University of Southern Queensland

Faculty of Engineering and Surveying

The Effect of Vandalism on Fibre Composite Structures

A Dissertation submitted by

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Abstract

With the emergence of fibre composite structures in real world civil engineering structures the effect of damage to these structures needs to be known. This study will limit to real world tools being used to tamper and damage the fibre composite to desired levels not just to destruction. The damage to the fibre composites will be from a cutting implement, a blunt impact implement, a sharp impact implement and small amounts of fire.

This project seeks to investigate the effect of common types of vandalism on fibre composite structures, define the typical kinds of vandalism and with what tools they occur with and whether any of these defects will have a negative effect on the structural integrity of the beam or structure. Define the amount of damage needed before noticeable negative effects start to occur in the structure and investigating whether these effects translate into large scale environments.

The objectives of this research were to research the background information regarding fibre composites design and the typical usage of the fibre composite materials. Investigate and document levels of vandalism for testing, analyse and test unaffected samples to provide a standard. Analyse and test vandalised samples with ranging levels of vandalism, and investigate the effect of vandalism in integrated fibre composite structures/elements.

For the sandwich composites the ease of cutting the material has been found and that has been found to be significant. The panels used also were found to be susceptible to burning of the skin but the inner core was immune to burning. With the blunt and sharp impact damage was found to be fairly significant in ultimate load but not very effective in reducing flexural stiffness. The blunt damage if excessive was very effective.

The pultrusions were found to be extremely resistant to burning where no damage was found or damage was irrelevant. The pultrusion was also found to be very resistant to blunt impact where little to no damage was able to be recorded. Like the pultrusions counterpart the ability to be cut was significant.

Further research is needed in to the fatigue behaviour of damaged fibre composites. The effect the damage has to the fibre composites needs further refinement and the ability of the damage to affect large specimen and full scale panels needs to be undertaken.

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

Limitations of Use

Professor Frank Bullen
Dean
Faculty of Engineering and Surveying

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Student Number: 0050057235

Signature

Date

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Introduction

1.1 Introduction

Fibre composites as a material have been around since the 19^{th} century as modern composites. These materials have been used in many forms and applications to date. The main areas that have been used have been military, aeronautical and marine applications. In recent years fibre composites have seen increasing use in civil engineering and civil infrastructure.

Composites and in particular fibre composites are materials that are made by combining a fibre with a resin. In this study two types of fibre composite will be examined. One of which is sandwich panels. Sandwich panels also referred to as laminate composites consist of two fibre reinforced skins bonded to a core material. Both the skin and the core vary in material and in property. Second of which is glass reinforced polymer composite. This is a pultruded section and is formed with a polymer resin and fibres, where both fibres and polymer resin can be varied to produce a wide range of properties.

Originally the Centre of Excellence in Engineered Fibre Composites was approached by the Department of Main Roads to investigate the effect of common types of vandalism on fibre composite structures, define the typical kinds of vandalism and with what tools they occur with and whether any of these defects will have a negative effect on the structural integrity of the beam or structure. Define the amount of damage needed before noticeable negative effects start to occur in the structure.

Figure 1.1 Vandalism on fibre composite bridge

1.2 Project Aim

This project seeks to investigate the effect of common types of vandalism on fibre composite structures, define the typical kinds of vandalism and with what tools they occur with and whether any of these defects will have a negative effect on the structural integrity of the beam or structure. Define the amount of damage needed before noticeable negative effects start to occur in the structure and investigating whether these effects translate into large scale environments.

1.3 Overview of the Project

The main objectives of this project are to:

- Research the background information regarding fibre composites design and the typical usage of the fibre composite materials.
- Investigate and document levels of vandalism for testing.
- Analyse and test unaffected samples to provide a standard.
- Analyse and test vandalised samples.

- Test ranging levels of vandalism.
- Investigate the effect of vandalism in integrated fibre composite structures/elements.
- Prepare documented vandalism report detailing procedure and results of vandalism.

1.4 Dissertation Overview

This dissertation covers the aim of the study and covers all the objectives described above. This dissertation describes the work which was undertaken and discusses the results and conclusions that where obtained. A literature review was undertaken to determine a background of knowledge about fibre composites, there usage and applications and the types of research that had been previously been completed in the field of damage on fibre composites.

Specimens were prepared of both sandwich composites and three different types and sizes of pultrusion. These specimens were tested without damage and with a range of different types of damage and are described along with the results of the tests. Finally conclusions are drawn from the results of the testing and areas are found that further research is needed.

Chapter 2

Literature Review and Fundamentals of Composites

2.1 Introduction

With the emergence of fibre composite structures in real world civil engineering structures the effect of damage to these structures needs to be known. This study will limit to real world tools being used to tamper and damage the fibre composite to desired levels not just to destruction. The damage to the fibre composites will be from a cutting implement, a blunt impact implement, a sharp impact implement and small amounts of fire. There has been a small amount of previous work done on some of these areas and these are discussed later.

2.2 Composite Materials

Composites are made from a mixture of a number of different materials. Most composites can be made from just two components, a matrix or binder which binds or holds the fibres together. A composite material can be varied to give specific properties which include strength, bending stiffness, chemical resistance etc. For the purpose of this study only two types of composite will be studied and these can be classified into two distinct groups, Sandwich or Laminated panels and Pultrusions. They are described later.

2.2.1 Fibre Reinforced Composites

Reinforcement in fibre composites come in three basic forms, fibres, particles and whiskers. Fibres are made of glass, other polymers, ceramics or metals. The reinforcement is required primarily to increase strength and stiffness of the composite. These fibres are the primary load carrying components of the fibre composite material. In today's market there are many types and forms of reinforcement. Varying from glass fibres to others forms like carbon and aramid fibres. In these different types of fibres the composition can change from one type to another also the properties of each type of glass or carbon fibre changes (Reinhart, 1998).

The use of each type of fibre also influences the resins used and the adhesive agents. The way the fibres are used differs between sandwich panels or laminate sections and pultruded sections. The resins are typically an epoxy, vinylester or polyester thermosetting plastic.

2.2.2 Sandwich Composites

The sandwich panels or laminates that will be used in this study consist of three parts that are formed together. This consists of two strong composite reinforcement layers bonded to a core material. The skins are designed to provide the strength and stiffness to the panel (Van Erp, G., Rogers, D 2008). These skins are made of woven fibres typically glass fibres layered in directions to provide the best possible strength and stiffness properties. There are numerous ways the fibres can be placed all with different and specific final characteristics. These fibre layers are combined in a resin to protect the fibres and ensure that the fibres remain in the most effective location and direction.

Figure 2.1 Typical Cross Section of a Sandwich Panel or Laminate

These skins that hold the fibre reinforcement are bonded to a core. This core provides the shear stiffness and the local structural performance (Van Erp, G., Rogers, D 2008). This core can be made from a number of materials with different properties and characteristics. This core is bonded to the skin of fibre reinforcing which means that the resin used in the skin has to not be chemically repelled by the core. The bond between the core and the skin has a major bearing on the final strength of the laminate.

2.2.3 Pultruded Sections

A pultruded sections differs from sandwich panels as it comes from a fibre composite manufacturing process producing continuous lengths of fibre reinforced polymer in a range of structural shapes. The pultrusion is made from a liquid resin and the reinforcing fibres (Van Herk, H., Rosselli, F. 2008). The liquid resin that is used contains not only resin but also fillers and specialised additives for specific applications. Some of the specialised additives are colour pigments and a catalyst.

Figure 2.2 Pultruded Section

The resins used in the pultrusions needs to be effective in binding with the fibres. There are a number of different types of resins used. The most typical fibre used is that of glass. The process of pultrusions is automated and because of this the process allows the control of resin quantities and reinforcement, this produces a consistent quality with well defined mechanical properties (Van Herk, H., Rosselli, F. 2008).

2.3 Use of Fibre Composite Materials

Fibre composites are not necessarily a new material but in regard to civil structural engineering applications they are. Fibre composites were developed early on in military types of applications and this was mainly in the aeronautical industry. This was during and around World War II in which a lot of money was spent and a lot of advancements were made (Ballinger, 1992). During the 40's and 50's the use of fibre composites was growing and the marine industry used fibre composites to a very large extent and continue to. Fibre composites were also being developed to be used in the automotive industry during this time and it was found to be feasible (Lubin, 1982). During recent time's fibre composites have begun begin used in a structural environment and for the purpose of this study only pultrusions and sandwich panels will be discussed below.

2.3.1 Use of Pultrusions

Pultrusions have been used in a wide range of applications these include applications such as cable ladders, stairways and cooling towers (Van Herk, H., Rosselli, F. 2008). The pultruded section has a widely established and strong niche market in the corrosion and electricity industry. In more recent times pultrusions have been used in more civil engineering or civil infrastructure situations. Civil applications that are now becoming far more common are bridge girders, boardwalks, cross arms and complete road bridges (Kemp, M. 2008). The bridge girder is going to become an ever increasingly common application of the pultruded section.

2.3.2 Use of Sandwich panels

Sandwich panels have been used in a wide range of applications. Panels in recent times have been specifically designed for civil engineering applications these include railway sleepers, bridge decks, bridge girders and water proof flooring (Van Erp, G., Rogers, D 2008). A composite bridge girder was developed and is replacing existing timber structures. This application of the sandwich panel is becoming more common and will increase in the years to come. The sandwich panels are also used in stairways as both the support to the structure and the walkway. They are beginning to be widely used as bridge decks in civil infrastructure. The same panels used in civil infrastructure and as decks in stairways are in recent times being bonded together to create versatile new bridge girders.

2.4 Properties of Sandwich Panels

The flexural properties of sandwich panels vary with the types, amounts and structure of the composite. There are numerous types of composite materials and with this consideration there are no common mechanical properties and the values being quoted can sometimes lead to a wide range of values for the same property of the same material (Soden, P, 1998). The direction of the fibres used no matter the type determines many of the properties.

2.4.1 Properties

A common failure mechanism of sandwich composites during flexure is the fracture or breakage of the reinforcing fibres. Therefore the main focus for the strength and properties of the composite are derived from the fibre reinforcement that is present. The basic types of fibres used in civil engineering field are glass fibres, carbon fibres and aramid fibre.

Glass fibres are the most common in the industry because of their wide availability which in turn makes the cost very attractive. There are a number of other factors these include handling ability, the useful properties and the history of good experience in the industry (Reinhart, 1998). Glass fibre properties do vary depending on type but have several characteristics that are common and stand out. One of which is the fibres possess a high tensile strength; they also possess a high heat resistance and thermal behaviour. The fibres also hold a good chemical, moisture and fire resistance.

Carbon fibres offer high performance reinforcing, they offer high strength, stiffness and offer low weight but these properties come at a heavily increased cost. There are other factors that they fibre stiffness, strength, low density and an increased long-time load performance. Aramid fibres are not widely used like carbon and glass fibres. Aramid fibres are used in specialised situations as there major advantage is their toughness and performance under impact. In the case of this study the sandwich composites are reinforced with glass fibres.

2.5 Properties of Pultrusions

Much like sandwich composites pultrusions can be varied to serve a particular purpose. There are a number of different types of fibres used in modern pultrusions and a number of different resins used. Some properties in pultrusions are determined primarily by the resins and the others are determined by the reinforcement.

2.5.1 Properties

Much the same as sandwich panels the direction of the fibre reinforcing can determine the overall strength and many of the properties (Van Herk, H., Rosselli, F. 2008). Pultruded sections are made in constant cross sections, typically in the shape of existing steel sections. Pultruded fibre composites commonly have high strength which can be stronger than structural steel on a kilogram-for-kilogram basis. Another common property is the light weight in which pultrusions are commonly 20-25% lighter than that of structural steel. Pultruded sections also hold some properties that sandwich composites hold like corrosion and rot resistant and also low temperature capabilities.

2.6 Flexural Testing

The main placement of both sandwich panels and pultruded sections for the purpose of this study in civil engineering and more specifically civil infrastructure applications are that of a bending environment. In case of the sandwich panels there usually in the form of bridge decks that are under bending being the main problem and this is also true for the bridge girders or beams. In the case of the pultruded sections this is also true. They are placed mainly as bridge girder or beams and this places them under bending or flexural environment.

The testing procedure for flexural testing in this project will be that of four point bending, which is a testing procedure like that of three point bending (Tagarielli, VL, Fleck, NA, Desphande, VS 2004). This test is done by applying two point loads onto the specimen while the specimen is simply supported. With the specimen situated in this way the specimen undergoes a flexural loading in the y direction. This allows flexural stiffness and flexural modulus of elasticity of the specimen to be calculated.

2.7 Types of Damage

The types of damage that this study will be focused on will be the effect of impact, cutting and fire or burning. The area of impact damage in recent times has been a strong topic for discussion; this can be attributed to the increase in use in the aerospace and marine industries. The investigation into impact on composite sandwich structures remains an active research topic and is receiving much attention (Schubel, P. M, et al, 2004). Cutting has not seen the activity of impact research but is never the less important; it will be focused on orthogonal cuts along the base of the samples. The effect of fire has been receiving attention in the form of bush fire protection of structures.

2.7.1 Effect of Impact

There have been several common failure modes of sandwich panels identified which include core indentation/cracking, facesheet buckling, delamination within the facesheet and debonding between the facesheet and core (Schubel, P. M, et al, 2004). The susceptibility of laminated composite structures to damage resulting from impact for compression-loaded structures is a well known phenomenon (Kärger, L, Baaran, J et al, 2009).

Shubel et al used woven-carbon/epoxy facesheets and a PVC foam core and studied the effect of central point impact in a drop mass apparatus. The impact testing consisted of a drop tower with a free-falling mass which was used to impact the sandwich plates. The free-falling mass was dropped from a range of heights to induce damage. He found that the surface damage was not the only form of damage to the sandwich composites there was also localised delamination around the impact zone that was not apart from the outside.

Luo et al investigated the effect of damage propagation in composite plates and evaluated the impact damage initiation. The impact tests were conducted using a drop mass apparatus. The investigation used low energy impact and the weight and height at which the mass was dropped was much smaller than that of Shubel et al investigation. Luo et al found that the main characters of impact damage can be predicted by two properties, threshold strength and propagation strength for matrix cracking. He found under the low energy impact there were no matrix failure at the impact centre and also there were no fibre breakage. The approach using the threshold strength and propagation strengths can predict whether the composite structure is damaged or by which extent the damage develops.

The tolerance assessment and damage resistance of composite structures under low-velocity impact was investigated by Andreas P. Christoforou. He found that for constant impact energy the nature of the response varied according to the type of impactor and structural characteristics. These factors influenced the type of damage and the extent of damage degradation to the fibre composite.

Three critical thresholds for high energy impacts have been investigated by Shyr and Pan. The investigation found that the three thresholds were; threshold of delamination failure, major damage threshold and perforation energy threshold. The thresholds were only apparent for high energy impacts and were not apparent for low energy impacts. It was found that thicker laminates were governed by fibre fracture were thinner laminates were more susceptible to delamination.

Chotard and Benzeggagh investigated the effect of low-velocity impacts on pultruded sections. The pultrusions were glass/polyester pultruded beams. The investigation found that much like sandwich composites the size of the impactor had a major influence. A big impactor would produce less delamination than a small-impactor. The study also found that filler quantities in the members also contributed to damage severity. It was found that all the samples had internal shear cracking and interfacial delamination and one sample with low filler quantity had catastrophic failure in the form of great open longitudinal cracks on the rear face.

Holden et al also investigated the static indentation and impact behaviour of pultruded sections. The study used three specimens each of a glass reinforced polymer pultrusions. The investigation found that backface cracking could be predicted by front face permanent indentation. Also the residual compressive strength of the material could be determined by the size of the backface crack.

2.7.2 Effect of Cutting

The effect of cutting damage or sharp impact damage in fibre composites is an area of limit resource. Most areas of interest and attract the most attention is in regard to impact behaviour of ranging size impactors but does not include point driven or sharp impactors. Madenci et al investigated the effect of centre-cracked composite laminates and provided a theory for damage prediction.

The study was centred on two-ply laminates and three-ply laminates of different fibre orientations with a centre crack. The study found that the damage produced matrix cracking and fibre breakage and delamination. In this case the damage occurred in the direction parallel to the fibres was primarily splitting. The study found that the splitting at the top and bottom of the crack produced delamination.

2.7.3 Effect of Fire

The effect of fire damage on fibre composites is another area that is receiving increasing discussion. Mathys and Burchill investigated the burning of polyester and vinylester fibre glass composites. This study focused on analysis of mass loss and damage depth by the combustion of styrenic resins and their fibre glass compositions. The study found that mass loss rates at selected heat flux were found to be linearly related to those at different heat flux. Damage depth was also found to be linearly related to mass loss and could be predicted as a function of time.

Mouritz and Gardiner investigated the effect fire-induced damage on the edgewise compression properties of polymer sandwich composites. The study used two types of sandwich composites, one highly flammable the other had a low flammability rating. It was found that the compression stiffness and strength of both sandwich composites decreased rapidly with increasing heat flux and heating time. This was found to be accredited to decomposition of the faceskin and foam core.

Gardiner et al investigated the tensile and compressive properties of FRP composites with localised fire damage. The study found that tensile stiffness, tensile strength and compressive stiffness is determined by the amount of charred damage whereas the compressive strength is determined by the size and depth of the delamination cracks.

2.8 Knowledge Gaps in Previous Research

There has been previous research conducted into the behaviour and the properties of both fibre reinforced sandwich panels and fibre reinforced pultruded sections (Chotard, TJ, Benzeggagh, Rosato, DV and Reinhart, TJ) along with many others. There has been limited research into the effect damage has had to fibre composites (Burchill, PJ, Mathys, Z, Gardiner, CP, Luo, B, Agwai, A, Madenci, E).

With the previous research conducted there however is a gap in the previous research in regard to the effect damage has on fibre composites. Burchill, PJ and Mathys, Z conducted research into the behaviour of fire damaged composites, this research was into high levels of fire damage from the likes of bush fires. This is at the extreme end of the damage spectrum and effect of lower levels of fire damage is needed, so that small amounts of damage are not ignored until the high levels are achieved.

Luo, B, Agwai, A, and Madenci, E conducted research into the effect of impacts on composite plates. This however leaves a knowledge gap of smaller impacts on both plates and structures. The impact damage to the pultrusions and the effect a smaller impact has on the sandwich panel is not known.

However, there is a knowledge gap in that in the previous research the effect of cutting damage has not been researched, with the effect the cutting damage has no both sandwich panels and pultrusions is not known. There is also the knowledge gap in that the effect a sharp impact has on fibre composites. With the fact the sharp impact is much like a cross between the blunt impact and the cut damage, the effect his has on fibre composites is not known.

2.9 Summary

This chapter has provided some background on both sandwich panels and fibre reinforced pultrusions. For the purpose of this project this chapter has also provided a brief overview of the usage of fibre composites in civil and structural engineering applications. Fibre composites have been proven to be capable materials in many fields and are commonly used in aeronautical and marine situations. They exhibit significant potential to become mainstream materials for civil applications.

There is increasing research into the use of fibre composites and an ever increasing push into civil applications. Though most of the research shown in this chapter is from fields other than civil engineering there is lessons learnt. It is clear from the studies completed by Gardiner, C.P, Mathys, Z, Mouritz A.P that damage is a serious problem to fibre composites. These studies hold valuable insight to what is needed for further studies into civil applications.

There is a lack of research into the flexural behaviour of all types of damage cover in this chapter. There is increasing research and attention on the impact damage to fibre composites. There is still a lack of this in the civil sector. The effect of fire damage is also attracting attention and has shown to be an area of needed research in the fact that its effect is so severe. There is also a lack of research in the area of cut or sharp damage.

Chapter 3
Experimental methodology for the evaluation of damage to fibre composites

3.1 Introduction

This study is investigating the effect various types of damage have to fibre composites. The test will be performed on both sandwich composites and three different types of glass fibre pultrusions. The types of damage will be of common occurring vandalism. These will include blunt impact, sharp impact, cutting and painting.

3.2 Sample Description

The sandwich panels used in this project are a commercially available material and manufactured by LOC composites. They are produced in large panels. The panels that were used have been surface treated with an asphalt top. These were also compared to unsurfaced samples. The samples were cut from both panels. The covered samples were cut to 500 mm x 50 mm. Some prepared samples can be seen in figure 3.1.

Figure 3.1 Prepared LOC Sandwich Panel

The first glass fibre pultrusions that were used in this study are also commercially available and these sections are manufactured by Wagners Composites. These pultrusions come in many standard structural sections. The sections used for this project were a commonly used standard section of 100mm x 100mm. This had a thickness of 5mm. The Wagners composite is made using a poly ester resin and uses glass reinforcing fibres in 0^o, 90^o and 45^o directions.

Figure 3.2 Prepared Wagners Pultrusion

The second glass fibre pultrusion that were used were also commercially available and these sections were manufactured by Exel Composites. There were two different types of pultrusion by Exel Composites used in the project. The first product was a 50mm x 50mm section with a 6mm thickness.

These pultrusions differed to the Wagners one in multiple facets. The Exel composite uses a poly ester resin and glass fibres in both the 0^o and 90^o directions. The pultrusion instead of using 45^o fibres as well 0^o and 90^o direction fibres uses a continuous filament mat to provide the shear strength and rigidness needed.

Figure 3.3 Exel Composites Square Pultrusion

The second is a wall panel of three square section connected by a thin flat section of pultrusions, these can be seen in Figure 3.4. The wall panel is m using a poly ester resin and uses loose unidirectional fibres to create the stiffness in all directions.

Figure 3.4 Exel Composite Wall Pultrusion

For both the sandwich composite and all the pultrusions undamaged samples were tested to find original properties and this was compared to damaged samples.

3.3 Damage Standard

Currently there is no standard to conduct damage to as the effect damage has on fibre composites has not been previously researched. This standard or means of damage needed to be developed. With no standard the damage needed to be able to be repeated with a strong level of accuracy and importantly have a high level of consistency. The damage was made so that it could be potentially reproduced at a later date. The procedures of each of the damage types are discussed later in this chapter. It is also discussed in a more detail in each chapter relating to the different fibre composites.

3.4 Damage and Sample Preparation

The standard for fibre composite testing is that five or six samples are tested to provide enough spread to ensure accurate results. Previous research has used only three specimens; this is to account for the already variable results in the amount of damage that is present.

Type of Material	**Number of Samples**				
	Control	**Blunt**	**Sharp**	**Cut**	**Fire**
Sandwich Panel - Cover	3	3	3	3	3
Sandwich Panel - No Cover	3	3	3	3	3
100x100mm Pultrusion	3	3	3	3	3
50x50mm Pultrusion	3	3	3	3	3
Wall Panel Pultrusion	2	2	2	2	2

Table 3.1 Sample Preparation

The variability of the damage combined with the variability of fibre composites in general have meant that the common standard for damage testing on fibre composites is three specimens for this reason the project used three specimens for each of the damage types including the control samples. For the size of the wall panel the literature suggested the use of only two samples per types of damage and control alike. For this project this was also followed.

3.4.1 Blunt Impact Test

The impact tests that were conducted followed the same procedure as the literature. The literature proposed using only three samples and this was followed. This meant three samples were used of both sandwich composite and all the glass fibre pultrusion.

These were subjected to a drop mass situation which has been used in the literature. This drop weight used the impactor as the head of a hammer as the possible vandal weapon, as the literature suggested impactor size was a major influence to damage response. The impact was into the centre of the specimen. The impactor can be seen in figure 3.5.

Figure 3.5 Blunt Impactor

The impact was conducted until obvious signs of damage had occurred. These were conducted on spare specimens and repeated using the final weight on the test specimens. These impacts were then cross checked by hand to see if the damage could be reproduced by hand by a potential vandal.

3.4.2 Sharp Impact Test

The literature proposed using three samples and this was followed. Three samples were used for both sandwich composites and glass fibre reinforced composites.

A drop weight apparatus was used in performing the damage. The impactor used was a screw driver. The sharp impactor can be seen in figure 3.6.

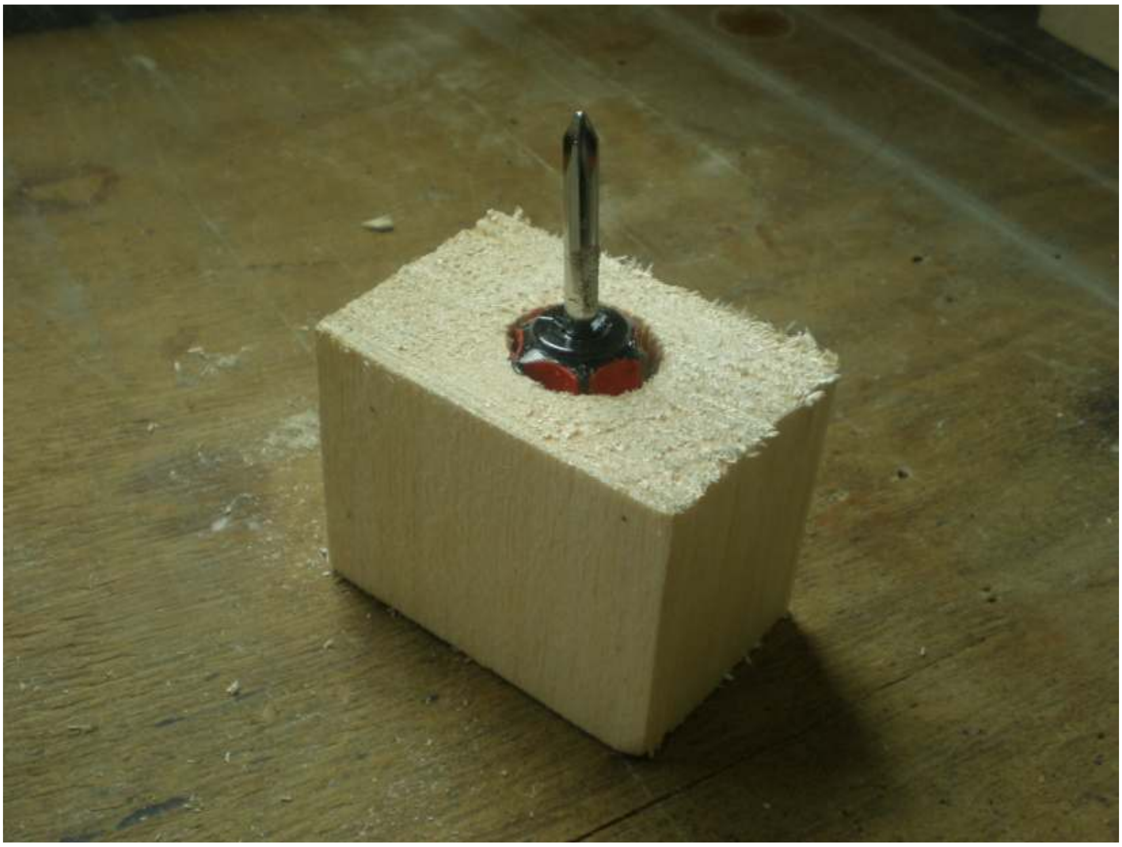

Figure 3.6 Sharp Impactor

This was again tested on spare samples in which the weight was altered till damage was apparent and this was then repeated on the test samples. This procedure was used for the sandwich panels only.

For the two different pultrusions the same screw driver impactor was used and was hammered into the pultrusion to approximately 2mm depth at the centre line.

3.4.3 Cut

The cutting damage to the fibre composites were completed with a Stanley knife. The literature did not have a method for this. The literature commonly used three samples in testing of damage so this was followed.

Three samples were prepared of both sandwich panel and glass fibre reinforced composite. The layout of the cut can be seen below in figure 3.7.

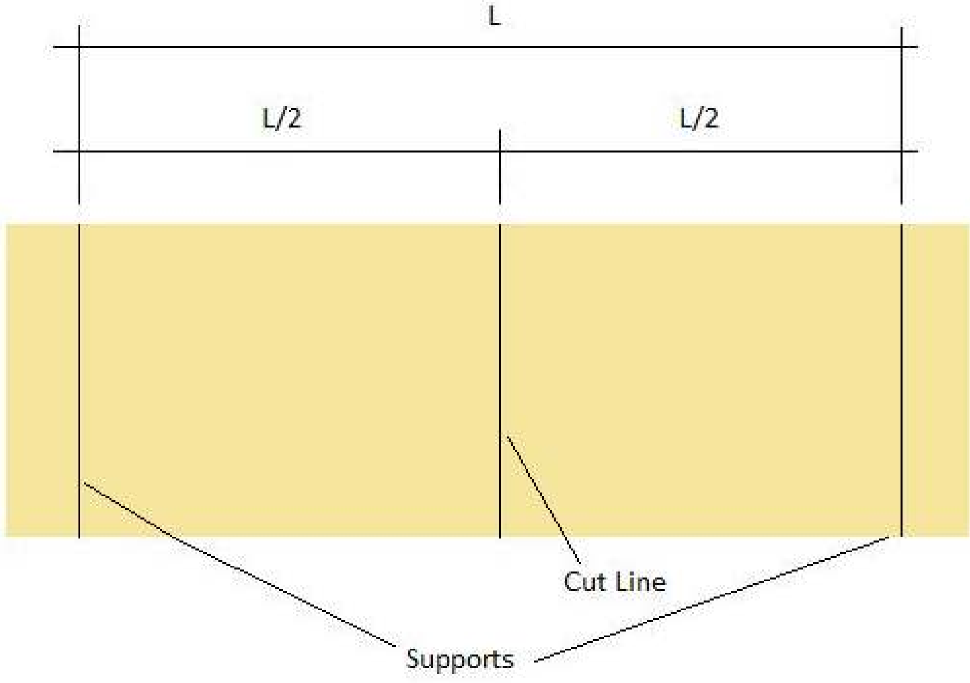

Figure 3.7 Layout of cut specimen both sandwich and glass fibre composite

The damage was made by placing a spare sample on scales and a range of pressures was applied. This was repeated till damage was obvious and this same pressure was repeated on each of the three samples. This procedure was used for the sandwich panel only.

For the two different types of pultrusion the samples were cut three times on the centreline. These cuts were to approximately 2mm deep.

For the wall panel the cut was 7 lines vertical lines as seen in figure 3.8. These cuts were to a depth of 1mm.

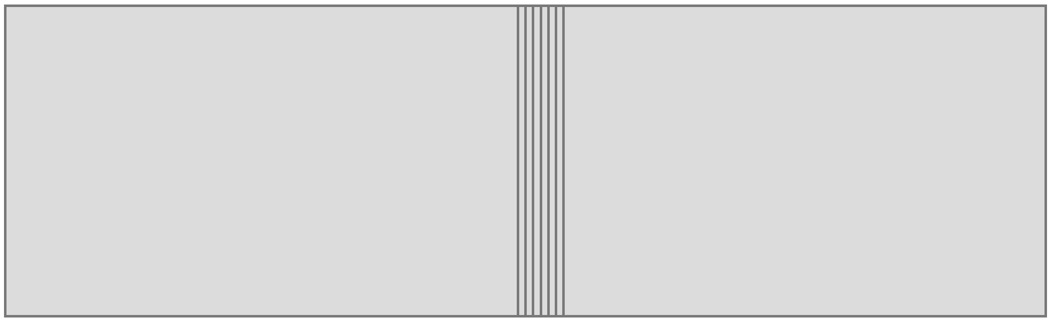

Figure 3.8 Cut Damaged Wall Panel

3.4.4 Fire Damage

This test was similar to that of the literature but on a much smaller scale. The literature was aimed at bush fire and extreme heats. The tests completed were of both sandwich composites and glass fibre composites. Three samples were again used to follow the literature. The lighter can be seen in figure 3.9.

Figure 3.9 BBQ Lighter

The fire damage tests were conducted using over the counter bbq lighters. These small bbq lighters were used on sample pieces to determine the length of flame required to cause damage this was then repeated for the similar time on the test specimens. The fire damage was done to the centre of the test specimens.

3.4.5 Paint Removal

This test was not designed to see property change; this test was designed to see the effect of paint and its attempted removal. This was not covered by literature. A sample of both sandwich composite and glass fibre reinforced composite were collected. These samples were painted with typical over the counter black spray paint. The spray was for a 5 second burst of paint. This was then attempted to be removed after dry by a common type of paint remover.

3.5 Flexural Test

The flexural tests were completed on the MTS Alliance RT/10 testing machine. The purpose of the test is to determine the flexural strength of the material before and after damage. The tests involved failing the specimens using a 4-point bending test. This can be seen below in figure 3.10.

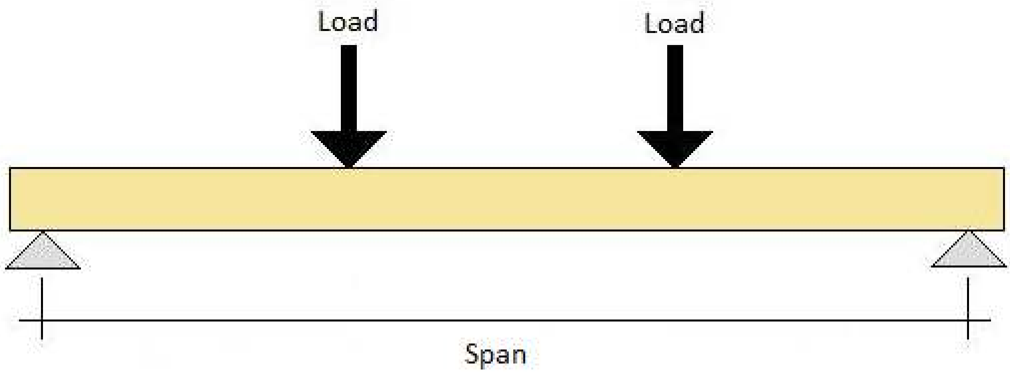

Figure 3.10 Four Point Bending Test

The test machine records the data during the test and displays many of the properties in real time. The program also records load and deflection, this can be seen in figure 3.11.

Figure 3.11 MTS testing machine used on the Sandwich Panels

The larger full sized samples were tested using a larger capacity machine, this can be seen below in figure 3.12.

Figure 3.12 MTS testing machine used on the Pultrusions

3.6 Summary

The methodology was followed and results obtained and analysed. The instrumentation was used and placed accordingly. The damage was under taken on all samples and documented. The loading of the samples was run accordingly and performed as appropriate using the test machine as stated earlier.

With no standard to conduct damage to as the effect damage has on fibre composites has not been previously researched. This meant a standard and a means of damage needed to be developed. The damage was made so that it could be potentially reproduced at a later date and levels of damage where recorded and could be matched. The procedures of each of the damage types are discussed later in this chapter. It is also discussed in a more detail in each chapter relating to the different fibre composites.

Chapter 4
Experimental Investigation into Fibre reinforced Sandwich Panels

4.1 Introduction

The sandwich panels used for this project were from LOC composites and where the Carbon LOC^{TM} panel. The samples were prepared to 500mm x 50mm size. The plain sandwich panel has a thickness of 20 mm. For the sandwich panels, two different types were used. One set of panels were of a plain sandwich panel. The other set of panels is the same sandwich composite but an asphalt cover or finish has been added to the top of the material, this cover was 5mm on top taking the final thickness to 25mm.

4.2 Damage

The samples were all damaged in the centre of the specimen on the tension side of the product; this was done as the samples would be placed in a flexure environment and the areas accessible to vandalism would be from beneath. The samples were prepared so that three samples were used as control un-damaged samples. For each of the damage type's three samples were also used.

4.2.1 Blunt Impact

The blunt impact was done by a drop weight of 14.78 kg weight which had a hammer head attached to the base of the weight. This was dropped to the centre of what would be the tension side of the specimen. Each specimen was only impacted once. For the uncovered samples the drop weight was dropped from a height of 685mm above the showing skin of the sample. For the covered samples the drop weight was dropped from a height of 680mm above the showing skin of the sample.

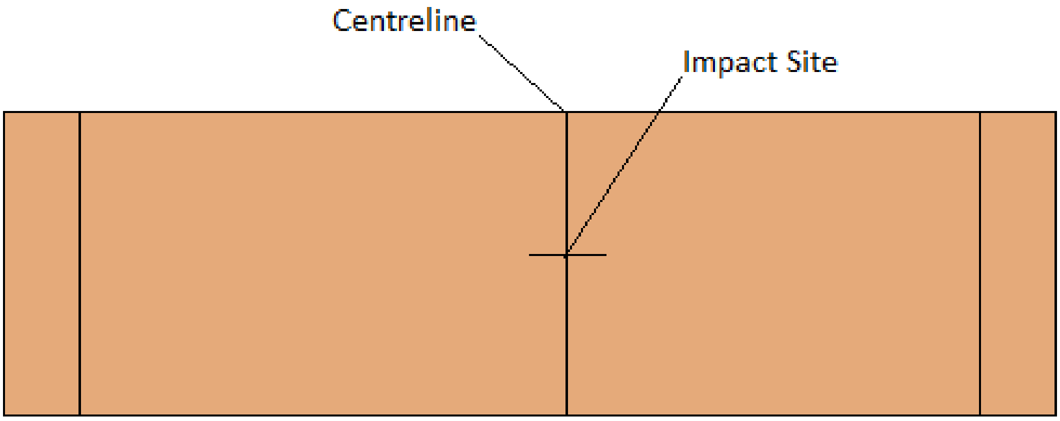

Figure 4.1 Blunt Impact Schematic

The damage from the impact left a circle the size of the hammer into the skin of the specimen for both the asphalt cover and the no cover. The indent was not deep but provided internal core crushing to some extent and skin ripples where it had impacted. This can be seen in figure 4.2. This correlated with the previous research done as the wide impactor was said to achieve this visible damage.

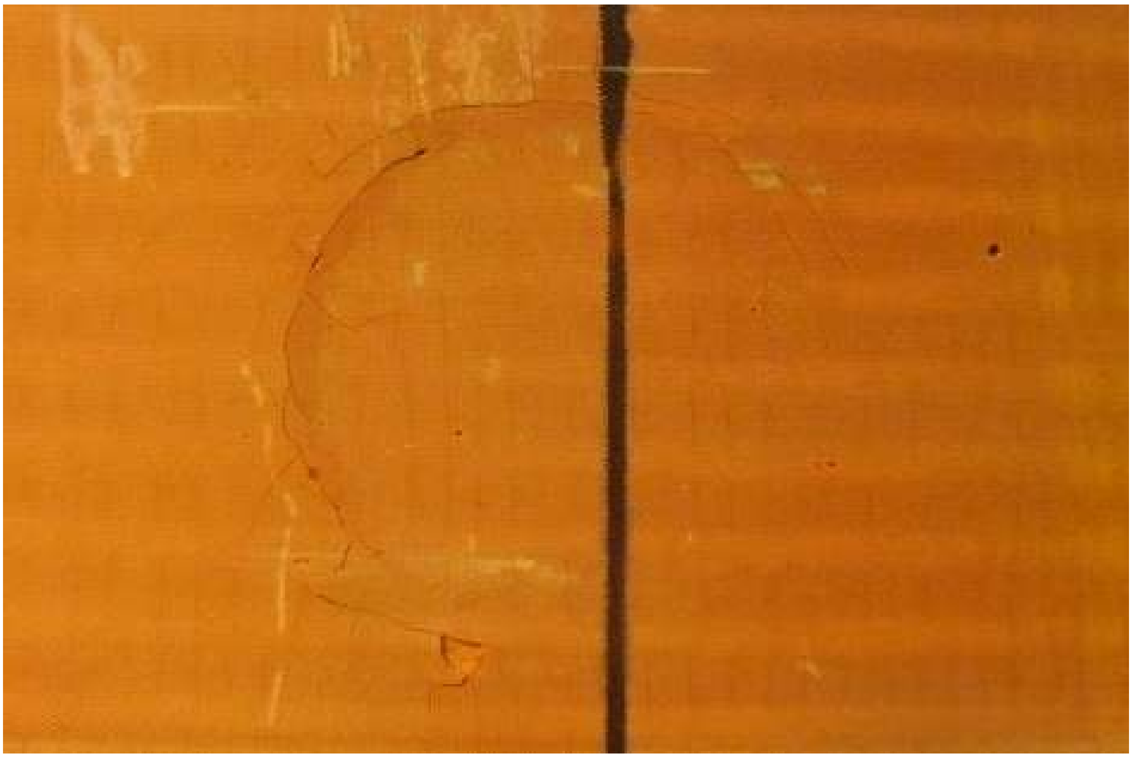

Figure 4.2 Blunt Impact Damage

4.2.2 Sharp Impact

The sharp impact was done by the same drop weight as the blunt impact though a screw driver head replaced the hammer head. This was dropped to the centre of what would be the tension side of the specimen. All samples were impacted three times along the centre line of the specimen. For the uncovered samples the drop weight was dropped from a height of 260mm above the showing skin of the sample. For the covered samples the drop weight was dropped from a height of 270mm above the showing skin of the sample.

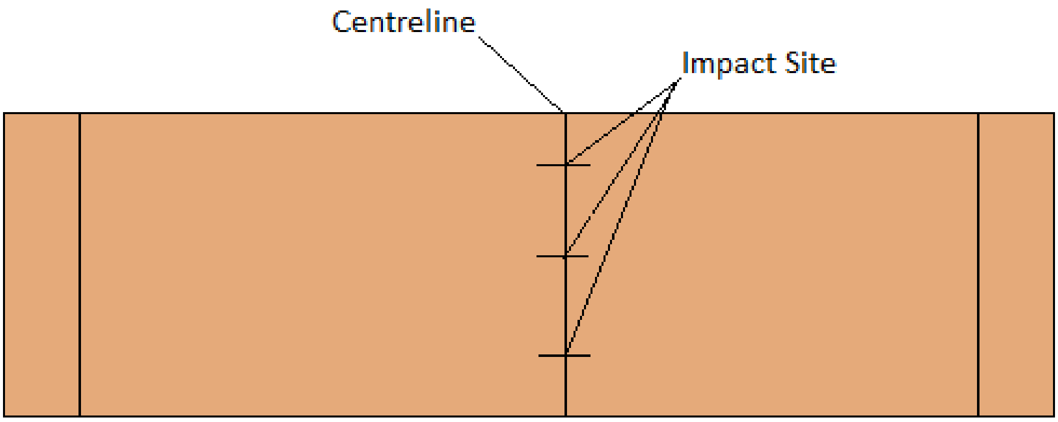

Figure 4.3 Sharp Impact Schematic

The sharp impact penetrated into the sample to just into the skin. The glass fibres were cut through completely in the small section of the impact zone this can be seen in figure 4.4. No core or other skin damage was observed.

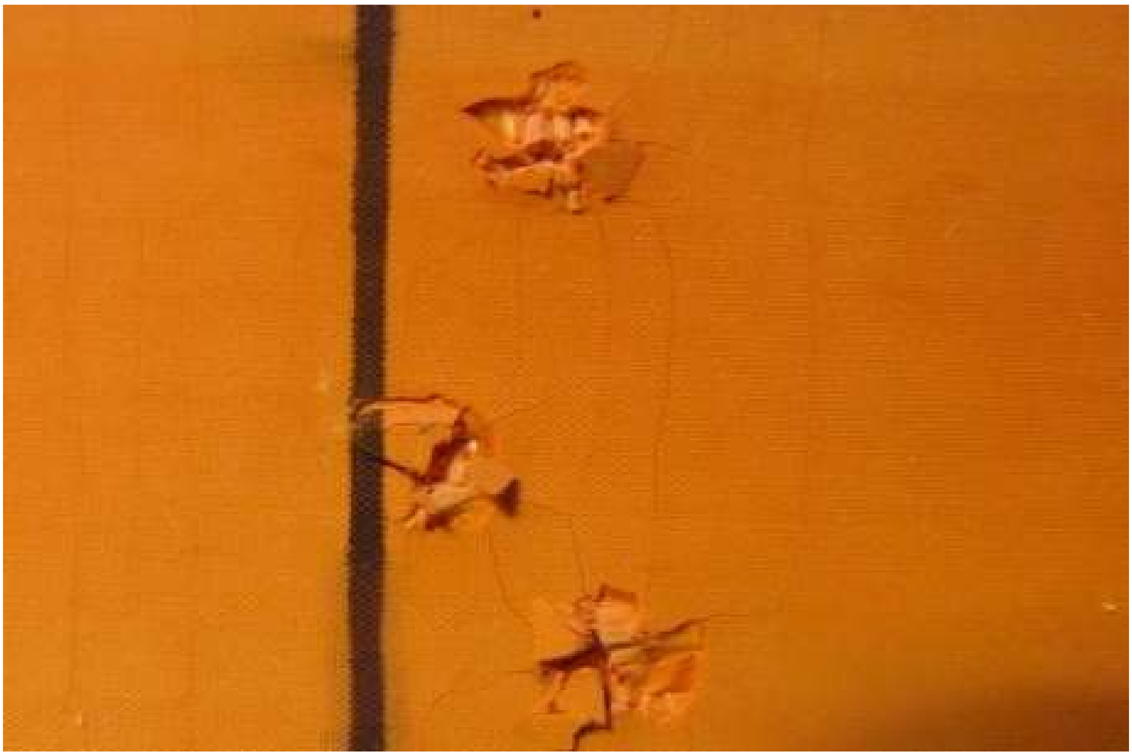

Figure 4.4 Sharp Impact Damage

4.2.3 Cut Damage

The cut damage was produced by placing the sample on a set of scales and applying approximately 4kg down and cutting across the centre line of the sample. The specimens were only cut once per specimen. With approximately 4kg of pressure the cut was approximately 1mm deep. The damage can be seen below in figure 4.5.

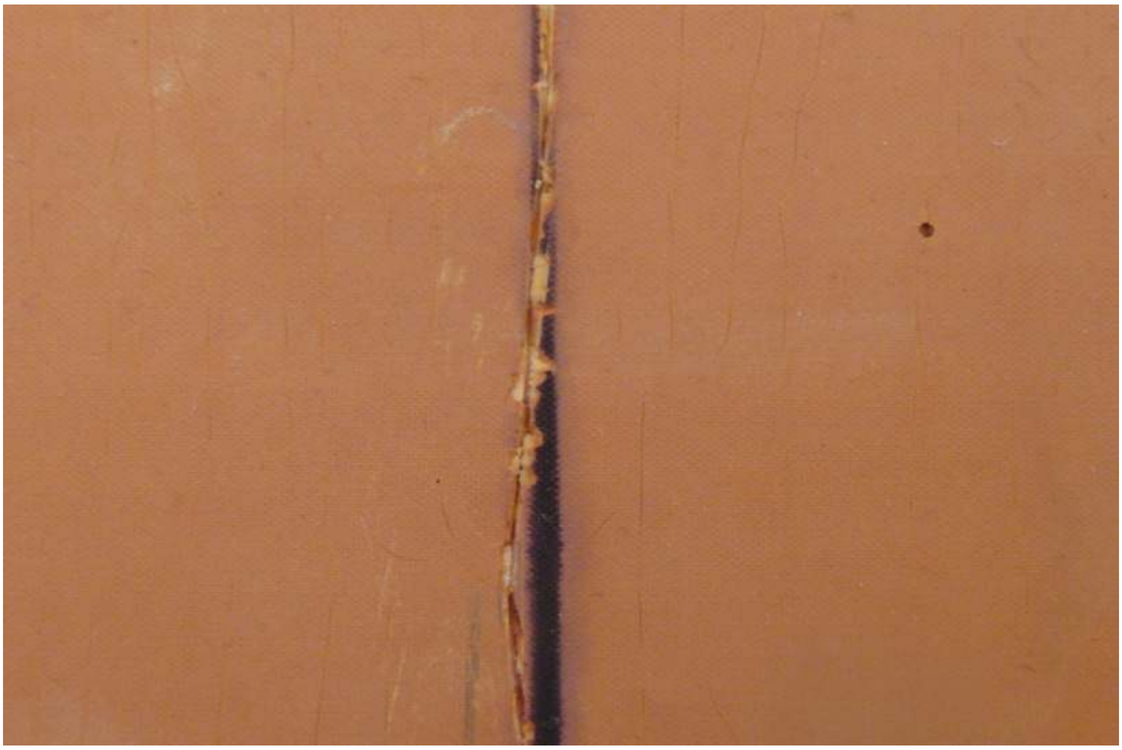

Figure 4.5 Cut Damage

4.2.4 Fire Damage

The fire damage was from a BBQ lighter. This lighter was held on the centre of each of the specimen for 2 min. Each specimen began to have the skin directly under the flame crack and chip. After a minute the skin chips off and the glass fibres begin to break and split. This can be seen below in figure 4.6.

This damage was easy to achieve, the effect of just the bbq lighter was immediate and instantly apparent. The core of the sandwich panel is immune to the effect of the bbq lighter but the skin of the sample is not immune. The skin of the panel does not itself catch alight but as long as flame is touching the sample damage is done.

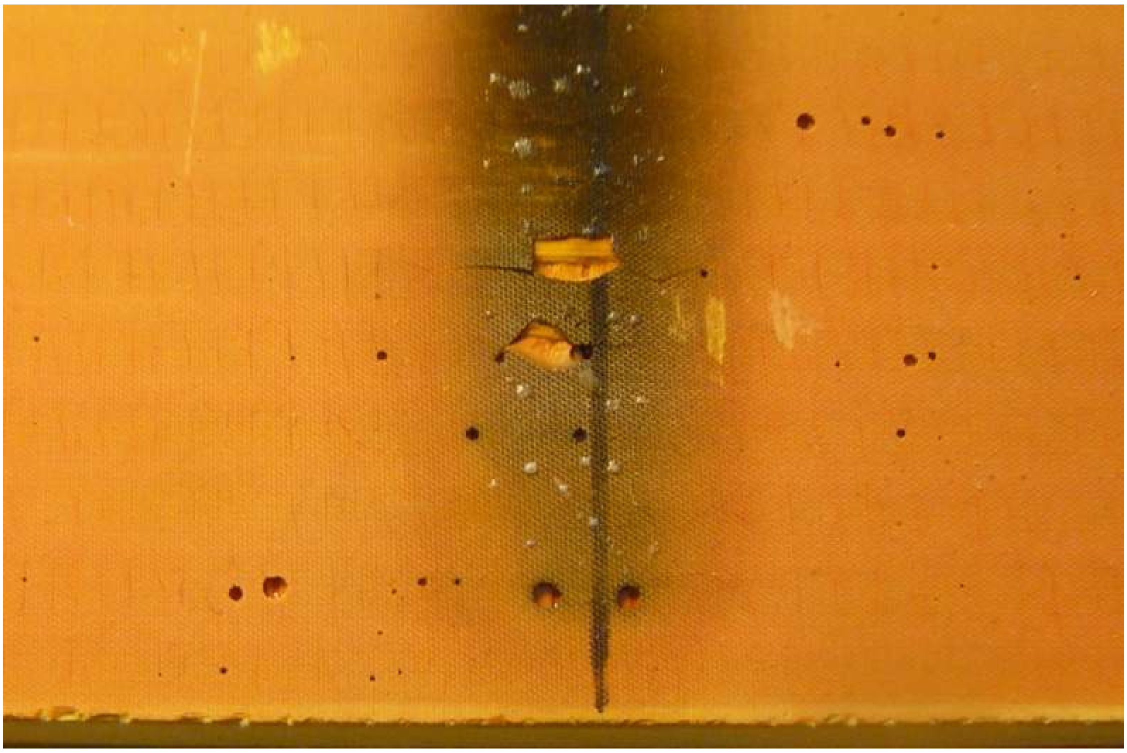

Figure 4.6 Fire Damage

4.3 Flexure Testing

The specimens as explained earlier were tested in flexure only. For both the asphalt covered and plain specimen they were tested at the same span and load configuration. This was set at 450 mm span with the load at 40mm from the centre at both sides. This can be seen in figure 4.7.

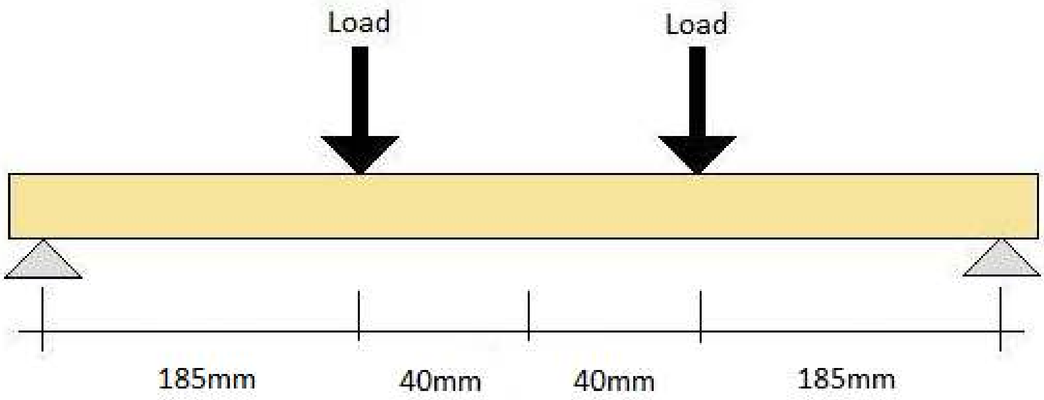

Figure 4.7 Sandwich Panel Flexure Test

4.4 Control Samples

Three control samples were tested as explained earlier to provide a control or standard to measure the effect the damage had on the specimen. The failures of the specimen were of a brittle failure as expected apart from the one sample control 3 which was more of a ductile failure in the no cover specimen.

The differences that can be seen between the results on the tests could be explained by the asphalt cover that was present on the specimen. The asphalt cover was not a perfect thickness and in some cases was not as compact as in other places. This can also be somewhat contributed to the longer failure time of Control (SP-C) specimen, the drops and reloading is due to large sections of the asphalt began to crack and lift off the sample. This can be seen in figure 4.8 where the asphalt cover has fallen from the section after failure.

Figure 4.8 Failure of Sandwich Panel with Cover

Figure 4.9 Control Specimen with Cover

The average ultimate load of the control with cover was 4917N, where the average ultimate load of the control specimen without cover was 4591N. The asphalt cover provided an increase of 6.6% in average ultimate load. The flexural stiffness an indicator of the flexural modulus of the covered specimen was 363N/mm and the non covered specimen had a flexural stiffness of 210N/mm an indicator of the flexural modulus, the cover providing an increase of 42%.

The graphs of the control samples can be seen in figure 4.9 and 4.10. The flexural modulus of the control samples with no cover 7681.01MPa and the flexural modulus of the control samples with cover was 8703.08MPa, the cover providing an increase of 11.7%.

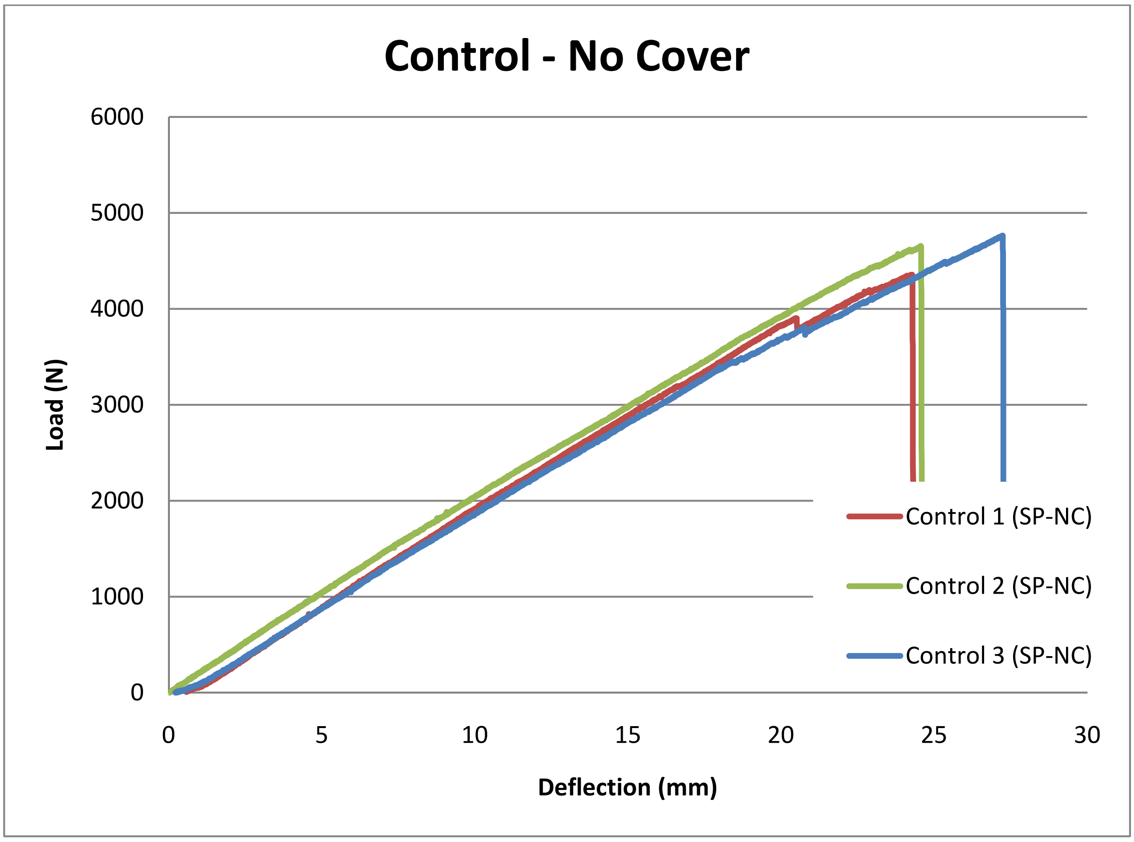

Figure 4.10 Control Specimen without Cover

4.5 Blunt Impact Damaged Samples

The specimen with the asphalt cover had a different failure to the control specimen as the samples had more of a ductile failure as the failure originated at the impact site. Where the samples had delaminated and had a rippling effect in the skin the impact site the tension cracks occurred. The blunt impact was very hard to reproduce by hand, was achievable but very difficult, especially if considered in real world the impact would be done above head and the hammer swung upward.

This can be best seen in figure 4.8 where the samples would fail and re-load as the cracks or tears would dissipate to the side. One side would typically go as the impacts were not directly centre and the shortest distance from the impact site to the edge would fail. It would continue to load until the other side would fail.

The blunt impacted covered samples had an ultimate strength of 4599N, in comparison to the control the blunt impact damage decreased average ultimate load by 6.5%. The covered samples had a flexural stiffness of 323N/mm an indicator of the flexural modulus, in comparison to the control the blunt impacted stiffness was reduced by 11%.

The blunt impact sample had a flexural modulus of 7602.75MPa, in comparison the flexural modulus was reduced by 12.6%.

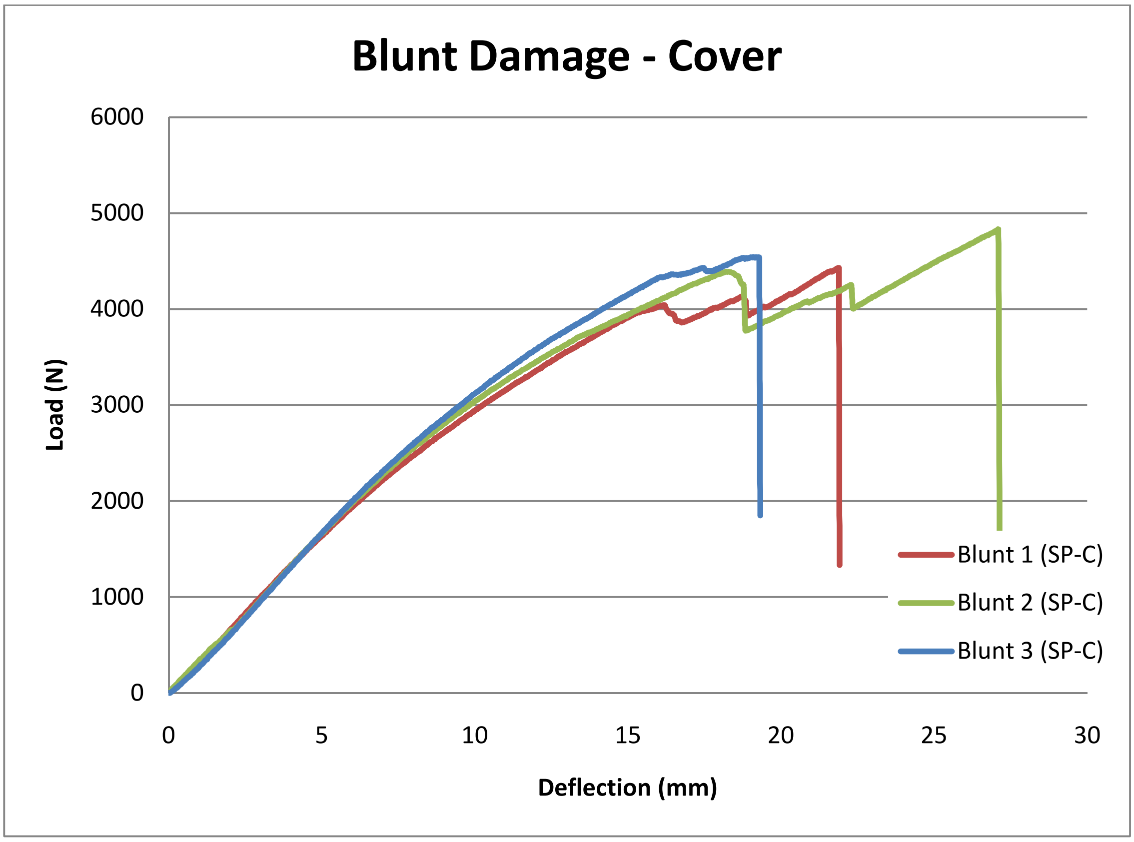

Figure 4.11 Blunt Damage with Cover

For the non covered blunt impact the amount of damage seemed too high for intended results. The asphalt had taken much of the effect out of the hammer and for the non covered samples the core actually took damage and in one case had quite extensive damage.

This is an explanation for the early failures of the samples as the failures were in the core and do not effective show the effect of the damage had on the specimen, thus the ultimate load was neglected. The flexural modulus of the blunt impacted samples without asphalt cover was 7354.78MPa; this was a reduction of 4.2%.

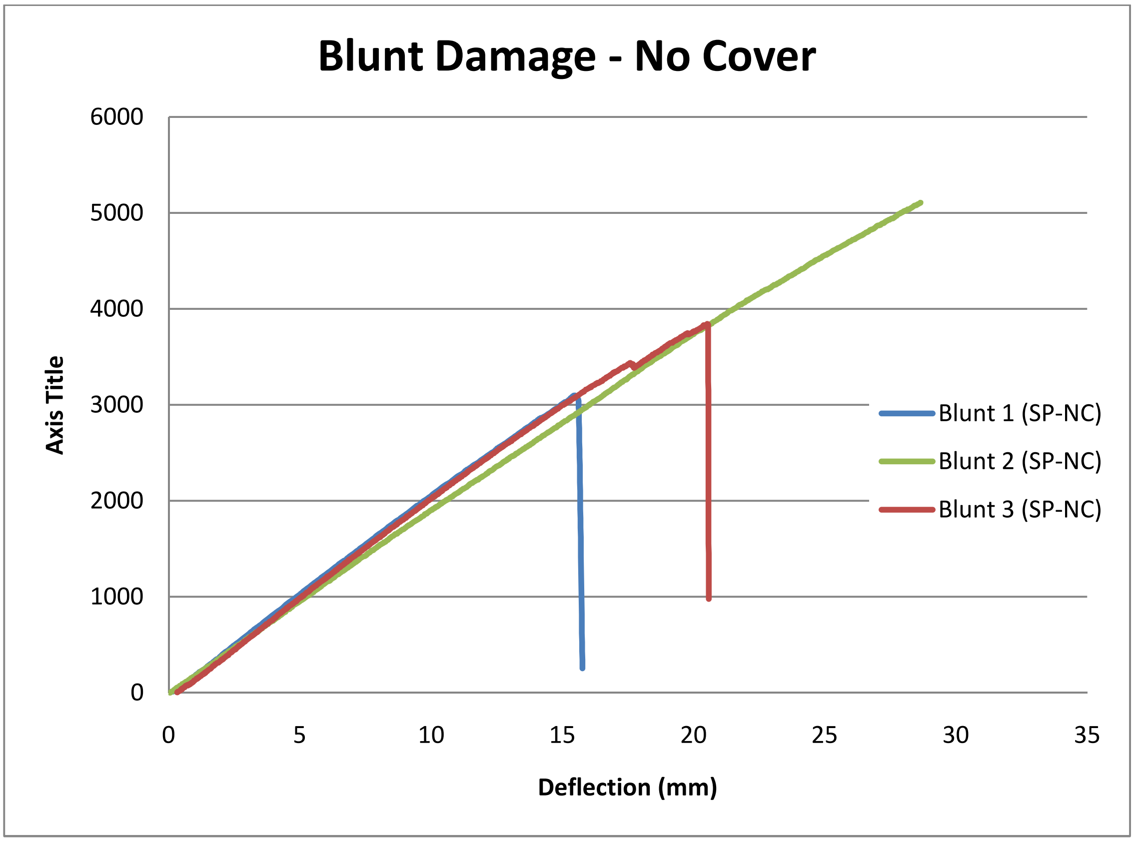

Figure 4.12 Blunt Damage without Cover

4.6 Sharp Impact Damaged Samples

Much like the blunt impacted specimen the asphalt covered specimen had a different failure to the control specimen as the samples had more of a ductile failure has the failure originated at the impact site. The sharp impact was very hard to reproduce by hand, was achievable but very difficult, especially if considered in real world the impact would be done above head and the screw driver swung upward. The only real way to achieve the same impacts as seen in figure 4.4 was to use a hammer as well as the screw driver. Damage was able to be achieved without the aid of a hammer if impact was repeated multiple times as the skin would chip away.

This ductile like failure can be best seen in figure 4.14 where the samples would fail and re-load as the cracks or tears would dissipate up the specimen. The literature reported that small strips would tear longitudinally up the specimen from the impact site; this can be seen in figure 4.13. This was what was found to be the case. As the load increased impact size strips would tear up the specimen which is seen in the multiple failure reloading spikes in the specimen.

Figure 4.13 Failure of Sandwich Composite with Cover Sharp Impact Damage

The sharp impacted covered samples had an ultimate strength of 3959N; this was a reduction of 19.5%. The covered samples had a flexural stiffness an indicator of the flexural modulus of 362N/mm; this is a reduction of 0.3%. As the ultimate load may be reduced the damage the overall flexural stiffness of the material remained unaffected by the damage.

The flexural modulus of the sharp impacted asphalt covered samples was 8217.30MPa; this is a reduction of 5.6%. For the flexural modulus Sharp 2 (SP-C) was neglected as the asphalt cover caused an increased stiffness as the asphalt thickness was larger in the centre section of the sample.

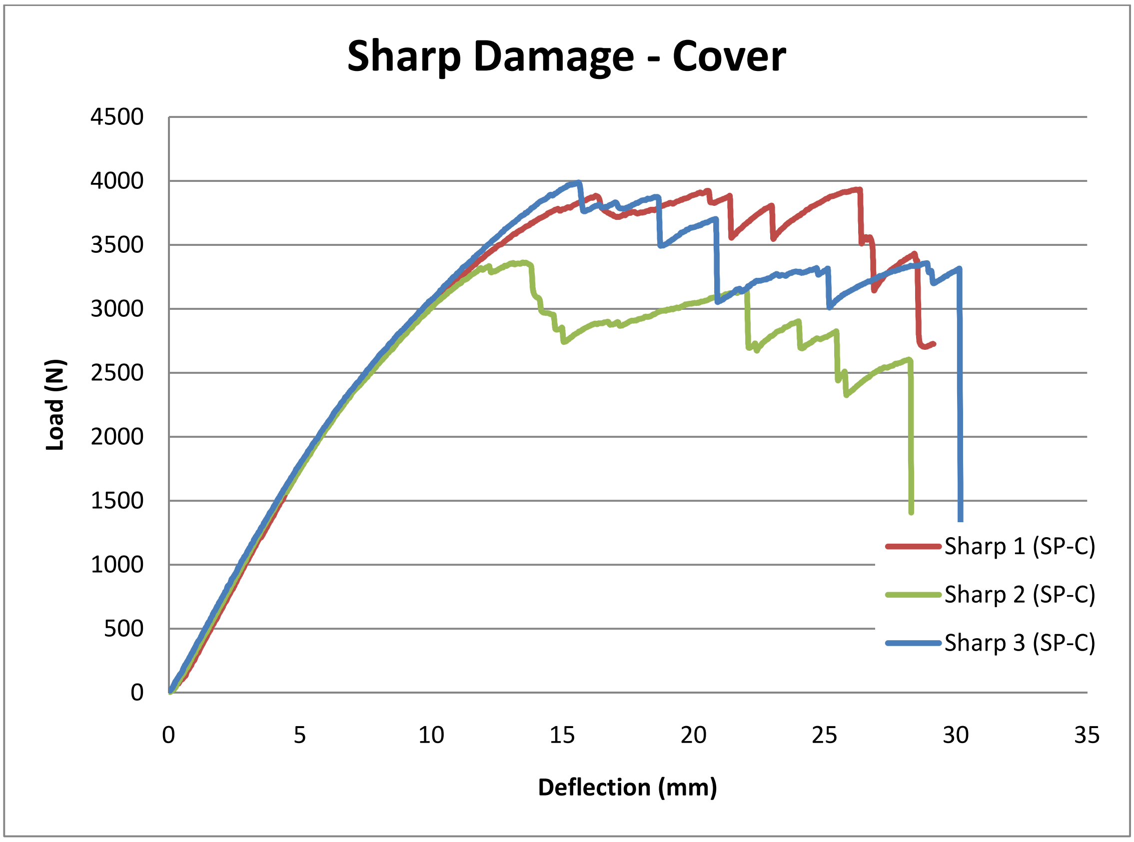

Figure 4.14 Sharp Damage with Cover

With the non covered samples the reduced compression stiffness caused the specimen to neglect the sharp impact damage and only reduce the ultimate load by a small margin, this is also apparent in the flexural stiffness.

This can be seen as the ultimate load for sharp impacted specimen is 4448N, sample Sharp 2 (SP-NC) was neglected in this calculation as the care had suffered damage and the load was reduced and caused the spread of results was too great. The flexural stiffness was 207N/mm an indicator of the flexural modulus. This is shown in the failures as they were a compression skin failure when at the ultimate load. The flexural modulus of the material 7157.62MPa, this was a reduction of 6.8%.

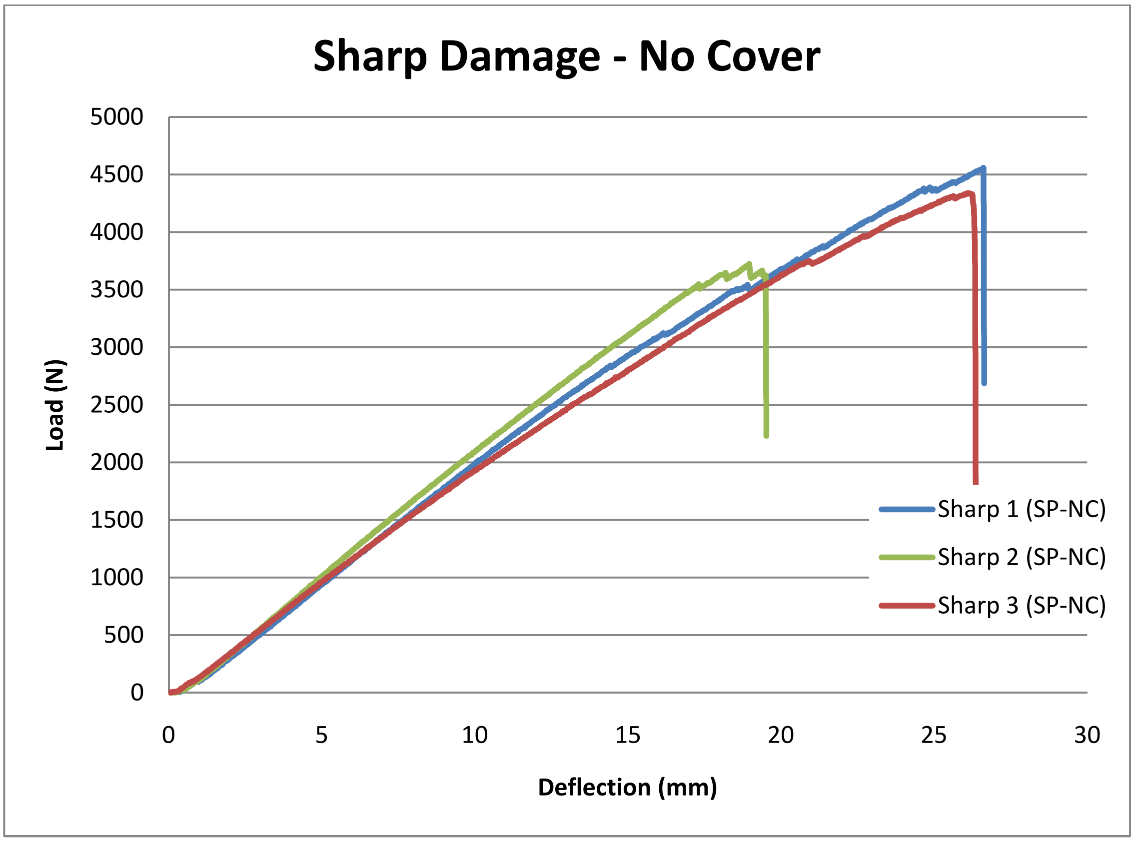

Figure 4.15 Sharp Damage without Cover

4.7 Cut Damaged Samples

The cut damaged samples had a varying degree in the ductile like failure which has distinguished earlier styles of damage. Some specimen showed a very ductile failure, this can be contributed to the varying nature of the damage.

Where the specimen had more depth in the cut and more fibres severed the effect was more noticeable. The cut had much the same effect as the blunt impact. Visible cracks were not observed as the crack was already started in the damage and this would be increased with more fibres breaking with increased load. This can be seen in figure 4.16 with the amount of broken fibres underneath the failed sample.

Figure 4.16 Sandwich Panel With Cover Cut damage

The cut damage was easy to achieve with a sharp knife or Stanley style knife. The damage could be easily increased especially after initial cut is achieved.

The covered samples had an ultimate load of 4609N; this was a reduction of 6.3%. The flexural stiffness an indicator of the flexural modulus was reduced to 343N/mm; this reduction was by 5.5%. The covered sandwich panels with cut damage had a flexural modulus of 7968.29MPa and this was a reduction of 8.4%.

It can be seen that sample Cut 2 (SP-C) failed in a manner like that of the sharp impact sample. Where the cut had penetrated more fibre sections would strip away causing the drops in load followed by reloading before ultimate failure.

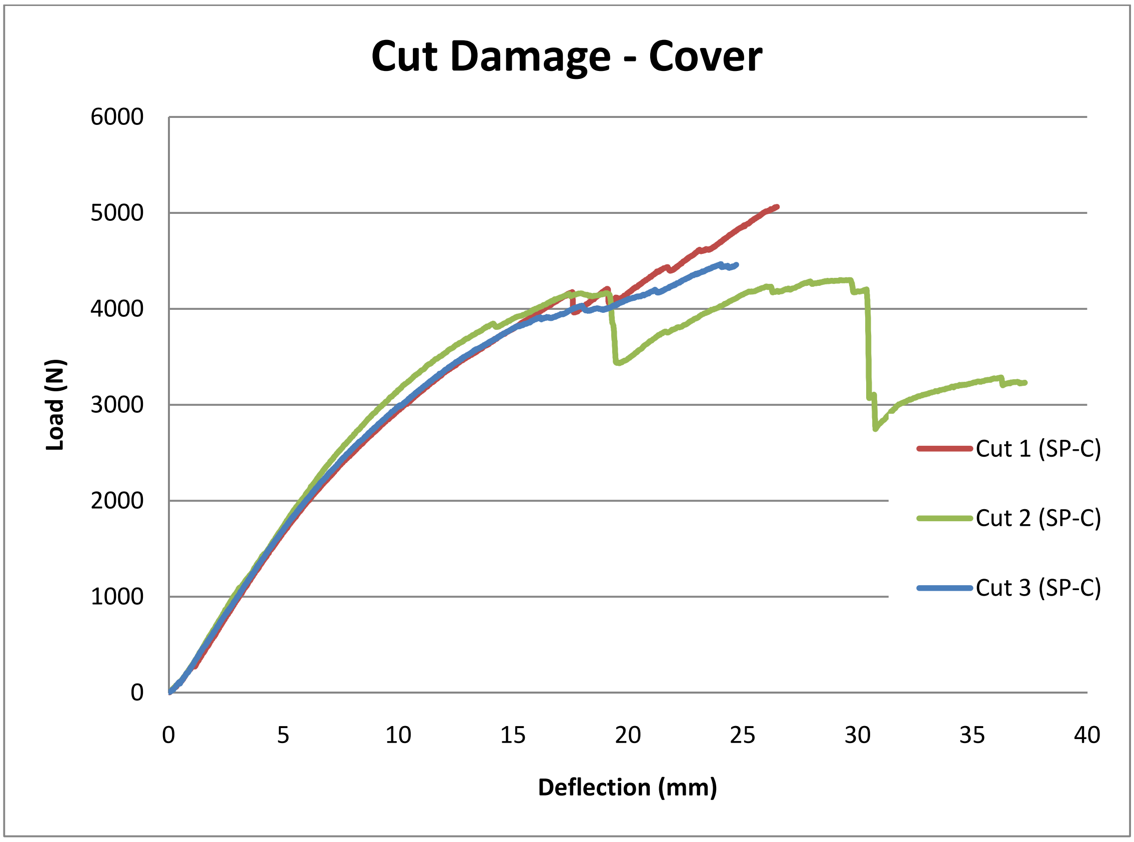

Figure 4.17 Cut Damage with Cover

The non covered samples had an ultimate load of 3833N, a 16.5% drop. The flexural stiffness an indicator of the flexural modulus is 205N/mm, a 2.2% drop. So this shows that the damage again has no effect until ultimate load. The non covered sandwich panel had a flexural modulus of 7160.28MPa which was a reduction of 6.8%.

The failure in Cut 1 (SP-NC) in figure 4.18 resembles that of the sharp impact samples as well. This was to a much smaller extent but small sections would strip away but not extend to far up the specimen.

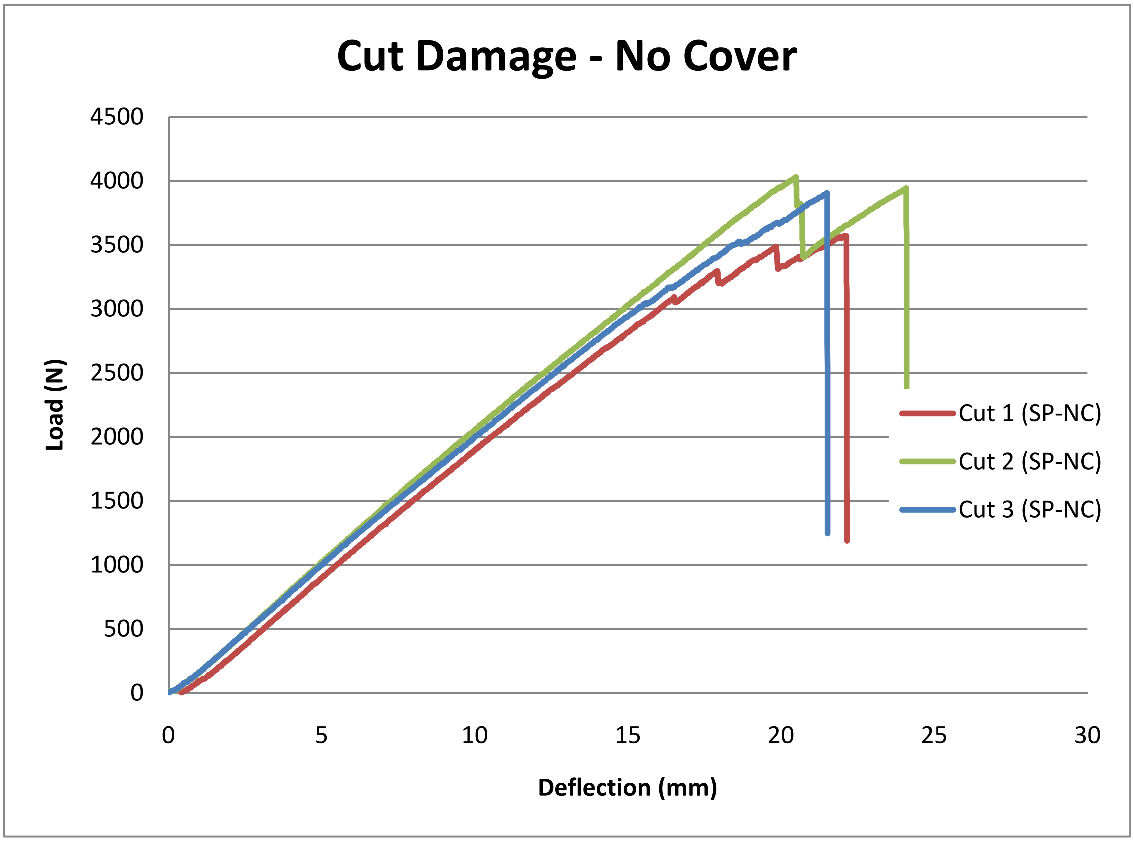

Figure 4.18 Cut Damage without Cover

4.8 Fire Damaged Samples

The fire damaged specimen showed similar failures to the cut damaged specimen. With the fire damage fibres were revealed and broken in some places and the skin cracked much like a cut. This is apparent in the variable failure modes.

The skin of the specimen was easy to burn using the lighter, with almost instant visible damage able to be achieved to the specimen. Firstly the skin would blacken and chips would fall from the burn zone, like the literature expressed the core would change colour in places. After the skin cracked the fibres would break and melt. This would take longer in a breeze but the effect would be the same.

For the covered specimen the ultimate load was 4867N, a 1% decrease. The flexural stiffness an indicator of the flexural modulus was decreased to 352N/mm, a 2.8% drop. The flexural modulus was 8109.20MPa and this was reduced by 6.8%. The failure in Fire 1 (SP-C) suggests a similar failure to that of the sharp impacts as well. The drop in load is a section that was damaged more than the other sections strips away and fails before the rest of the material and the ultimate failure.

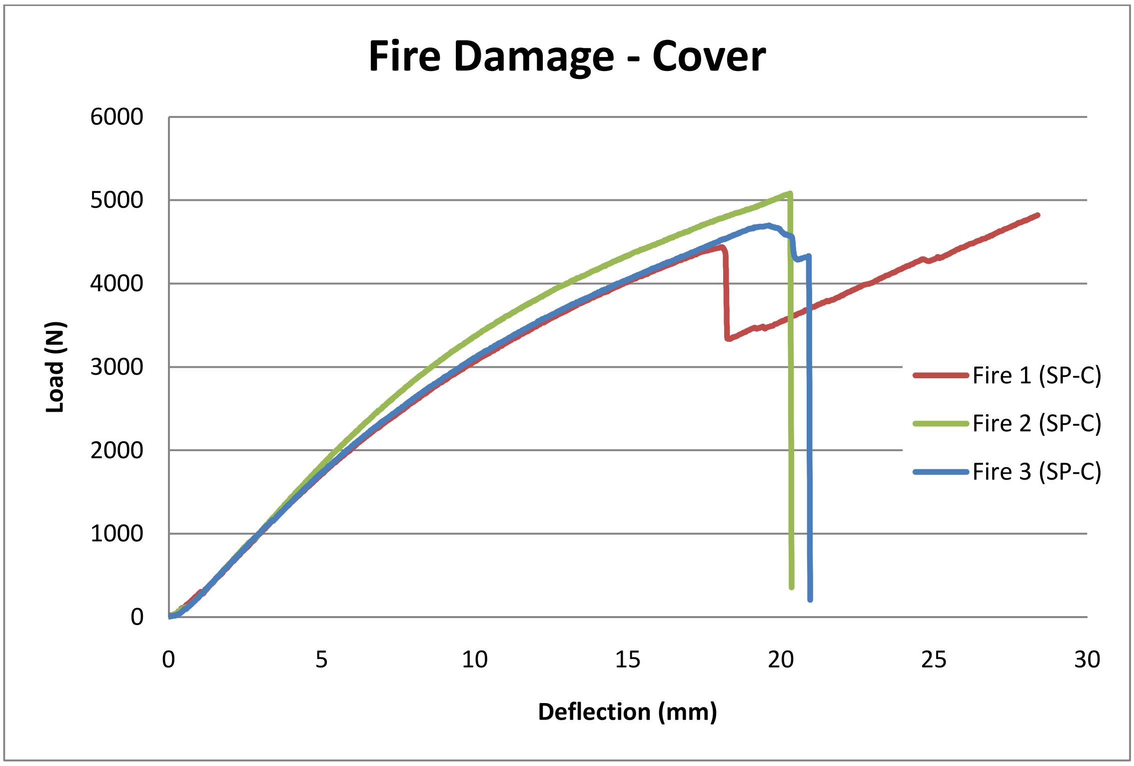

Figure 4.19 Fire Damage with Cover

The sandwich panel without cover had a flexural modulus of 7234.91MPa; this is a reduction of 5.8%. The failure of Fire 1 (SP-C) in figure 4.19 is also apart in a smaller scale in figure 4.20 in failures in samples Burn 2 (SP-NC) and Burn 3 (SP-NC).

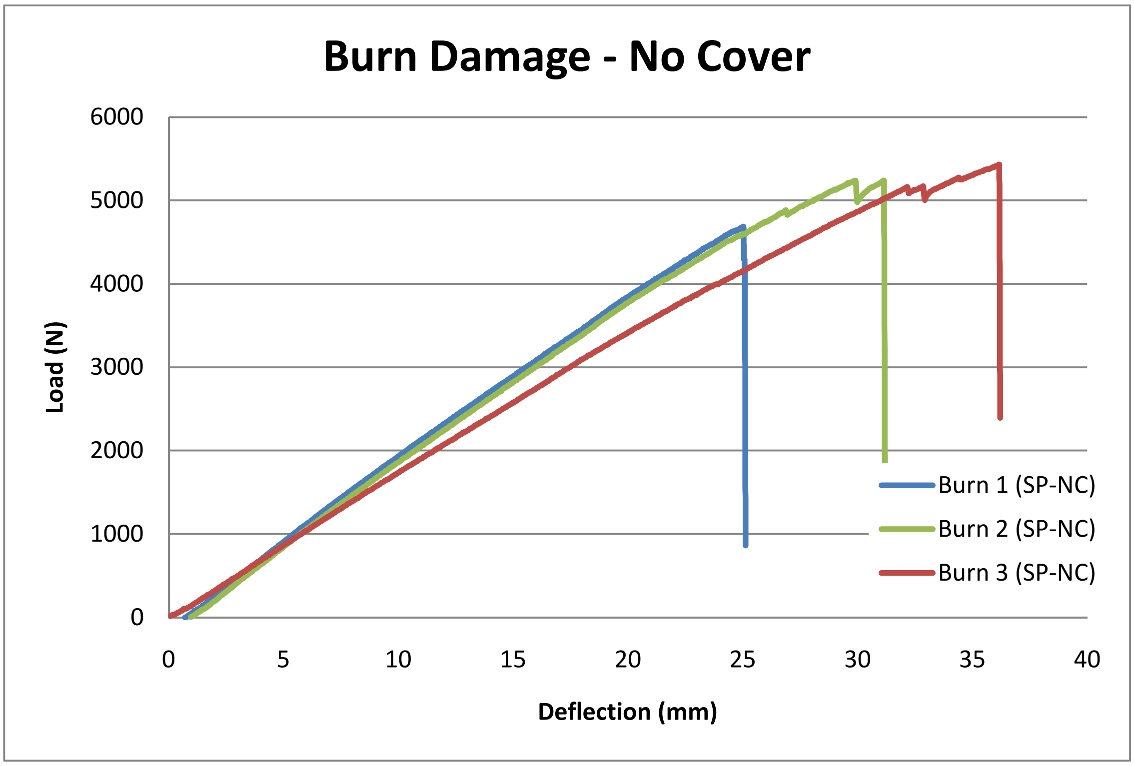

Figure 4.20 Fire Damage without cover

4.9 Ease of Damage

Damage Type	Ease
Blunt Impact	Very Hard
Sharp Impact	Very Hard
Cutting Damage	Easy
Fire Damage	Easy

Table 4.1 Ease of Damage to Sandwich Panels

4.10 Paint Remover

Both the asphalt covered and the non asphalt covered sandwich panels were treated to a thick coating of flat black enamel spray paint, typical off the shelf spray paint. It was allowed to dry.

Common fast acting paint remover was used for the removal of the spray paint. The paint remover was an off the counter paint remover and was a Dichloromethane mixture paint stripper. The instructions for the paint remover were followed and the paint was removed.

The results of the paint remover were that the majority of the paint was removed with great ease. With wire brushing during the paint removal the amount of paint removed is increased. Not all of the paint can be removed as some of the paint is soaked into the sandwich panel and is left after removal. There was no visible damage done to the sandwich panel from the paint stripper. There was no visible damage to the skin or core of the sample.

4.11 Conclusion

A total of 15 non covered and 15 asphalt covered specimen were tested using a range of different damages. The damages were of a blunt impact, a sharp impact, a Stanley knife cut and a bbq lighter burn. The effect ranged from very noticeable to visible but not effective.

The burning was the easiest to achieve visible damage but the actual effect of the burning was not as effective compared to the visible damage.

The cut was easy to achieve and the effect from a small cut was noticeable on both the ultimate load and flexural stiffness of the material.

The blunt impact was hard to achieve especially when considered in actual environment. To achieve the required damage when the vandal is required to do an up-swing to the product the ability to cause damage is severely hampered. But if achieved it could be very effective. The damage is very noticeable and the capacity is reduced heavily because of the damage to the core.

The sharp impact was much like the blunt impact where the effect was hard to achieve. The damage is achievable when combined with a hammer. The damage is achievable without the hammer but would take a large amount of impacts to achieve this.

The paint stripper was very effect of removing a large amount of the spray paint. There was residue of paint left after removal but there was no visible damage done to the specimen.

To confirm that these damages would cause the same effect to an entire slab element further research is needed. In case for the blunt and sharp impact to damage a sufficient amount of the slab to achieve the same results would be extremely hard. The same could be said about the burning from a bbq lighter. An effect would be achievable but the ultimate load and stiffness of an entire slab element would take a considerable time. The cut damage would be the most easiest to achieve especially once the outer layer has been cut away.

Chapter 5

Experimental Investigation into Fibre reinforced Pultruded Sections

5.1 Introduction

The first glass fibre reinforced pultruded sections used in this project are commercially available 100mm x 100mm in size. The pultrusions had a thickness of 5 mm and were approximately 1.2 m in length. These products were subjected to the same damage types as the sandwich panels.

5.2 Damage

For the pultruded section the samples were all damaged in the centre of the specimen on the tension side of the product; this was done as the samples would be placed in a flexure environment and the areas accessible to vandalism would be from beneath. The samples were prepared so that three samples were used as control or un-damaged samples. For each of the damage type's three samples were also used.

5.2.1 Blunt Impact

For the pultruded section the drop mass was not used. The damage was attempted using hand tools and human force only. This was done to ensure that if damaged the damage was real world feasible and also to ensure damage was not excessive.

The damage was done by using a similar hammer to the one used for the blunt impact damage done to the sandwich panels. The force used on the pultrusion started at a simple tap to a large impact. During all of the attempts at damage to the pultrusion it remained undamaged to the eye. It bounced the hammer away making it more dangerous for the vandal rather than the pultrusion itself.

5.2.2 Sharp Impact

The sharp impact was also done by hand. This was done to ensure the damage was also feasible in real world situations. The damage was again on the tension side of the sample.

This time the sharp impact was done using both a screw driver and a hammer. The hammer was used to impact the screw driver in the sample to a 1-2mm depth. This was done along the centre line of the sample; this can be seen in figure 5.1.

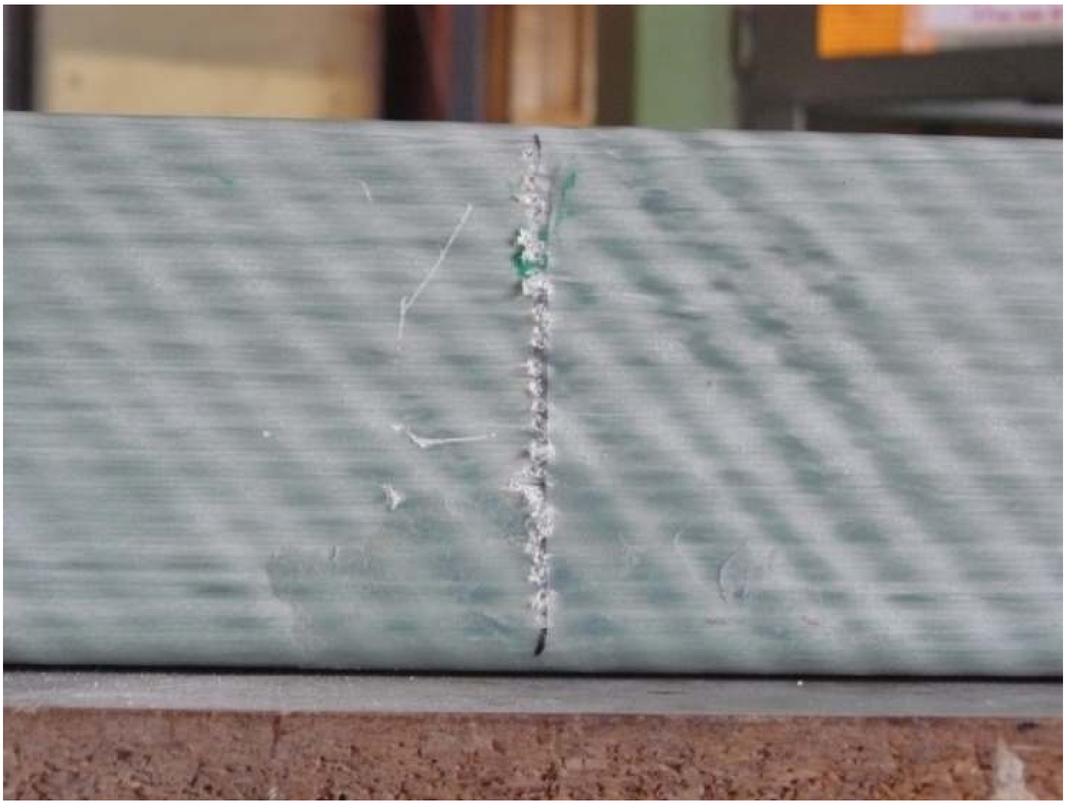

Figure 5.1 Sharp Impact on 100x100mm section

This damage was easy to achieve using the combined force of the hammer and the screw driver. Without the hammer the sharp impact was much like the blunt impact and was very hard to achieve.

5.2.3 Cut Damage

The cut damage was also done using a Stanley knife. The cut was three 1-2mm cuts along and beside the centre line. This can be seen in figure 5.2. The cut damage was very easy to achieve using the Stanley knife, especially when the outer skin of the pultrusion has been cut away in inner white material is easy to get through.

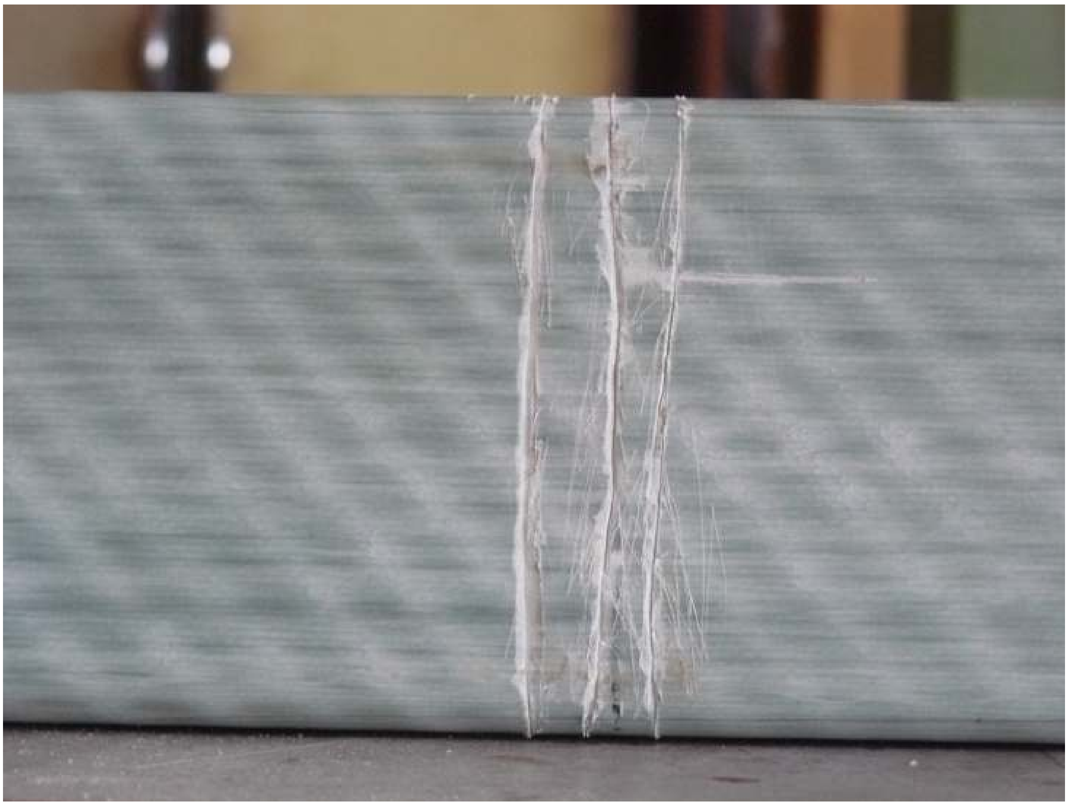

Figure 5.2 Cut Damage to 100x100mm section

5.2.4 Fire Damage

The fire damage was done by using the bbq lighter. The flame was kept on the material for 10min with no effect other than smoke discolouration on the burn site. The flame was not able to reach a high enough temperature to cause visible damage especially if attempted in any wind.

If the pultrusion was subjected to higher temperature the material is not immune and very susceptible to the flame like all epoxy resins. This was able to be achieved using a hand oxy torch but this type of damage was not tested as this was not deemed to be a reasonable or feasible vandal tool.

5.3 Flexure Testing

The specimens as explained earlier were tested in flexure only. This was set at a 1 m span with the load at 1500 mm from the centre at both sides. This can be seen in figure 5.3.

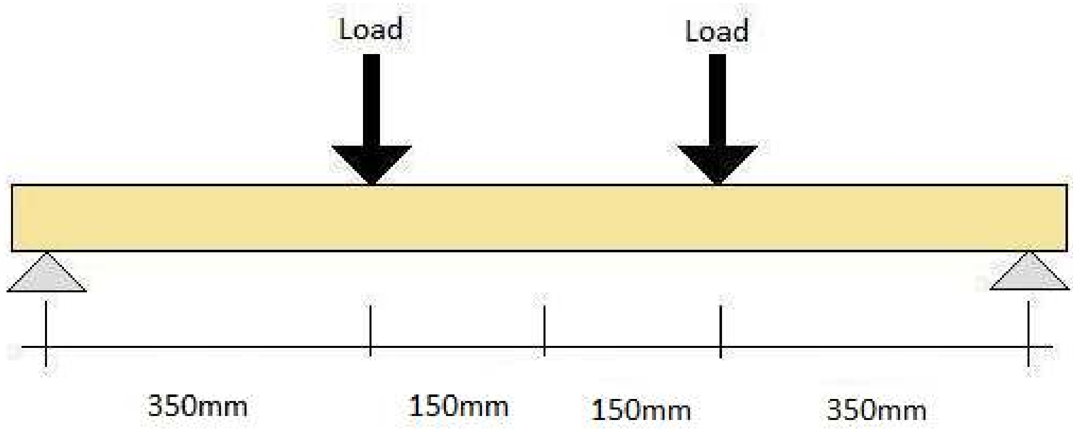

Figure 5.3 Flexure test on 100x100mm section

5.4 Control Samples

Three control samples were tested as explained earlier to provide a control or standard to measure the effect the damage had on the specimen. The failures of the specimen were of a buckling type failure in the compression side of the sample. This buckled and caused the sides of the samples to also buckle. The points under the loads buckled and had a crashing failure.

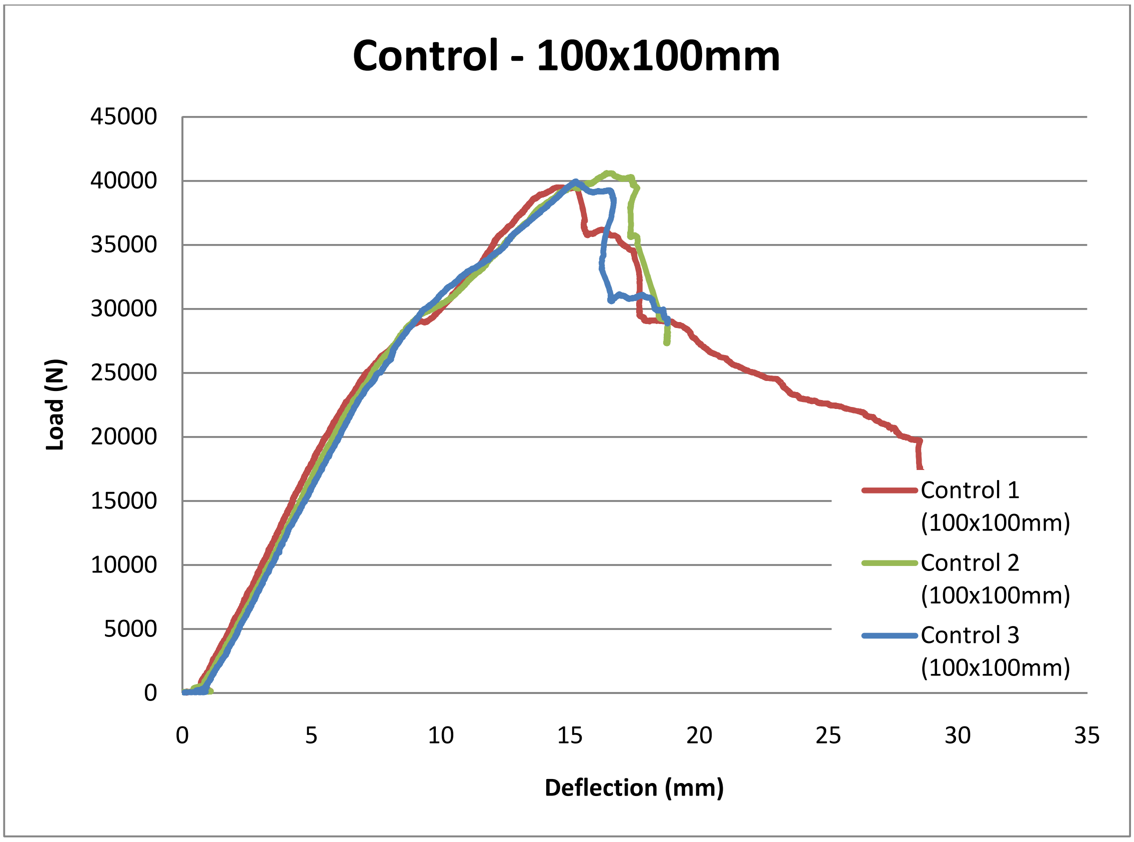

Figure 5.4 Control Results of 100x100mm section

At approximately 8mm of deflection the samples began to buckle and crush around the load points. This continued as the side walls buckled which led to ultimate failure. The control samples had an ultimate load of 40 068N. The samples also had a flexural stiffness of 3 896N/mm; an indicator of the flexural modulus. The control samples had a flexural modulus of 19 731.07MPa.

5.5 Blunt Impact Damaged Samples

The blunt impact damaged samples also had the same failure mode as the control samples. This was not unexpected as the blunt impact did no visible damage to the samples.

The damage if any was not visible and the failure of the samples did not originate at the damage site.

The ultimate load of the samples was 38 407N and the samples had a flexural stiffness an indicator of the flexural modulus of 3 870N/mm. The flexural modulus of the blunt damaged samples is 23123.84MPa. This is a small amount smaller than the control samples but is not deemed to be because of the damage.

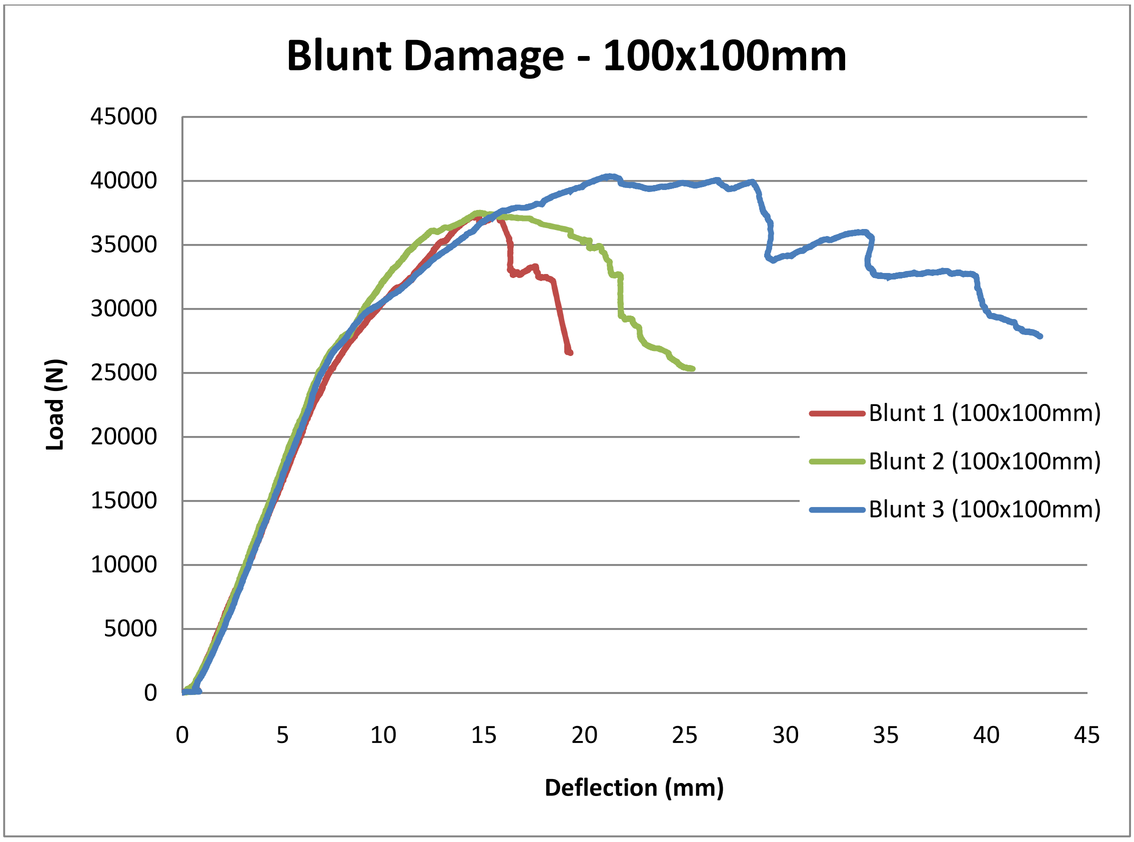

Figure 5.5 Blunt Damaged Results of 100x100mm section

5.6 Sharp Impact Damaged Samples

The sharp impacted samples had the same failure as the control and as the blunt impacted samples. The damage seemed to not contribute to the failure of the samples. The failures did not originate at the damage site. Once failed the damage site still remained as if it were only just damaged.

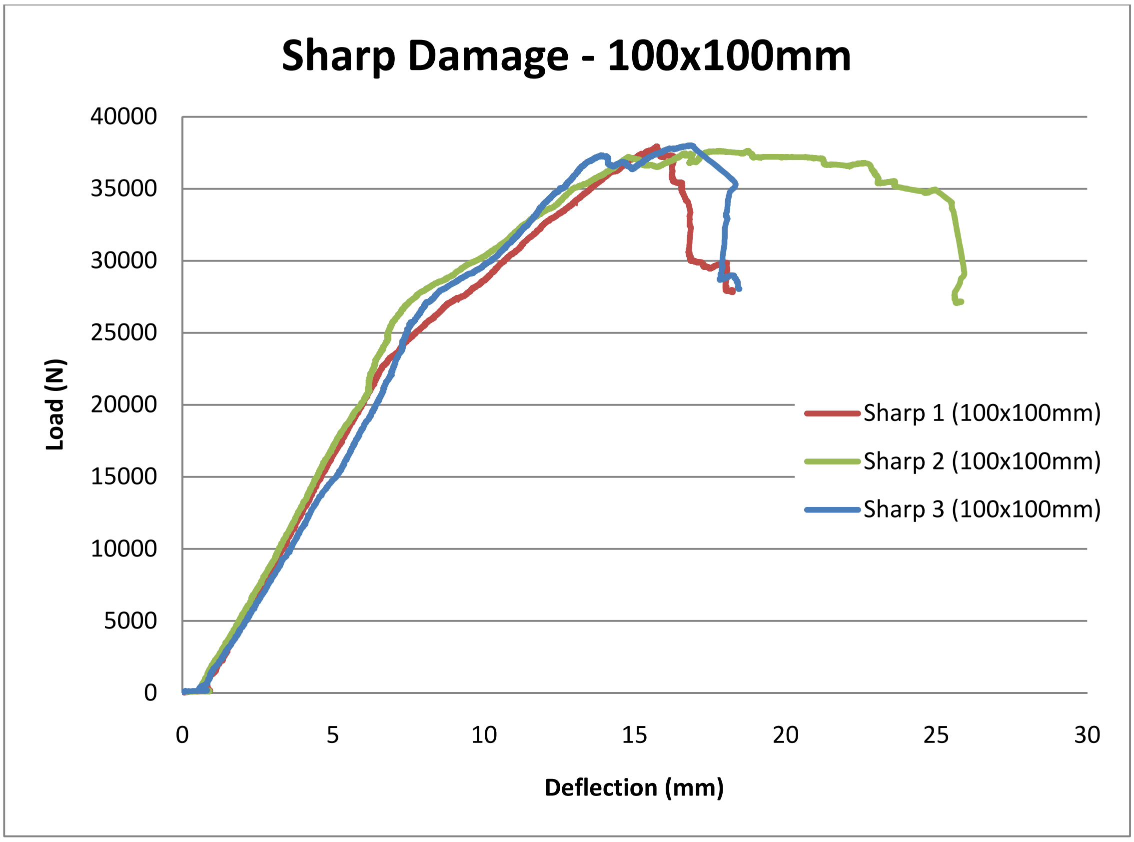

Figure 5.6 Sharp Damaged Results of 100x100mm section

The sharp impacted sample had an ultimate load of 37 850N. The samples had a flexural stiffness an indicator of the flexural modulus of 3830 N/mm, the flexural modulus of the material is 22 169.43MPa. This confirms the damage had no effect on ultimate load or flexural stiffness as the difference is marginal.

5.7 Cut Damaged Samples

With the cut damage the samples also failed in a buckling type mode. With like the other types of damage the areas of damage did not contribute to the failure of the sample at any stage of the testing.

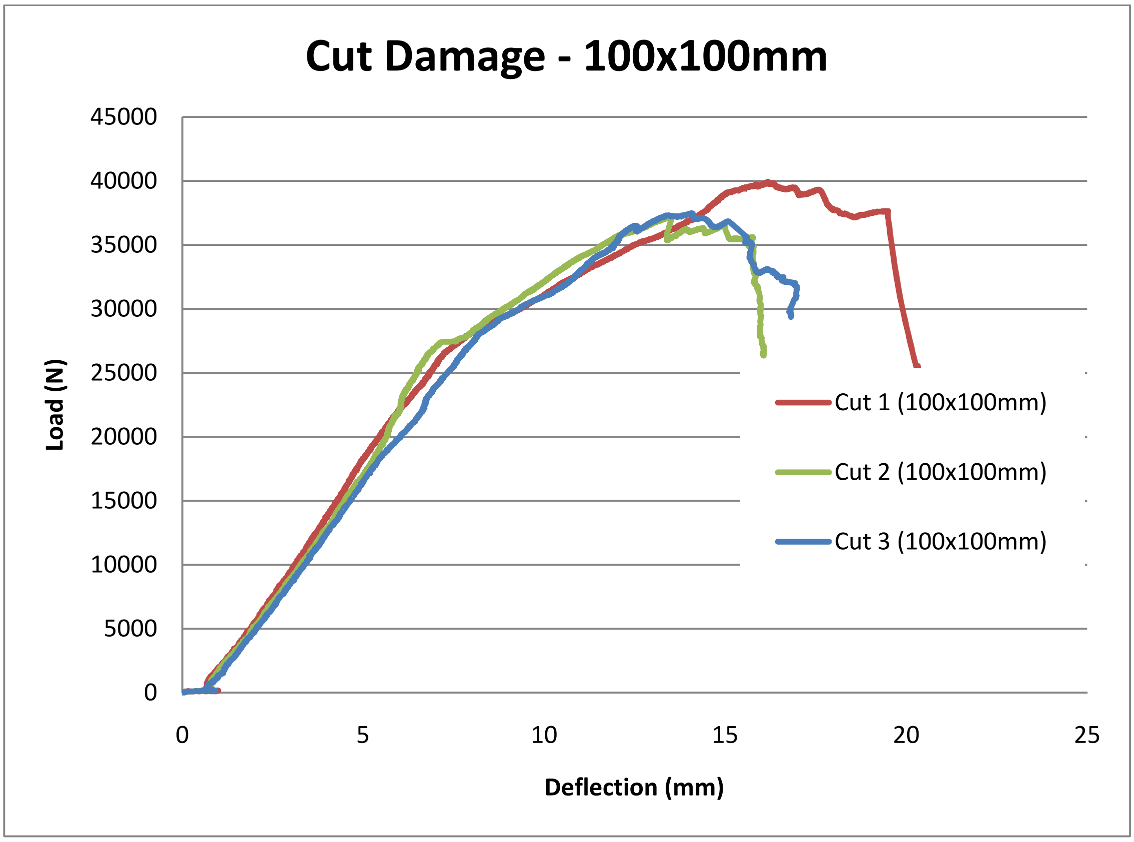

Figure 5.7 Cut Damaged Results of 100x100mm section

The ultimate load of the cut damaged samples was 38 184N with a flexural stiffness an indicator of the flexural modulus of 3863N/mm. This damage again had no effect on either the ultimate load or flexural stiffness as the failure mode is the same and the difference in ultimate load and flexural stiffness is marginal.

5.8 Fire Damaged Samples

With no visible damage recorded the expectation was the fire samples would fail identical to the other types of damage and this was the case. The burn site did not contribute to the failure of the samples.

At approximately 7mm of deflection the samples began to buckle and crush around the load points. This continued as the side walls buckled which led to ultimate failure.

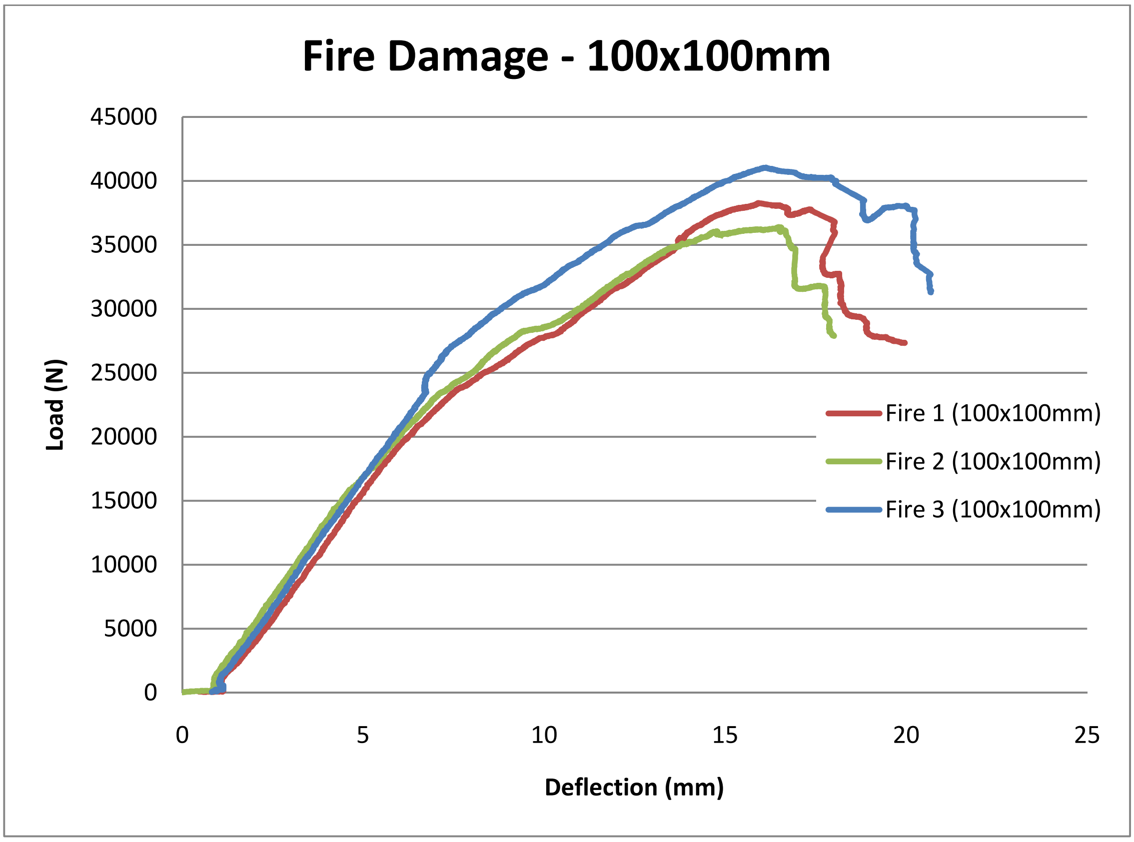

Figure 5.8 Fire Damaged Results of 100x100mm section

The fire damaged samples had an ultimate load of 38 574N and a flexural stiffness an indicator of the flexural modulus of 3958N/mm, with the flexural Modulus of the fire damaged samples is 23 535.95MPa. This damage again had no effect on the samples as the ultimate load; flexural stiffness and failure mode were near identical to the other specimen.

As the fire damage was immune to low degrees of heat such like the heat from the bbq lighter, higher temperatures are significantly more dangerous. The heat from a hand held oxy torch cause great damage and causes the pultrusion to catch alight for short periods of time.

5.9 Ease of Damage

Damage Type	Ease
Blunt Impact	Extremely Hard
Sharp Impact	Very Hard
Cutting Damage	Easy
Fire Damage	Extremely Hard

Table 5.1 Ease of Damage to 100x100mm section

5.10 Paint Remover

The 100x100mm section was treated to a thick coating of flat black enamel spray paint, typical off the shelf spray paint. It was allowed to completely dry.

Common fast acting paint remover was used for the removal of the spray paint. The paint remover was an off the counter paint remover and was a Dichloromethane mixture paint stripper. The instructions for the paint remover were followed and the paint was removed.

The results of the paint remover were that the majority of the paint was removed with great ease. With wire brushing during the paint removal the amount of paint removed is increased. Only a very small amount of paint is left as it is soaked in, shorter the time between vandalism and cleaning would limit this. There were no obvious signs of damage though the sample looked cleaner than original suggesting discolouration and potential removal of some of the outer layer of specimen. This was marginal and only small amounts not visible layers.

5.11 Conclusion

A total of 15 specimens were tested using a range of different damages. The damages were of a blunt impact, a sharp impact, a Stanley knife cut and a bbq lighter burn.

The blunt impact was very hard to achieve especially when considered in actual environment, could be classified as immune to a normal attack. The sharp impact was much like the blunt impact where the effect was extremely hard to achieve. The samples could be classified as immune to burn damage from a bbq lighter or similar product especially when considered in the actual environment.

The cut however was easy to achieve, this would be the easiest damage type to get a result with. Especially once the outer skin or cover was cut.

The paint removal was able to easily remove the spray paint. The removal method looked to not affect the pultrusion.

All samples failed due to buckling and not as a result of the damage. All sample had ultimate load of around the 38 000 N and a flexural stiffness of 3 900 N/mm. Because of this common failure mechanism further research with larger specimen is needed to ensure that there is no effect from the damage.

Chapter 6

Experimental Investigation into Fibre reinforced Pultruded Sections

6.1 Introduction

The fibre reinforced pultruded sections used for this project were commercially available sections. Two different forms of pultrusion were used. One of the sections used was a 50x50mm square section with a 6mm thickness. The other section used was a wall panel. The wall panel was 460mm wide with a 40x40mm square section at each side with a 65x40mm section in the middle as stiffeners, all of which had a 2mm thickness. Both of these products differed significantly to that of the 100x100mm pultruded composite.

6.2 Damage

The 50x50mm samples were all damaged in the centre of the specimen on the tension side of the product; this was done as the samples would be placed in a flexure environment and the areas accessible to vandalism would be from beneath. The wall panels however were damaged on the compression side of the samples as this is the only side that would be accessible to damage.

The samples were prepared so that three samples of the 50x50mm section and two of the wall panel were used as control un-damaged samples. For each of the damage type's on the 50x50mm section three samples were used and two for each of the damage types were used for the wall panel.

6.2.1 Blunt Impact

All the pultrusions were damaged by hand to ensure the damage was feasible. The 50x50mm sections were damaged in the centre of the specimen. They were only impacted once. This was done using a moderate amount of force. A small imprint was left on the surface of the specimen showing that the sample crushed at the point a small amount.

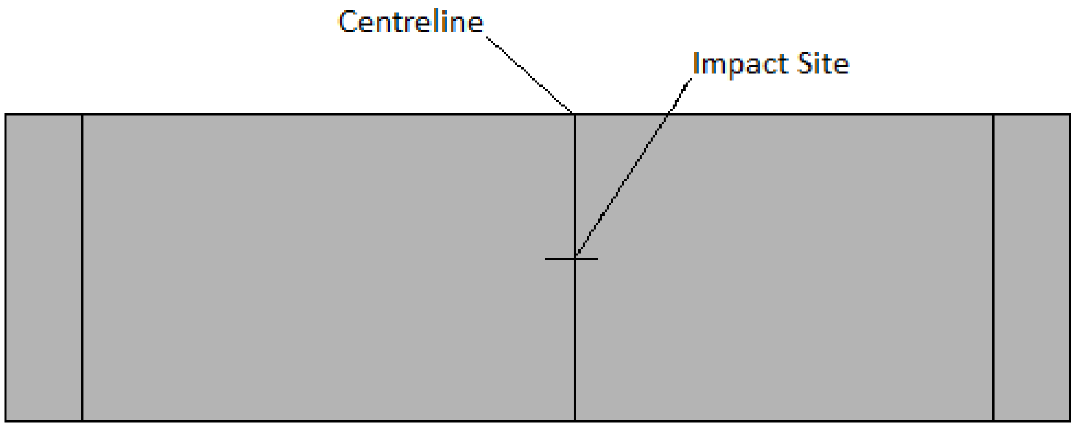

Figure 6.1 Blunt Impact Schematic (50x50mm Section)

The wall panel was impacted 9 times, three impacts on each of the stiffeners, on and around the centre line. This left the same indent as on the 50x50mm section. The area between the impact sites was unable to be damaged as the section was too flexible for the hammer to damage. This meant 68% of the specimen was immune to the blunt impact. The impact on the wall panel can be seen in figure 6.3.

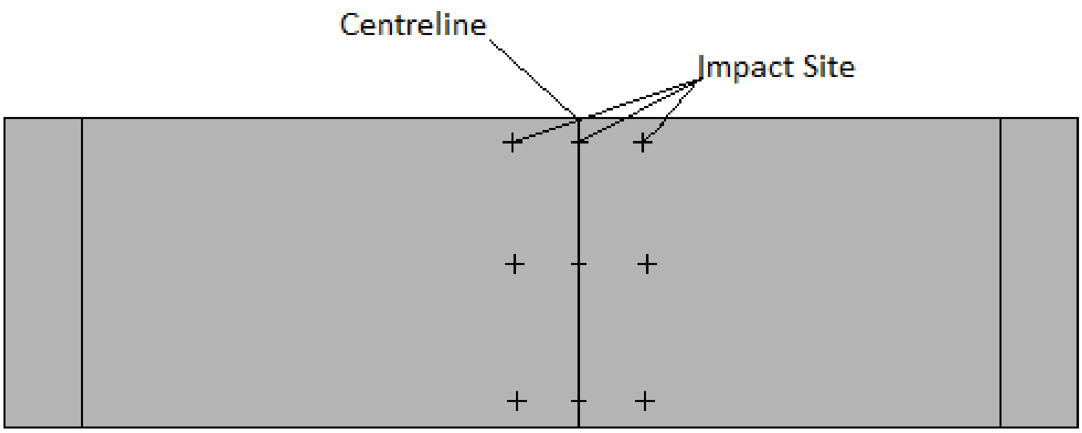

Figure 6.2 Blunt Impact Schematic (Wall Panel)

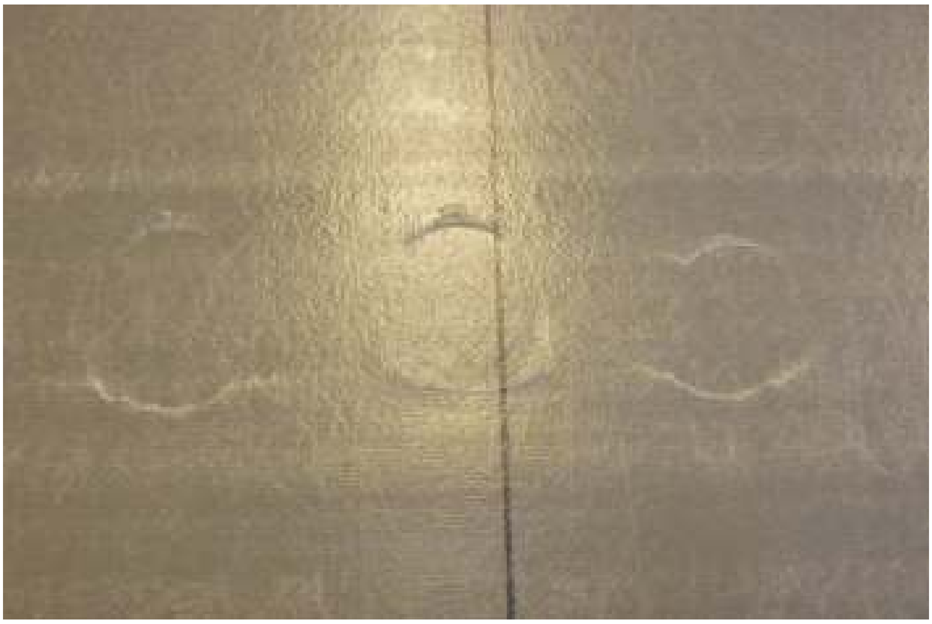

Figure 6.3 Blunt Impact Damage to Exel Composite

6.2.2 Sharp Impact

The sharp impact was also done by hand. This was done to ensure the damage was also feasible in real world situations. The damage was again on the tension side of the sample for the 50x50mm sections and done on the compression side again for the wall panel.

This time the sharp impact was done using both a screw driver and a hammer. The hammer was used to impact the screw driver in the sample to a 1-2mm depth. This was done along the centre line of the sample; this can be seen in figure 6.5 for the wall panel. For the 50x50mm section four rows of three impacts were done along the centre line of the specimen. This can be seen below in figure 6.4.

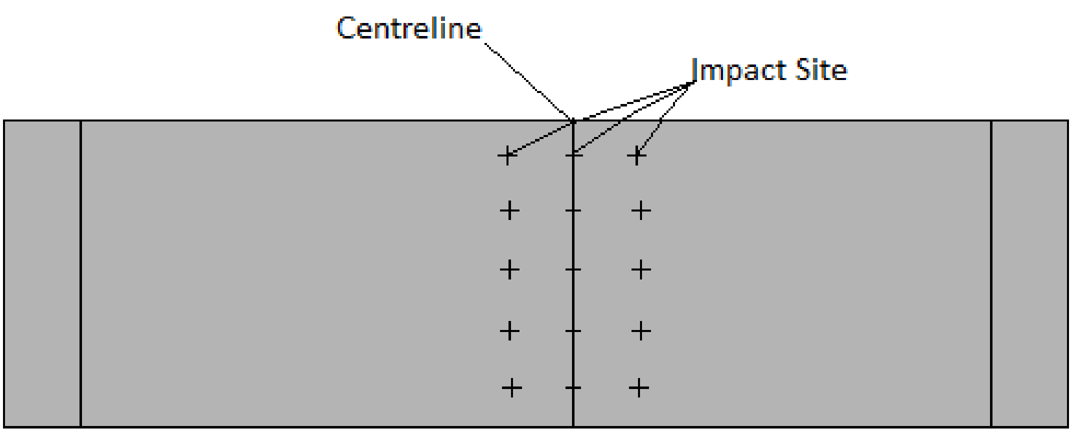

Figure 6.4 Sharp Impact Schematic (50x50mm Section)

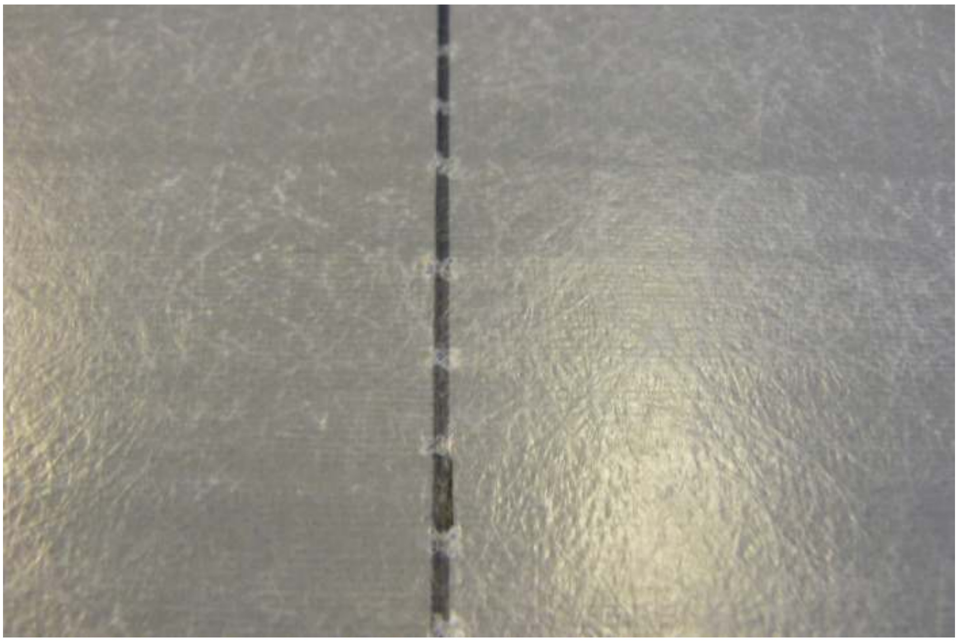

Figure 6.5 Sharp Impact to Exel Composite

6.2.3 Cut Damage

The cut damage was also done using a Stanley knife. The cut was three 1-2mm cuts along and beside the centre line for the 50x50mm section. The wall panel was cut the same but only to a depth of 1mm, it was also cut 7 times around the centre line, this can be seen in figure 6.6. The cut damage was very easy to achieve using the Stanley knife, especially when the outer skin of the pultrusion has been cut away in inner white material is easy to get through.

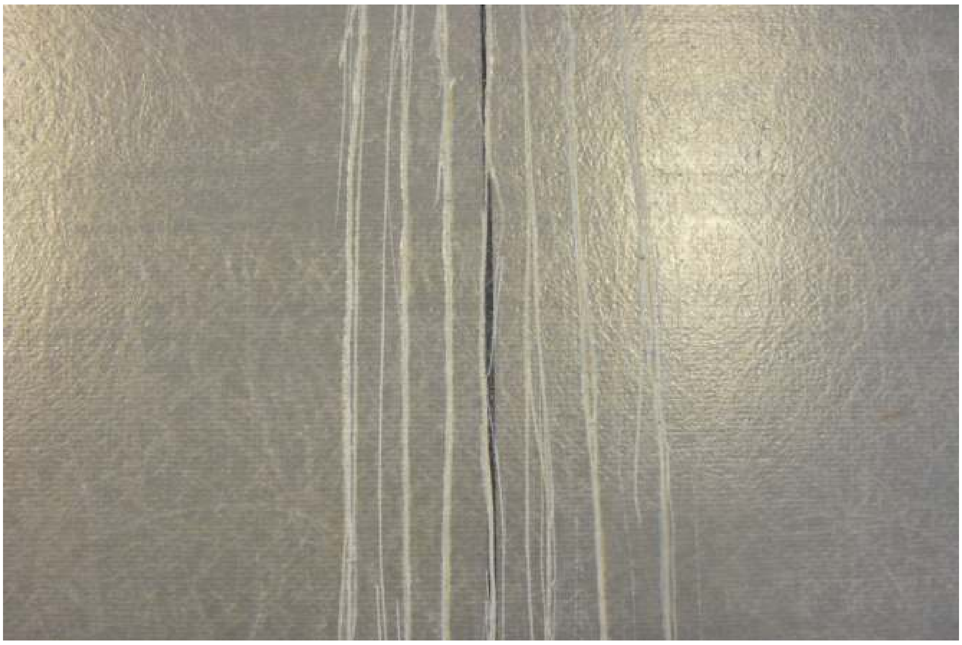

Figure 6.6 Cut Damage to Exel Composite

6.2.4 Fire Damage

The fire damage was done by using the bbq lighter. The flame was kept on the material for 5min there was a small section that had a melted appearance. The flame was not able to reach a high enough temperature to cause mass amounts of damage especially if attempted in any wind.

The amount of damage that was caused by the bbq lighter in 5 min made the bbq lighter against the wall panel unfeasible as it would take some 45min to achieve a limited amount of damage especially when considered in wind.

6.3 Flexure Testing

The specimens as explained earlier were tested in flexure only. This was set at a 1 m span with the load at 40 mm from the centre at both sides. This can be seen in figure 6.7.

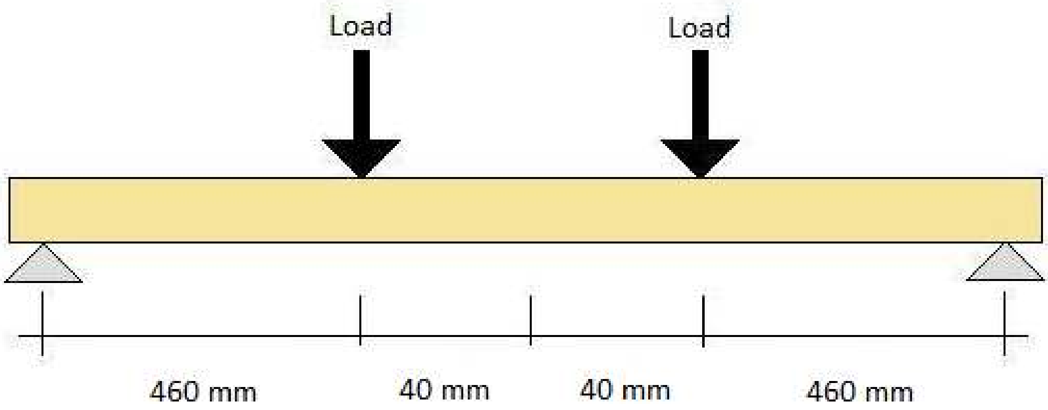

Figure 6.7 Flexure Testing of Exel Composites

6.4 Control Samples

For the 50x50mm section three samples were tested and two wall panels were tested without damage to provide the standard. Both the 50x50mm section and the wall panel had a very sudden failure as can be seen from figure 6.8 and figure 6.9 with the sudden drop in load capacity.

The 50x50mm section failed due to a tear in the tension side followed by shear cracks or tears up the side walls of the section. Complete failure when the side tears reached the top compression section which had a crushing type failure.

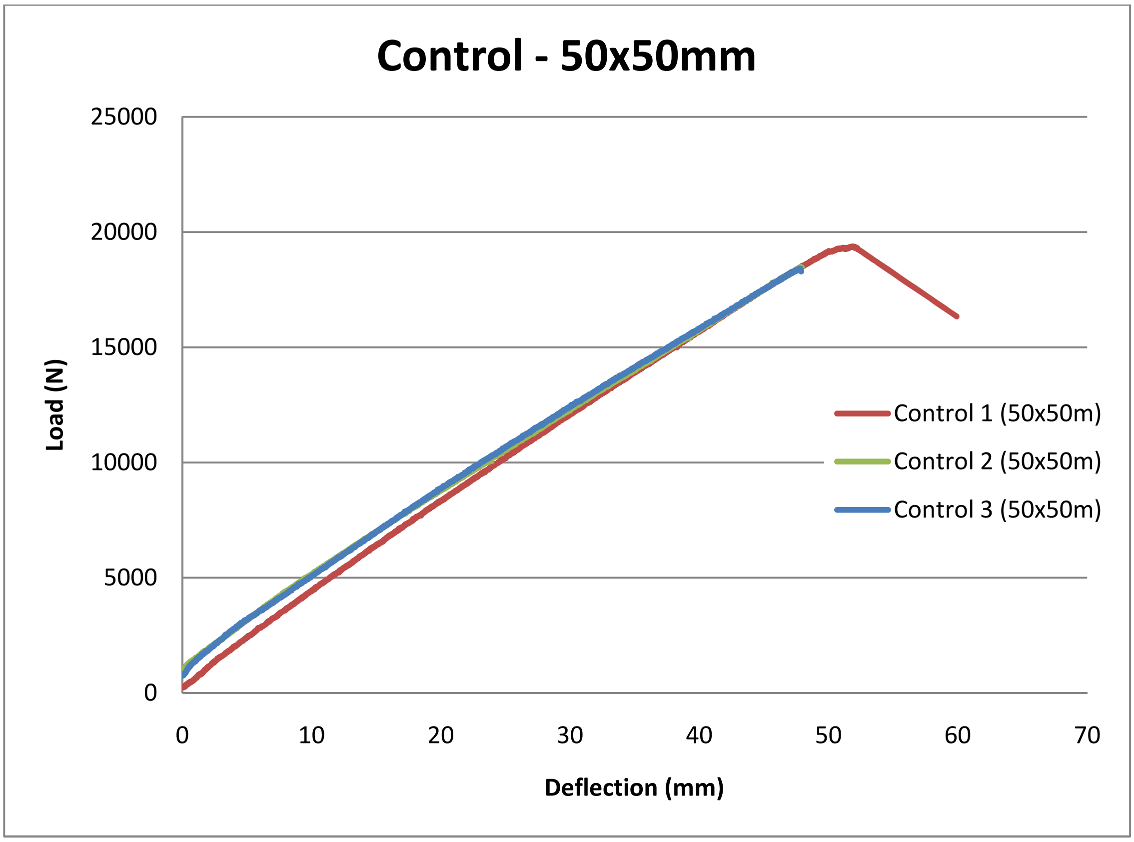

Figure 6.8 Control Results of 50x50mm Samples

The 50x50mm sections had an ultimate load of 18 758N and a flexural stiffness an indicator of the flexural modulus of 432N/mm. The control samples also had a flexural modulus of 19 731.07MPa. The failure of the sample was very sudden as can be seen in figure 6.8 by the very sudden decrease in load capacity. There were no signs of failure before ultimate failure for the control samples.

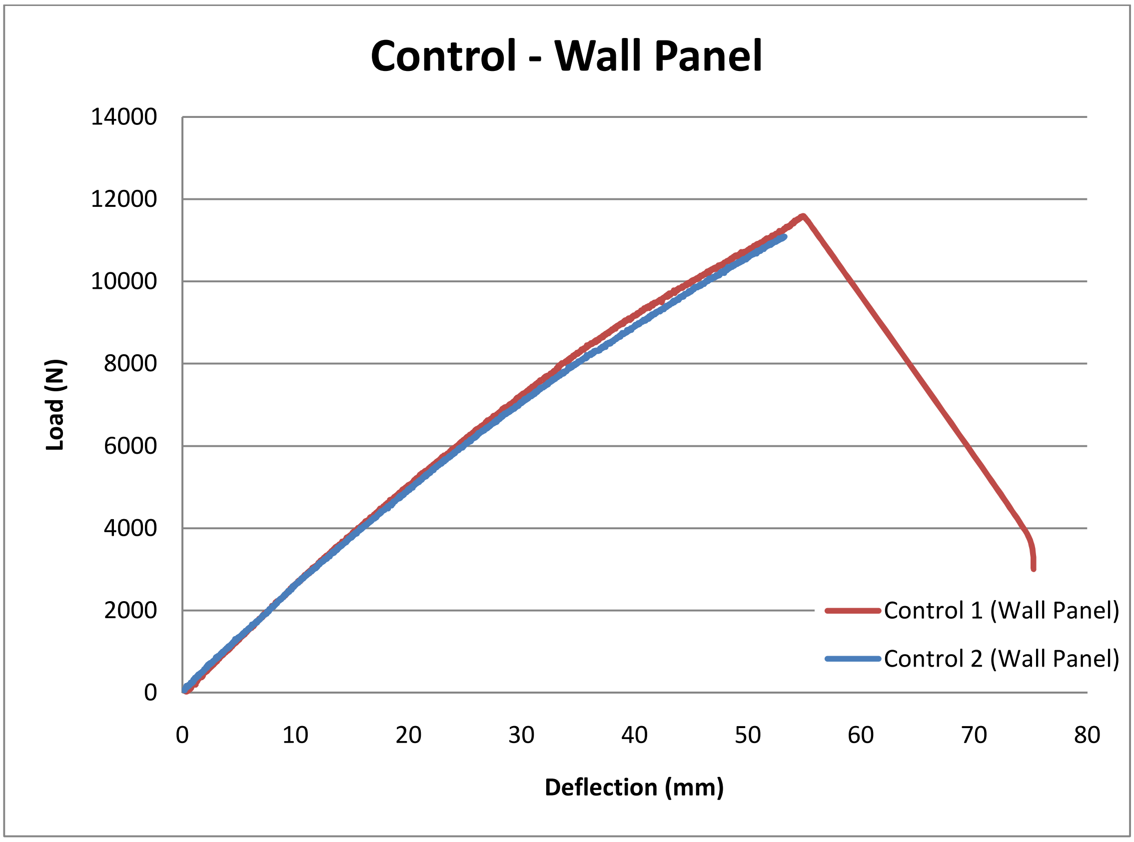

Figure 6.9 Control Results of Wall Panels

The wall panels had an ultimate load of 11 532N, with a flexural stiffness an indicator of the flexural modulus of 255N/mm. The control wall panels had a flexural modulus of 5706.9MPa. The failure was a sudden failure much like that of the 50x50mm sections. There is a change in flexural stiffness and this is when the stiffening sections begin showing tears and cracks forming.

6.5 Blunt Impact Damaged Samples

The blunt impact damaged samples also had the same failure mode as the control samples. The blunt impact left a small indent in the tension skin. The failure of the sections originated on the edge of this impact site. The impact has cracked and began the tear; this was the case for all three sections.

The ultimate load of the 50x50mm samples were 18 883N and the samples had a flexural stiffness of 464N/mm; an indicator of the flexural modulus. The flexural modulus of the material is 20 926.09MPa. This is no decrease from the control samples. Therefore as the damage may have been visible and been the site for the failure to occur the actual ultimate load and flexural stiffness and the flexural modulus of the section was not affected by the damage.

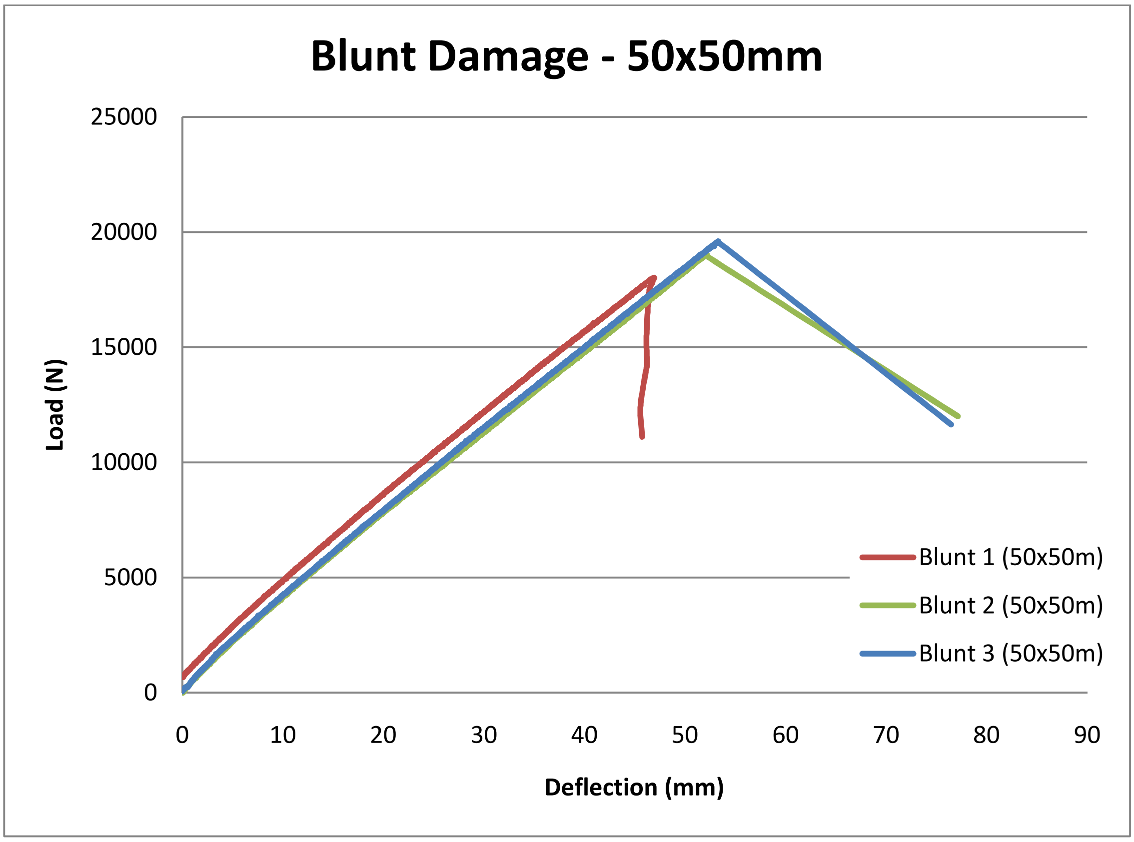

Figure 6.10 Blunt Impact Results of 50x50mm Samples

The wall panels had an ultimate load of 9 347N, 18.9% decrease in average ultimate load and a flexural stiffness an indicator of the flexural modulus of 258N/mm, no decrease. The wall panel also had a flexural modulus of 5783.1MPa. Therefore the wall panel unlike the 50x50mm section had a significant decrease in ultimate load where as the flexural stiffness and flexural modulus of the material was not affected. Like the 50x50mm section the wall panel's damage sites were the originators of the damage. The failure in the compression side followed the blunt impact edges; this can be seen in figure 6.11.

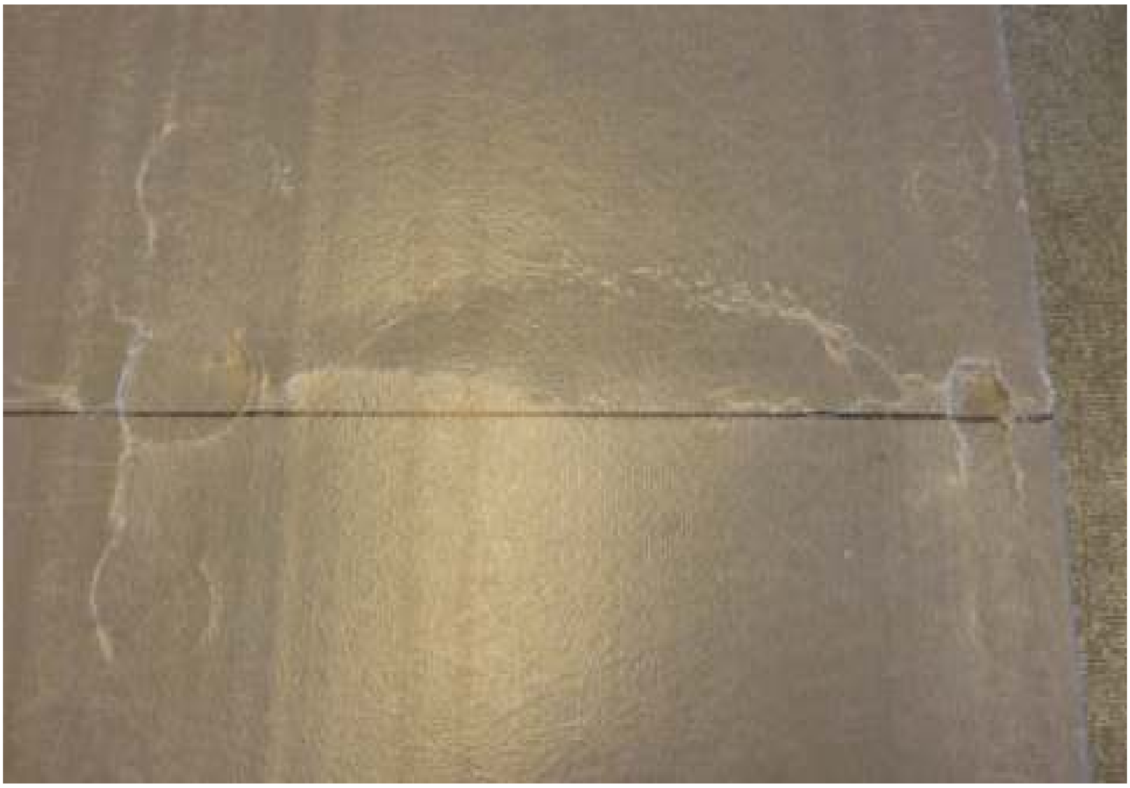

Figure 6.11Blunt Impact Failure on Wall Panel

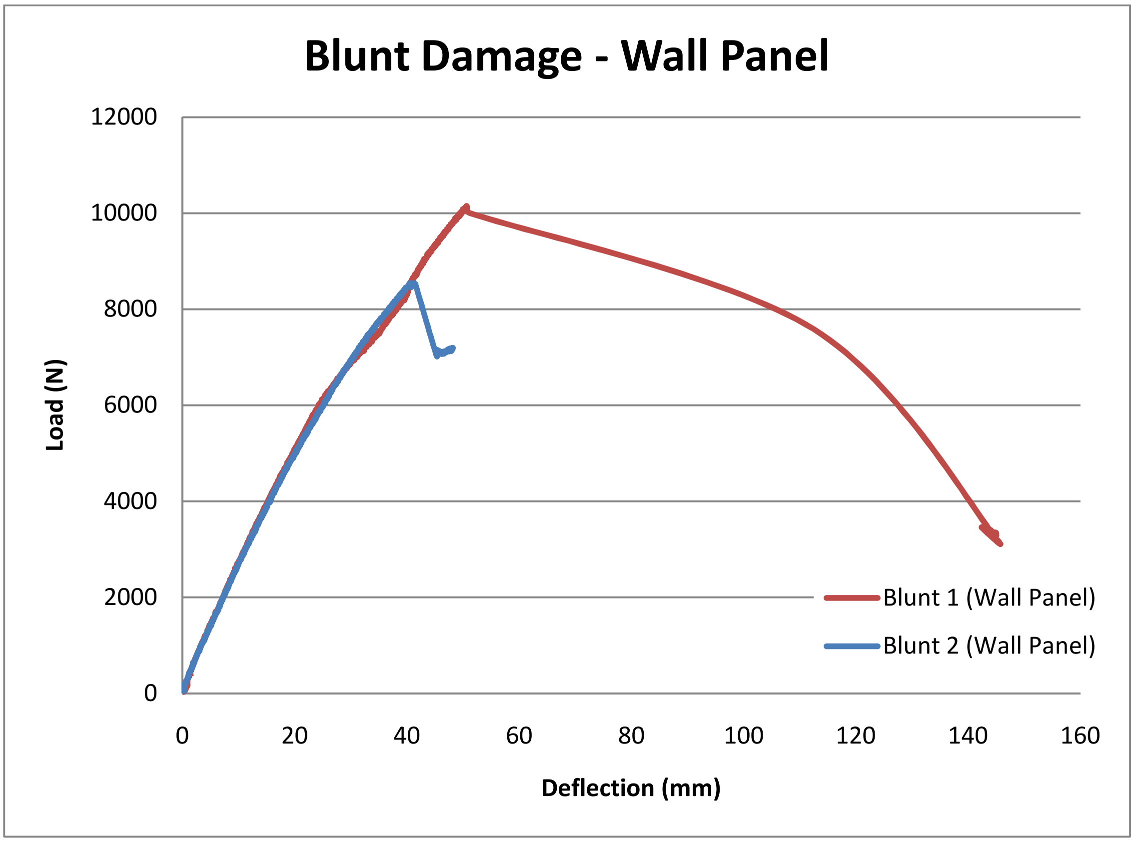

Figure 6.12 Blunt Impact Results of Wall Panels

6.6 Sharp Impact Damaged Samples

The sharp impact for both the 50x50mm section and the wall panel the failure was the same as previously recorded. The failure originated at the damage zone.

The tension tear originated along one side of the sharp impacts as can be seen below in figure 6.12. This was followed by shear tears along the side walls before ultimate failure when the compression side had a crushing type failure; this failure was a sudden failure.

This failure was quick much like that of the control and blunt impact damage apart from the failure initiation site being visible. The flexural stiffness of the material was reduced during the load once the tension tear had begun propagating across the sample along the sharp impacts. But ultimate failure was still a sudden and typical failure.

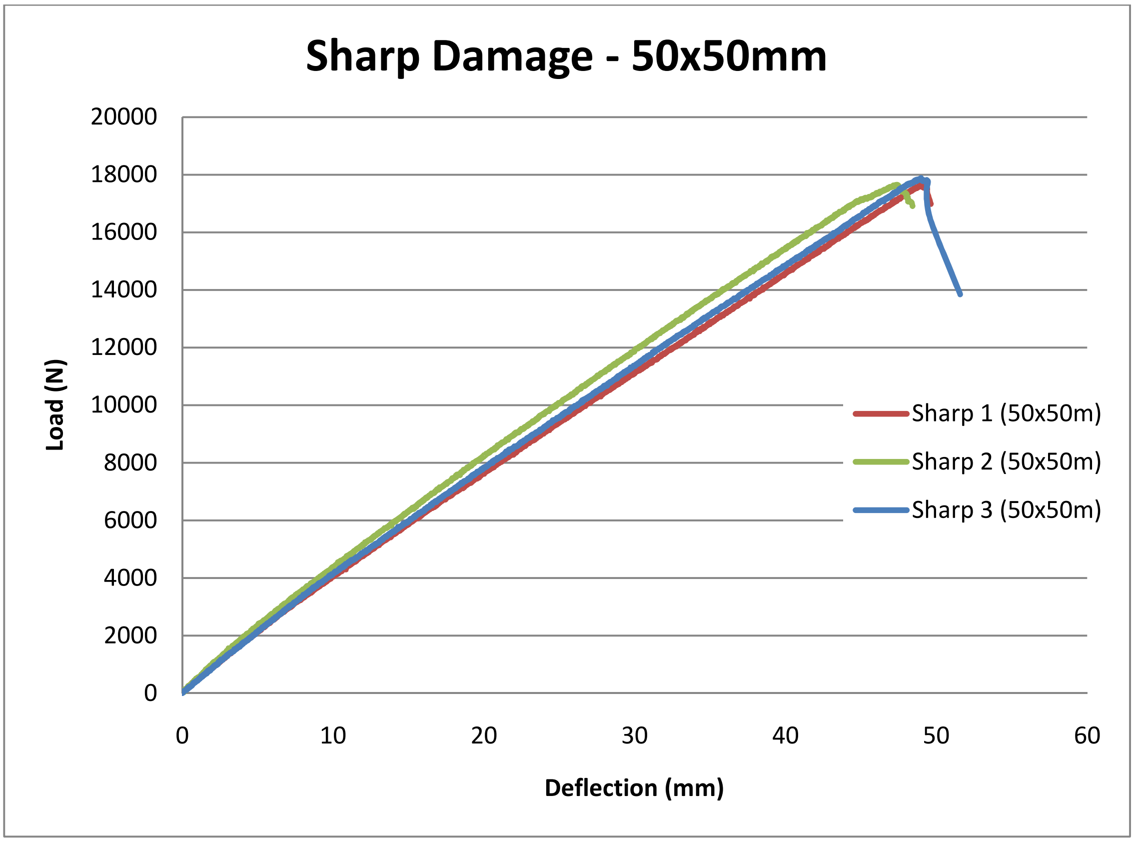

Figure 6.13 Sharp Impact Results of 50x50mm Samples

The 50x50mm sections had an ultimate load of 17 723N, a 5.5% decrease from the undamaged control samples. The section also had a flexural stiffness an indicator of the flexural modulus of 434N/mm, which is not decreased. The 50x50mm section had a flexural modulus of 20 442.27MPa, which is not decreased from the control samples.

Therefore the 50x50mm section had a 5.5% reduction in ultimate load but the initial stiffness of the material and flexural modulus is not affected by the sharp damage. The failure can be seen in figure 6.13.

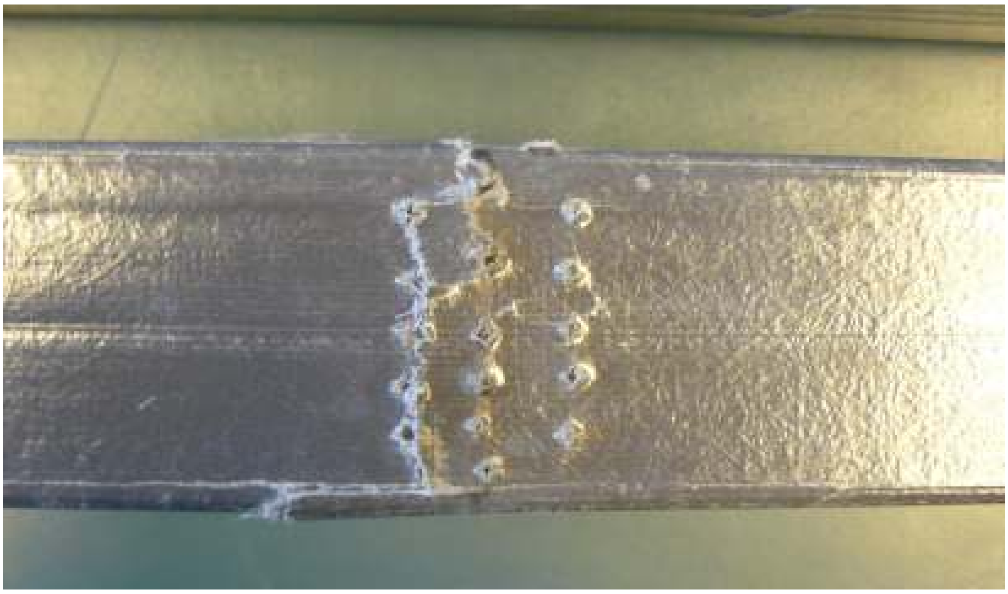

Figure 6.14 Sharp Impact Failure

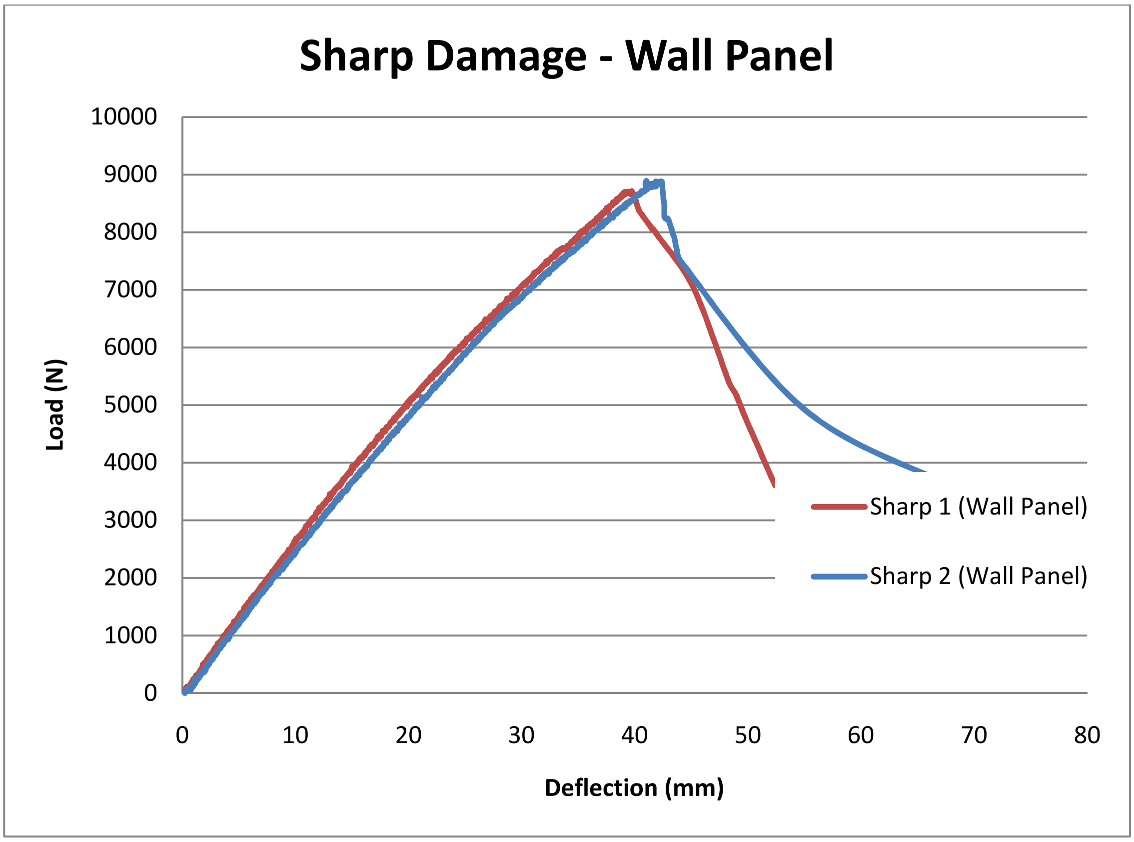

Figure 6.15 Sharp Impact Results of Wall Panels

The wall panel had an ultimate load of 8 804N, which was a large reduction in average ultimate load. The section also had a flexural stiffness of 259N/mm, which was not a reduction and is an indicator of the flexural modulus. The wall panel also had a flexural modulus of 6201.5MPa, which was also not a reduction. Therefore the wall panel much the same as the 50x50mm section had a small reduction in ultimate load but the initial stiffness of the material does not get affected.

The large reduction in ultimate load can be contributed to the large amount of damage the sharp impact did. Each impact caused indentation and at places tears or punctures through the section.

6.7 Cut Damaged Samples

For the cut damage the failure again originated at the damage site. This was the case for not only the 50x50mm section but also the wall panel as well.

For the 50x50mm section the failure originated at the tension side and the tear would be a continuation of one of the damage cuts, this would then shear up the side wall of the section in multiple directions. This can be seen in figure 6.12.

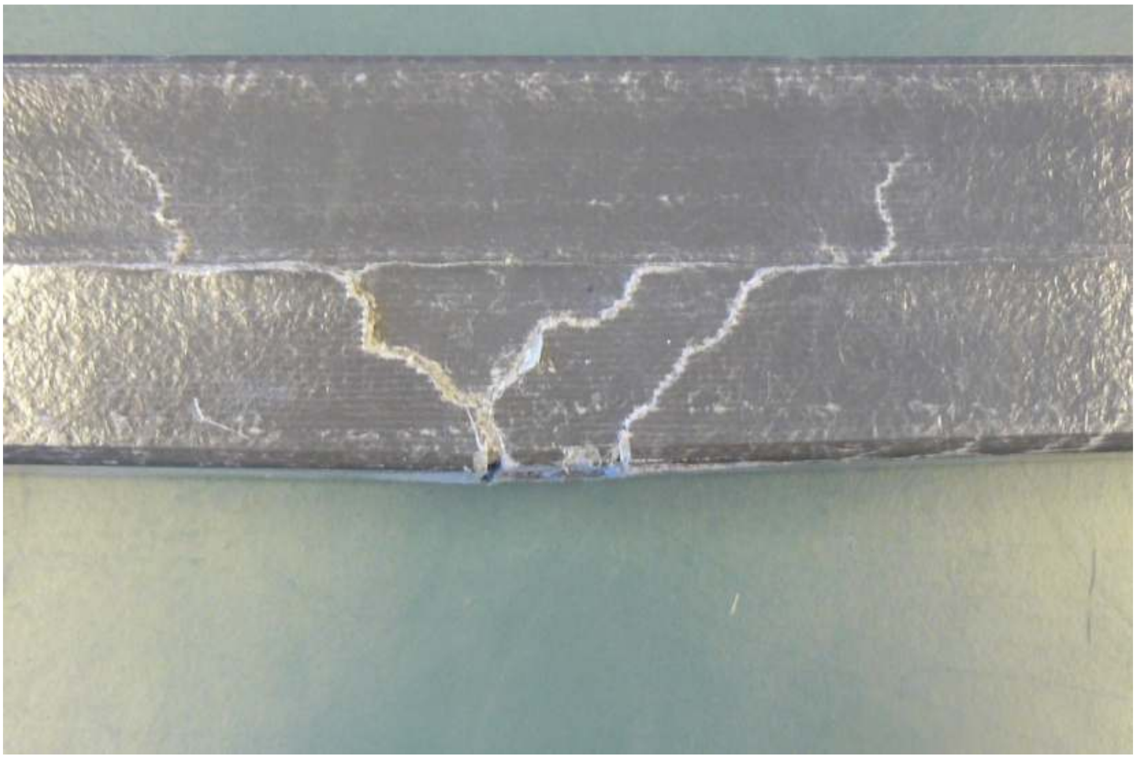

Figure 6.16 Cut Failure in 50x50mm section

The 50x50mm section had an ultimate load of 17 366N, a 7.4% reduction in average ultimate load. The section also had a flexural stiffness of 419N/mm, a reduction of 2.8% which is an indicator of the flexural modulus. The wall panel also had a flexural modulus of 19 044.44MPa, a reduction of 3.5 %. The cut damage has had the largest effect to both ultimate load, flexural stiffness and the flexural modulus of the material.

As the cut has penetrated the outer coating or layer of the sample the inner material begins to fail earlier in comparison to damage to the inner section like the blunt impact where the inner material has been damaged but the outer layer still holds the tension forces. The cut removes this ability with the cuts opening up and causing multiple shear tears in side walls in comparison to the other types of damage which a single shear tear is present, this is the cause of the reduction in stiffness and flexural modulus.

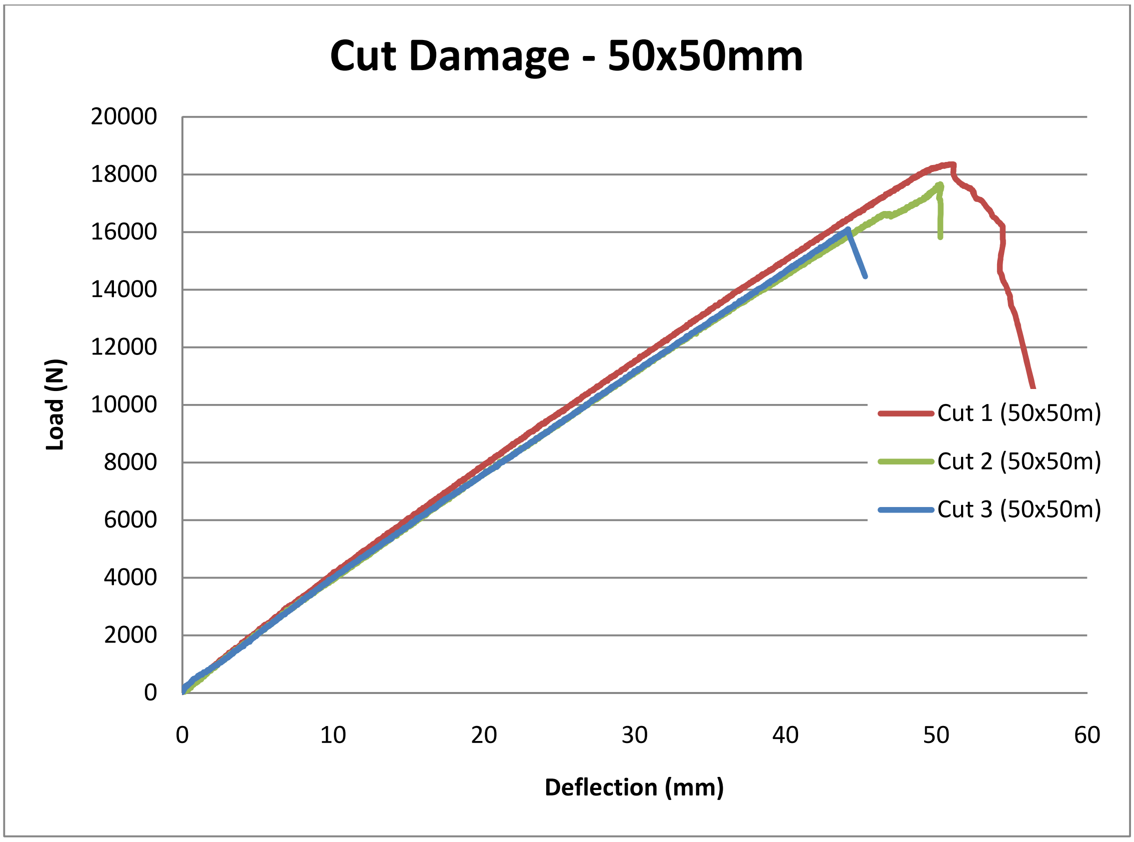

Figure 6.17 Cut Damage Results of 50x50mm Samples

The same cannot be said about the effect the cut damage has on the wall panel. The ultimate load of the wall panel is 10 571N, an 8.3% decrease in average ultimate load. The section also had a flexural stiffness an indicator of the flexural modulus of 253N/mm and a flexural modulus of 6013.2MPa, both of which are not decreased by the damage.

The cut has caused a decrease in ultimate load but this is not as significant as the 50x50mm section. The flexural stiffness and flexural modulus of the material remains unaffected by the cut damage.

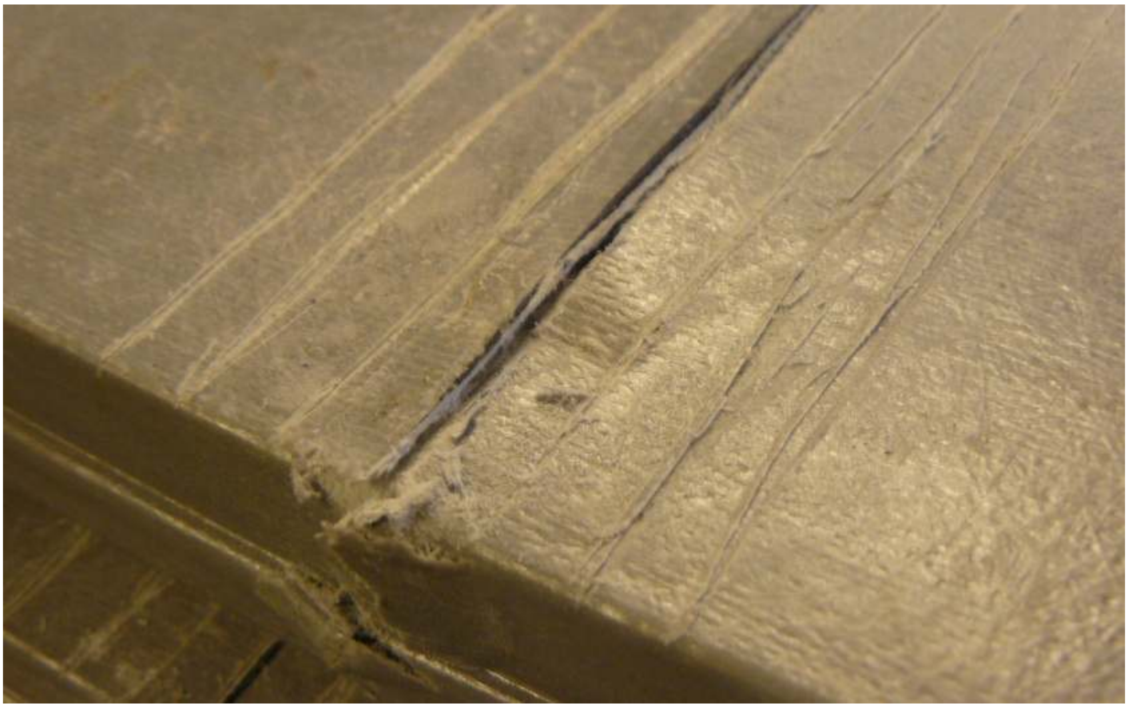

Figure 6.18 Cut Damage Failure of Wall Panel

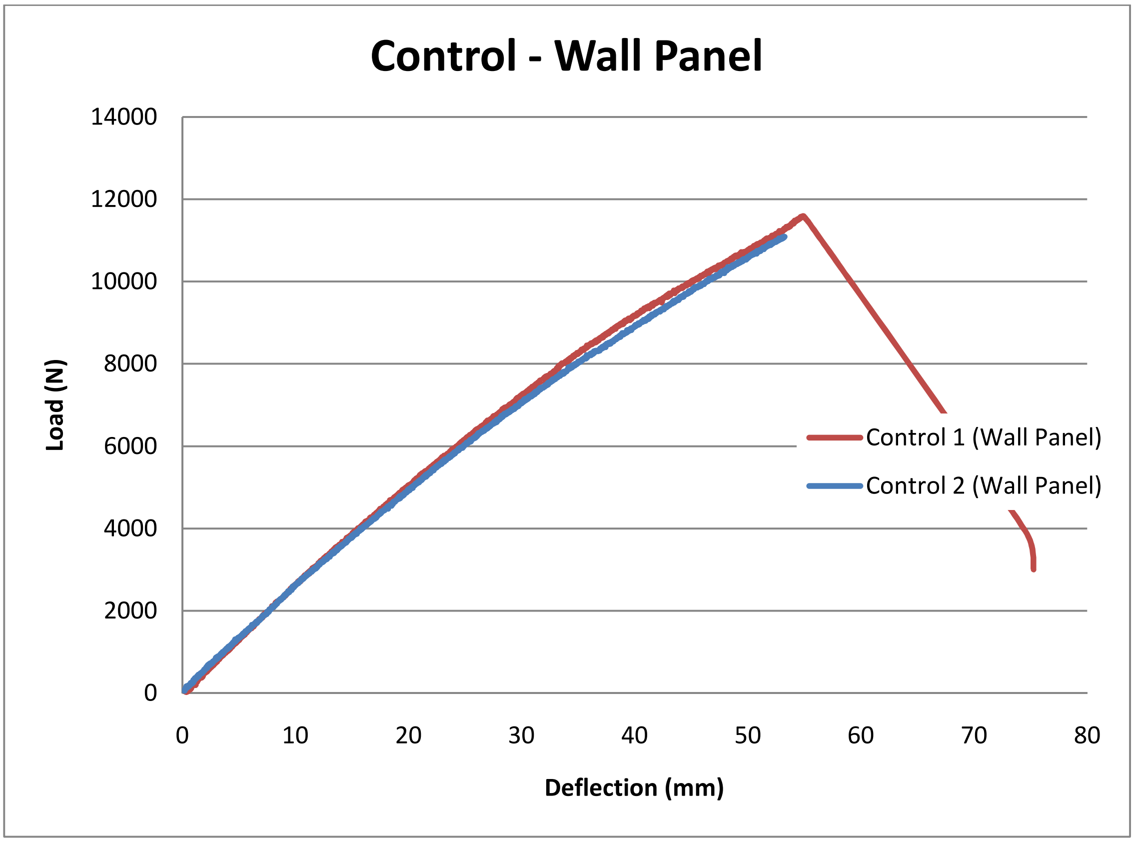

Figure 6.19 Cut Damage Results of Wall Panels

6.8 Fire Damaged Samples

The fire damage was only conducted on the 50x50mm section as this damage was hard to achieve. The section had a small melted section where the fire had managed to reach a sufficient temperature to cause damage, once cooled the area returned hard but with an altered appearance.

With the fire damage to the wall panel the bbq lighter was tested but could not reach a sufficient temperature to cause damage, any damage that was cause look like the damage caused by the lighter against the 50x50mm section. This was deemed to be unreasonable for a vandal or alike to attempt as it would take up wards of 45min to damage only a small section. For this reason only 50x50mm sections were tested damaged by the bbq lighter.

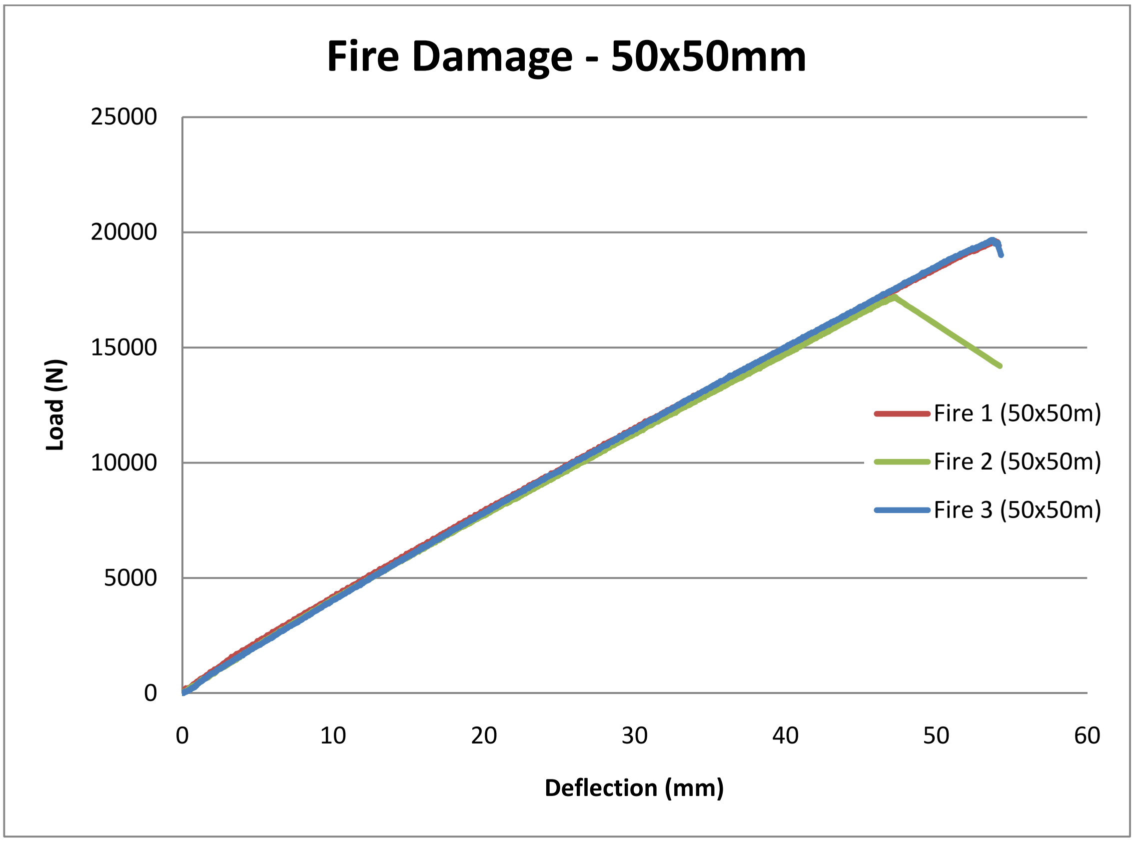

Figure 6.20 Fire Damage Results to 50x50mm Samples

The ultimate load of the fire damaged 50x50mm section was 18 837N, which was no decrease. The sections also had a flexural stiffness an indicator of the flexural modulus of 425N/mm and a flexural modulus of 19879.16 MPa. The fire damage has not reduced the ultimate load or the flexural stiffness by any noticeable margin; it has in fact increased both the average ultimate load and the flexural modulus.

6.9 Ease of Damage

Damage Type	Ease
Blunt Impact	Hard
Sharp Impact	Very Hard
Cutting Damage	Easy
Fire Damage	Hard

Table 6.1 Ease of Damage to 50x50mm section

Damage Type	Ease
Blunt Impact	Moderate
Sharp Impact	Hard
Cutting Damage	Easy
Fire Damage	Extreme

Table 6.2 Ease of Damage to Wall Panel

6.10 Paint Remover

Both the 50x50mm section and the wall panel pultrusions were treated to a thick coating of flat black enamel spray paint, typical off the shelf spray paint. It was allowed to dry.

A Dichloromethane mixed common over the counter paint remover was used in the removal of the spray paint. The instructions for the paint remover were followed and the paint was removed. Circumstance

The results of the paint remover were that the vast majority of the paint was removed with great ease. With wire brushing during the paint removal the amount of paint removed is increased. Only a very small amount of paint is left as it is soaked in, shorter the time between vandalism and cleaning would limit this to a great extent. It could be seen that the grey outside coating of the material had also been removed with the spray paint. This could cause a problem if continual use of the paint remover was used and the grey coating was not replaced after each use of the paint remover.

6.11 Conclusion

A total of 15 50x50mm square section glass fibre reinforced pultrusions and 8 glass fibre reinforced pultruded wall panels were tested using a range of different damages. The damages were of a blunt impact, a sharp impact, a Stanley knife cut and a bbq lighter burn. The effect ranged from very noticeable to visible but not effective.

The cut damage was the easiest to achieve in both the 50x50mm section and the wall panel. The cut damage was the most effective in the 50x50mm section where it not only decreased the ultimate strength it also decreased the flexural stiffness.

The fire damage was the hardest to achieve, the effect was visible but the effect to the ultimate strength and flexural stiffness was very negligible, especially when considered in wind and actual environment.

The blunt and sharp impact were fairly hard to achieve but were not as effective especially in the sharp impacts case. The sharp impact required a large amount of impacts to achieve any kind of damage, the only damage that could be easily achieved is when the sharp impact is combined with a hammer.

The paint remover was very effective against the spray paint. The material was also very resistant to both the spray paint and the paint remover with only the outside grey paint coat being also removed with the spray paint.

The wall panel's most effective damage type was the sharp impact. This was mainly due to the sharp impact in the 2 mm thickness causing small indents that pushed out the other side to the damage.

Chapter 7

Findings and Conclusions

7.1 Introduction

For this research project two different types of fibre reinforced sandwich panels and three different types of fibre reinforced pultruded sections. All of these different types of fibre composite were subjected to the same types of damage. These types of damage were blunt impact (a hammer), a sharp impact (a screw driver), a cut (Stanley knife) and burn damage (a bbq lighter).

For the sandwich panel a plain sandwich panel was used and a sandwich panel with an asphalt cover was used. For the pultrusion a 50x50mm square section, a 100x100mm square section and a 460x40mm wall panel.

This project has completed all the specifications that were planned including the extra work. This project has researched the background to fibre composites, there design and there typical usage. The project has also investigated different levels of vandalism. It has also investigated the effect the damage has had on integrated fibre composite structures and elements and the project has tested full scale vandalised beams.

7.2 Findings

The project has investigated ranging and different types of vandalism on three different styles of fibre composite. This has shown ranging levels of effectiveness from completely immune to very effective. The ability to damage the fibre composites has ranged also from immune to very easy.

7.2.1 Blunt Impact

For the sandwich fibre composite the blunt impact was hard to achieve especially when considered in actual environment. To achieve the required damage when the vandal is required to do an up-swing to the product the ability to cause damage is severely hampered. But if achieved it could be very effective. The damage is very noticeable and the capacity is reduced heavily because of the damage to the core.

For the 50x50mm pultrusion the blunt impact was fairly hard to achieve but was able to be achieved. The results of the impact were marginal on the average ultimate load, flexural stiffness and flexural modulus. For the pultruded wall panel 68% of the width of each of the wall panels was immune to blunt impact damage, the other regions were moderately hard to damage. The panel could be potentially destroyed in these regions but local non destructive damage was able to be implemented.

For the pultruded 100x100mm section the blunt impact was very hard to achieve especially when considered in actual environment, could be classified as immune to a normal blunt attack.

7.2.2 Sharp Impact

For the sandwich panel the sharp impact was much like the blunt impact where the effect was hard to achieve. The damage is achievable when combined with a hammer. The damage is however achievable without the hammer but would take a large amount of impacts to achieve this.

For the 50x50mm pultruded section the sharp impact required a large amount of impacts to achieve any kind of damage, the only damage that could be easily achieved is when the sharp impact is combined with a hammer.

The pultruded wall panel's most effective damage type was the sharp impact. This was mainly due to the sharp impact in the 2 mm thickness causing small indents that pushed out the other side to the damage; this was again only achievable in combination with a hammer.

For the 100x100mm pultruded section the sharp impact was much like the blunt impact where the effect was extremely hard to achieve.

7.2.3 Cut Damage

For the sandwich panels the cut was easy to achieve and the effect from a small cut was noticeable on both the ultimate load and flexural stiffness and flexural modulus of the material.

For the 50x50mm pultruded section the cut damage was the easiest this was also true for the wall panel. The cut damage was the most effective in the 50x50mm section where it not only decreased the ultimate strength it also decreased the flexural stiffness and flexural modulus.

For the 100x100mm pultruded section the cut however was easy to achieve, this would be the easiest damage type to get a result with. Especially once the outer skin or cover was cut.

7.4 Fire Damage

For the sandwich panel the burning was the easiest to achieve visible damage but the actual effect of the burning was not as effective compared to the visible damage.

For the 50x50mm pultruded section the fire damage was the hardest to achieve, the effect was visible but the effect to the ultimate strength and flexural stiffness was very negligible, especially when considered in wind and actual environment.

For the 100x100mm pultruded section the samples could be classified as immune to burn damage from a bbq lighter or similar product especially when considered in the actual environment. When faced against a flame of higher temperature the effect is extreme.

7.3 Conclusion

In conclusion all the tasks specified to the project specification have been completed. Three different types of fibre composite were used and subjected to a range of damages that would likely be carried out by a vandal. The damages were done by using real world tools that would be available to a common vandal.

A common result to all the fibre composites is the ease of cut damage. This was easy to achieve on all 4 types of product. For all the products once the outer coating or skin was cut the inner material was easier to cut and the ability to cause large amounts of damage increases. This also had at times a large effect to ultimate load and flexural stiffness.

A common immunity for all the fibre composites was that of blunt and sharp impact. In the case of blunt impact damage the effect was very hard to achieve and at times completely unreasonable to think a normal vandal would be able to achieve a sufficient amount of damage to cause problems. With the sharp impact combined with a hammer could achieve large amounts of damage to all types of fibre composites.

With the composites the effect to flexural stiffness is not apparent until high loads. The initial flexural stiffness of the fibre composites is not affected by the damage but as the load increases the flexural stiffness is affected by the damage.

7.4 Future Research

Further research in line with this project would be that of the fatigue behaviour to the composites with the damage. The effect short term can be seen from this project and the effect the damage has to the composite. The effect this damage has to the long term performance of the fibre composites is not known and needs to be researched as one of the benefits to fibre composites are the longer viability of the products.

Further research is needed into ranging effects of certain types of damage. This would be ranging degrees of damage of the different types of damage. Further research is also needed into the effect these damages have on full size slab elements of sandwich panel as the ability to damage a large section is needed. Research could be carried out with the specimen in actual environments to investigate the types of restraints the product have to see if they contribute to the effect of the damage.

Further research could be into the effect of chemicals against the different pultrusions and whether these had effects on the flexural behaviour of the fibre composites. This could be accompanied with different common maintenance practices and see if these have an effects on the fibre composites.

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Appendix

Appendix A – Project Specification

University of Southern Queensland
FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project

Project Specification

FOR: Tristan Rennie

TOPIC: Effect of Vandalism of Fibre Composite Beams

SUPERVISOR: A/Prof Thiru Aravinthan

SPONSERS: QLD Department of Main Roads
Centre of Excellence in Engineered Fibre Composites

ENROLLMENT: ENG 4111, ONC - SEMESTER 1 2009
ENG 4112, ONC - SEMESTER 2 2009

PROJECT AIM: This project seeks to investigate the effect of common types of vandalism on fibre composite structures, define the typical kinds of vandalism and with what tools they occur with and whether any of these defects will have a negative effect on the structural integrity of the beam or structure. Define the amount of damage needed before noticeable negative effects start to occur in the structure and investigating whether these effects translate into large scale environments.

PROGRAMME: Issue A; 24th March 2009

1. Research the background information regarding fibre composites design and the typical usage of the fibre composite materials.
2. Investigate and document levels of vandalism for testing.
3. Analyse and test unaffected samples to provide a standard.
4. Analyse and test vandalised samples.
5. Test ranging levels of vandalism.
6. Investigate the effect of vandalism in integrated fibre composite structures/elements.
7. Prepare documented vandalism report detailing procedure and results of vandalism.

As time permits:

8. Analyse and test full scale vandalised beams.

AGREED:

______________________________ (Student)________________________

(Supervisor) ___ /___ /2009 ___ / ___ / 2009

Examiner/Co-examiner:____

Appendix B – Specimen Measurements

Testing - No Asphalt Cover

	Thickness			Width			Damage
TR-NC-1	20.03	19.89	19.81	50.04	49.56	49.92	Blunt
TR-NC-2	19.56	19.94	19.32	48.84	49.64	50.02	
TR-NC-3	20.66	20.22	20.56	49.46	49.27	49.41	
TR-NC-4	20.63	19.97	20.73	49.97	49.84	49.79	Sharp
TR-NC-5	20.68	20.08	20.53	49.6	50.03	50.32	
TR-NC-6	19.92	19.74	19.84	49.61	49.44	49.43	
TR-NC-7	19.78	19.62	19.84	49.92	49.68	49.99	Cut
TR-NC-8	20.15	20.28	20.32	49.48	49.52	49.63	
TR-NC-9	20.05	19.84	20.06	50.03	50.04	50.1	
TR-NC-10	20.36	20.23	20.1	49.3	49.45	49.67	Fire
TR-NC-11	19.93	19.82	19.89	49.67	49.53	49.54	
TR-NC-12							

Table Appendix B.1 Specimen Measurements Non Covered Sandwich Panels

Testing - Asphalt Cover

	Thickness		Width			Damage
TR-C-T-1	25.63	25.67	49.46	48.86	49.11	Cut
TR-C-T-2	25.34	25.85	49.04	49.16	48.93	
TR-C-T-3	26.25	25.92	49.17	48.19	47.4	
TR-C-B-1	25.66	25.36	49.59	49.13	49.41	Blunt
TR-C-B-2	25.4	25.59	48.86	48.91	49.84	
TR-C-B-3	25.89	25.55	49.46	49	49.35	
TR-C-S-1	25.68	25.61	48.93	48.78	49.27	Sharp
TR-C-S-2	25.58	25.67	49.2	49.63	49.27	
TR-C-S-3	25.24	25.46	48.97	49.46	49.41	
TR-C-C-1	25.93	24.98	49.2	49.52	49.66	Control
TR-C-C-2	25.61	25.76	48.47	47.92	47.56	
TR-C-C-3	24.96	25.16	48.09	47.61	48.96	
TR-C-F-1	26.26	26.2	48.34	47.8	47.12	Fire
TR-C-F-2	26.38	25.77	48.78	48.76	48.9	
TR-C-F-3	25.14	25.78	48.78	48.76	48.81	

Table Appendix B.2 Specimen Measurement Asphalt Covered Sandwich Panels

Testing – 100x100mm Pultrusions

	Height			Width			Thickness		Damage
TR-P-1	100.51	100.45	100.5	100.71	100.37	100.35	5.24	5.23	Control
TR-P-2	100.49	100.77	101.2	100.43	100.59	100.32	5.17	4.99	
TR-P-3	100.48	100.6	100.36	100.79	100.49	100.64	5.06	4.98	
TR-P-4	100.56	100.52	100.55	100.32	100.43	100.33	5.02	5.1	Blunt
TR-P-5	100.33	100.25	100.21	100.53	100.55	100.66	5.33	5.31	
TR-P-6	100.68	100.8	100.54	100.67	100.64	100.62	4.97	4.99	
TR-P-7	100.49	100.5	100.69	100.38	100.42	100.32	5.13	5.07	Sharp
TR-P-8	100.35	100.46	100.35	100.46	100.45	100.46	5.07	5.24	
TR-P-9	100.49	100.58	100.58	100.44	100.34	100.43	4.97	5.14	
TR-P-10	100.65	100.56	100.58	100.68	100.58	100.44	5.29	5.27	Cut
TR-P-11	100.68	100.79	100.73	100.6	100.35	100.3	5.18	5.17	
TR-P-12	100.39	100.43	100.37	100.41	100.44	100.55	5.12	5.14	
TR-P-13	100.5	100.47	100.6	100.36	100.4	100.35	5.05	5.03	Fire
TR-P-14	100.76	100.58	100.53	100.36	100.29	100.51	5.2	5.21	
TR-P-15	100.52	100.62	100.5	100.44	100.55	100.56	5.1	5.28	

Table Appendix B.3 Specimen Measurement 100x100mm Section

Testing – 50x50mm Pultrusions

	Height		Width		Thickness		Damage
TR-XP-1	50.83	51.14	51.38	50.95	6.82	6.88	Control
TR-XP-2	51.06	51.27	50.83	51.17	6.39	6.12	
TR-XP-3	51.23	50.99	50.92	51.24	5.97	6.23	
TR-XP-4	51.03	50.97	50.95	51.15	6.86	5.79	Blunt
TR-XP-5	51.02	51.06	50.99	51.09	5.84	6.58	
TR-XP-6	51.11	50.93	51.38	51.22	6.38	6.09	
TR-XP-7	50.95	51.05	51.04	51.01	6.61	5.9	Sharp
TR-XP-8	50.85	51.16	51.13	51.2	5.99	6.12	
TR-XP-9	51.06	51.16	50.91	51.29	6.61	6.03	
TR-XP-10	51.06	51.04	50.9	51.05	6.54	5.81	Cut
TR-XP-11	51.45	51.01	51	51.16	6.01	6.38	
TR-XP-12	50.87	51.2	51.01	51.2	6.32	5.91	
TR-XP-13	50.87	50.91	50.96	51.14	6.32	6.13	Fire
TR-XP-14	50.62	50.99	51.01	50.97	6.04	6.29	
TR-XP-15	51.15	50.94	51.18	50.98	6.28	6.48	

Table Appendix B.4 Specimen Measurement 50x50mm Section

Testing – Wall Panel Pultrusions

	Height		Width		Thickness		Damage
TR-WP-1	38.36	38.3	460.12	459.98	2.7	2.59	Control
TR-WP-2	38.3	38.54	459.89	459.96	2.67	2.61	
TR-WP-3	38.09	38.01	460.18	460.21	2.59	2.58	Blunt
TR-WP-4	38.02	38.14	459.86	459.98	2.76	2.84	
TR-WP-5	39.18	38.36	460.06	460.13	2.34	2.38	Sharp
TR-WP-6	38.41	38.06	459.87	459.96	2.52	2.45	
TR-WP-7	38.44	38.15	460.1	459.96	2.62	2.65	Cut
TR-WP-8	38.03	38.04	460.08	460.1	2.39	2.46	

Table Appendix B.5 Specimen Measurement Wall Panel

Appendix C – Results Tables

Asphalt Covered Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
Control Samples		
1	5026.826	406.25
2	4696.494	350
3	5028.169	333.33
Avg	4917	363.19
Blunt Impacted Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	4428.098	307.14
2	4827.418	328.57
3	4543.077	333.33
Avg	4599	323.01
Sharp Impacted Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	3931.089	341.67
2	3361.568	300
3	3986.144	381.82
Avg	3958.62	361.745
Cut Damaged Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	5062.41	325
2	4300.363	358.33
3	4464.858	346.15
Avg	4609	343.16
Fire Damaged Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	4822.214	342.86
2	5081.21	369.23
3	4698.508	345.45
Avg	4867.31	352.51

Table Appendix C.1 Covered Sandwich Panel

Non Covered Samples

Control Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	4355.39	212.87
2	4654.499	210.53
3	4764.376	205.73
Avg	4519.42	209.71
Blunt Impacted Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	3095.187	213.79
2	5105.38	
3	3843.806	206.67
Avg	3469	210.23
Sharp Impacted Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	4558.183	208.89
2	3722.953	224.24
3	4337.291	204.25
Avg	4447.7	206.57
Cut Damaged Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	3568.529	200
2	4027.1	210
3	3904.233	205
Avg	3833.29	205
Fire Damaged Samples		
Sample Number	**Ultimate Load (N)**	**Flexural Stiffness (N/mm)**
1	4686.422	218.18
2	5238.99	210.52
3	5430.341	175
Avg	5118.58	214.35

Table Appendix C.2 Non Covered Sandwich Panel Results

100x100mm Square Section

Control Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	39613.4	4000
2	40615.5	3883.49
3	39975.3	3804.35
Avg	40068	3895.95

Blunt Impacted Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	37344.6	3714.28
2	37511.6	4000
3	40365	3894.74
Avg	38407	3869.65

Sharp Impacted Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	37943.1	3870.97
2	37623	3789.47
3	38012.7	3434.34
Avg	37860	3698.28

Cut Damaged Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	39905.7	4000
2	37177.5	3855.42
3	37469.8	3734.94
Avg	38184	3863.45

Fire Damaged Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	38277.1	3958.33
2	36398.1	3894.74
3	41047	4021.74
Avg	38574.07	3958.27

Table Appendix C.3 100x100mm Pultrusion Results

50x50mm Square Section

Control Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	19375.2	431.82
2	18484.4	422.5
3	18414.8	439.26
Avg	18758.13	431.26

Blunt Impacted Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	18025.1	441.67
2	19027.2	450
3	19597.9	500
Avg	18883.4	463.89

Sharp Impacted Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	17635.3	407.14
2	17649.2	475
3	17885.9	431.58
Avg	17723.47	437.91

Cut Damaged Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	18345.2	421.05
2	17663.2	417.39
3	16090.3	383.78
Avg	17366.23	419.2

Fire Damaged Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	19625.7	458.33
2	17203.8	411.76
3	19681.4	404.76
Avg	18836.97	424.95

Table Appendix C.4 50x50mm Pultrusion Results

460x40mm Wall Panel

Control Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	11594.5	263.16
2	11469.2	247.06
Avg	11531.8	255.11

Blunt Impacted Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	10146.9	258.33
2	8546.2	257.14
Avg	9346.55	257.7

Sharp Impacted Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	8713.3	264.28
2	8894.2	253.85
Avg	8803.75	259.06

Cut Damaged Samples

Sample Number	Ultimate Load (N)	Flexural Stiffness (N/mm)
1	11330	255.6
2	9812.9	250
Avg	10571.45	252

Table Appendix C.5 Pultruded Wall Panel Results

Appendix D – Flexural Stiffness Results

Testing - No Asphalt Cover

Specimen Name	Description	I (eff) (mm^4)	EI (Nmm^2)	E (eff) Mpa
TR-NC-1	Blunt	32780.122	2.43E+08	7407.7
TR-NC-2	Blunt	31091.040	2.39E+08	7690.8
TR-NC-3	Blunt	35347.581	2.46E+08	6965.8
	Blunt mean	33072.91	2.43E+08	7354.78
	Std Dev	2143.32	3.55E+06	365.43
	COV	6.48	1.46	4.97
TR-NC-4	Sharp	35504.567	2.52E+08	7092.2
TR-NC-5	Sharp	35518.046	2.55E+08	7170.9
TR-NC-6	Sharp	32177.522	2.32E+08	7209.8
	Sharp mean	34400.05	2.46E+08	7157.62
	Std Dev	1924.77	1.24E+07	59.91
	COV	5.60	5.02	0.84
TR-NC-7	Cut	31994.951	2.35E+08	7352.0
TR-NC-8	Cut	34283.019	2.41E+08	7027.6
TR-NC-9	Cut	33287.753	2.36E+08	7101.3
	Cut mean	33188.57	2.38E+08	7160.28
	Std Dev	1147.25	3.01E+06	170.03
	COV	3.46	1.27	2.37
TR-NC-10	Fire	34133.245	2.48E+08	7260.1
TR-NC-11	Fire	32461.936	2.39E+08	7366.1
TR-NC-12	Fire	33780.437	2.39E+08	7078.5
	Fire mean	33458.54	2.42E+08	7234.91
	Std Dev	880.93	5.02E+06	145.40
	COV	2.63	2.07	2.01
TR-NC-13	Control	24716.092	1.91E+08	7742.2
TR-NC-14	Control	24612.759	1.89E+08	7689.1
TR-NC-15	Control	24296.331	1.85E+08	7611.7
	Control mean	24541.73	1.89E+08	7681.01
	Std Dev	218.71	3.27E+06	65.62
	COV	0.89	1.74	0.85

Table Appendix D.1 Flexural Results Non Covered Sandwich Panel

Testing - Asphalt Cover

Specimen Name	Description	I (eff) (mm^4)	EI (Nmm^2)	E (eff) Mpa
TR-C-T-1	Cut	69110.729	5.26E+08	7605.0
TR-C-T-2	Cut	68527.381	5.79E+08	8456.4
TR-C-T-3	Cut	71370.477	5.60E+08	7843.5
	Cut mean	69669.53	5.55E+08	7968.29
	Std Dev	1501.66	2.73E+07	439.19
	COV	2.16	4.92	5.51
TR-C-B-1	Blunt	68308.052	4.97E+08	7271.6
TR-C-B-2	Blunt	67948.258	5.31E+08	7820.1
TR-C-B-3	Blunt	69857.688	5.39E+08	7716.6
	Blunt mean	68704.67	5.22E+08	7602.75
	Std Dev	1014.62	2.26E+07	291.43
	COV	1.48	4.32	3.83
TR-C-S-1	Sharp	68859.498	5.53E+08	8024.2
TR-C-S-2	Sharp	69222.006	5.82E+08	8410.4
TR-C-S-3	Sharp	66899.573	6.17E+08	9229.8
	Sharp mean	68327.03	5.84E+08	8217.30
	Std Dev	1249.43	3.25E+07	273.15
	COV	1.83	5.57	3.32
TR-C-C-1	Control	67981.723	6.28E+08	9231.4
TR-C-C-2	Control	67756.019	5.66E+08	8353.7
TR-C-C-3	Control	63239.607	5.39E+08	8524.1
	Control mean	66325.78	5.78E+08	8703.08
	Std Dev	2675.09	4.54E+07	465.39
	COV	4.03	7.85	5.35
TR-C-F-1	Fire	71815.356	5.54E+08	7720.7
TR-C-F-2	Fire	72115.758	5.97E+08	8280.0
TR-C-F-3	Fire	67091.179	5.59E+08	8326.9
	Fire mean	70340.76	5.70E+08	8109.20
	Std Dev	2818.23	2.35E+07	337.28
	COV	4.01	4.12	4.16

Table Appendix D.2 Flexural Results Asphalt Covered Sandwich Panel

Testing - 100x100mm Section				
Specimen Name	**Description**	**I (eff) (mm^4)**	**EI (Nmm^2)**	**E (eff) Mpa**
TR-P-1	Control	3.02E+06	7.10E+10	23467.3
TR-P-2	Control	2.97E+06	6.89E+10	23192.2
TR-P-3	Control	2.92E+06	6.75E+10	23098.4
	Control mean	2.97E+06	6.91E+10	23252.65
	Std Dev	51021.32	1.75E+09	191.75
	COV	1.72	2.53	0.82
TR-P-4	Blunt	2.94E+06	6.59E+10	22416.2
TR-P-5	Blunt	3.05E+06	7.10E+10	23255.5
TR-P-6	Blunt	2.92E+06	6.91E+10	23699.8
	Blunt mean	2.97E+06	6.87E+10	23123.84
	Std Dev	72595.59	2.56E+09	651.83
	COV	2.44	3.73	2.82
TR-P-7	Sharp	2.96E+06	6.87E+10	23195.2
TR-P-8	Sharp	2.98E+06	6.73E+10	22579.3
TR-P-9	Sharp	2.94E+06	6.09E+10	20733.8
	Sharp mean	2.96E+06	6.56E+10	22169.43
	Std Dev	19493.15	4.12E+09	1280.85
	COV	0.66	6.28	5.78
TR-P-10	Cut	3.06E+06	7.10E+10	23222.3
TR-P-11	Cut	3.01E+06	6.84E+10	22718.3
TR-P-12	Cut	2.97E+06	6.63E+10	22338.9
	Cut mean	3.01E+06	6.86E+10	22759.84
	Std Dev	44842.24	2.36E+09	443.18
	COV	1.49	3.44	1.95
TR-P-13	Fire	2.93E+06	7.02E+10	23978.8
TR-P-14	Fire	3.02E+06	6.91E+10	22903.0
TR-P-15	Fire	3.01E+06	7.14E+10	23726.0
	Fire mean	2.99E+06	7.02E+10	23535.95
	Std Dev	48441.12	1.13E+09	562.51
	COV	1.62	1.60	2.39

Table Appendix D.3 Flexural Results 100x100mm Section

Testing - 50x50mm Section

Specimen Name	Description	I (eff) (mm^4)	EI (Nmm^2)	E (eff) Mpa
TR-XP-1	Control	403266.306	7.66E+09	19003.4
TR-XP-2	Control	383995.456	7.50E+09	19526.5
TR-XP-3	Control	377446.543	7.80E+09	20663.3
	Control mean	388236.10	7.65E+09	19731.07
	Std Dev	13422.08	1.51E+08	848.66
	COV	3.46	1.97	4.30
TR-XP-4	Blunt	383832.397	7.84E+09	20420.9
TR-XP-5	Blunt	380155.397	7.99E+09	21007.5
TR-XP-6	Blunt	382371.974	8.16E+09	21349.8
	Blunt mean	382119.92	8.00E+09	20926.09
	Std Dev	1851.41	1.63E+08	469.77
	COV	0.48	2.04	2.24
TR-XP-7	Sharp	381025.703	7.23E+09	18963.4
TR-XP-8	Sharp	374253.564	8.43E+09	22524.3
TR-XP-9	Sharp	386063.808	7.66E+09	19839.2
	Sharp mean	380447.69	7.77E+09	20442.27
	Std Dev	5926.30	6.10E+08	1855.47
	COV	1.56	7.85	9.08
TR-XP-10	Cut	378588.653	7.47E+09	19737.5
TR-XP-11	Cut	383414.904	7.41E+09	19319.6
TR-XP-12	Cut	376790.631	6.81E+09	18076.3
	Cut mean	379598.06	7.23E+09	19044.44
	Std Dev	3425.56	3.65E+08	864.09
	COV	0.90	5.04	4.54
TR-XP-13	Fire	377968.429	8.13E+09	21520.3
TR-XP-14	Fire	373723.701	7.31E+09	19553.4
TR-XP-15	Fire	386950.291	7.18E+09	18563.8
	Fire mean	379547.47	7.54E+09	19879.16
	Std Dev	6753.20	5.17E+08	1504.94
	COV	1.78	6.85	7.57

Table Appendix D.4 Flexural Results 50x50mm Section

Testing - Wall Panel

Specimen Name	Description	I (eff) (mm^4)	EI (Nmm^2)	E (eff) Mpa
TR-WP-1	Control	792087.527	4.67E+09	5896.1
TR-WP-2	Control	794640.599	4.38E+09	5517.6
	Control mean	793364.1	4.53E+09	5706.9
	Std Dev	1805.3	2.02E+08	267.6
	COV	0.2	4.5	4.7
TR-WP-3	Blunt	764761.347	4.58E+09	5994.8
TR-WP-4	Blunt	819106.414	4.56E+09	5571.3
	Blunt mean	791933.9	4.57E+09	5783.1
	Std Dev	38427.8	1.49E+07	299.5
	COV	4.9	0.3	5.2
TR-WP-5	Sharp	736267.922	4.69E+09	6370.3
TR-WP-6	Sharp	746763.270	4.50E+09	6032.7
	Sharp mean	741515.6	4.60E+09	6201.5
	Std Dev	7421.3	1.31E+08	238.7
	COV	1.0	2.8	3.8
TR-WP-7	Cut	787945.984	4.54E+09	5755.9
TR-WP-8	Cut	723269.298	4.54E+09	6270.6
	Cut mean	755607.6	4.54E+09	6013.2
	Std Dev	45733.3	0.00E+00	364.0
	COV	6.1	0.00	6.1

Table Appendix D.5 Flexural Results Wall Panel