition products formed under fire conditions. - Nature of decomposition products not known.

## 11. TOXICOLOGICAL INFORMATION

**Acute toxicity**

LD50 Oral - rat - > 20,000 mg/kg
Remarks: Behavioral:Altered sleep time (including change in righting reflex). Behavioral:Somnolence (general depressed activity). Behavioral:Muscle weakness.

**Irritation and corrosion**

no data available

**Sensitisation**

no data available

**Chronic exposure**

This product is or contains a component that is not classifiable as to its carcinogenicity based on its IARC, ACGIH, NTP, or EPA classification.

IARC: 3 - Group 3: Not classifiable as to its carcinogenicity to humans (Ethenol, homopolymer)

**Signs and Symptoms of Exposure**

To the best of our knowledge, the chemical, physical, and toxicological properties have not been thoroughly investigated.

**Potential Health Effects**

| | |
|---|---|
| **Inhalation** | May be harmful if inhaled. May cause respiratory tract irritation. |
| **Skin** | May be harmful if absorbed through skin. May cause skin irritation. |
| **Eyes** | May cause eye irritation. |
| **Ingestion** | May be harmful if swallowed. |

**Additional Information**
RTECS: TR8100000

## 12. ECOLOGICAL INFORMATION

**Elimination information (persistence and degradability)**

no data available

**Ecotoxicity effects**

no data available

**Further information on ecology**

no data available



## 13. DISPOSAL CONSIDERATIONS

**Product**
Observe all federal, state, and local environmental regulations.

**Contaminated packaging**
Dispose of as unused product.

## 14. TRANSPORT INFORMATION

**ADR/RID**
Not dangerous goods

**IMDG**
Not dangerous goods

**IATA**
Not dangerous goods

## 15. REGULATORY INFORMATION

**Labelling according to EC Directives**

Further information:
The product does not need to be labelled in accordance with EC directives or respective national laws.

## 16. OTHER INFORMATION

**Further information**

The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of the product. Sigma-Aldrich Co., shall not be held liable for any damage resulting from handling or from contact with the above product. See reverse side of invoice or packing slip for additional terms and conditions of sale.