



UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

The Response of Singly Curved Fibre Reinforced Sandwich and Laminate Composite Panels subjected to Localised Blast Loads

Dissertation presented in partial fulfilment of the requirements
of the degree MSc (Mechanical Engineering)

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Abstract

This report presents results from a study on the response of singly curved fibre reinforced polymer (FRP) sandwich and laminate panels subjected to localised blast loads. The aim of the project was to investigate and compare the blast mitigation potential of each panel type and the influence of curvature on the response.

Three radii of curvature were examined for both panel types, namely infinite (flat), 1000mm and 500mm. The FRP laminate panels were designed to consist of 15 layers of E-glass fibre reinforced epoxy sheets. The FRP sandwich panels consisted of a PVC foam core with 6 layers of FRP sheets on either side. Vacuum infusion, with the aid of three moulds, was used to manufacture the panels. The average thicknesses and areal densities of the FRP sandwich and laminate panels were 18.7mm and 4.9mm; and 8628g/m² and 8458g/m² respectively.

Three point quasi-static flexural tests were conducted on FRP sandwich and laminate specimens where the localised compression failure beneath the central loading bar was evident on both types of structures. The presence of the core reduced the damage observed on the back face of the FRP sandwich specimens.

Blast tests were conducted on a horizontal ballistic pendulum at the Blast Impact and Survivability Research Unit (BISRU), University of Cape Town. Localised blasts were generated by detonating circular cylinder PE4 plastic explosives, placed at a constant standoff distance of 100mm. The charge mass ranged from 10g to 32.5g across all the panels. The failure modes of the blast loaded panels were identified by a post-test inspection.

The failure mode initiation charts for the FRP sandwich panels revealed that failure modes were initially observed on the front face sheet and core material with slight appearance of delamination on the back face sheet. Increasing the charge mass resulted in the rupture of the front face sheet and penetration of the core. Additional failure of the back face sheet was also evident as the charge mass increased. The failure mode initiation charts of the FRP laminate panels exhibited less severe failure modes across a greater charge mass range that eventually lead to complete fibre rupture at higher charge masses.

Delamination of the front face sheet of the flat FRP sandwich panels was initially observed in the centre of the panel and spread into the exterior region for increasing charge mass. The failure of the core material initially reduced the delaminated area on the back face sheet, however once

the rupture of the front face sheet occurred, the delaminated area of the front face sheet reduced and the delaminated area of the back face sheet increased. This was similar for the curved FRP sandwich panels except that the delaminated area was predominately parallel to the axis of curvature prior to rupture and perpendicular to the axis of curvature subsequent to rupture.

Delamination in the flat FRP laminate panels was initially observed in the centre of the panel and along the clamped boundary. Increasing charge mass resulted in the delaminated region spreading across the panel. As with the FRP sandwich panels, the delaminated area of the curved FRP laminate panels was initially observed parallel to the axis of curvature prior to rupture.

Debonding of the FRP sandwich panels was initially observed at both of the front and back interfaces. For the front interface, the debonded lengths were observed in the centre and in exterior test area of the panel, but only in exterior test area for the back interface. With the rupture of the front face sheet, the debonded length of the front interface decreased and the back interface increased and spread across the entire test area.

The blast rupture threshold of the two panel types were compared in terms of largest charge mass resisted. For each radii category, the FRP laminate panels outperformed the FRP sandwich panels, namely by 5g for the flat panels (25g vs 20g) and 9g for the 1000mm curved panels (27.5g vs 18.5g). However, for the 500mm curved panels the FRP laminate and sandwich panels ruptured at identical charge masses of 27.5g.

Declaration

I know the meaning of plagiarism and declare that all the work in this document is my own.

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Gregory Sinclair

August 2014

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Chapter 1

Introduction

A brief background to the present work, objectives and an outline of the report is presented in the section to follow.

1.1 Motivation

The media is either saturated with headlines of terror attacks, military conflict or on-going rivalry between religious and political groups, which often results in the destruction of infrastructures, modes of transportation, homes and human life. This motivates research attempts to mitigate the impact of such events by means of testing, measuring and analysing structural failure properties of materials.

Explosive materials are often used as the source of these attacks and result in a high pressurized blast wave propagating towards the desired structure. Once the blast wave strikes the surface of the structure, the severity of damage is determined by load distribution of the blast, the structural geometry and its material properties. In other words, if the load transfer of the blast wave through the material is resisted, it has the potential of reducing the risk of damage to valuable items or bodies that it is designed to house and/or protect. Industries especially vulnerable to such attacks include aerospace, transport, military and naval; of which contain structures of flat, curved and complex geometries [1].

Composite materials are increasingly being used in these industries yet little is known of their blast mitigation capabilities. Composites are made up of two or more constituent materials that maintain their individual characteristic properties [2]. Sandwich structures, which often employ composite materials, usually consists of two thin face sheets separated by a lightweight core material. Deformable core materials are preferred for their large energy absorption properties under compression and hence improved blast protection [3].

The majority of studies in the literature, for the dynamic response of lightweight materials have been focused on flat panel configurations, with less attention to curved and non-metallic structures such as fibre reinforced composites [4]. Research into the blast loading response of fibre reinforced polymer composite sandwich panels is increasing, although little attention has been given to curved sandwich panels. This project aims to study the response of flat and curved fibre reinforced composite sandwich and laminate panels subjected to localised blast loading.

1.2 Objectives

All work in this report took place at the Blast Impact and Survivability Research Unit (BISRU), University of Cape Town. The objectives of this dissertation are to report on:

- The design and development of a small scale manufacturing process, where fibre reinforced composite sandwich and laminate panels of consistent singly curved radii can be constructed.
- The material properties of these panels under quasi-static loading.
- The response of flat and curved fibre reinforced sandwich and laminate panels to localised blasts loads and include the study of their associated failure modes.
- The influence of curvature and the blast resistance of glass fibre reinforced composite sandwich and laminate panels.

1.3 Report Outline

Chapter 2 reviews the basic principles of blast theory, composite materials, sandwich structures and curved structures. Current literature was reviewed for these topics and the response to localised blast loads.

Chapter 3 discusses the manufacturing process used and the design of the fibre reinforced sandwich and laminate panels.

Chapter 4 discusses the results of the quasi-static three point bend tests of the fibre reinforced sandwich and laminate specimens; and quasi-static compression tests of the core material.

Chapter 5 elaborates on the blast testing procedure and apparatus used. The results of the test panels were examined and the failure modes for each panel were identified and recorded. Tables that list the failure modes and comparable failure modes are provided for comparison purposes.

Chapter 6 discusses and compares the results recorded in chapters 4 and 5 for the fibre reinforced sandwich and laminate panels. These include the comparison of failure mode initiation charts and delaminated areas. The debonded lengths of the FRP sandwich panels were also compared. The two are then compared for each radii.

Chapter 7 lists the key conclusions discussed in chapter 6.

Chapter 8 lists the recommendations for future work on the project.

Chapter 2

Literature Review

This chapter gives an overview of the literature reviewed in order to help understand the response of singly curved composite panels subjected to localised blast loads. This includes the investigation of blast theory, composite materials, sandwich panels and curved structures.

2.1 Blast theory

The relevant theory and literature pertaining to the current research is discussed, namely the development and characteristics of a blast wave and current findings from experimental work.

2.1.1 An Explosion

An explosion occurs when a potentially explosive material/substance undergoes a rapid change of state and thus releases energy into the surrounding environment in a short period of time. According to Smith and Hetherington [5] explosions are categorised into three types according to their origin - namely physical, nuclear or chemical. Chemical explosions are defined by a rapid oxidation of fuel elements into heat and product gases by a process of detonation.

2.1.2 A Blast Wave

Cooper [6] describes the detonation process in terms of a detonation wave that moves through the explosive material at a supersonic speed and results in highly pressurised products being formed. When the pressure of the surrounding medium of the explosive is significantly lower, the reaction products expand supersonically and force out the volume it occupies. This in turn causes the layer of the surrounding medium to be compressed/shocked and then propagates through the surrounding medium. This formation of a shock wave is called a blast wave [7].

2.1.2.1 Pressure Profile of an Air Blast Wave

Blast waves that occur in air create a propagating pressure profile that is initially observed as an abrupt pressure front followed by a decaying profile [7]. In Figure 1 the propagation of an air blast wave is shown for five progressive time intervals along the axis of the blast wave by means of pressure and distance. With time, the pressure behind the front may drop to below the ambient pressure thus creating a partial vacuum behind the blast wave.

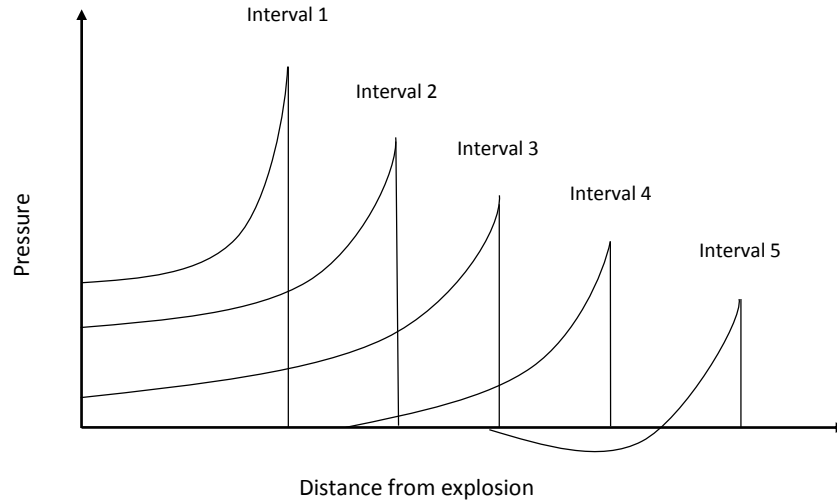


Figure 1: Decay properties of a blast wave with respect to distance [7]

The profile shown in Figure 2 is typical for far-field free-air explosions, when the blast wave has had sufficient time and space to fully develop before impinging on a structure. When the distances between the explosive source and the structure are very short, a more complex pressure time history results. This is known as a near-field explosion. For the purpose of basic blast theory, far-field free-air explosions are discussed. A far-field free-air blast wave impinging on a surface a combined pressure time relationship can be drawn, for a single point on the axis of the air blast wave, as illustrated in Figure 2. The pressure expands supersonically from atmospheric pressure P_0 to a peak pressure P_s at an arrival time t_a and is viewed as a discontinuous pressure. After this peak pressure is reached, an approximate exponential decrease in pressure occurs down to the pre-shock level reached at time $t_a + t_d$, where t_d is the time interval for the peak pressure to decay to ambient. The pressure continues to drop and a negative pressure or suction phase follows; subsequently the pressure will asymptotically approach ambient pressure.

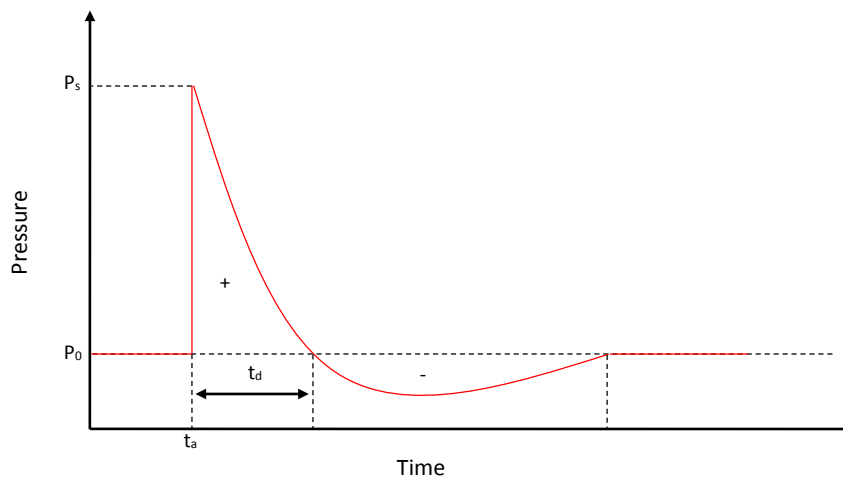


Figure 2: Pressure profile of a far-field blast wave with respect to time [8]

2.1.2.2 Impulse of a Blast Wave

The Friedlander waveform is commonly used to describe the pressure developed as a result of a far-field explosion. It is an empirical description of the pressure variation of the positive pressure behind the shock wave and is given by Equation 1 [9], where ‘ α ’ is the decay rate and ‘ t ’ is any point in time throughout the curve illustrated in Figure 2.

$$P(t) = P_0 + P_s \left[1 - \frac{1}{t_d} \right] e^{-\alpha t/t_d} \quad (1)$$

This equation indicates that the characteristic pressures of a blast wave are dependent on the peak and ambient pressures. The energy of the explosion is a measure of the peak pressure at a certain distance from the explosion. Blast wave parameters such as the specific impulse (I_s) can be calculated integrating the positive phase of the blast wave, shown by Equation 2 [10].

$$I_s = \int_{t_a}^{t_a+t_d} P(t) dt \quad (2)$$

2.2 Blast Experimental Literature

Small scale testing is a means of investigating the different parameters of an explosion that can be extrapolated to real life conditions. A selection of topics are discussed relating to the current research.

2.2.1 Blast Scaling

In order to achieve small scale tests, scaling laws are applied. A common scaling technique is to scale by distance. Hopkinson-Cranz Blast Scaling [11], shown in Equation 3, states that for similar charge geometries and materials, a scaled distance can be calculated to produce similar blast waves.

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad (3)$$

‘Z’ is the scaled distance for both small and large scale explosions; ‘R’ is the distance between the centre of the explosive and the contact surface and ‘W’ is the mass of the explosive.

2.2.2 Plastic Explosive Materials

Plastic explosives are characterised as an explosive material which contains a putty consistency. Plastic explosives are formed by mixing a high energy explosive material with a chemical binder and plasticizer [6,8]. Different plastic explosive materials can be produced by different composition ratios. The putty consistency of a plastic explosive allows for the material to be moulded and retained into a desired shape. Common plastic explosives are C4 and PE4, which are both based on an explosive component called RDX. RDX has a detonation velocity of 8800m/s [6].

2.2.3 Loading Conditions

For experimental purposes, the blast loading of the test specimens are commonly separated into localised or uniform loading conditions. Localised loading conditions are defined whereby the majority of the blast load is concentrated in a local region of the test area and intended to expose a structure to intense loads, which result in local deformation, shear and rupture. Uniform loading conditions are evenly distributed over the test area where less severe failures occur.

2.2.3.1 Methods

In order to achieve localised and uniform loads, Marchand and Alfawakhiri [12] state that if the standoff distance (distance between the explosive and the exposed surface of the test specimen) is greater than half the specimen dimension, then the load can be assumed to be uniform. Anything less than this is termed localised. This is illustrated in Figure 3.

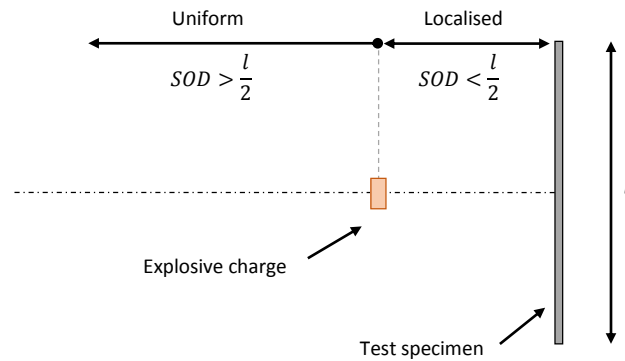


Figure 3: Schematic showing the conditions for localised or uniform loading

Within laboratory-scale investigations, localised and uniform loading conditions are achieved using different techniques. Localised loads are achieved by the use of polystyrene pads [13,14], polystyrene bridges [3], suspending the explosive from a wooden frame [15] or attaching it to the end of a piece of wire [16]. Uniform loading conditions are achieved in two common methods. Firstly by allowing the blast wave to expand within a steel tube, with the explosive and test specimen on either end, as achieved by Langdon et al [17]. Secondly, by employing an explosive annuli on a polystyrene pad, as achieved by Chung Kim Yuen et al [18] shown in Figure 4.

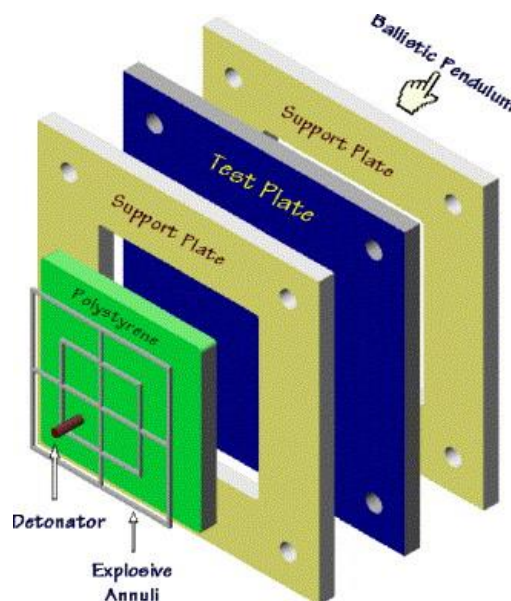


Figure 4: Schematic showing uniform loading with an explosive annuli [18]

2.2.3.2 Response of Different Materials

A simple comparison of localised or uniform loading is illustrated in Figure 5 and Figure 6 that show the different responses of clamped steel plates. Localised loading results in the deformation of a local dome imposed on a global dome that, with further increase in loads, lead to thinning in the local area and along the clamp boundary. Uniform loading results in a global dome observed and with increased loads lead to thinning and tearing at the clamp boundary.

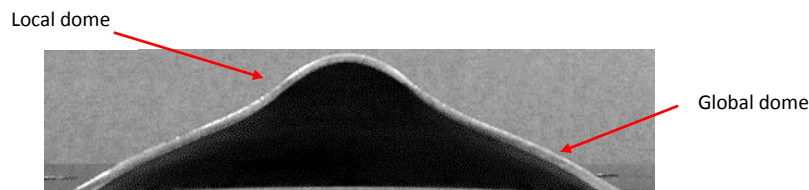


Figure 5: Photograph of a cross-sectioned steel plate subjected to localised blast load, exhibiting global and local domes [17]

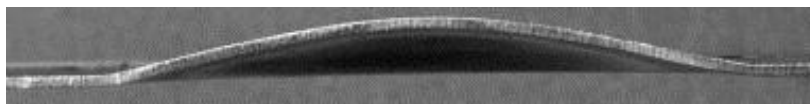


Figure 6: Photograph of a midpoint cross section of a uniformly blast loaded steel plate [17]

Figure 7 and Figure 8 respectively illustrate composite sandwich panels subjected to uniform and local loading conditions. The metallic face sheets in Figure 7 result in a permanent dome deformation as observed with the steel plate in Figure 6. Figure 8 illustrates a fibre reinforced face sheet sandwich panel with soft foam core where no permanent domes were observed. A local concentration of failure was however observed in the central region of the panel indicative of the local dome imposed on the global dome observed for the steel plate in Figure 5.

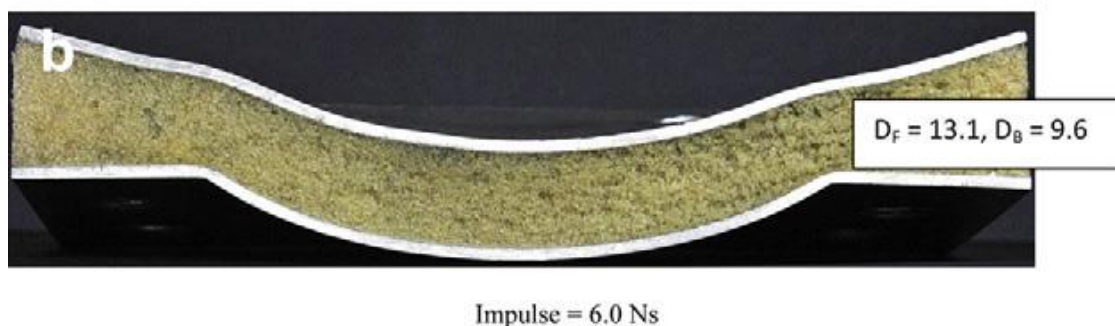


Figure 7: Photograph of a cross-sectioned composite sandwich panel subjected to uniform blast load [19].



Figure 8: Photograph of a cross-sectioned composite sandwich panel subjected to localised blast load [3]

2.2.4 Influence of Explosive Charge Parameters

Charge parameters affect the manner in which the load is transferred from the explosive material to the test specimen. Important properties such as charge mass and charge geometry are discussed below.

The charge mass of an explosive is the mass of explosive material used for a particular test. For cylindrical charge geometries of PE4, Jacob et al [17] defined an approximate relationship of 1:2 for charge mass and impulse imparted to the test specimen for lab scale experiments, employing a blast tube, to direct the wave towards the specimen.

The geometry of the plastic explosives can be varied as the putty consistency allows for the explosive charge to be moulded into a desired shape. Cooper [6] clarifies that a shock wave is generated and propagated from the point of detonation and continues to move through the rest of the explosive material. After which the shock wave moves into the surrounding air, creating a blast wave. For different charge geometries (such as spherical and cylindrical) the point of detonation differs. The spherical shape is commonly detonated from the centre of the charge and expands into a spherical blast wave, whereas the cylindrical shape is usually detonated from a chosen flat end and expands from one end of the explosive to the other, forming a more cylindrical blast wave with more forward momentum, because of the rear position of the detonator. The cylindrical blast wave produces larger impulses and a more concentrated/localised relative to the spherical blast wave [6].

2.3 Composite Materials

A composite material is defined as the combination of two or more constituent materials that result in a material that obtains characteristics and properties that differ from the individual materials from which it was constructed. In contrast to metal alloys, each constituent material retains its separate chemical, physical and mechanical properties [2].

The sections to follow elaborate on fibre reinforced composite materials and some current experimental work pertaining to quasi-static flexural tests and blast loading.

2.3.1 Reinforced Composite Materials

Reinforced composite materials consist of one or more reinforcing filler material embedded within a matrix component [20]. Three common characteristic filler materials are of particulate, whisker or fibrous form and are usually stronger and stiffer than the matrix. The reinforcing material is known for improving the mechanical properties of the matrix constituent, as the matrix serves to distribute any applied load to it [21].

2.3.1.1 Fibrous Materials

Of the three filler materials, fibrous materials are categorized by its length being greater than its cross sectional dimension. The extent to which the fibre may contribute to the composites performance, is directly determined by its shape and dimension. A relationship of fibre length (l) and the cross sectional dimension (d), called the aspect ratio, shown in Equation 4, helps divide fibrous materials into continuous or discontinuous [21].

$$Aspect\ ratio = \frac{l}{d} \quad (4)$$

Larger aspect ratios correspond to continuous fibres, where smaller aspect ratios correspond to discontinuous fibres [21]. Both discontinuous and continuous fibres can be further divided into a random or directional layout, as seen in Figure 9 (a) to (b) and Figure 9 (c) to (d) respectively.

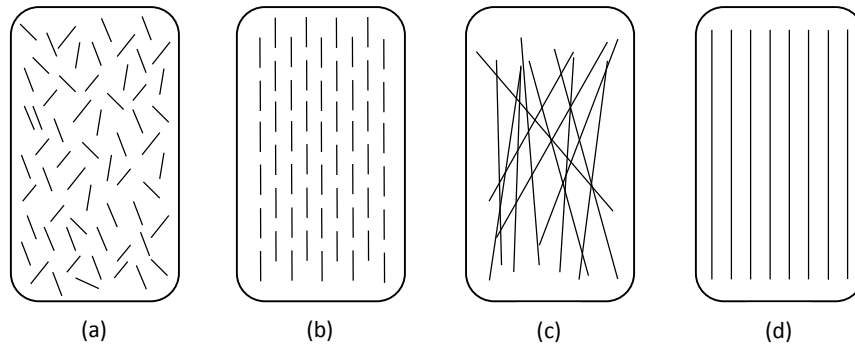


Figure 9: Categories of fibrous reinforcing materials [21]: (a) random discontinuous, (b) directional discontinuous, (c) random continuous, (d) unidirectional continuous

Long continuous fibres are collected together in parallel bundles to form what is called a roving or yarn. A roving has no twisting in its formation, whereas a yarn does incorporate twisting in its formation. Rovings/yarns are placed together to form fabrics. Woven fabrics incorporate patterns that combine longitudinal and horizontal yarns/roving in what is called the warp and weft directions. Common fabrics are called plain, basket, satin and twill weaves and are shown in Figure 10 (a), (b), (c) and (d) respectively.

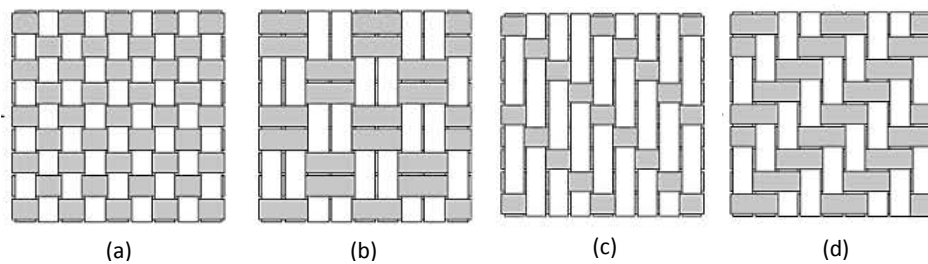


Figure 10: Common woven fabric patterns [22]: (a) plain, (b) 2x2 basket, (c) 4x1 satin and (d) 2x2 twill

Woven fabrics provide an efficient and effective means for manufacturing. However, given the ‘waviness’ present through the thickness of the structure, a slight reduction in stiffness results. The waviness results from warp and weft crossover points and reduces the tensile strengths. For plain and basket weaves the reduction in stiffness is more prominent, as crossover points occur more frequently. However the reduction in stiffness is far more uniform in the warp and weft directions compared to the satin and twill weaves [22].

Another factor in fibre reinforced composites is the presence of anisotropy. Anisotropy results from the modulus of elasticity being greater in the direction parallel to the fibres, rather than being perpendicular. This is most prevalent in unidirectional structures and more complex in woven fabrics. However, with loads parallel to the fibres, the composite stiffness resembles that of the fibres, whereas a load perpendicular to the fibres, resembles that of the less stiff matrix [2].

Campbell [2] defines unidirectional fibre reinforced composites as orthotropic materials. This is attributed to the fact that they obtain properties in three mutually perpendicular axes, namely x , y and z . A load applied parallel to these axes produces only normal strains, whereas loads not applied parallel, produce normal and shear strains. Figure 11 shows this by applying tensile load parallel to the fibre orientation (a) and at 45° to the fibre orientation (b). The deformed shape (shown by the dotted line) of a parallel load results in an elongation in the y direction and a contraction in the x direction. For the 45° layup the load is resisted more in the stiffer AD direction compared to the weaker BC direction. Figure 11 (b) illustrates the deformed square element into a parallelogram and induces a shear strain within the composite.

When layers of fabrics are stacked on top of one another they form what is called a laminate. When unidirectional fabrics are placed in 0° , 45° , 90° and -45° directions the laminate is said to be quasi-isotropic. Fabrics that induce a fibre orientation of 0° and 90° in a single sheet can be used to form quasi-isotropic laminates.

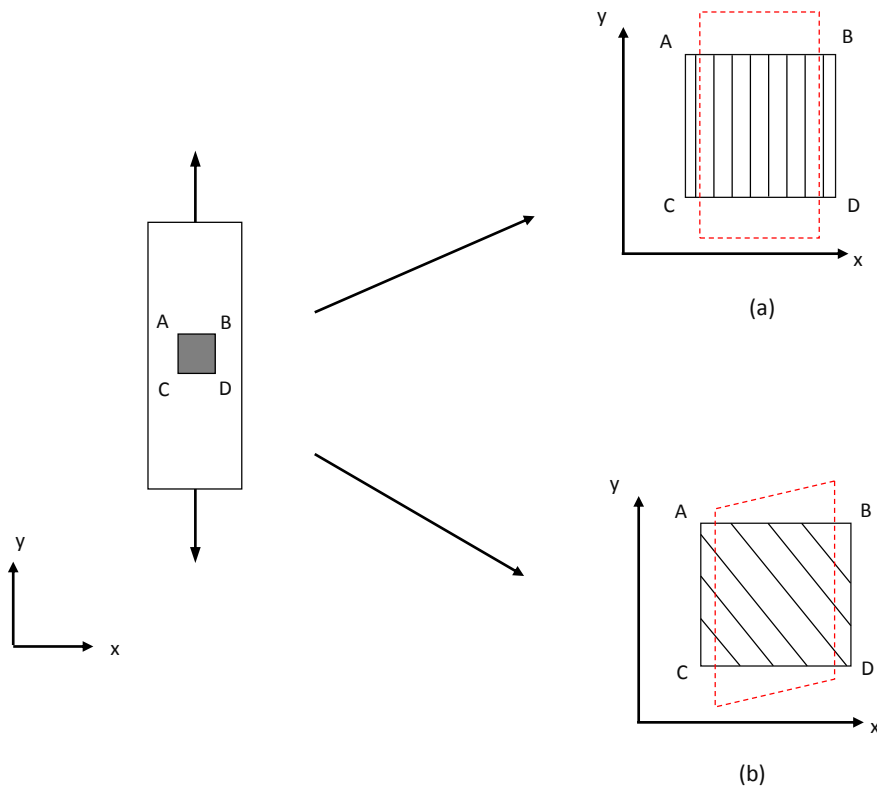


Figure 11: Tensile loading of unidirectional fibre reinforced composite specimen: (a) fibres parallel to load, (b) fibres 45° to load [2]

2.3.1.2 Matrix Properties

Matrix materials maintain the orientation and spacing of the fibrous material in conjunction with transferring applied loads to them. The effectiveness of the load transfer is dependent upon the shear properties at the interface of the fibre and matrix.

Matrix materials are commonly polymer, ceramic, metallic or a combination. Polymer matrix composites are often favoured for fabrication, for their low cost and ease of fabrication. Polymer matrixes are traditionally divided into two groups; thermoplastic or thermosetting materials. Thermoplastic materials characteristically have great ductility and high processing speeds, as they melt immediately by heating the material above the glass transition temperature (20). Thermosetting materials cure gradually by complete polymerization and associated cross-linking of the polymer molecules. Cross-linking results from a chemical reaction that is driven by heat and is an irreversible process, contrary to the reheat ability of thermoplastics.

Thermosetting matrices include resins such as polyesters, vinyl-esters, epoxies, bismaleimides, cyanate esters, polyimides and phenolics. Epoxies are the most common matrix material used for high performance composites, as they have an excellent combination of strength, adhesion, low shrinkage and processing versatility [20].

2.3.1.3 Composite Manufacturing

A successful manufacturing process requires repeatable products. Different manufacturing processes are used for different constituent materials. This section elaborates on the manufacturing of polymer matrix composites, explicitly using thermosetting epoxies.

Manufacturing processes for thermosetting materials are generally divided into processes for discontinuous materials (particulates, loose fibres) and continuous materials. Discontinuous materials commonly use processes that mix the reinforcement and resin prior to manufacturing to form a slurry or dough. This is then placed in a mould and allowed to set. Continuous fibres usually use processes where the resin is allowed to impregnate the reinforcing material during the manufacturing process. Continuous processes include wet layup, filament winding and Liquid Composite Moulding (LCM). The section to follow will elaborate on liquid moulding processes.

When the LCM process is aided with a vacuum pump, it is called Vacuum Assisted Transfer Moulding (VARTM) process. A type of VARTM process exists where a single sided mould is used where a vacuum bag serves as the other side of the mould. This is called Vacuum Infusion (VI) [23]. Figure 12 shows a cross section schematic of the of the VI setup where the dry materials are laid up on the mould surface and covered with a vacuum bag. Before infusion, the vacuum pump is turned on and once a complete vacuum is achieved, the resin is allowed to flow into the

mould. To assist the impregnation of the reinforcement, flow promotion media are used, as well as release plies to ensure smooth surface finishes.

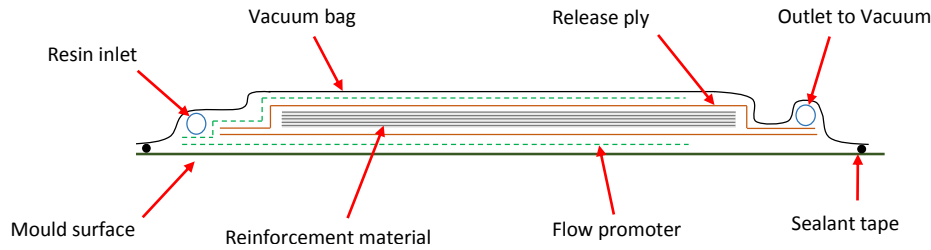


Figure 12: Schematic showing cross section of the VARTM setup

Mathur et al [24] investigated the flow front of VARTM by computational and experimental means, giving insight into the shape and flow of the resin during fabrication. Figure 13 shows a schematic of the analytical model used. The flow promoter is represented by the top material and fibres by the bottom material. The flow of resin is governed by Darcy's law. Mathur et al [24] stated that the flow can be divided into two regions, namely a saturated region and a flow front region. The saturated region has no through thickness flow whereas the flow front region contains resin infiltrating the fibres from the promoting material. This phenomenon was expected for the current project where promoters are placed on both sides of the fibrous material.

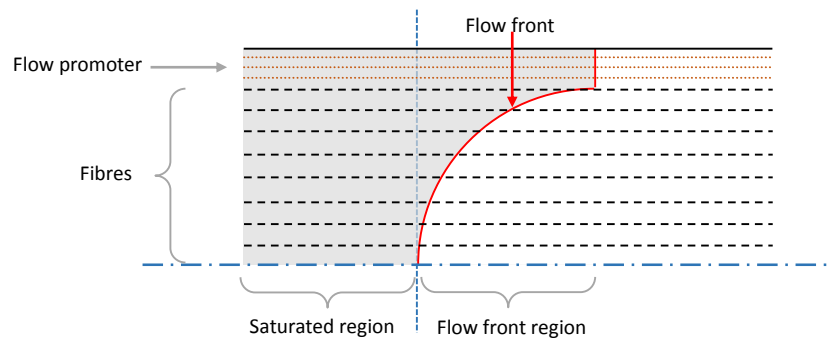


Figure 13: Flow front model of two materials of different permeability's [24]

The quality of fibre composite products is governed to a large extent by the process parameters and materials used. Another important aspect to ensure good quality when manufacturing, is to circumvent void content, whilst wetting out of the preform. Hoa [25] states a list of properties a fibre reinforced polymeric matrix manufactured composite should incorporate, including:

- good bonding between matrix and fibres
- proper orientation of the fibres
- sufficient fibre volume fraction
- uniform distribution of fibres
- proper curing or solidification of resin
- limited voids and defects
- good dimensional control of final part

2.4 Response of Composite Panels to Blast Loading

The section to follow reports on experiments on the behaviour of fibre reinforced thermosetting polymer matrix composites subjected to blast loading.

2.4.1 Characterisation of Manufactured Composites

In order to study a material under blast loading, the mechanical properties need to be known and with a manufactured composite material they would need to be experimentally obtained. The method of acquiring different material properties is called characterisation. Different methods exist to characterise manufactured composites of which quasi-static testing is included. Data from these tests also help clarify repeatability of the product.

One attribute owing to blast resistant capability of a material is the flexural strength. This is commonly investigated prior to blast loading in laboratory conditions. Figure 14 shows the typical flexural response of an E-glass fibre and a vinyl ester resin composite specimen from a three-point bend test [3]. The response of the specimens showed a linear elastic behaviour up to failure, which can be seen by the initiation of fibre fracture at approximately a strain of 0.38. The specimen failed in bending due to localised compression under the central loading bar.

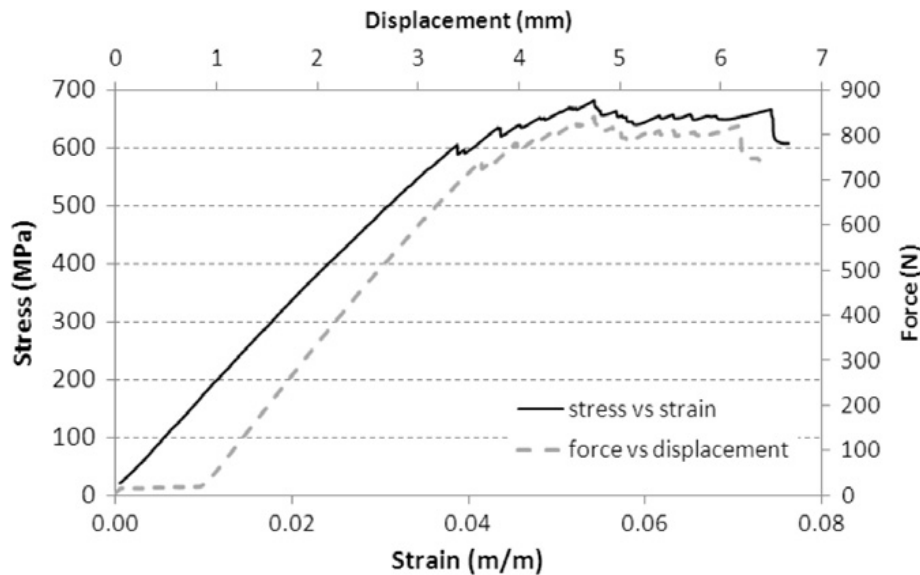


Figure 14: Flexural behaviour of fibre reinforced composite material under three-point bending [3]

2.4.2 Behaviour of Fibre Reinforced Materials under Shock Loading

The behaviour of different fibre reinforced materials under shock loading was investigated and elaborated on below.

2.4.2.1 Circular Carbon and Glass Fibre Panels Subjected to Localised Blast Loads

Edwards et al [26] investigated the effect of explosives on polymer matrix composites by blast loading unidirectional carbon and glass fibre epoxy resin composites. Specimens were clamped between two circular plates to which a plastic explosive, PE4, was detonated at various standoff distances that ranged from 80-500mm. The failure of both fibre panel types resulted in delamination and fibre breakage.

The carbon fibre composites ruptured at a higher charge than the glass fibre composites, owing to a greater tensile strength of the carbon fibres. The investigation also looked at near field explosives, by placing the charge on the surface of the specimens. This highly localised loading caused holes to form with extensive delamination around the hole periphery. Figure 15 shows fibre breakage and delamination in the carbon panels. Edwards et al [26] noted the difference observed on aluminium sheets, where petaling and tearing were seen near the hole periphery. The damaged observed on the back surface exceeded that of the front surface.

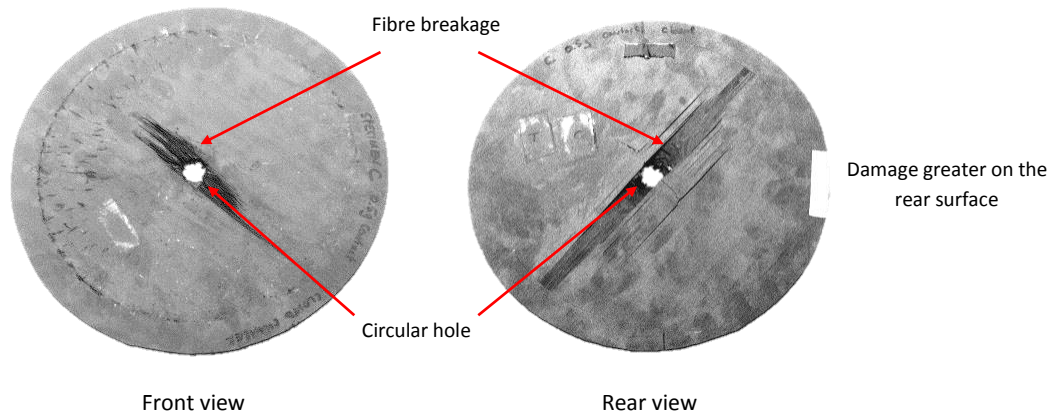


Figure 15: Photograph of the front and rear view, illustrating the fibre breakage of carbon fibre specimen subjected to a surface charge [26]

2.4.2.2 Square Carbon and Glass Fibre Panels Subjected to Localised Blast Loads

Shukla et al [27] also investigated the dynamic response of fibre based composites constructed with carbon and E-glass fibre. Shukla et al [27] compared the response between an air blast in a shock tube and an explosive blast. Specimens were constructed by VARTM with a vinyl ester resin and fixed to a rigid clamping fixture. Similar failure modes such as permanent deformation, delamination and fibre breakage were observed.

The shock pressure tests resulted in the carbon fibre panels showing no damage until a certain shock pressure threshold of 0.62MPa, after which prominent delamination and fibre breakage were observed, illustrated in Figure 16 (a). The E-glass panels showed an increasing progression of permanent deformation, delamination and fibre breakage, as illustrated in Figure 16 (b), showed more resistance to the extent of damage observed on the rear face. Similar failure modes were detected for the explosive blast tests, with the exception of a central burn region, shown in Figure 17.

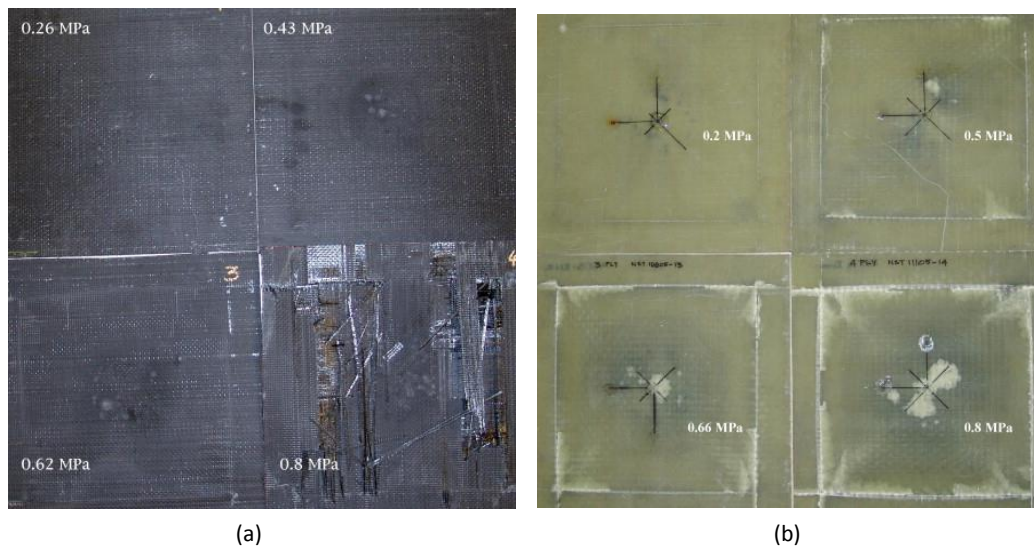


Figure 16: Rear face damage progression from air blasts: (a) carbon fibre panels, (b) E-glass fibre panels [27]

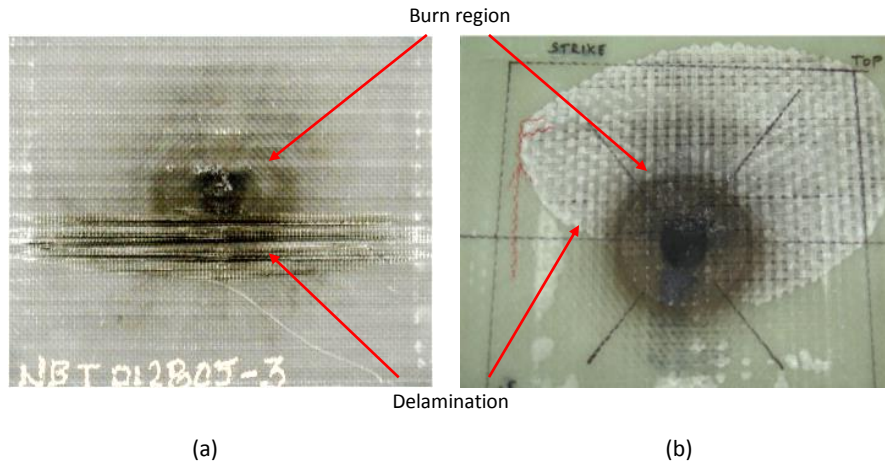


Figure 17: Front surface damage resulting from blast loading: (a) carbon fibre panel, (b) E-glass fibre panel [27]

2.4.3.2 Circular Glass Fibre Panels Subjected to Localised Blast Loads

Langdon et al [28] investigated the experimental and numerical response of glass fibre reinforced vinyl ester panels subjected to localised blast loads. The panels were clamped to a ballistic pendulum and exposed to blast loading, arising from detonating PE4 explosives. Failure modes of permanent deformation, delamination and fibre breakage were observed. Figure 18 illustrates a midpoint cross section showing delamination and ruptured layers that began at the back surface. It was concluded that a common failure in fibre reinforced composites was delamination/interlaminar cracking between composite layers, due to the relatively weak interlaminar strengths. The permanent back face deflections were a consequence of the internal delamination of the fibre layers and delamination.



Figure 18: Photograph of a midpoint cross section of glass fibre reinforced vinyl ester panel subjected to a blast load generated from a 13.0g PE4 explosive [28]

Langdon et al [28] also showed that the delamination of the fibre layers starts in the front layer and spreads through the thickness of the panel. The extent of the delamination increased throughout the panel thickness, as the impulse was increased and eventually caused rupture to occur (originating from the back layer). This was due to the tensile load being maximised at the outer layer of the composite material.

2.5 Sandwich structures

A sandwich structure typically consists of two thin face sheets separated by and bonded to a lightweight core material. Face sheets are commonly chosen to be strong and stiff, and are usually combined with a soft and deformable core material. With the core material having a lower density than the face sheets, sandwich structures are advantageous for weight reduction applications, while maintaining sufficient stiffness. This combination mimics the I-beam principle, where the face sheets support bending loads and the core material transfers the shear loads between them.

The following section gives an overview of the behaviour of sandwich structures under quasi-static and dynamic loads. The current literature on the behaviour of sandwich structures under blast loading was also investigated.

2.5.1 Quasi-static Properties

As discussed in section 2.3.1, quasi-static properties help characterise a material. The quasi-static tests commonly associated with sandwich panels include flexural tests of the sandwich structure and compression tests of the core material.

2.5.1.1 Flexural Properties

The effectiveness of a sandwich structure is observed when exposed to bending. The bending of a sandwich structure exposes compressive and tensile loads to the top and bottom face sheets, respectively and thus a shear load is induced on the core material, as illustrated in Figure 19.

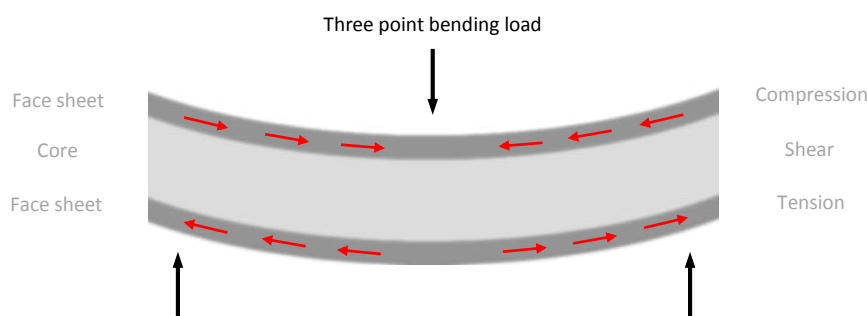


Figure 19: Load distribution in sandwich structures under bending conditions

An important parameter in solid mechanics is the elastic modulus of a material. The bending rigidity or stiffness of a sandwich structure is comprised of the elastic moduli of the different components and shown by Equation 8 [29]. Where subscripts ' f ' and ' c ' denote the face sheet and core properties respectively.

$$\text{Bending rigidity} = \frac{E_f b t_f^3}{6} + \frac{E_f b t d^2}{2} + \frac{E_c b t_c^3}{12} \quad (8)$$

The rigidity is a function of elastic moduli ' E ', width ' b ', distance between face sheets ' d ' and thickness ' t '. For applications where the thickness of the face sheets is less than the core material and the elastic modulus of the core material is significantly less than the face sheets, Equation 8 can be reduced to Equation 9, where two important properties pertaining to the construction of sandwich structures are highlighted. They are the elastic modulus of the face sheet material and the distance between the two face sheets, namely the thickness of the core material. It is therefore favourable to incorporate a stiff face sheet material and to ensure a reasonable distance between them.

$$\text{Bending rigidity} = \frac{E_f b t d^2}{2} \quad (9)$$

Figure 20 illustrates an example of the flexural response of two composite sandwich structures under quasi-static three point bend tests. The two types of sandwich structures were constructed from glass fibre reinforced vinyl ester face sheets, separated by two different density PVC foam cores, namely 80kg/m³ (H80) and 200kg/m³ (H200). The response of the sandwich structures differed and therefore illustrated that the density of the core influenced the strength and failure of the structure. An initial elastic region was observed that lead up to a peak point and further deformation resulted in an abrupt drop in strength. The failure resulted from the compressive rupture of the top face sheet [28]. Figure 21 illustrates the point of failure under the loading bar where local indentation (core densification) was also observed. It is evident from Figure 21 that the peak force and energy absorbed is greater in the H200 sandwich beam and the 80kg/m³ core provided less structural support to the top face sheet than the denser foam.

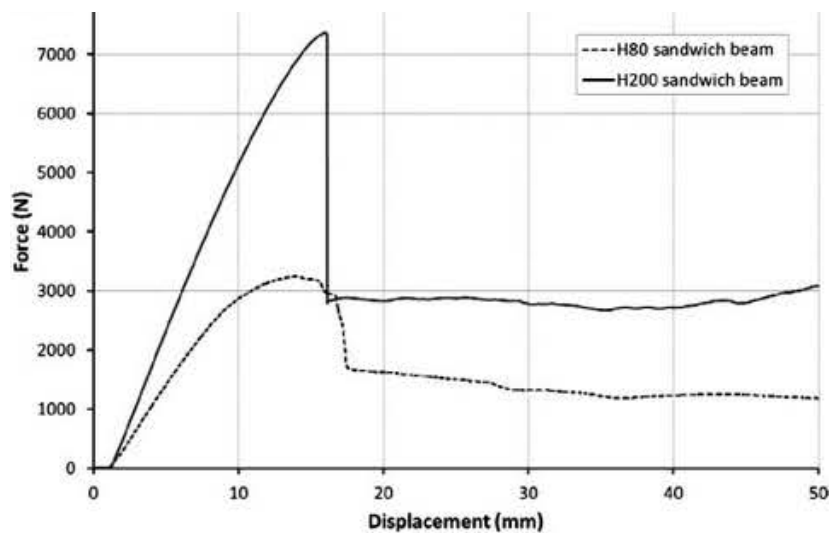


Figure 20: Flexural response of composite sandwich structure under quasi-static three point bending [28]

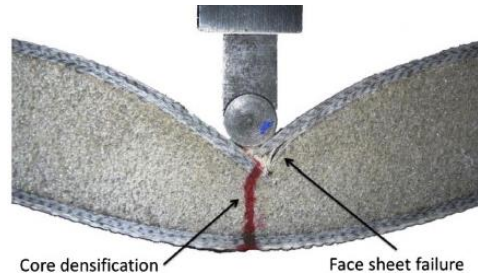


Figure 21: Compressive face sheet failure of fibre reinforced sandwich structure [28]

2.5.1.2 Compressive Properties of the Core Material

The compressive properties of a cellular material commonly consist of a linear elastic region, a plateau region, followed by a sharp rise known as densification. Different cellular core materials under compression are shown in Figure 22. The linear elastic region was a result of the elastic bending of the cellular walls and the approximate plateau region represented the constant load required, to cause plastic deformation of the cellular walls. The densification followed, when the complete collapse of the cellular walls occurred, resulting in a steep rise in stress. The aluminium honeycomb showed a 50% drop in stress prior to the plateau region, where the PVC foams close to a 10% drop in stress. Figure 22 (b) shows that the denser PVC foam has a higher compressive strength.

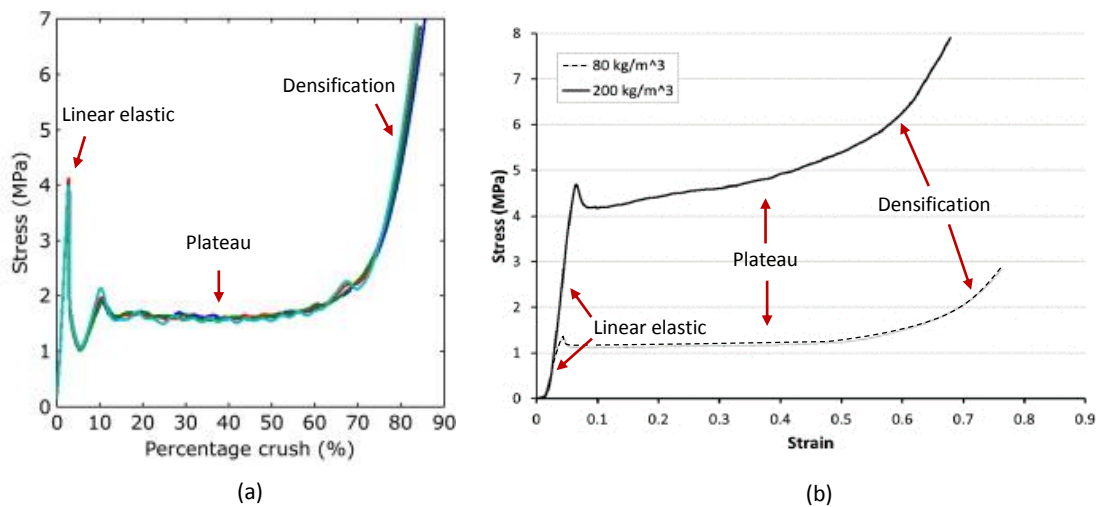


Figure 22: Compressive behaviour of cellular materials: (a) aluminium honeycomb (30), (b) PVC foams [28]

The area under the stress-strain graphs, indicated the energy absorption capability of the core material. The majority of the energy absorption was highly attributed to the behaviour in the plateau region. The mitigation of the shock load is thus dependent on the cellular structure core materials, as it controls the dispersion of the mechanical impulse, transmitted through the structure [3,31].

2.6 Response of Sandwich Panels to Blast Loading

This section reports on the current literature on the behaviour of sandwich panels subjected to blast loading.

2.6.1 Metallic Sandwich panels

The response of metallic sandwich structures subjected to blast loads, has been thoroughly investigated [32,33] and gave insight to the behaviour of sandwich panels to blast loads. Lu et al [34] investigated the response of an aluminium honeycomb core and face sheet sandwich panel structure subjected to localised blast loads. The failure of the sandwich panel is illustrated in Figure 23, where a local and global response can be seen (as observed with the metallic monolithic panels subjected to localised loads). The presence of the core influenced the response of the panel, with fully, partially and absent folded core regions observed. This resulted in the deformation of the front face sheet, contrary to that of the back face sheet. The local and global deformation was less distinguished on the back face sheet.

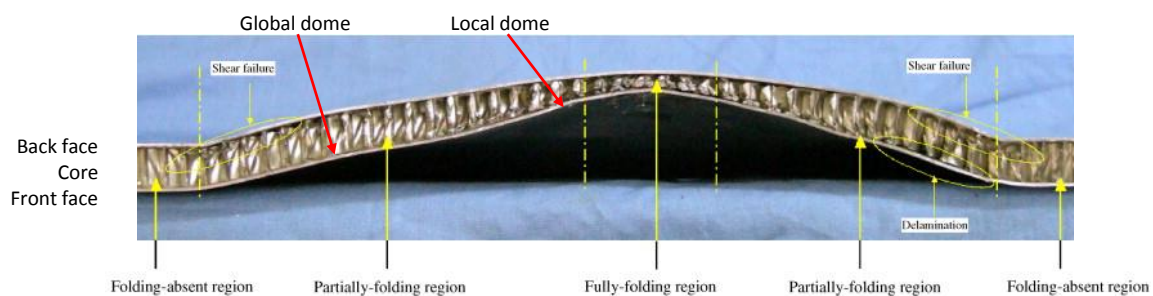


Figure 23: Internal failure modes of aluminium honeycomb and face sheet sandwich structure [34]

2.6.2 Composite Sandwich panels

Langdon et al [3,28] investigated the response of composite sandwich panels subjected to blast loads, comprised of E-glass fibre reinforced vinyl-ester face sheets separated by a PVC foam core material. Vacuum infusion was used to fabricate the panels and were subjected to localised plastic explosive, PE4. At low impulses, the local damage was observed on the front face sheet, as with the metal sandwich panels [34]. The failure modes of the fibre reinforced face sheets were delamination, matrix failure, fibre fracture and face sheet rupture. The delamination was more prominent in the direction of the fibres and delamination increased across the test area with increased charge mass, as illustrated in Figure 24.

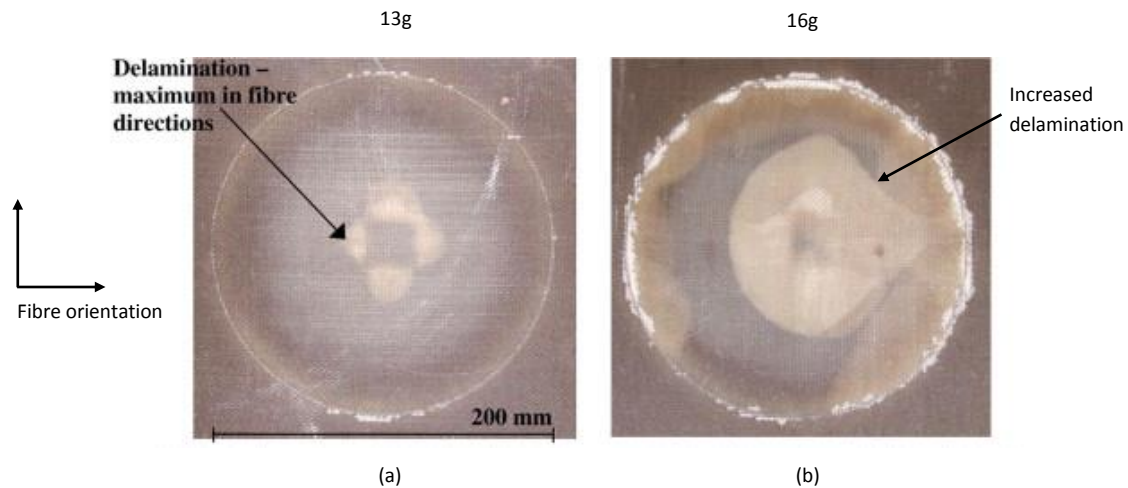


Figure 24: Photograph of the back face sheets of fibre reinforced sandwich panels [3]: (a) delamination prominent in the fibre orientation, (b) increased delamination with increasing charge mass

Midpoint cross sectional views illustrated rupture of the face sheets and failure of the core material, seen in Figure 25. As with the metal sandwich panels, the local compression of the core material was observed. Failure modes of fragmentation and penetration were also noted, as well as debonding of the front and back face sheets with the core material. The debonding of the front face sheet resulted from the recovery of the stiff face sheet to its approximate position, with the core material compressed during the initial stages of the blast test [3]. The plastic deformation of the back face sheet, resulted in a debonded area from the core material, as observed in Figure 25.

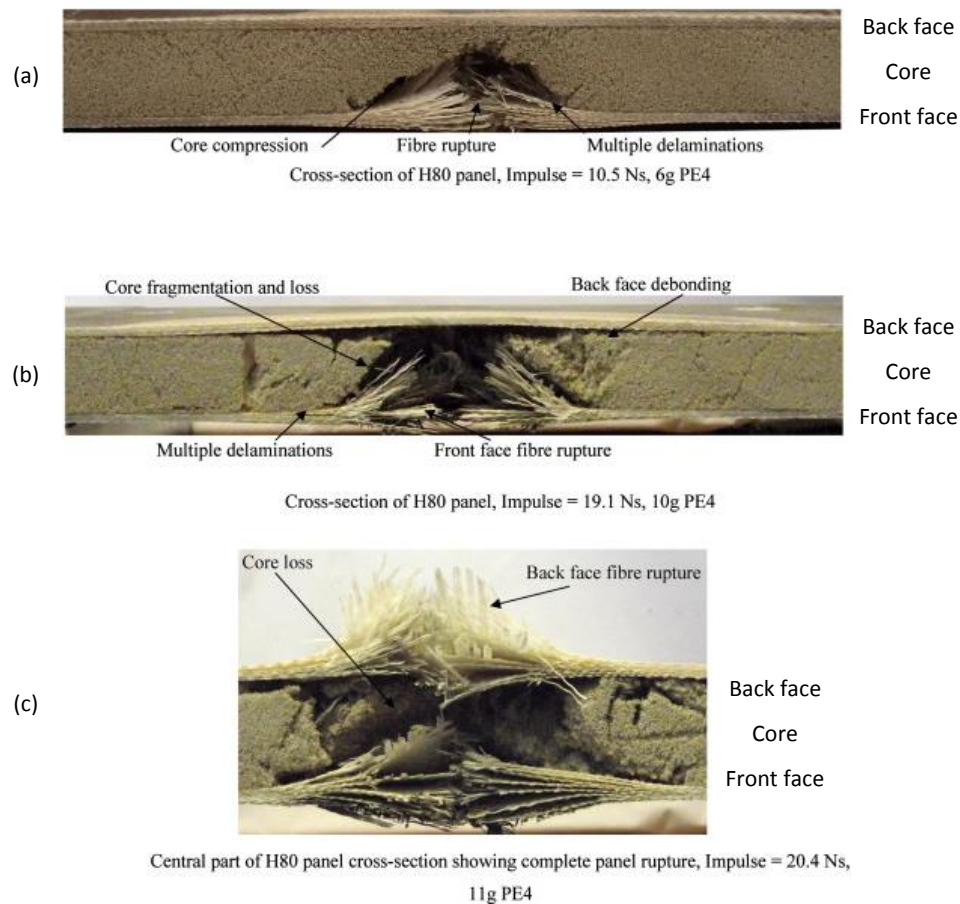


Figure 25: Photographs of the midpoint cross section fibre reinforced face sheets and polymer foam core subjected to blast loads of: (a) 6.0g, (b) 10.0g, (c) 11.0g [28]

Langdon et al [3] proposed a failure progression of the composite sandwich panels for increasing charge mass. The failure progression, shown in Figure 26, gave insight to the energy absorption due to the failure of different components. The failure and energy dissipation, was initiated at the front face sheet and core material. This limited the force transfer to the back face sheet, however, back face sheet delamination was present. Core compression increased with impulse and was more evident on the side closest to the blast, indicating the front face sheet deformed significantly into the core, before recovering elastically. With an increase in impulse, the failure modes exhibited in laminate structures arose in the front face sheet, such as matrix failure and fibre fracture. Once considerable damage of the front face sheet and core material had occurred, force was transferred to the back face sheet, causing plastic deformation and debonding of the back face sheet.

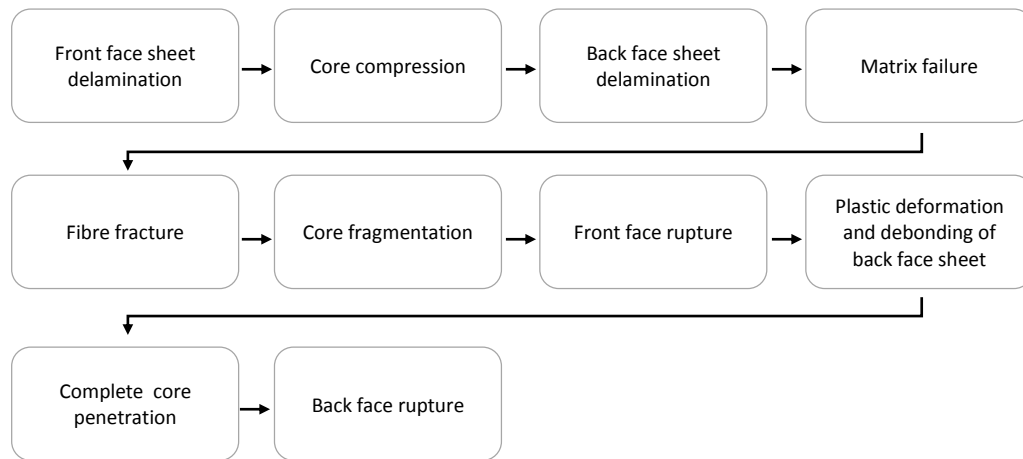


Figure 26: Failure progression seen in fibre reinforced face sheets and polymer foam core sandwich structures subjected to blast loads [3]

2.7 Curved Structures

Curved structures are found in applications such as infrastructure and transport; in land, water and air domains. The effect of curvature to blast loading, is an important feature and requires more attention [35].

This section investigates the behaviour of curved structures subjected to blast loads, by analysing and comparing the failure modes observed in various experimental investigations. The current research pertains to loads projected to a convex curve and with little experimental literature on the topic; monolithic metallic and simple composite laminates are initially investigated followed by metallic sandwich structures.

2.7.1 Curved Structures Subjected to Blast Loading

Curved structures subjected to blast loads were investigated by analysing experimental work on the response of different curved panels to blast loads.

2.7.1.1 Singly Curved Monolithic Aluminium Panels Subjected to Shock Loading

Singly curved monolithic aluminium panels were investigated by Shukla et al [35], where the three curvatures were subjected to shock loads. The specimens of 2mm thicknesses consisted of curvatures of a flat, 304.8mm radius and 111.8mm radius and were titled panel A, B and C respectively. The specimens were clamped in a square clamp frame to the end of a circular shock tube, where the shock wave struck the central region of the specimens.

Digital Imaging Correlation (DIC) analysis was conducted and illustrated in Figure 27. The colour contours indicated the amount of deflection observed for all three curvatures with the axis of curvature in the horizontal direction. The results indicated that the deflection of flat panel A initially showed a central circular deformation, followed by a square response as a result of boundary effects. The introduction of single curvature in Panel B and C (where curvature of Panel C was greater than Panel B) resulted in an elliptical deflection contour. Panel B's response transitioned from an elliptical contour to a square, as an effect of the boundary, however this was not observed on panel C.

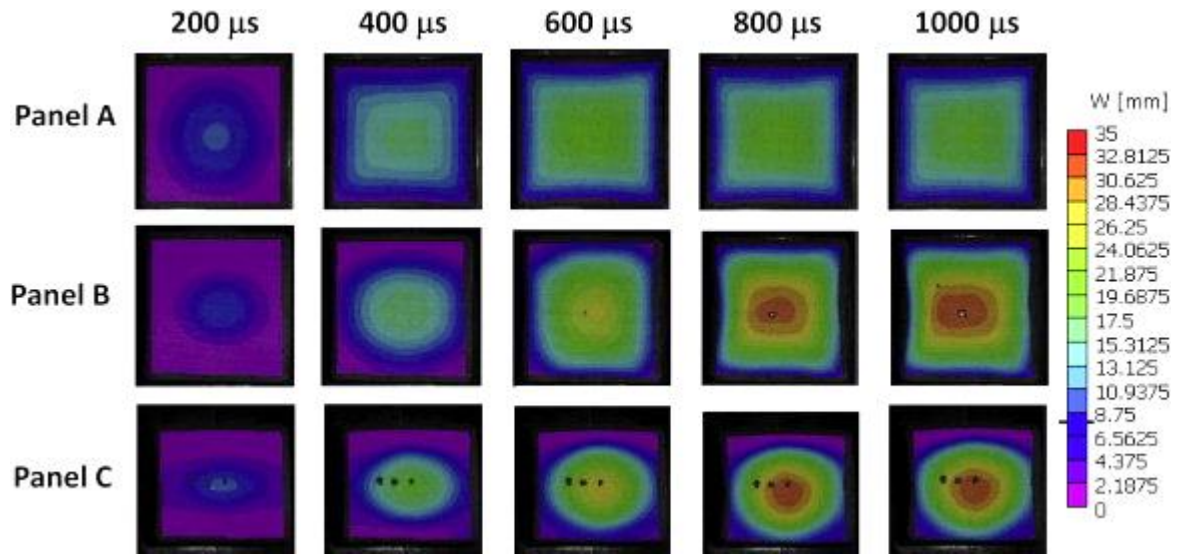


Figure 27: Deflection contours of curved aluminium panels from DIC analysis [35]

As a result, Shukla et al [35] defined the deflection of the panels by two modes, an initial indentation mode followed by a flexural mode. The indentation mode indicated a localised deflection of the panel and the flexural mode an overall deflection of the panel, as noted in Figure 28. Panel A and B experienced this transition with the introduction of the curvature retarding it. No transition was observed for Panel C where only an indentation mode was seen.

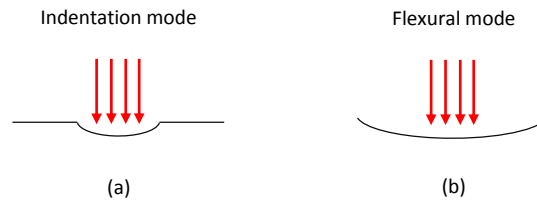


Figure 28: Schematic illustrating the deflection by: (a) indentation mode, (b) flexural mode [35]

The deflection-time history is illustrated in Figure 29 where the permanent deflection of panel B and C is greater than Panel A. It was concluded that the indentation mode produced larger displacements than the flexural mode and the deflections were more localised.

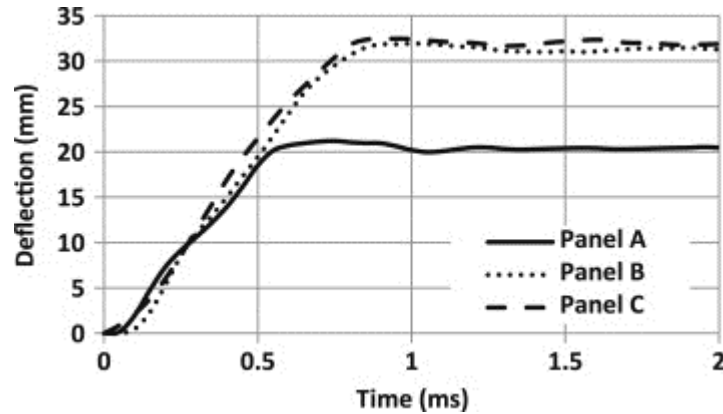


Figure 29: Graph of deflection-time history of the centre of the three curved aluminium panels [35]

2.7.1.2 Singly Curved Carbon Composite Panels Subjected to Shock Loading

Shukla et al [36] further investigated the effect of curved panels subjected to shock loads, with the blast response of carbon composite panels which comprised of the same three radii and thicknesses. Similar DIC images to [35] were obtained and it showed similar responses, as illustrated in Figure 30. Note: the axis of curvature situated in the vertical direction is the image shown. Panel B of the composite structure resisted the effect of the boundary and panel C again showed no effect from the boundary.

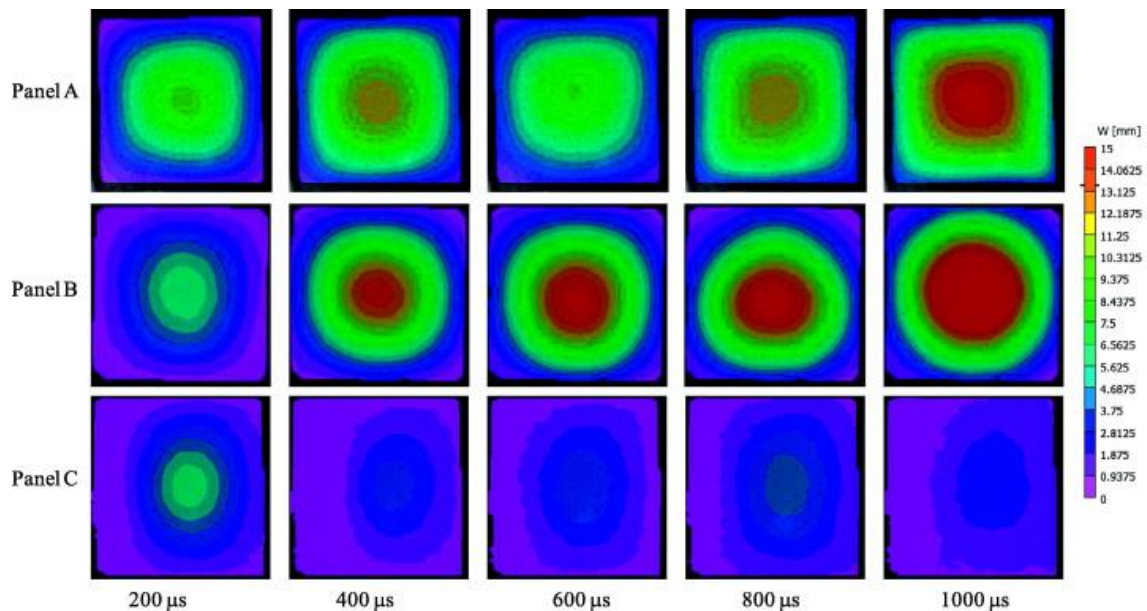


Figure 30: Deflection contours of curved carbon fibre panels from DIC analysis [36]

Shukla et al [36] concluded that the failure was again a result of flexural or indentation modes. The response of the composite panels resulted in an initial indentation deflection. The introduction of the curvature again resisted the size of the initial indentation and the transition

of the overall flexural deflection of the panel. The increase in curvature resisted the magnitude of the initial deflection and the growth of the indentation and further resisted the transition to overall flexural deflection. The response of flat versus curved is summarised in Figure 31.

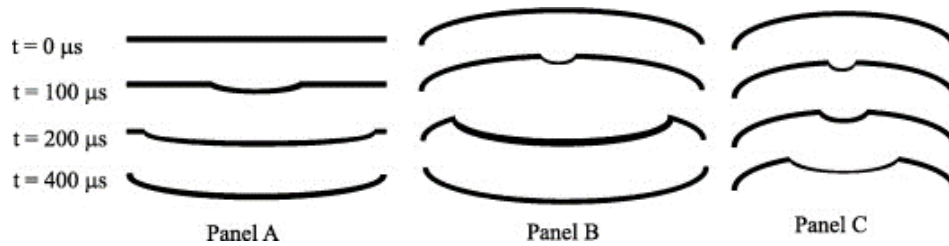


Figure 31: Indentation and overall flexural response of the carbon fibre panels [36]

The deflection-time history is illustrated in Figure 32 where the deflection of Panel A and B are similar and greater than the deflection of Panel C. This resulted in the greatest curvature producing the least deflection when subjected to shock loads.

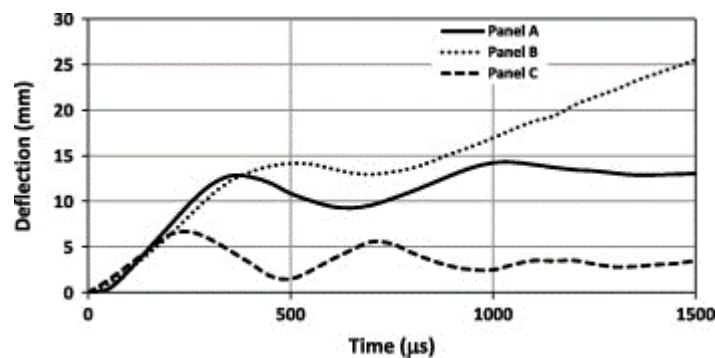


Figure 32: Graph of the deflection-time history of the centre of all three carbon composite panels [36]

2.7.1.3 Singly Curved Aluminium Sandwich Panels Subjected to Blast Loading

Lu et al [16] investigated the response of singly curved aluminium sandwich panels subjected to blast loads. The aluminium face sheets were bonded to the aluminium foam core with an epoxy adhesive glue. The panels had mid-panel radii of 300mm or 600mm. Panels were clamped to a ballistic pendulum and exposed to TNT explosive detonations. The localised blast loading of the panels was analysed by the response of the different constituent components.

The failure of the curved aluminium sandwich panels resulted in a localised deformed area surrounded by wrinkling failure. The deformation was resisted more along the curvature of the panel, thus producing an elliptical deformed area. Indentation and flexural deflection modes were also observed as identified for the monolithic panels [35,36]. The blast load on the larger curved panel resulted in an overall flexural deformation, however the smaller curved panel resulted in

an indentation deformation producing shallow “U” and “M” shapes, respectively along the curvature of the panels, as seen in Figure 33.

Lu et al [16] concluded that three distinct effects are seen with the introduction of curvature in sandwich structures. Firstly, a reduction of the impulse imparted on the front face sheet as the blast wave is deflected by the curvature. Secondly, the introduction of the wrinkling failure mode on the back face sheet. And thirdly, the curvature changed of deformation regimes of bending and stretching. Flat sandwich panels experience bending and stretching, whereas curved sandwich panels divide its response into three regimes. These regimes are bending only, bending along the curved axis and stretching along the longitudinal axis and stretching along both axes.

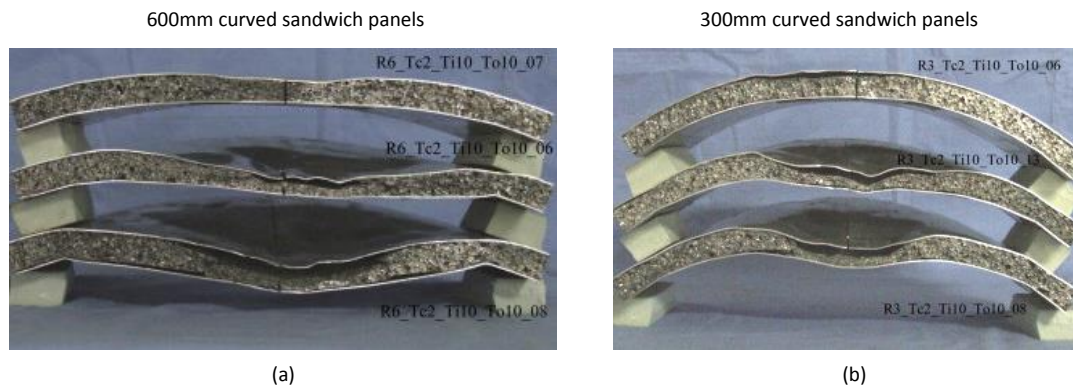


Figure 33: Photographs of the midpoint cross section of the: (a) 600mm curved and (b) 300mm curved sandwich panels [16]

Chapter 3

Manufacturing of Panels

Two types of composite panels were designed and manufactured as described in Table 1. The panels were constructed with three radii, namely infinite (flat), 1000mm and 500mm; and were confined to equal areal densities. The panels were constructed from a vacuum infusion process with the aid of three moulds. This chapter elaborates on the manufacturing parameters, mould design, panel design, the manufacturing procedure and the measurements of the manufactured panels.

Panel type	Definition
Fibre-reinforced Polymer (FRP) laminate panel	Panel consisting of 15 layers of fibre reinforced composite material manufactured by vacuum infusion
Fibre-reinforced Polymer (FRP) sandwich panel	Panel consisting of FRP laminate face sheets that contain 6 layers of fibre reinforced composite material on both sides of a foam core material manufactured by vacuum infusion

Table 1: Definition of two manufactured panels used

3.1 Manufacturing Parameters

The manufacturing parameters describe the design considerations for the manufactured panels. These include panel requirements, constituent materials, chosen manufacturing process and consumable materials.

3.1.1 Panel Requirements

The panel radii were chosen as infinite (flat), 1000mm and 500mm where the radii were measured from the outer surface of each panel. All panels consisted of a singly curved form, as shown in Figure 34.

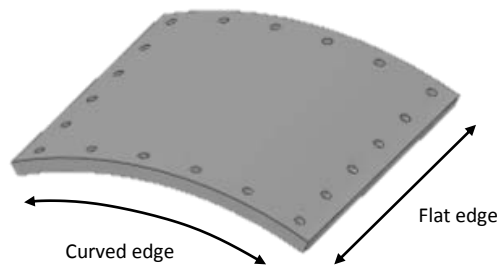


Figure 34: Singly curved panel design illustrating the curvature and flat regions of the panels

Each panel was to be clamped to a ballistic pendulum and subjected to a localised blast load where these loads are expected to concentrate failure in a localised region of the panel. To ensure that failure was concentrated in this local region, the panels were designed with an area of 400mm x 400mm, as shown in Figure 35 (a). For comparable reasons, the curved panels were designed to incorporate a projected area of 400mm x 400mm, illustrated in Figure 35 (b) for the 1000mm and 500mm curved panels.

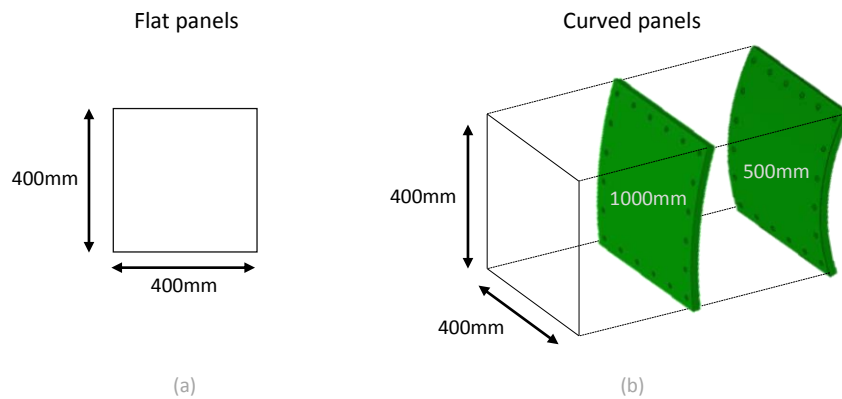


Figure 35: Dimensions for the: (a) flat panels, (b) 1000mm and 500mm curved panels

3.1.2 Constituent Materials

The constituent materials used for the FRP sandwich panels consisted of a woven E-glass fibre, PVC foam material and epoxy resin. The FRP laminate panels consisted of a woven E-glass fibre and epoxy resin. The difference owed to the absence of the core material. These materials are further described as follows.

3.1.2.1 Woven E-glass Fibre Material

Woven E-glass fibre material was used in the construction of the face sheets of the FRP sandwich panels and the construction of the entire FRP laminate panel. The E-glass fibre material consisted of a plain weave woven structure with a mass per square meter of 400g/m².

3.1.2.2 Airex C70.75

Airex C70.75 is a PVC foam material used for the core component in the construction of the FRP sandwich panels. Airex C70.75 is a cross linked polymer with a unique closed cell structure. Nominal properties of Airex C70.75 are listed in Table 2.

Property	Unit	Airex C70.75
Nominal Density	kg/m ³	80
Compressive strength	MPa	1.3
Compressive modulus	MPa	83
Shear strength	MPa	1.2
Shear modulus	MPa	30
Shear elongation at break	%	23
Maximum working temperature	°C	90

Table 2: Properties of Airex C70.75 PVC foam [37]

3.1.2.3 Prime 20 LV Resin

Prime 20 LV resin is a low viscosity epoxy resin used to construct the FRP sandwich and laminate panels. Epoxy resins are characteristic for their low viscosity properties and thus allowed for long working times, making the resin ideal for vacuum infusing large structures. Properties of the Prime 20 LV resin and hardeners are listed in Table 3.

Property	Unit	LV Resin	LV Slow Hardener
Mix ratio by weight	-	100	26
Mix ratio by volume	-	100	31.4
Shelf life	months	12	12
Density	g/cm ³	1.123	0.936
Mixed density	g/cm ³		1.084
Gel time (25°C)	hours:min		3:20
Demould time (20°C)	hours		21
Cure schedule (50°C)	hours		16
Tensile strength	MPa		73.0

Table 3: Prime 20 LV resin and LV slow hardener properties [38]

3.1.3 Manufacturing Process

Vacuum infusion (VI) was used to manufacture the FRP sandwich and laminate panels. The VI procedure followed the placement of the constituent materials on a mould surface, sealing the mould off with a vacuum bag and allowing a pressure difference, created by the vacuum pump, to draw resin through the mould. Flow promoters and release plies enclosed the dry materials and promoted and retarded the flow of resin through the mould respectively. The components of the VI process are shown in Figure 36 illustrating the direction of flow. The inlet pipe was submerged into the resin bucket and the outlet pipe was connected to the vacuum pump via a resin trap. The resin trap ensured that resin did not enter the vacuum pump during the manufacturing process.

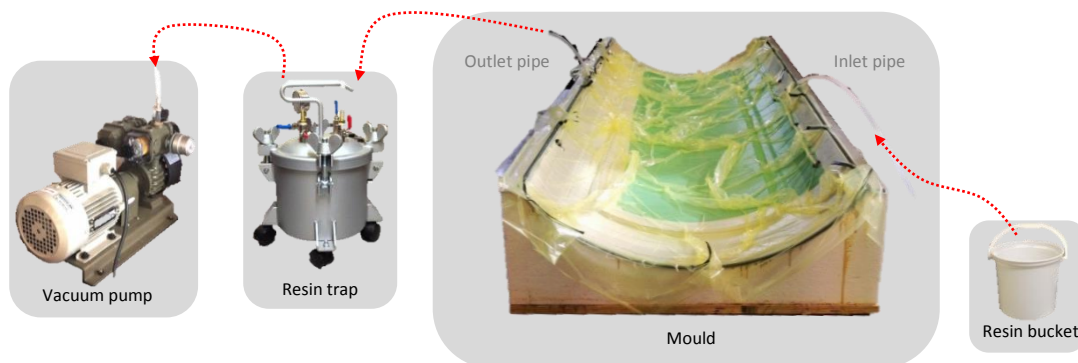


Figure 36: Photographs illustrating the setup of the vacuum infusion process

3.1.4 Consumable Materials

The consumable materials for each manufacturing process included a flow promoter, peel ply, vacuum bag, plastic tubing, spiral bind tubing and tacky tape.

3.1.4.1 Greenflow 75 (flow promoter)

Greenflow 75 is a high permeable material used in the manufacturing process to assist the flow of resin through the mould. The greenflow provided a flow path of least resistance thus promoting resin over the fibrous material.

3.1.4.2 Peel Ply

Peel ply is a smooth woven nylon fabric impregnated with a release agent. The peel ply protected the product from the greenflow and provided a smooth and even surface for potential secondary bonding.

3.1.4.3 Vacuum Bag

The vacuum bag served to enclose and complete the mould. The vacuum bag was attached to the aluminium surface with tacky tape and care was taken to ensure no leaks were present. Any leaks were secured before manufacturing began.

3.1.4.4 Tubing

The inlet and outlet pipes consisted of plastic tubing that were attached to the mould with the spiral bind tubing. The solid tubing provided a path way for the resin to enter and exit the mould, while the spiral bind tubing distributed flow of resin across the mould.

3.1.4.5 Tacky tape

The tacky tape was used to attach the vacuum bag to the mould surface and provide an air tight seal between the two.

3.2 Mould Design

Three moulds were used in order to manufacture the two different panel types. The requirements of the moulds were to produce large FRP sandwich and laminate panels from which test specimens would be cut. The panels were to have a smooth surface and consistent radius.

3.2.1 Flat Mould Design

The flat mould consisted of a flat aluminium sheet attached to a flat surface. Eight possible 400mm x 400mm specimens could be generated from the flat mould per manufacturing process, as shown in Figure 37.

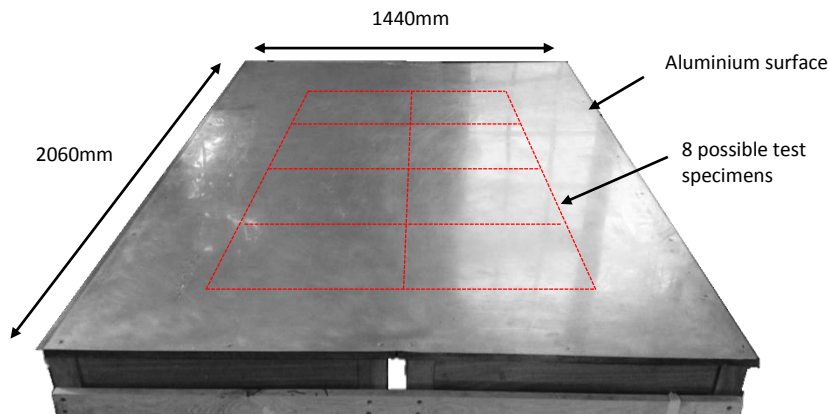


Figure 37: Photograph of the flat panel mould illustrating the potential eight test specimens per manufacturing process

3.2.2 Curved Mould Design

Two curved moulds were designed and built in order to manufacture the curved panels. The shape of the moulds was achieved by cutting from large, high density polystyrene blocks with the use of a CNC wire cutter. The polystyrene blocks were cut to the desired radius of 998mm and 498mm for the 1000mm and 500mm curved panels, respectively, to account for the adhesive and aluminium sheet thicknesses. The polystyrene blocks were attached to 21mm thick ply wood sheets for stability with general wood glue. Mechanically rolled aluminium sheets were attached to the curved polystyrene surfaces with a polyurethane adhesive.

Figure 38 (a) and (b) illustrate the 1000mm and 500mm curved moulds respectively. These moulds allow for four curved test specimens to be produced per manufacturing process.

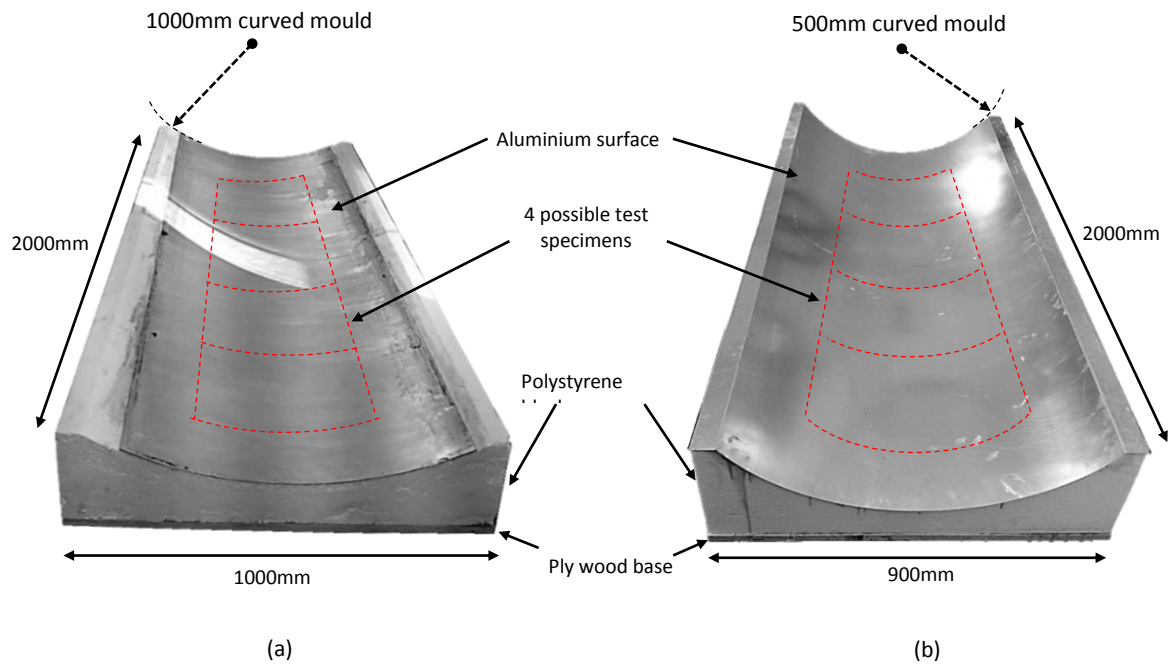


Figure 38: Photographs of the curved panel moulds: (a) 1000mm curved mould, (b) 500mm curved mould

3.3 Design of the Fibre Reinforced Polymer Sandwich and Laminate Panels

The FRP sandwich panels were designed with thin face sheets relative to the core thickness. The design of the FRP laminate panels was to match the aerial density of the FRP sandwich panels. The procedure followed the construction of the flat FRP sandwich and laminate panels, followed by the construction of the curved panels.

3.3.1 Construction of the Fibre Reinforced Polymer Sandwich Panels

The FRP sandwich panels consisted of E-glass reinforced fibre face sheets, separated by perforated Airex C70.75 PVC foam core material. The core material was perforated with 2mm in diameter holes. The face sheets were constructed with six layers of plain weave E-glass fibre, separated by a 15mm thick core material. The average thickness of the flat FRP sandwich panels was 18.7mm with a measured areal density of 8593g/m². The open celled structure of the core material resulted in resin settling in them and created an effective face sheet thickness. The average front and back face sheet thicknesses were thus measured as approximately 2.3mm and 2.4mm, respectively, for the flat FRP sandwich panels. This in turn reduced the core material thickness to 14.0mm, as seen in Figure 39.



Figure 39: Photograph of a section of the flat FRP sandwich panel, illustrating the effective thicknesses and overall thickness

3.3.1.1 Curved Fibre Reinforced Polymer Sandwich Panels

The curved FRP sandwich panels were constructed with an identical design as the flat panels, with each face sheet consisting of six layers of E-glass fibre separated by a nominally 15mm thick Airex C70.75 core material. In order to achieve the desired radius the core material was thermoformed prior to the manufacturing.

The thermoforming of the core material was achieved using a voltage driven heating mat. The heating mat was covered with an insulating cloth, to reduce heat dissipation and enclosed by a vacuum bag and tacky tape. The vacuum forced the core to take the shape of the mould.

Figure 40 illustrates the thermoforming process in a 1000mm curved mould and Table 4 lists the procedure used to thermoform all core material sheets.

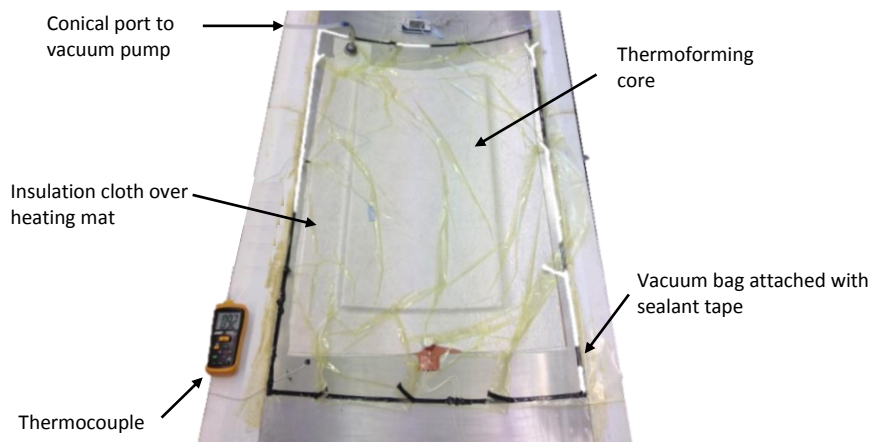


Figure 40: Photograph illustrating the thermoforming of the core material in 1000mm curved mould

Step	Procedure
1	Cut desired size and perforate core material
2	Placed core material in the centre of mould under the heating mat
3	Attached conical port, inserted thermocouple and sealed vacuum bag to mould surface
4	Switched heating mat on and adjusted voltage dial until thermocouple reaches 90°C
5	Maintained temperature of 90°C for 15 minutes to ensure heat dissipates throughout thickness
6	Switched vacuum pump on
7	Monitored and adjusted temperature for 15 minutes to ensure temperature remains at 90°C
8	Switched heating mat off
9	Allowed core material to cool down under ambient conditions
10	Once thermocouple reached ambient temperature, switched pump off and removed core material

Table 4: Thermoforming procedure of the core material

3.3.2 Construction of the Fibre Reinforced Polymer Laminate Panels

The FRP laminate panels were designed to match the FRP sandwich panels with an identical areal density. This was achieved by replacing the mass of the core material with additional E-glass fibre sheets, each with an areal of 400g/m^2 . In order to produce a similar areal density three additional sheets were added to the layup.

The FRP laminate panels consequently consisted of fifteen layers of plain weave E-glass fibre sheets, that once manufactured, produced an areal density of 8590g/m^2 . The average measured thickness of the FRP laminate panels was 4.8mm , 26% of the flat FRP sandwich panel thickness. The E-glass fibre did not require any preforming and therefore were manufactured in an identical manner to the flat panels. All three moulds used to manufacture the FRP sandwich panels, were used to manufacture the FRP laminate panels.

3.4 Manufacturing Procedure

The sections to follow elaborate on the steps taken to produce the FRP sandwich and laminate panels.

3.4.1 Mould Preparation

The mould surfaces were prepared before each manufacturing process by “smoothing” the surface with wet abrasive paper of increasing grit of 400, 600 and 800µm. Once cleaned, four coats of wax was applied to the surface. The “smoothing” preparation assisted with the removal of the manufactured panel from the mould surface. This ensured minimal damage to the panel and mould surface during the demoulding stage.

3.4.2 Layup and Dimensions of Materials

The constituent and consumable materials were laid on the mould according to the schematics provided in *Appendix A1*. Figure 41 illustrates the laid up materials before the vacuum bag was placed on the mould for a 1000mm curved FRP laminate panel.

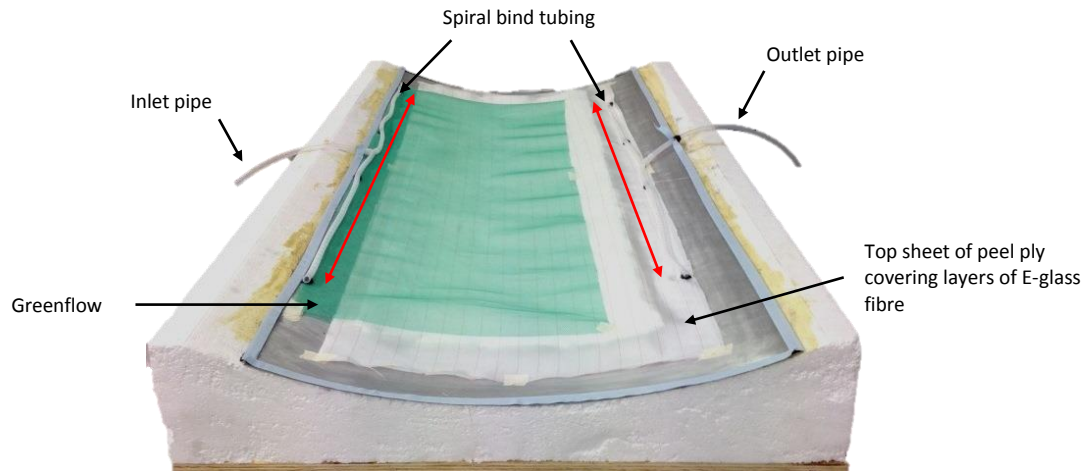


Figure 41: Photograph illustrating the laid up materials of 1000mm curved FRP laminate panel without the vacuum bag attached

3.4.3 Post Curing

The panels were removed from the mould surfaces at the earliest demoulding time indicated by Table 3 in section 3.1.2.3. The greenflow and peel ply were carefully peeled off the manufactured panel to ensure no damage was inflicted.

All panels were cut to the desired dimensions of a projected 400mm x 400mm area, with a table saw.

The cut panels were then post cured in an oven with a curing schedule of 16 hours at 50 °C, as illustrated in Figure 42. Once the panels were post cured, the panels were drilled with twenty equally spaced ($\varnothing$ 14mm) holes. A chosen clamp width of 50mm was chosen, as illustrated in Figure 43.

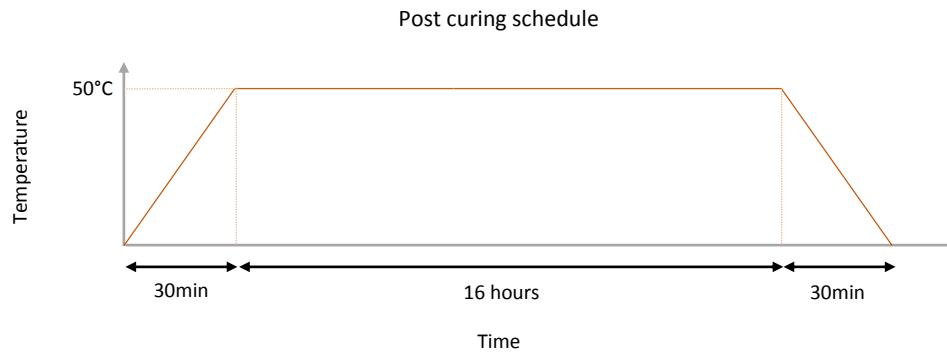


Figure 42: Post curing schedule for all manufactured panels

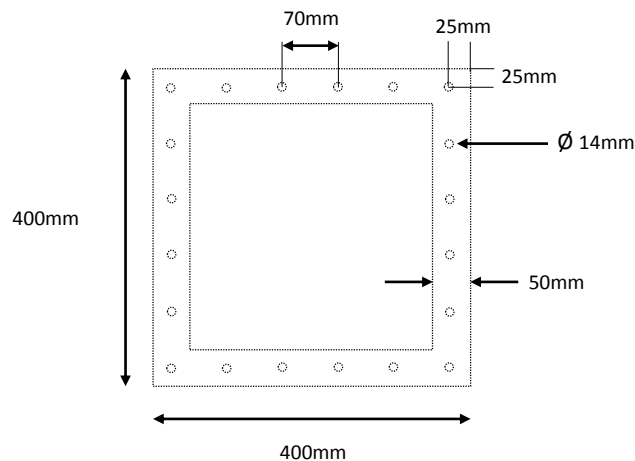


Figure 43: Schematic illustrating the placement of the drilled holes and dimension of the clamped area

3.5 Measurements of the Manufactured FRP Sandwich and Laminate Panels

All measurements of the FRP sandwich and laminate panels are listed in *Appendix A2*. Table 5 lists the face sheet thickness, overall thicknesses and core thickness (as described in 3.3.1) and the areal density of the FRP sandwich panels. Table 6 lists the thickness and areal density of FRP laminate panels.

The mean average areal density of the FRP sandwich and laminate panels were 8628g/m^2 and 8458g/m^2 , a difference of 170g/m^2 (or a difference of 2%). This is the same order as the standard deviation of the mean density for each panel type.

FRP sandwich panels	Thickness				Aerial Density (g/m ²)
	Front	Back	Overall	Core	
Flat	2.3	2.4	18.7	14.0	8596
1000mm_i	2.5	2.4	18.8	13.9	8615
1000mm_ii	2.3	2.5	18.5	13.7	8531
500mm_i	2.5	2.7	18.9	13.7	8955
500mm_ii	2.5	2.5	18.4	13.4	8442
Mean	2.5	2.5	18.7	13.7	8628
Std dev.	0.09	0.11	0.19	0.21	174

Table 5: Measurements of the FRP sandwich panels

FRP laminate panels	Thickness (mm)	Aerial Density (kg/m ²)
Flat	4.8	8477
1000mm_i	5.0	8748
1000mm_ii	4.8	8470
500mm_i	4.9	8315
500mm_ii	4.8	8279
Mean	4.9	8458
Std dev.	0.08	166

Table 6: Measurements of the FRP laminate panels

Chapter 4

Material Characterisation

As discussed in section 2.4.1 and 2.5.1, the material characterisation tests were performed in order to determine the basic mechanical properties of the panels. These were obtained by conducting quasi-static three-point flexural tests on the FRP sandwich and laminate specimens and compression tests on the core material of the FRP sandwich panel. This chapter reports the results of the characterisation tests.

4.1 Fibre Reinforced Polymer Laminate Panel Characterisation

The flexural properties of the FRP laminate panels was obtained from three point by investigating the flexural properties.

4.1.1 Quasi-static Three-point Flexural Tests

The three-point flexural tests were conducted according to ASTM international standard D7264/D7250M-07 [39]. The specimen limitations were as follows [39]:

- desired span to thickness ratio of 32:1 (with optional ratios 16:1, 20:1, 40:1, or 60:1)
- standard width of 13mm
- length of specimen to be 20% longer than the span
- test speed of 1mm/min
- comparable data requires identical span to thickness ratios between specimens

The flexural specimens were cut from a flat FRP laminate panel with Table 7 listing the dimensions of specimens LF1-LF5.

Specimen #	Length (mm)	Span (mm)	Width (mm)	Thickness (mm)	Span to thickness Ratio
LF1	105.3	84	16.2	4.9	17.14
LF2	105.4	84	16.2	5.0	16.80
LF3	105.4	84	16.1	4.9	17.14
LF4	105.0	84	15.7	4.9	17.14
LF5	105.6	84	15.9	4.9	17.14
Mean	105.4	84	16.02	4.92	17.08
Std dev.	0.196	0	0.194	0.040	0.136

Table 7: FRP laminate three-point flexural test specimen dimensions

The tests were conducted on a Zwick Universal testing machine at a constant crosshead speed of 1mm/min. Each specimen was placed on two round support bars with a central loading bar located above the specimen. Force and displacement data were recorded for each test.

Equation 10 and 11 [39] were used to calculate the equivalent stresses and strains,

$$\sigma = \frac{3FS}{2bh^2} \quad (10)$$

$$\varepsilon = \frac{6\delta h}{S^2} \quad (11)$$

where F = force, S = support span, b = specimen width, h = thickness and δ = deflection.

A typical stress versus strain and equivalent force versus displacement graph, is illustrated in Figure 44, for specimen LF2.

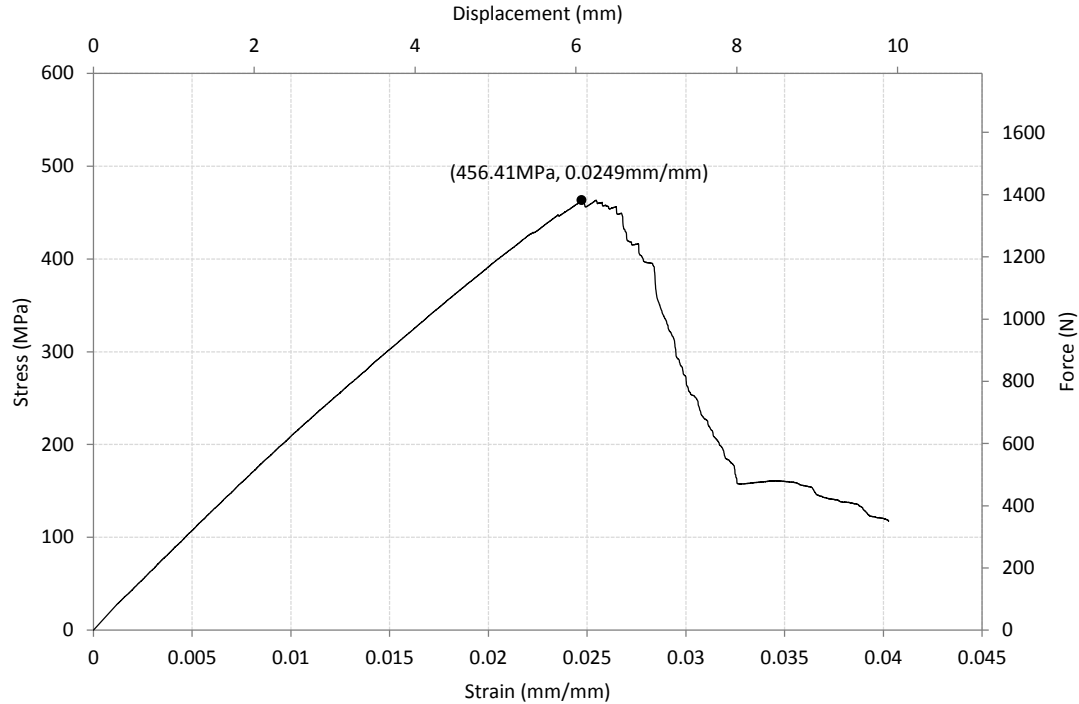


Figure 44: Graph illustrating the stress versus strain relationship from a three-point flexural test of LF2

As observed in Figure 14, the FRP laminate specimens exhibited an initial linear elastic region that with further deformation reached a peak point. Following this peak region a sudden drop in load carrying capacity was observed. The peak point of the specimen shown was observed at a stress and strain of 456.41MPa and 0.0249mm/mm, respectively. Table 8 lists this failure point for all FRP laminate specimens. The average peak stress and strain were 483MPa and 0.026mm/mm respectively.

Specimen #	Stress (MPa)	Strain (mm/mm)
LF1	459.27	0.0270
LF2	456.41	0.0249
LF3	491.64	0.0275
LF4	496.46	0.0258
LF5	511.30	0.0252
Mean	483.02	0.026
Std dev.	21.57	0.001

Table 8: Peak three point flexural stress and strain of the FRP laminate panels

4.2 Fibre Reinforced Polymer Sandwich Panel Characterisation

The flexural and compression behaviour of the FRP sandwich panels were determined using data obtained from three point flexural tests on the FRP sandwich panels and compression tests on samples cut from the foam cores.

4.2.1 Quasi-static Three-point Flexural Tests

The three-point flexural tests were conducted according to ASTM international standard D7250/D7250M-06 [40]. These specimen limitations were as follows [40]:

- a width greater than twice and less than six times specimen thickness
- a width greater than three times core cell diameter
- a width less than half the span length of specimen
- a length equal to the span plus 50mm
- an operating crosshead speed of 6mm/min

The flexural specimens were cut from a flat FRP sandwich panel with Table 9 listing the dimensions of specimens SF1-SF5.

Specimen #	Length (mm)	Span (mm)	Width (mm)	Face sheet Average	Core
SF1	350	299	49.8	2.4	14.1
SF2	351	301	49.9	2.4	14.1
SF3	351	302	50.0	2.4	14.0
SF4	349	299	48.8	2.4	13.9
SF5	350	301	49.2	2.5	13.9
Mean	350	300	49.5	2.4	14.0
Std dev.	0.8	1.2	0.46	0.04	0.08

Table 9: Dimensions of the three-point flexural tests of the FRP sandwich specimens

The tests were conducted on a Zwick Universal testing machine at a constant crosshead speed of 6mm/min. The test procedure was identical to the flexural tests of the FRP laminate specimens. A typical force versus displacement graph is illustrated in Figure 45 for specimen SF5.

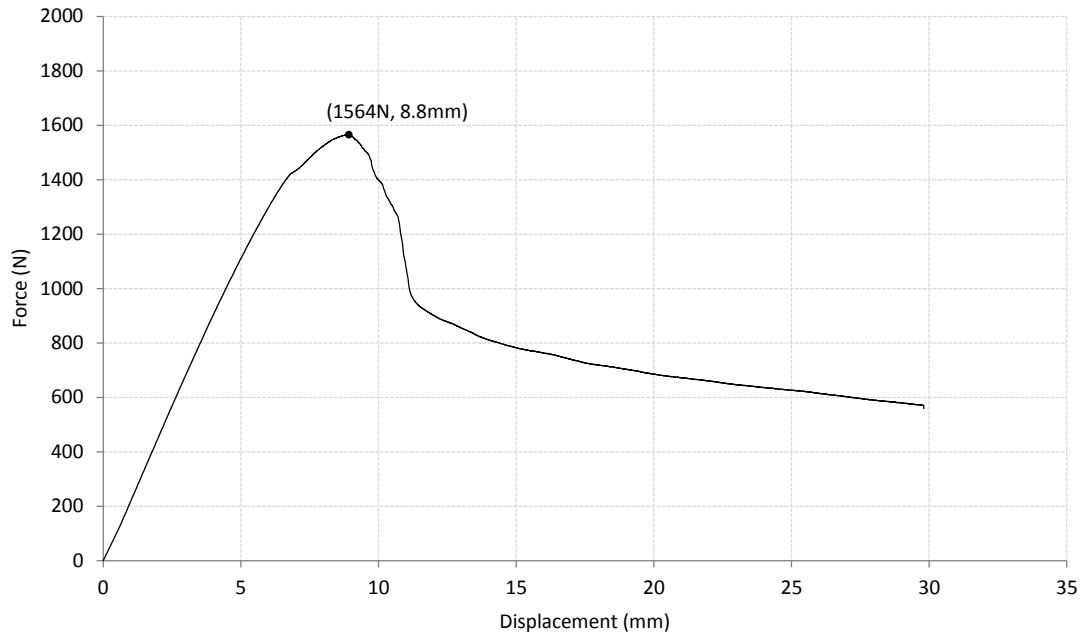


Figure 45: Graph illustrating the force versus displacement of specimen SF5 illustrating a typical relationship for three point flexural tests

When the results are compared to bend test data from similar tests on sandwich panels (shown in Figure 20) a similar response was observed herein for the FRP sandwich specimens. An initial linear elastic region was observed, and a peak point was reached as displacement increased, after which a sudden drop in load carrying capacity was observed. The point of failure of the specimen shown was observed at a force and displacement of 1564N and 8.8mm respectively. Equation 12 was used to calculate the ultimate facing strength with Table 10 listing the peak force resisted by the FRP sandwich specimens. The average peak force and ultimate facing stress was 1542N and 83MPa respectively.

$$\sigma_f = \frac{F_{max}S}{4bt(d-t)} \quad (12)$$

where F = force, S = support span, b = specimen width, t = face sheet thickness and d = core height.

Specimen #	Displacement (mm)	Force (N)	Ultimate facing stress (MPa)
SF1	8.6	1449	77.46
SF2	8.6	1543	82.87
SF3	9.3	1473	79.21
SF4	10.1	1683	91.81
SF5	8.8	1564	82.49
Mean	9.1	1542	82.77
Std dev.	0.57	82	4.95

Table 10: Face sheet shear yield stress calculated from FCS specimens under three-point flexural tests

4.2.2 Quasi-static Compression Tests

The compressive properties of the Airex C70.75 foam core were determined by conducting quasi-static compression tests on five specimens cut from the foam sheets. The compression tests complied with ASTM international standard D1621-04a [41]. The specimen limitations were as follows:

- a square or circular cross sectional area
- a cross sectional area between 2580mm² and 23200mm²
- a height between 25.4mm and the width or diameter of the specimen
- a recommended crosshead test speed of 2.5mm/min

Five compression specimens were cut to a diameter of 67mm, that resulted in a cross sectional area of 3525mm².

The tests were conducted on a Zwick Universal testing machine where the specimens were placed between two metal plates. The top plate moved down towards the bottom plate at a constant test speed of 2.5mm/min (strain rate of 2.78x10⁻³s⁻¹) compressing the core material. For each test, force and displacement data were recorded and the stress and strain were calculated using Equations 13 and 14 respectively,

$$\sigma = \frac{F}{A} \quad (13)$$

$$\varepsilon = \frac{\delta}{\delta_0} \quad (14)$$

where F = force, A = cross sectional area, δ = displacement and δ_0 = original thickness.

Figure 46 illustrates a typical stress versus strain and corresponding force versus displacement relationship of specimen 4 under quasi-static compression.

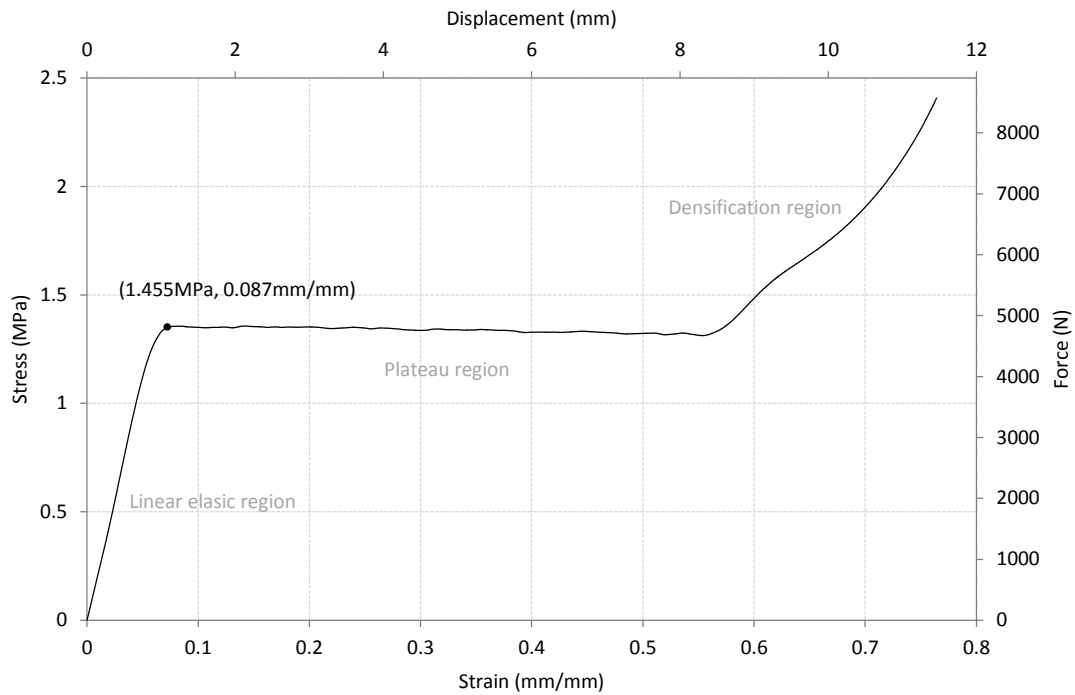


Figure 46: Graph illustrating the stress versus strain relationship of compression test for Airex C4

The Airex foam compression resulted in an initial linear elastic region, followed by a plateau region and then a densification region, a typical cellular material response, as illustrated in Figure 22. The initial linear elastic region was due to the elastic bending of the cell walls of the core material, where all deformation was recoverable [28,30]. With further compression the plateau stress region was observed where a roughly constant load was observed. This plateau region occupies the majority of the energy absorption capabilities of Airex C70.75. The complete collapse of the cells caused a steep rise in stress as the densification region was reached and further compression resulted in the behaviour of a typical solid material. A plateau stress was chosen as the load required to enter the plateau region as illustrated in Figure 46. Table 11 lists the plateau stress for all compression specimens, with an average stress of 1.4MPa and average strain of 0.08mm/mm.

Specimen #	Plateau stress (MPa)	Plateau strain (mm/mm)
Airex C1	1.455	0.087
Airex C2	1.446	0.071
Airex C3	1.365	0.086
Airex C4	1.369	0.086
Airex C5	1.309	0.084
Mean	1.389	0.082
Std dev.	0.054	0.0059

Table 11: Plateau stresses and strains of Airex foam core under compression

Chapter 5

Blast Testing

All manufactured panels were mounted to a ballistic pendulum and subjected to a series of localised blast loads. For each panel type, the charge mass was increased in order to obtain panel responses ranging from minimal failure to complete failure. The corresponding impulses were calculated and the failed panels inspected to determine probable failure modes and progression. The section to follow elaborates on the test apparatus, the blast procedure and the identified failure modes.

5.1 Test apparatus and procedure

All panels were clamped to a ballistic pendulum as illustrated in Figure 47. By detonating an explosive charge placed in front of the test specimen, the energy transferred caused the pendulum to sway back and forth. The maximum forward and backward displacements of the pendulum were measured, which allowed the impulse to be calculated. This procedure is further explained in *Appendix B1*.

5.1.1 Ballistic Pendulum

The ballistic pendulum consists of a central I-beam structure that is suspended by four steel cables to which front and back attachments were placed. The front attachments consisted of a mounting plate, four spacers and a clamped specimen, while balancing masses were mounted to the back to ensure the centre of mass was approximately coincident with the centre of the pendulum swing.

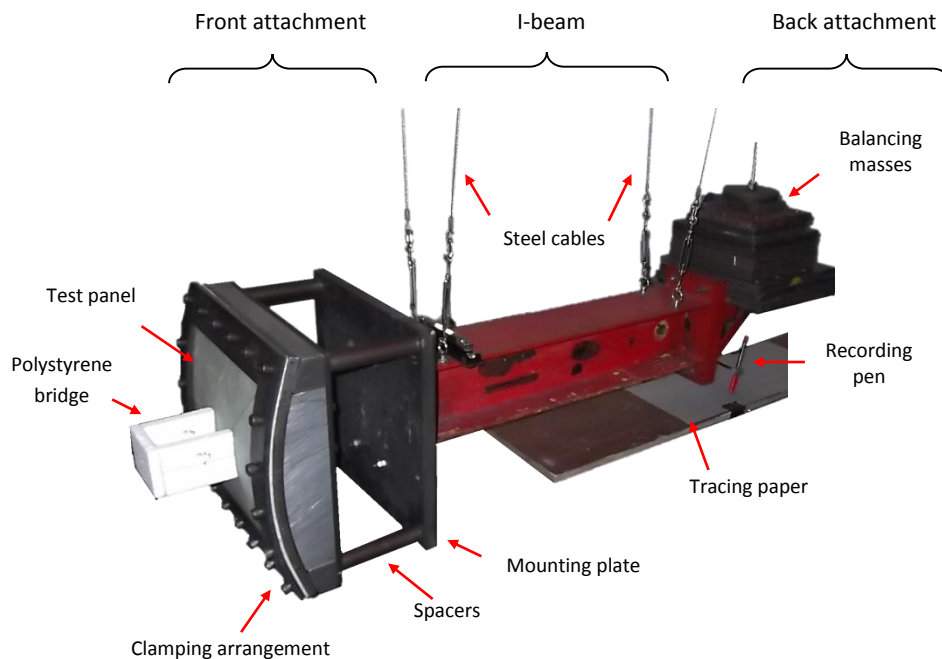


Figure 47: Photograph of the ballistic pendulum arranged with a 1000mm FRP laminate panel ready for testing

5.1.2 Clamping Arrangement

Each manufactured panel comprised of a total 400mm x 400mm projected area, with the FRP sandwich and laminate panels having nominal thicknesses of 18.7mm and 4.9mm respectively. The clamping arrangements were designed in order to clamp the panels along the edges (leaving a projected test area of 300mm x 300mm) and to incorporate the three different radii and the two different panel thicknesses. As with the manufacturing process, the outer/exposed radius of the panel was kept constant. Figure 48 illustrates the front and back clamps for all three clamping systems. Detailed drawings of the clamping arrangements are shown in *Appendix E*.



Figure 48: Clamping arrangement for all three panel categories

The specimens were clamped between the front and back clamps using twenty equally spaced bolts. Note: care was taken to ensure the core was not compressed during clamping of each FRP sandwich panel.

The flat clamping arrangement consisted of two flat mild steel clamps, while the 1000mm and 500mm curved clamping arrangements consisted of a mechanically rolled front clamp and an assembled back clamp. The curved back clamps were machined from mild steel blocks with radii 1000mm and 500mm minus a panel thickness. An example is shown in Figure 49 (a) of a clamped 500mm curved FRP sandwich panel.

Due to the exposed radius of the curved panels being kept constant, the inner radius between the FRP sandwich and laminate panels differed. This difference was small for the 1000mm curved panels and considered negligible however, it needed to be taken into account with the 500mm FRP sandwich and laminate curved panels. To compensate for this difference, a mechanically rolled clamp insert, with matching holes to the clamping arrangement, was inserted. This is shown in Figure 49 (b).

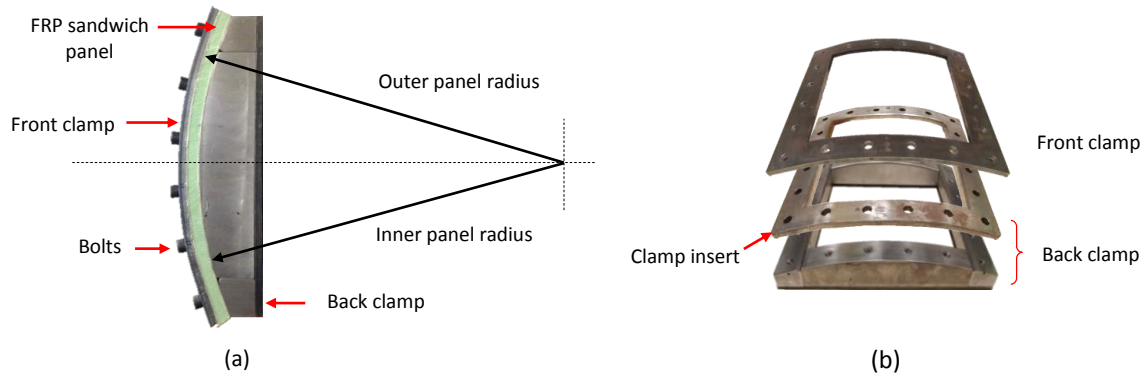


Figure 49: Photographs of the 500mm curved arrangement: (a) clamped FRP sandwich panel, (b) placement of the clamp insert panel

5.1.3 Test Parameters

A plastic explosive, PE4, was used for the blast loading of all panels. A circular cylinder charge geometry was chosen with a constant diameter of 38mm. A constant standoff distance of 100mm between the charge and test panel was used and was achieved by placing the explosive charge on a polystyrene bridge. These bridges were adjusted as charge heights varied for the different charge masses. The bridge, placement of the charge and standoff distance are illustrated in Figure 50. Table 12 lists the test programme of the tests performed for each panel type.

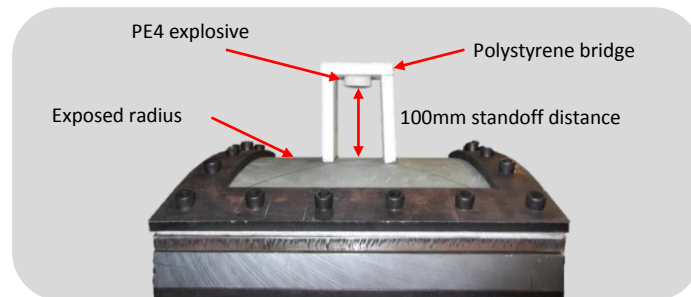


Figure 50: Photograph illustrating the test setup of the 100mm standoff distance for a 500mm curved FRP laminate panel

Panel	Charge diameter (mm)	Stand-off distance (mm)	Tests conducted
Flat FRP sandwich	38	100	5*
Flat FRP laminate	38	100	4
1000 FRP sandwich	38	100	8
1000 FRP laminate	38	100	7*
500 FRP sandwich	38	100	8
500 FRP laminate	38	100	8*

* including 1 repeat test

Table 12: Summary of the test programme

5.2 Failure Modes

The FRP sandwich and laminate panels displayed similar failure modes to those described in in sections 2.4 and 2.6 [3,27,28].

The failure modes of the panels were identified by visual inspection of the surface and midpoint cross section of each panel. Photographs were taken of the front and back surfaces of each panel which were used to digitally render the different surface failure modes in different colours for separation. The midpoint cross section gave further insight into the through thickness failure behaviour.

For the purpose of discussion, each curved panel is displayed with axis of curvature in the horizontal plane. The rendered images of the curved panels therefore follow the format as illustrated in Figure 51.

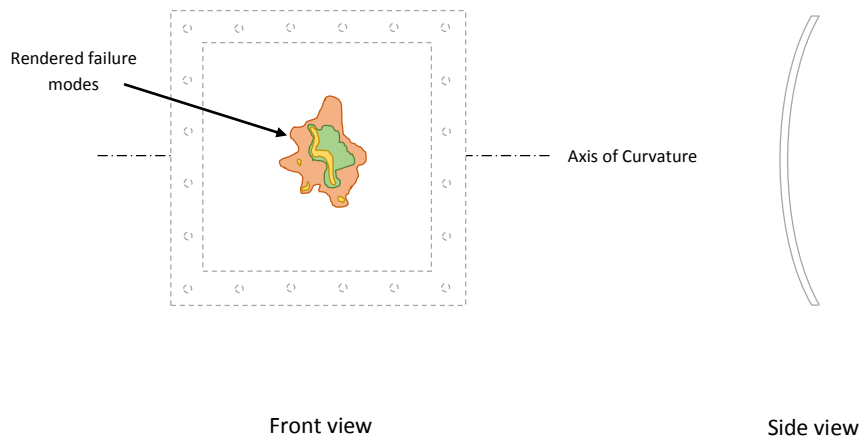


Figure 51: Format of the rendered images illustrating curved and flat axes

5.2.1 Identified Failure Modes

The failure modes and their definitions are listed in Table 13 and Table 14 for the FRP sandwich and FRP laminate panels, respectively and are illustrated in Figure 52 and Figure 53. It should be noted that the failure modes observed on the flat panels were also seen on the curved panels.

The failure modes observed on the face sheets of the FRP sandwich panels and on the FRP laminate panels were delamination, matrix failure and fibre fracture. The failure modes of the core material within FRP sandwich panels were compression, shear and fragmentation failures. A debonding failure was observed between the interface of the face sheets and core material.

Component	Failure mode	Abbrev.	Description
Face sheets	Delamination	DL	Appearance of white regions indicating interfacial separated FRP layers
	Matrix failure	MF	Appearance of intact weave with resin missing
	Fibre fracture	FF	Appearance of ruptured fibres
		FF _R	Complete rupture, fibre fracture through the face sheet thickness
Core material	Compression	C	Crushing of the core material
	Shear	S	Cracking of the core material
	Fragmentation	F	Breakage of the core material into pieces
		F _P	Fragmentation resulting in complete core penetration
Interface	Debonding	Deb	Separation of core material and face sheet

Table 13: Identified failure modes of the FRP sandwich panels

Failure mode	Abbrev.	Description
Delamination	DL	Appearance of white regions indicating interfacial separated FRP layers
Matrix failure	MF	Appearance of intact weave with resin missing
Fibre fracture	FF	Appearance of ruptured fibres
	FF _R	Fibre fracture through the panel thickness

Table 14: Identified failure modes of the FRP laminate panels

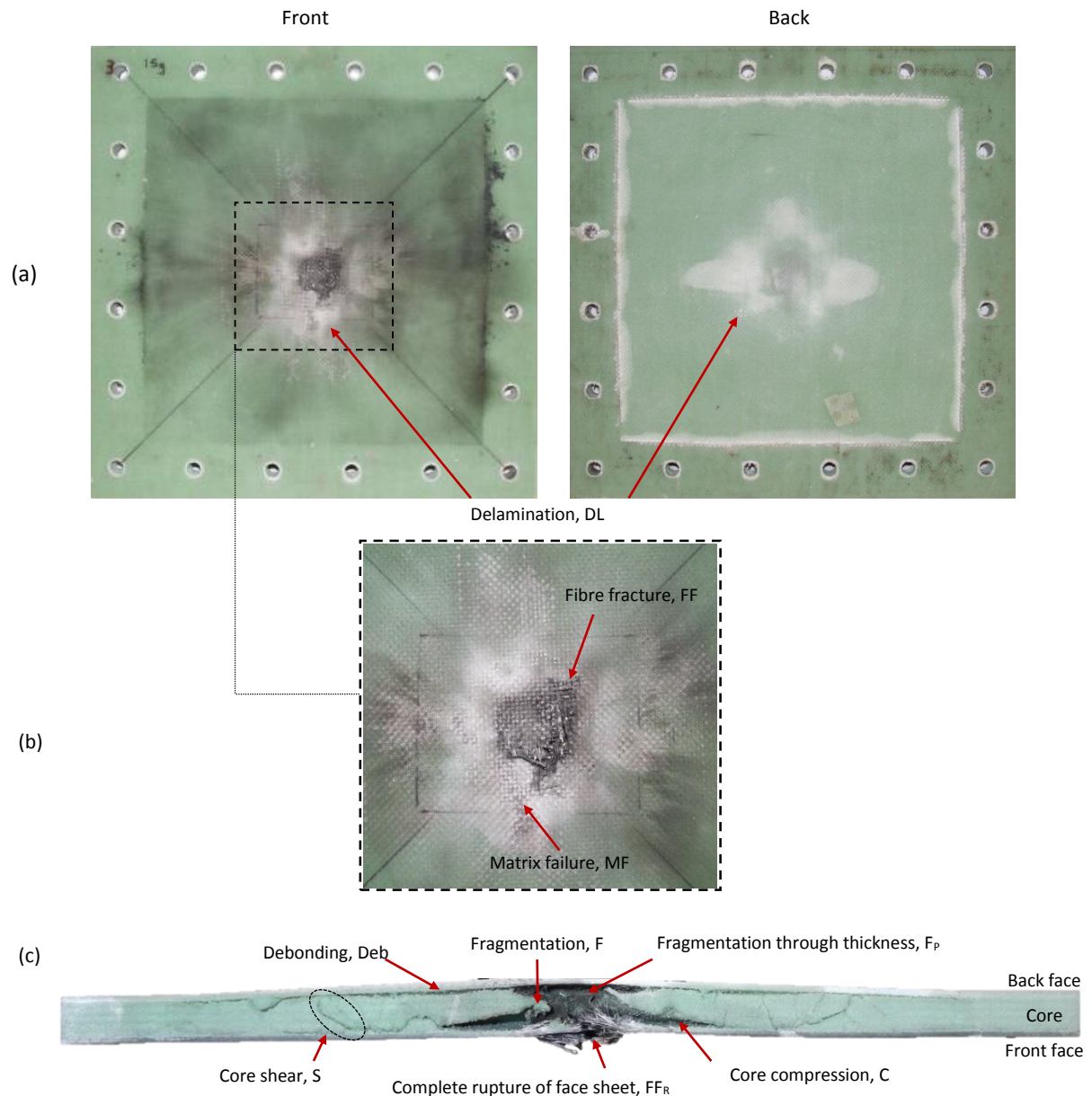


Figure 52: Photographs of a flat FRP sandwich panel subjected to a charge mass of 15g illustrating the observed failure modes: (a) front and back face sheets illustrating delamination, (b) detailed view of front face sheet illustrating matrix failure and fibre fracture, (c) midpoint cross section illustrating core compression, core shear, fragmentation, debonding and indicating fibre fracture through the front face sheet

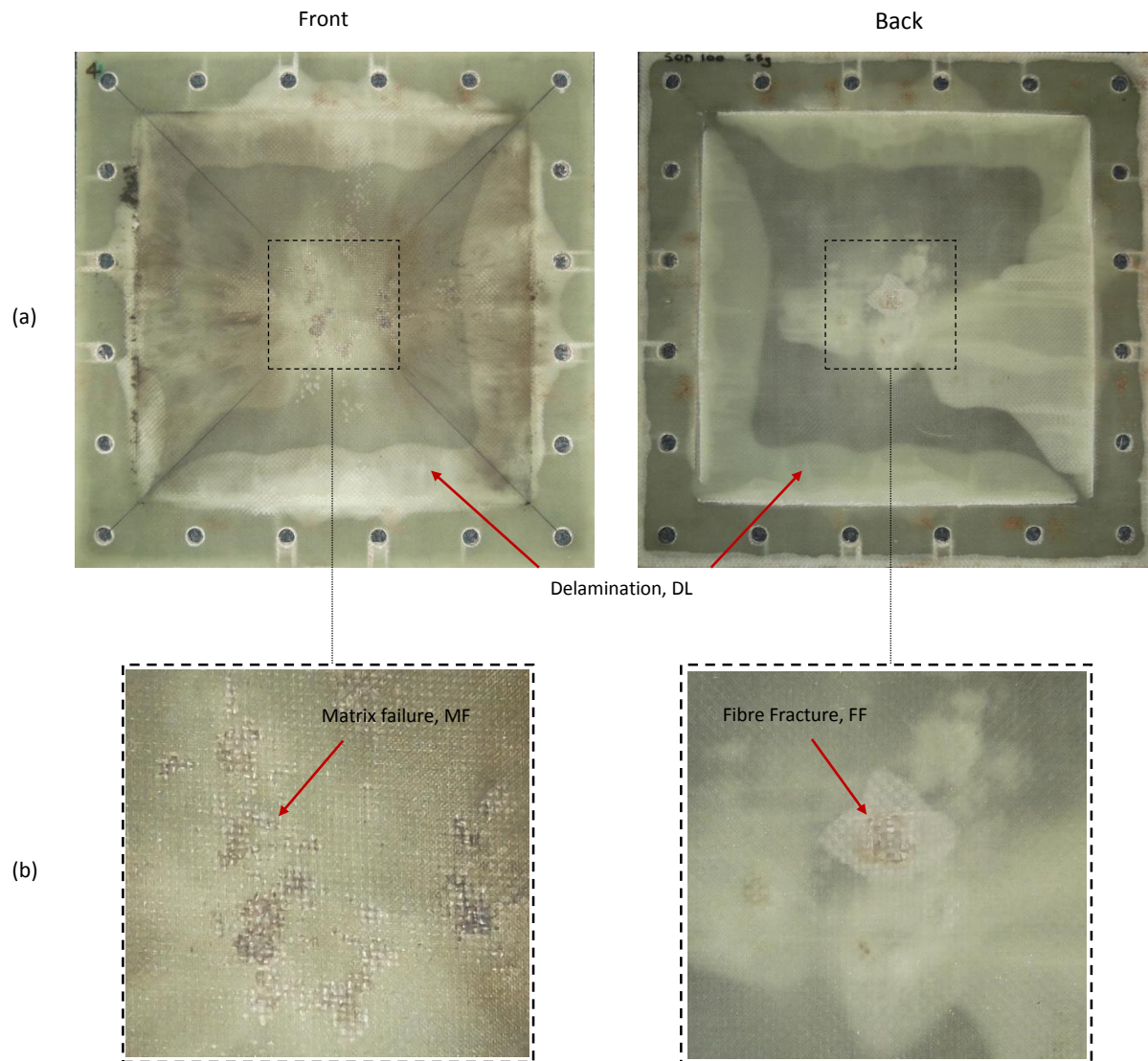


Figure 53: Photographs of a flat FRP laminate panel subjected to a charge mass of 25g illustrating the observed failure modes: (a) front and back surfaces illustrating the delamination, (b) detailed view illustrating matrix failure on front surface and fibre fracture on the back surface

5.2.2 Comparative Failure Modes

Particular failure modes were identified and are qualitatively described herein to give further insight to the progressive behaviour of the different panel categories and types. These failure modes (for both FRP sandwich and FRP laminate panels) are a proposed failure mode initiation chart, area of delamination and (for the FRP sandwich panels only) a midline debonded length.

5.2.2.1 Failure Mode Initiation Chart

The failure modes for each panel were identified and recorded for an increasing charge mass, as seen in section 5.4. Charts for the FRP sandwich panels were divided into the front and back face sheets, the core material and the interface between them. Due to the ambiguity of failure mode depth through the panel thickness, the failure mode initiation chart for the FRP laminate panels was identified for the panel as a whole with no separation.

Rendered images were also constructed from the photographs taken of each panel (and discussed in chapter 6) to visually display the extent to which a particular failure mode changed with the change in charge mass. A typical rendered failure map is shown in Figure 54 of the front face sheet of a FRP sandwich panel subjected to a charge mass of 15g.

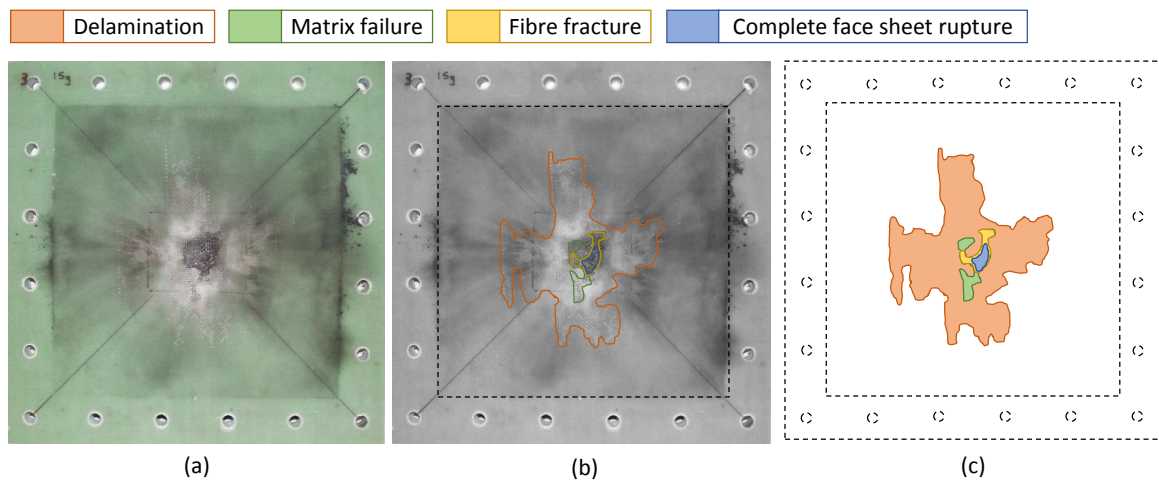


Figure 54: Digital rendering of the flat FRP sandwich panel front face sheet subjected to a charge mass of 15g: (a) Midpoint perpendicular photograph, (b) marked failure modes according to colour scheme, (c) shaded failure modes

5.2.2.2 Delaminated Areas

The delaminated areas marked in the rendered images allowed a projected delaminated area to be calculated for each panel. These areas were calculated as a percentage within the 300mm x 300mm test area only. Any delamination that occurred within the clamped region was discarded. The method used to calculate the percentage of delaminated area, is further explained in *Appendix C*.

For the FRP sandwich panels, the delaminated areas were calculated for both front and back face sheets, as these are separated by the core material. An example of the delaminated area of the front and back face sheets is shown in Figure 55 for a 1000mm curved FRP sandwich panel, subjected to a charge mass of 17.5g. In this case, the front and back face sheet delaminated areas were 8.5% and 15.3%, respectively.

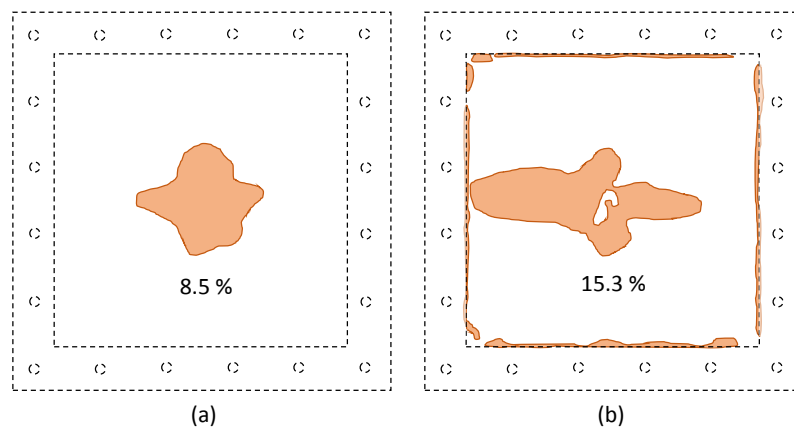


Figure 55: Delamination mapping of a 1000mm curved FRP sandwich panel, subjected to a charge mass of 17.5g: (a) front face sheet, (b) back face sheet

For the FRP laminate panels the delamination occurred within different layers throughout the thickness and it was not possible to determine the exact location without destroying the panel. Alternatively, a combined area affected by delamination was calculated by considering the rendering of any part of the area that had delaminated at some point through the panel thickness. This was achieved by shining a light through the panel and marking a combined delaminated area. Opaque regions indicated delamination had occurred. This light intensity method is shown in Figure 56 of a 1000mm FRP laminate panel, subjected to a charge mass of 20g, where the darker regions represent delaminated regions. In this case a percentage of delamination that fell within the exposed area was 62.3%.

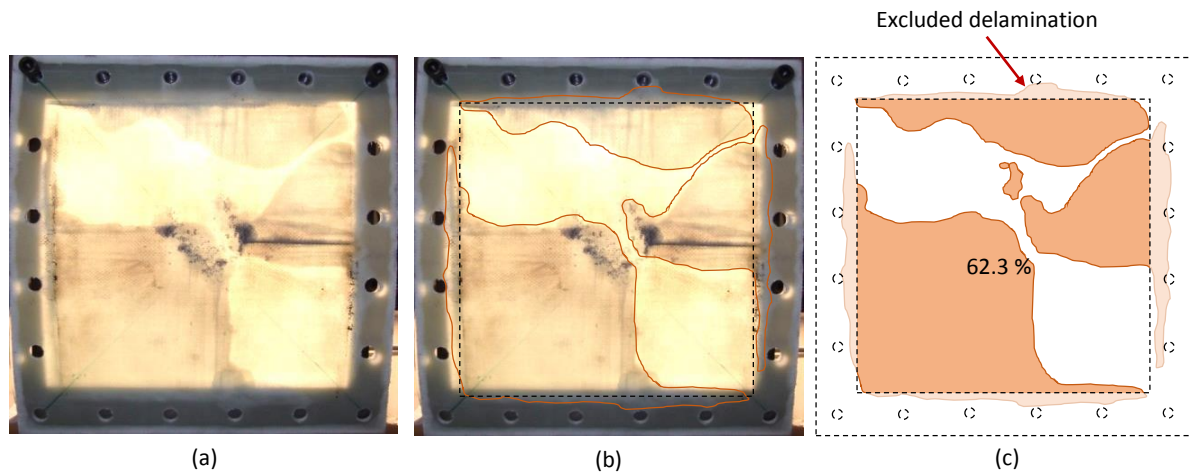


Figure 56: Photographs of a 1000mm curved FRP laminate panel subjected to a charge mass of 20g, illustrating the light intensity method used to mark the delaminated areas of FRP laminate panels

5.2.2.3 Debonded Lengths of the FRP Sandwich Panels

Debonding was defined as the separation between the face sheet and core material and was identified and measured from the midpoint cross sections of the FRP sandwich panels. Debonded lengths were measured for the front and back face sheet and core interfaces. Any separation between the face sheet and core was measured, totalled and converted to a percentage debonded length. The percentage debonded lengths for the curved FRP sandwich panels was calculated according to their respective arc lengths. An example is illustrated in Figure 57, for a 500mm curved FRP sandwich panel subjected to a charge mass of 17.5g. With a front and back face sheet test area arc length of 305mm and 293mm respectively, the resulting debonded lengths were 72.5% and 57.0%.

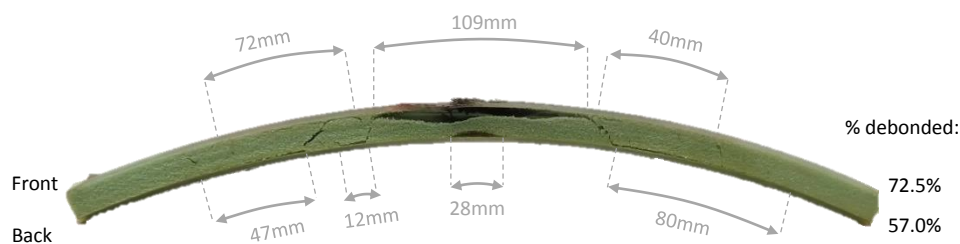


Figure 57: Photograph of a midpoint cross section of a 500mm curved FRP sandwich panel subjected to a charge mass of 17.5g, illustrating the debonded lengths

5.3 Detailed Failure Mode Descriptions

Two regions of response within the panel test area resulted from the localised nature of the blast load [28], namely a central region, dominated by local failure and an exterior region, with failures caused by global panel response, notably bending and stretching. A schematic illustration (not to scale) of the division between local and global panel response, is shown in Figure 58.

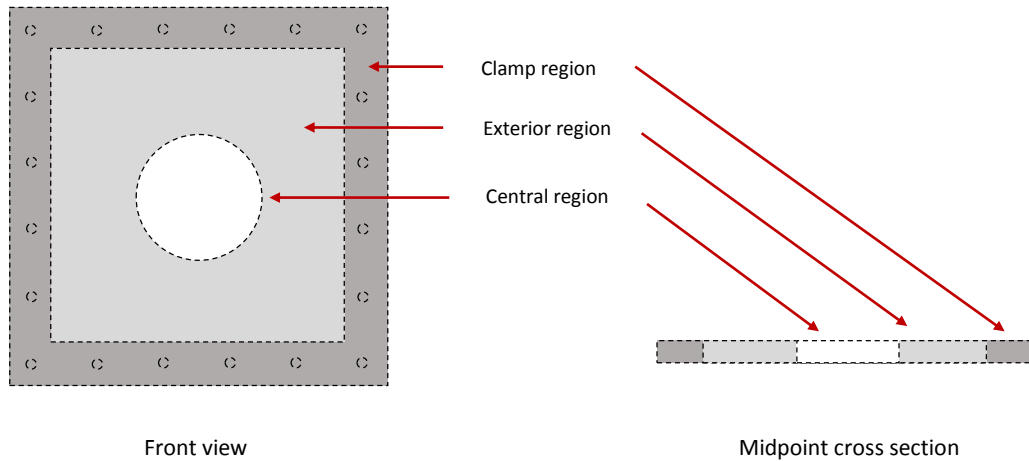


Figure 58: Schematic indicating the local and global response: white indicates the central locally loaded region, light grey indicates the global response region and the dark grey indicates the clamped region of each panel

5.3.1 FRP Sandwich Panels

As listed in section 5.2, the failure modes of the FRP sandwich panels were defined for the face sheets, the core material and their interface. The failure modes, as listed in Table 13, are described further in the sections to follow, giving more detail on how failure modes were identified and separated.

5.3.1.1 Delamination

The delamination indicated areas where interfacial separation of the FRP layers had occurred and was observed by the white colouration on the face sheets. Areas of full and partial white colouration were observed as seen in Figure 59. Figure 59, also shows that delamination mainly occurred in directions parallel to the fibre orientation, as seen in literature (3), (28). Both full and partial regions were combined in the calculation of the delaminated areas.

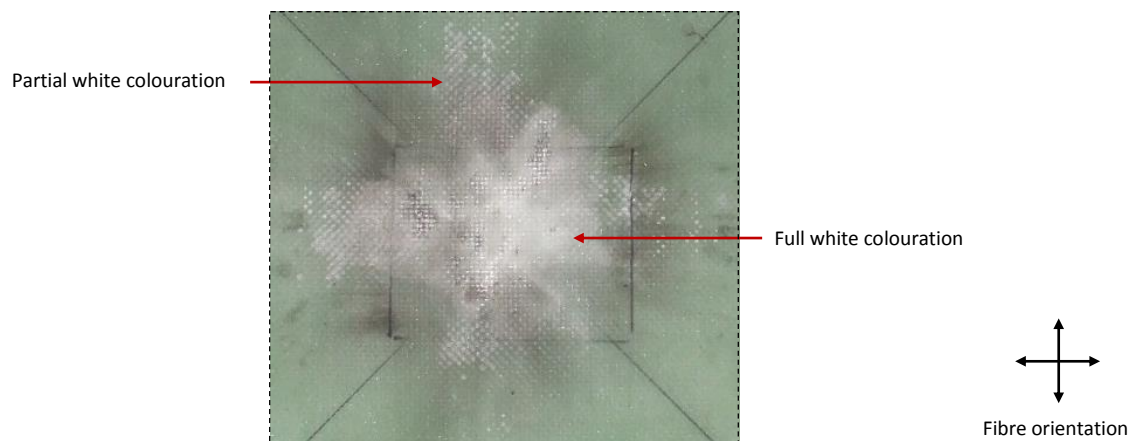


Figure 59: Section of a photograph of the front face sheet of a flat FRP sandwich panel subjected to a charge mass of 10.0g, illustrating the full and partial white delamination failure

5.3.1.2 Matrix Failure

The matrix failure was simply identified by the appearance of an intact weave of the FRP layers that resulted from the absence of the surface layer of resin, as illustrated in Figure 60.

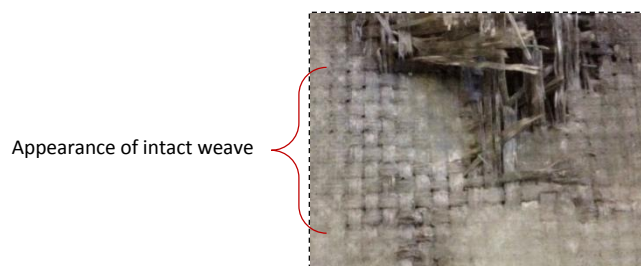


Figure 60: Section of a photograph of the front face sheet of a flat FRP sandwich panel subjected to a charge mass of 15g, illustrating the matrix failure

5.3.1.3 Fibre Fracture

The appearance of ruptured fibres of the FRP face sheets was identified as fibre fracture, as seen in the literature (28). For the FRP sandwich panels, the depth of the fibre fracture through the face sheet was identified by the midpoint cross section of the panel. This is illustrated in Figure 61 (b) and in the top section of Figure 60. Fibre fracture through the thickness of the face sheet, was termed complete rupture and denoted as FF_R .

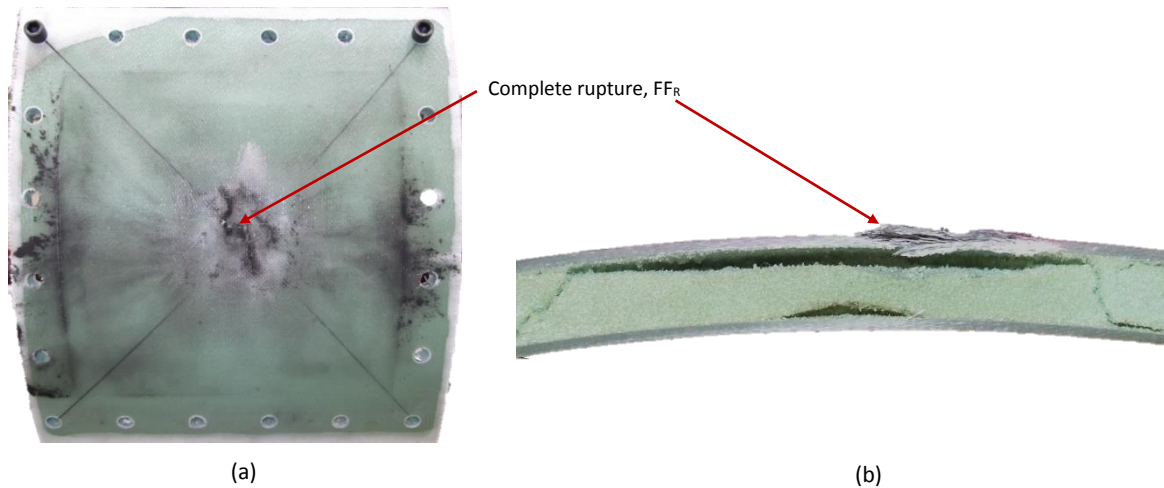


Figure 61: Photograph of a 500mm curved FRP sandwich panel subjected to charge mass of 17.5g illustrating complete rupture of the face sheet: (a) front face sheet, (b) midpoint cross section

Primary and secondary fibre fracture regions were identified and suggest fibre fracture due to local and global panel responses. Fibre fracture also occurred in a manner where a straight line of ruptured fibres were observed. Both these phenomena are illustrated in Figure 62 (a) and (b) respectively.

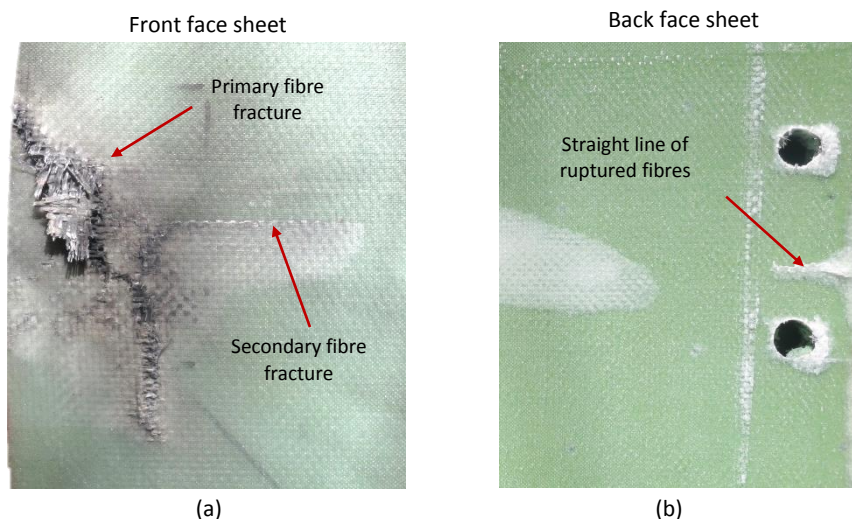


Figure 62: Photographs of a 500mm curved FRP sandwich panel subjected to a charge mass of 22.5g illustrating fibre fracture: (a) primary and secondary (b) located in clamp region

5.3.1.4 Core Compression

The midpoint cross sections of the FRP sandwich panels revealed the core compression failure. The permanent crushing of the core material and elastic rebound of the face sheet resulted in the compressed region, as shown in Figure 63. Core compression was also observed at the back face sheet interface.



Figure 63: Photograph of a midpoint cross section of a 1000mm FRP sandwich panel subjected to a charge mass of 15g illustrating the compression of the core material

5.3.1.5 Core Shear

The midpoint cross sections of the FRP sandwich panels revealed cracks within the core material resulting from shear failure. Primary and secondary shear cracks were identified and suggested shear failure due to local and global panel responses. The primary shear cracks were identified at the edge of the compressed region, where the secondary shear cracks were identified in the exterior region of the panel, as illustrated in Figure 64.

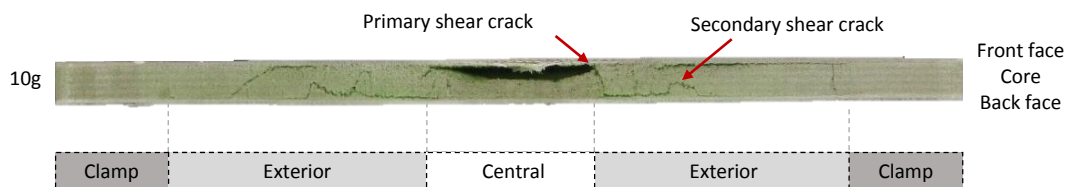


Figure 64: Photograph of a midpoint cross section of a flat FRP sandwich panel subjected charge mass of 10.0g illustrating the primary and secondary shear cracks.

5.3.1.6 Core Fragmentation

Core fragmentation was identified by the breakage of the core material into pieces. Core fragmentation that resulted in the complete penetration of the core material was denoted by F_p . The penetration of the core was not always clearly visible at the midpoint cross section of the panel and occurred anywhere within the central region. This is explained further in Figure 65 (a) where penetration was identified. Fragmentation occurred where the penetration was observed in the central region, Figure 65(b), and where severe breakage was observed, Figure 65 (c).

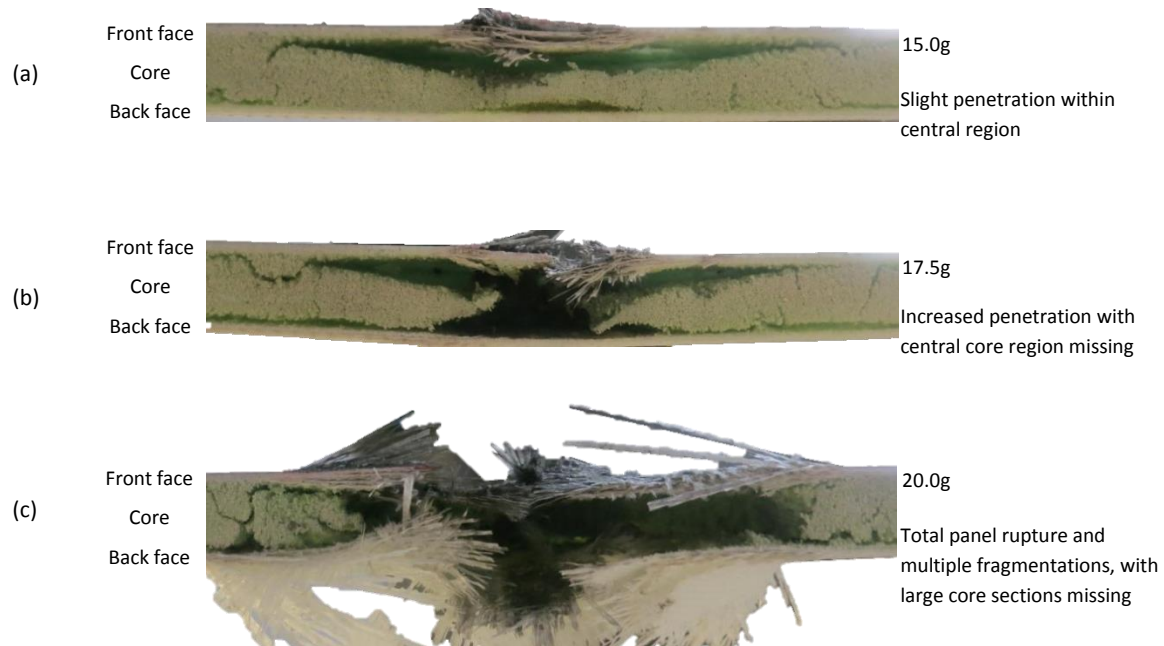


Figure 65: Photograph of the midpoint cross section of flat FRP sandwich panels illustrating different severities of core fragmentation: (a) 15.0g, (b) 17.5g, (c) 20.0g

5.3.1.7 Debonding

Debonding occurred by the separation of the face sheet and core material for the FRP sandwich panels. The debonding was observed in central and exterior regions. The debonding in the central test area occurred during elastic rebound of the front face sheet after core compression, while the debonding in the exterior region, appeared to be related to the relative face sheet and core movement. Shear cracks appeared to alternate the debonding between the front and back face sheets and separate the central debonding from the exterior, as shown in Figure 66.

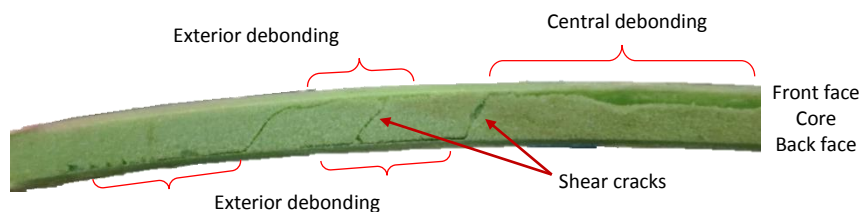


Figure 66: Photograph of a section of the midpoint cross section: (a) 1000mm curved FRP sandwich panel subjected to charge mass of 10.0g, (b) 500mm curved FRP sandwich panel subjected to charge mass of 22.5g

5.3.2 FRP Laminate Panels

As listed in section 5.2, the failure modes of the FRP laminate panels were delamination, matrix failure and fibre fracture. The failure modes, as listed in Table 14, are described further in the sections to follow, giving more detail on how failure modes were identified and separated.

5.3.2.1 Delamination

As discussed earlier, the delamination of the FRP laminate panels occurred within the different layers throughout its thickness and to detect the exact location through the thickness was not possible. Areas of delamination appeared to be closer to either the front or back surface, however, could not be precisely located. The transparent appearance of the FRP laminate panels enabled a light intensity method to identify delaminated areas, as illustrated in Figure 56 and Figure 67. The delamination was then observed by the different shades produced by the light and was defined as a combination of all observable areas.

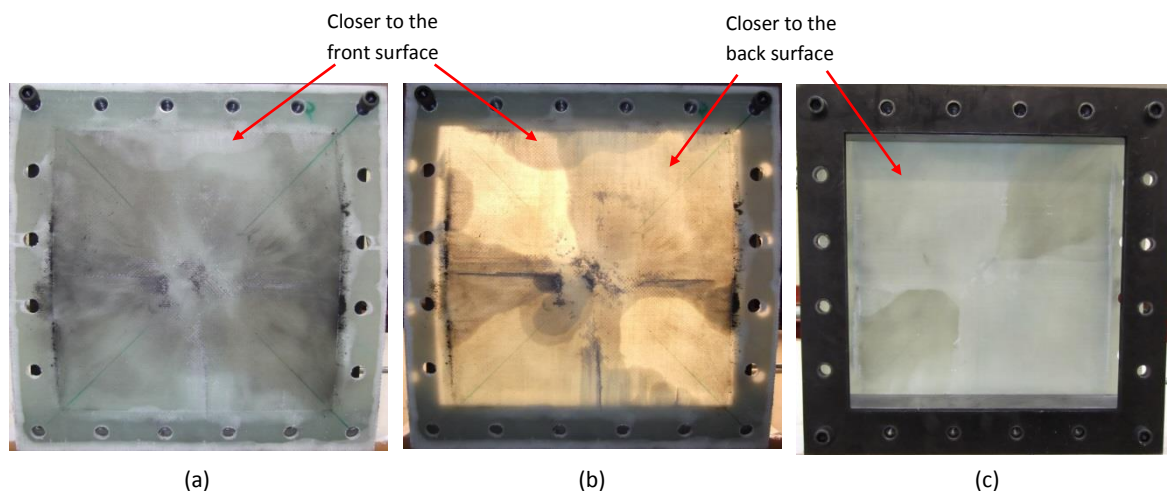


Figure 67: Photograph of the 1000mm curved FRP laminate panels illustrating the delamination failure: (a) front surface, (b) illuminated front surface, (c) back surface

5.3.2.2 Matrix failure

Matrix failure occurred on the FRP laminate panels as seen on the face sheets of the FRP sandwich panels, as seen in Figure 68.

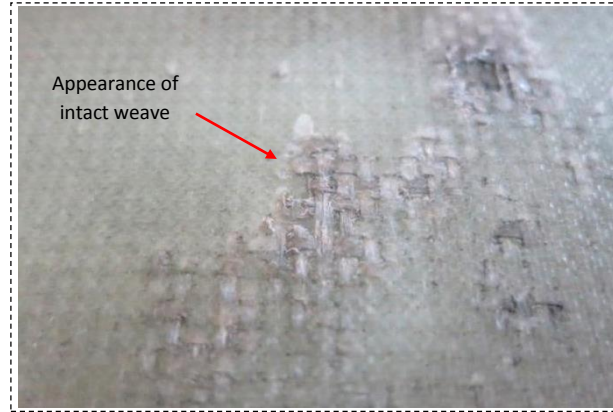


Figure 68: Photograph of a section of a 1000mm curved laminate panel subjected to a charge mass of 20.0g illustrating matrix failure for a FRP laminate panel

5.3.2.3 Fibre Fracture

Fibre fracture was identified by the appearance of the ruptured fibres of the FRP layers, as seen for the FRP sandwich panels. Fibre fracture was observed in regions on the front and back panel surfaces. Prior to rupture, small broken fragments on the front surface were observed, as seen in Figure 69 (a), with ruptured fibres observed on the back surface of the panel. The midpoint cross sections indicated the depth of fibre fracture through the thickness. The complete rupture through the thickness was denoted with FF_R and is illustrated in Figure 69 (b). Primary and secondary fibre fracture was also observed on the FRP laminate panels, as seen in Figure 69 (c), suggesting local and global responses of the panel.

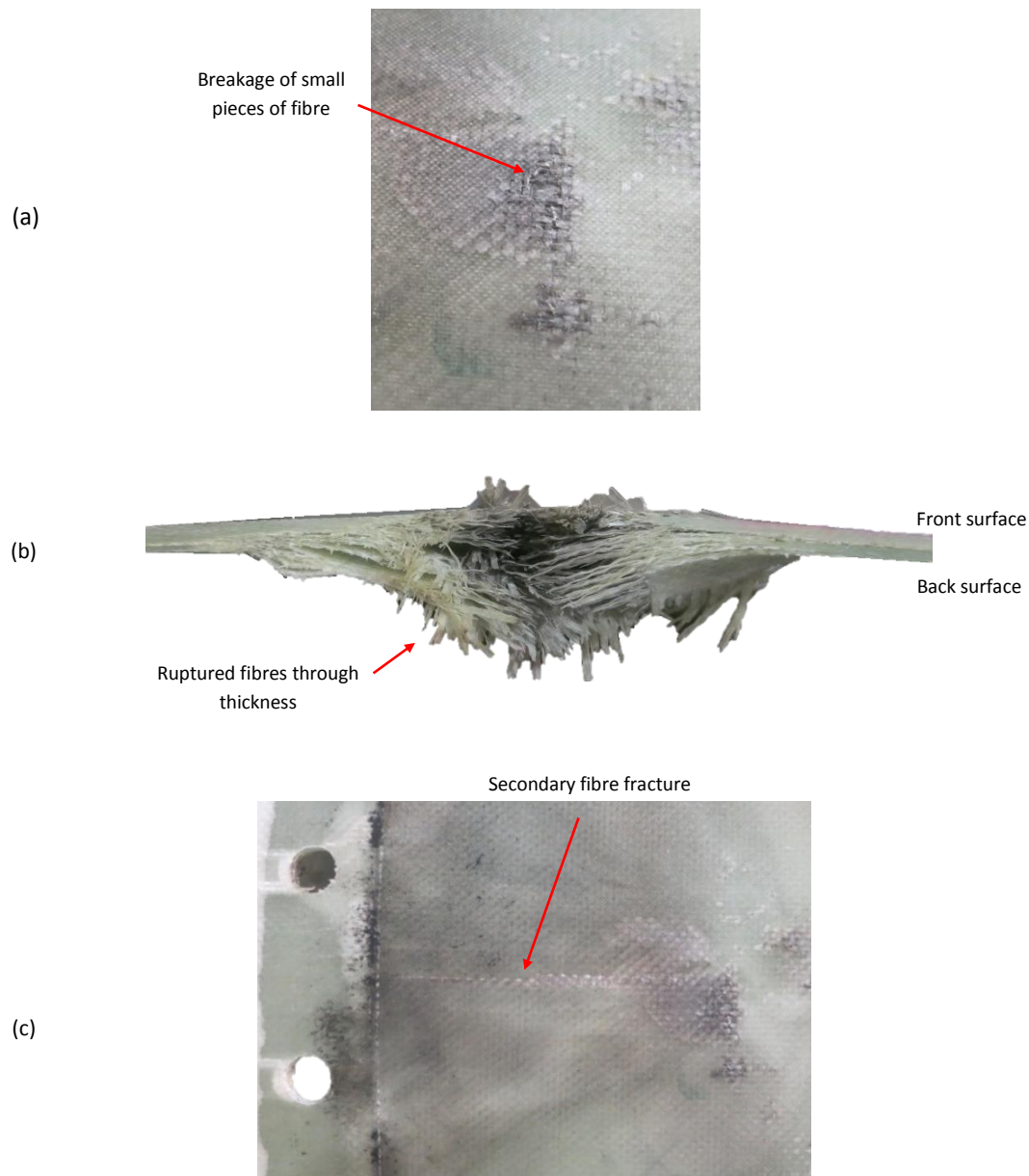


Figure 69: Photograph of the 1000mm curved FRP laminate panels: (a) subjected to charge mass of 25g illustrating fibre fracture of small pieces on the front surface, (b) subjected to charge mass of 27.5g illustrating fibre fracture of the back surface and the complete rupturing through the thickness of the panel, (c) subjected to charge mass of 25g illustrating the secondary fibre fracture

5.4 Quantitative results

The section to follow lists the quantitative results from the blast tests on the FRP sandwich and FRP laminate panels.

Table 15 lists the failure mode progression of the FRP sandwich panels for increasing charge mass. Table 16 lists the percentage delaminated areas and debonded lengths of the front and back face sheets of the FRP sandwich panels, for increasing charge masses.

Table 17 lists the failure mode progression and percentage delaminated areas of the FRP laminate panels for increasing charge mass.

The results are discussed and described in detail in Chapter 6.

Panel category	Charge mass (g)	Panel #	Impulse (Ns)	Front face-sheet	Back face-sheet	Core	Front-core interface	Back-core interface
Flat FRP sandwich	10.0	1e	17.41	DL, MF, FF	DL	C, S	Deb	Deb
	15.0	1c	25.95	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	15.0*	1b	26.58	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	17.5	1g	35.13	DL, MF, FF _R	DL, MF	C, S, F _P	Deb	Deb
	20.0	1f	37.66	DL, MF, FF _R	DL, MF, FF _R	C, S, F _P	Deb	Deb
1000 FRP sandwich	10.0	2a	15.64	DL	DL	C, S	Deb	Deb
	12.5	1d	18.67	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	13.5	2b	21.60	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	15.0	1a	24.48	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	17.5	1c	27.26	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	18.5	2c	28.47	DL, MF, FF _R	DL, MF, FF _R	C, S, F _P	Deb	Deb
	20.0	1b	30.53	DL, MF, FF _R	DL, MF, FF _R	C, S, F _P	Deb	Deb
	22.5	2d	33.39	DL, MF, FF _R	DL, MF, FF _R	C, S, F _P	Deb	Deb
500 FRP sandwich	10.0	1c	15.83	DL, MF	DL	C, S	Deb	Deb
	12.5	2d	19.42	DL, MF, FF	DL	C, S	Deb	Deb
	15.0	1a	22.79	DL, MF, FF _R	DL, MF	C, S, F _P	Deb	Deb
	17.5	1b	26.14	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	20.0	1d	29.74	DL, MF, FF _R	DL	C, S, F _P	Deb	Deb
	22.5	2c	32.86	DL, MF, FF _R	DL, MF	C, S, F _P	Deb	Deb
	25	2a	35.96	DL, MF, FF _R	DL, MF, FF	C, S, F _P	Deb	Deb
	27.5	2b	39.33	DL, MF, FF _R	DL, MF, FF _R	C, S, F _P	Deb	Deb

Table 15: Failure progression of the FRP sandwich panels for increasing charge masses

* repeated test

DL – Delamination, MF – Matrix failure, FF – Fibre fracture (subscript _R – fibre fracture through the thickness of the face sheet)C – compression, S – shear failure, F – fragmentation (subscript _P – fragmentation resulting in complete core penetration)

Deb – Debonding

Panel category	Panel #	Charge mass (g)	Impulse (Ns)	Delaminated area (%)		Debonded length (%)	
				Front	Back	Front	Back
Flat FRP sandwich	1e	10.0	17.41	11.6	1.1	56.6	54.0
	1c	15.0	25.95	16.4	19.8	87.0	75.3
	1b	15.0*	26.58	17.7	18.23	82.2	80.3
	1g	17.5	35.13	19.9	31.4	57.7	100.0
	1f	20.0	37.66	16.4	31.5	55.0	100.0
1000 FRP sandwich	2a	10.0	15.64	5.7	0.7	57.3	44.4
	1d	12.5	18.67	6.7	8.3	61.9	78.3
	2b	13.5	21.60	7.3	8.8	84.1	64.4
	1a	15.0	24.48	8.5	8.4	90.1	57.6
	1c	17.5	27.26	8.5	15.3	61.3	100.0
	2c	18.5	28.47	8.5	11.6	36.4	100.0
	1b	20.0	30.53	10.7	15.8	34.8	100.0
	2d	22.5	33.39	10.8	22.2	31.5	100.0
500 FRP sandwich	1c	10.0	15.83	2.6	0.7	63.9	53.9
	2d	12.5	19.42	5.2	0.7	34.4	46.7
	1a	15.0	22.79	9.3	16.0	57.7	63.1
	1b	17.5	26.14	8.1	11.0	72.5	57.0
	1d	20.0	29.74	10.9	12.9	100.0	78.5
	2c	22.5	32.86	14.2	14.4	94.1	70.3
	2a	25.0	35.96	12.5	19.7	100.0	76.4
	2b	27.5	39.33	17.7	24.8	87.2	100.0

Table 16: Percentage delaminated areas and debonded lengths of the FRP sandwich panel for increasing charge masses

* indicates repeated test

Panel category	Charge mass (g)	Panel #	Impulse (Ns)	Failure Modes	Delaminated Area (%)
Flat FRP laminate	10.0	1b	18.67	DL, MF	5.4
	15.0	1c	28.79	DL, MF	60.8
	20.0	2c	37.34	DL, MF, FF	53.7
	25.0	1c	44.62	DL, MF, FF	67.8
1000 FRP laminate	15.0	1b	24.47	DL, MF	21.5
	17.5	1c	28.54	DL, MF, FF	17.9
	20.0	2c	32.86	DL, MF, FF	62.3
	20.0*	1a	32.37	DL, MF, FF	59.2
	25.0	2a	39.09	DL, MF, FF	76.6
	27.5	2d	41.26	DL, MF, FF _R	53.2
	30.0	2b	45.34	DL, MF, FF _R	44.5
500 FRP laminate	15.0	1a	22.67	DL, MF, FF	66.6
	17.5	2a	25.75	DL, MF, FF	16.3
	20.0	1b	29.57	DL, MF, FF	45.1
	22.5	2d	31.74	DL, MF, FF	65.7
	22.5*	2b	33.17	DL, MF, FF	69.2
	25.0	1c	35.91	DL, MF, FF	27.1
	27.5	1d	37.55	DL, MF, FF _R	61.4
	30.0	2c	41.54	DL, MF, FF _R	44.7

Table 17: Failure mode progression and percentage delaminated areas of the FRP laminate panels for increasing charge masses

* indicates repeated test

DL – Delamination, MF – Matrix failure, FF – Fibre fracture (subscript _R – fibre fracture through thickness of panel)

Chapter 6

Discussion

The section to follow elaborates on the results obtained, as described in chapter 4 and 5, of the FRP sandwich and laminate panels. These include the material characterisation, failure mode initiation charts and comparative failure modes.

6.1 Material Characterisation

The results from the quasi-static flexural tests of the FRP sandwich and laminate panels as discussed below.

6.1.1 Flexural Behaviour of the FRP Sandwich and Laminate Panels

The FRP sandwich and laminate beams both failed by localised compression of the FRP layers beneath the central loading bar, as seen in Figure 70 and Figure 71 respectively. The localised compression of the FRP sandwich and laminate panels was similar to that observed in the literature [3,28].

The FRP sandwich specimens failed due to the localised compression of the top face sheet, shown in Figure 70 (a). This deformation was resisted by the core material, as permanent compression was observed in the local region beneath the central loading bar, as seen Figure 70 (b). No distinct deformation was visible on the bottom face sheet. This suggested that this localised compression of the core material reduced the local load transfer to the bottom face sheet, as shown in Figure 70 (c). The strength of the FRP sandwich specimens was therefore related to the resistance to failure of the top face sheet and once failure of the top face sheet occurred, the strength of the specimen dropped, as seen in Figure 45. The plastic deformation of the core material allowed the flexural displacement to continue without significant failure observed on the bottom face sheet. An average ultimate facing strength for the face sheets was calculated at $83 \text{ MPa} \pm 6\%$ from the maximum force observed per specimen.

The local compression of the FRP laminate specimens was observed on the top and bottom layers, as seen in Figure 71 (a) and (b), with the failure more severe on the top layers. Due to large number of fibre glass sheets, the local compression of the top layers was resisted by underlying layers within the specimens and lead to the wrinkling of the top layers. The bottom layers appeared to fail in a tensile manner. The average strength of the FRP laminate panels was calculated at $483 \text{ MPa} \pm 5\%$ from the maximum force observed for each specimen. Compared to the strength observed on the FRP sandwich panels suggested that the substitution of the FRP sheets for a core material resulted in a significant increase in quasi-static flexural strength.

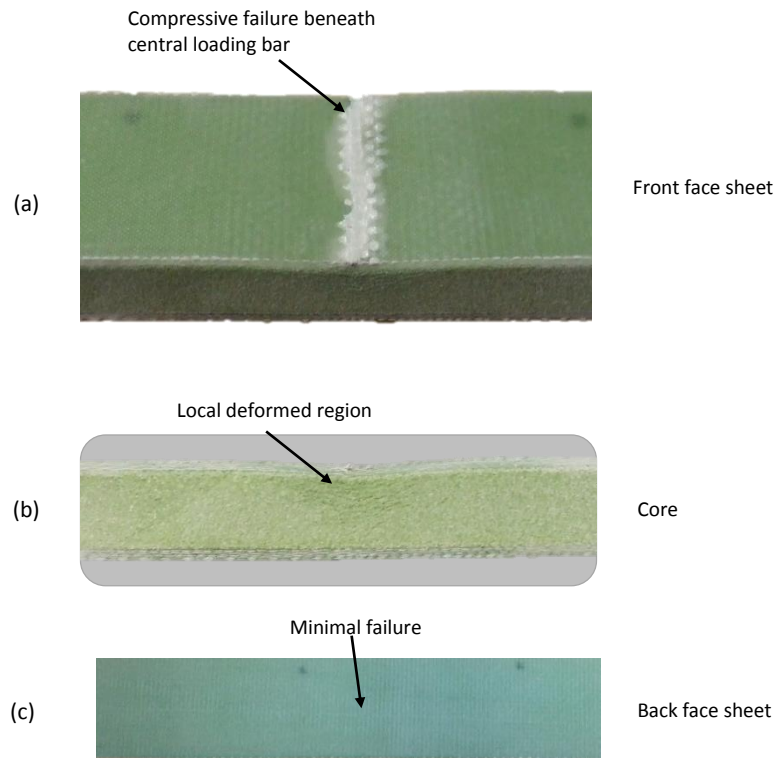


Figure 70: Photograph of SF3 specimen illustrating the: (a) front face sheet, (b) compression of the core, (c) back face sheet

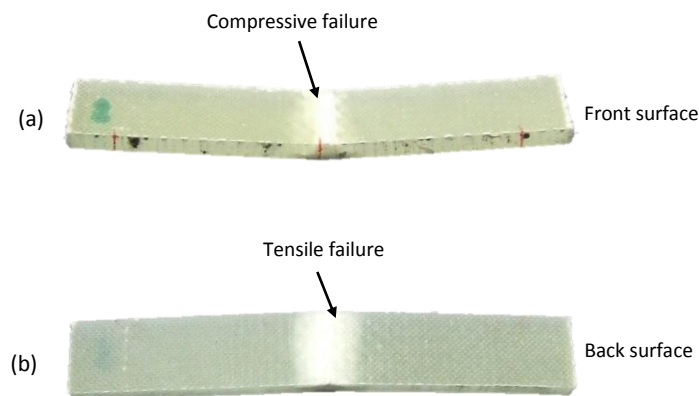


Figure 71: Photographs of LF2 specimen: (a) front illustrating local compression and wrinkling, (b) back surfaces illustrating tensile failure

6.2 Response of the Fibre Reinforced Polymer Sandwich Panels to Blast Loading

The calculated impulses of the flat and curved FRP sandwich panels, as seen in Table 15 (page 73), were plotted per charge and shown in Figure 72. The orange and purple trend lines respectively represent the flat and curved panels (1000mm and 500mm combined). A combined trend line was inserted for the 1000mm and 500mm curved panels as minimal difference in impulse was observed for increasing charge mass. The initial 10g charge mass resulted in similar impulses for the flat and curved panels, where minimal damage was observed. However, as the impulse was increased, the response of the curved panels deviated from the flat panels where the impulse of the curved panels was lower than the flat panels. The gradient of the flat panel's trend line was greater than the gradient of the curved panels trend line (by 33.3%) and illustrated that the curvature of FRP sandwich panels reduced impulse imparted.

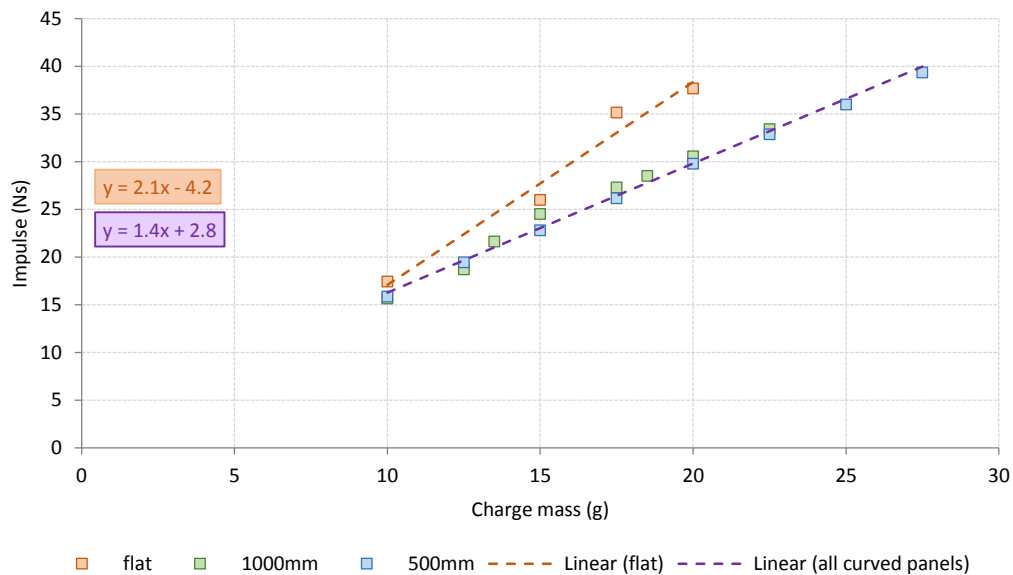


Figure 72: Graph illustrating the calculated impulse per charge mass for the flat, 1000mm curved and 500mm curved FRP sandwich panels

6.2.1 Flat Panels

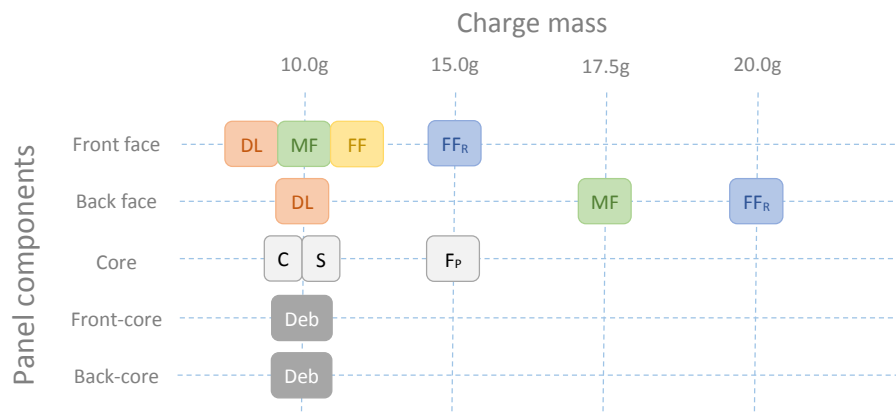
The flat FRP sandwich panels were exposed to a charge mass range of 10g to 20g. The failure mode initiation chart, delaminated areas and debonded lengths are discussed below.

6.2.1.1 Failure Mode Initiation Chart

Langdon et al [3] observed a failure progression for flat FRP sandwich panels, where initially the damage was concentrated on the front face sheet and core material and little damage observed on the back face sheet. An increase in charge mass resulted in an increase in damage of the front face sheet and core material that transferred the load to the back face sheets. Langdon et al [3] documented this transition of failure, as shown in Figure 26 (page 27).

The failure progression observed by Langdon et al [3] lead to the construction of failure mode initiation charts. With the use of Table 15, a failure mode initiation chart was constructed and illustrated in Figure 73. This lists each failure mode corresponding to the charge mass at which it was first observed. Insight was gained regarding the appearance of different failure modes over the charge mass range.

For the flat FRP sandwich panels, an initial charge mass of 10.0g resulted in delamination, matrix failure and fibre fracture on the front face sheet. Delamination was observed on the back face sheet, where compression and shear cracks were observed on the core material. Debonding was observed at the front and back interfaces of the core material and face sheets. At 15g, complete rupture of the front face sheet and fragmentation penetrating through the thickness of the core material was observed. A charge mass of 17.5g resulted in the appearance of matrix failure on the back face sheet and 20g resulted in the complete rupture of the back face sheet.



DL – Delamination, MF – Matrix failure, FF – Fibre fracture, FF_R – complete face sheet rupture
 C – compression, S – shear failure, F – fragmentation, F_p – fragmentation penetrating through core
 Deb – Debonding

Figure 73: Failure mode initiation chart of the flat FRP sandwich panels for increasing charge mass

6.2.1.2 Delaminated Area of the Front Face Sheet

The delaminated areas of the front face sheets of the flat FRP sandwich panels are listed in Table 18. The rendered images of the front face sheets are illustrated in Figure 74 for increasing charge mass and gave insight to the progression of the delaminated areas.

Charge Mass (g)	Delaminated Area (%)
10.0	11.6
15.0	16.4
17.5	19.9
20.0	16.4

Table 18: Percentage delaminated areas of the front face sheets of the flat FRP sandwich panels

The initial delaminated area of 11.6% was observed in the central and exterior region, with the delaminated area in the exterior region predominantly in the direction of the fibre orientation, as shown in Figure 74 (a). At 15g an increase to 16.4% was observed with the delaminated area propagated further in exterior region in the direction of the fibre orientation, as seen in Figure 74 (b). At this charge mass the complete rupture of the front face sheet was observed. At 17.5g, the delaminated area spread out between the fibre orientation directions and increased to 19.9%. For 20g the delaminated area decreased to 16.4% in the exterior region in the fibre orientation direction.

The progression of the delaminated area gave insight to the behaviour of the front face sheet for an increased local load. The response of the front face sheet initially appeared in local manner and with an increased load resulted in an increase in the global manner of the face sheet, namely the propagation of the delaminated area into the exterior region. An increased charge mass resulted in an increase in failure in central region (by the increase of matrix failure and fibre fracture) and exterior region (by increase of delaminated area). A charge mass exists where the global response of the face sheet reduced and where severe local failures were observed.

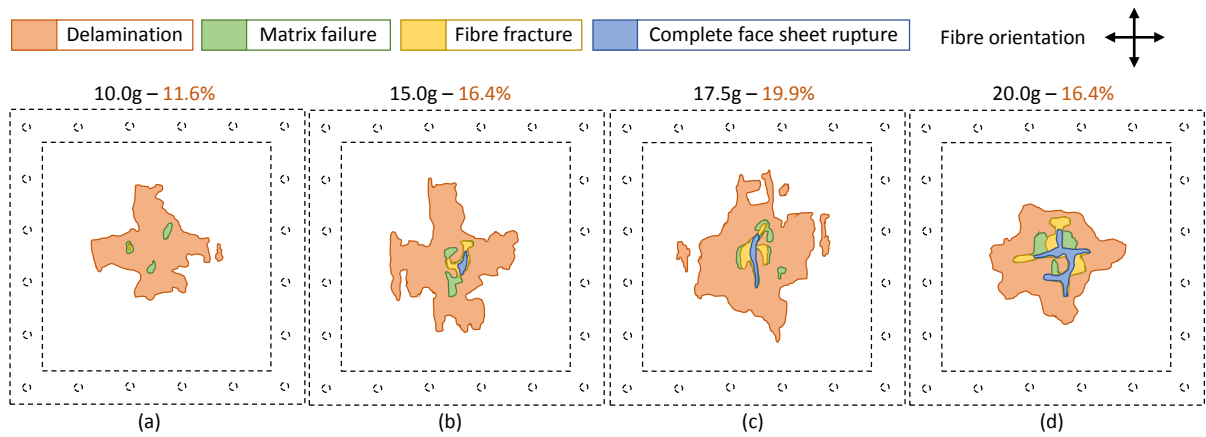


Figure 74: Rendered images of failure modes of the front face sheet of the flat FRP sandwich panels subjected to: (a) 10.0g, (b) 15.0g, (c) 17.5g, (d) 20.0g

6.2.1.3 Delaminated Area of the Back Face Sheet

The delaminated area of the back face sheets are listed in Table 19. The rendered failure modes of the back face sheets are illustrated in Figure 75 for increasing charge mass and gave insight to the progression of the delaminated areas.

Charge Mass (g)	Delaminated Area (%)
10.0	4.6
15.0	19.8
17.5	31.4
20.0	31.5

Table 19: Percentage of delaminated areas of the back face sheets of the flat FRP sandwich panels

Initially the delaminated area of 4.6% was observed in small areas within the central region, predominantly along the fibre orientation directions. These appeared to surround a region of no delamination in the centre of the panel, as seen in Figure 75 (a). The midpoint cross section of the panel, seen in Figure 76 (a), illustrated the local compression of the core within the central region and appeared to reduce the load transfer to the centre of the back face sheet. Small delaminated regions were also observed along the boundary of the exterior region, which were not observed in the front face sheet responses.

At 15g, a large increase in delaminated area of 19.8% was observed, with delaminated area propagated into the exterior region in the fibre orientation directions, as seen in Figure 75 (b). At 15g, the complete rupture of the front face sheet and the penetration of the core material was observed, as seen in the failure mode initiation chart in Figure 73, and resulted in the large

increase in delaminated area of back face sheet. The delaminated regions extended along the full boundary edges and into the corners.

The complete rupture of the front face sheet and penetration of the core, shown in Figure 76 (b) to (d), resulted in a large increase in delaminated area of the back face sheet for charge masses 17.5g and 20g, of 31.4% and 31.5% respectively. At 20g, the delaminated area decreased in the exterior region, as seen in Figure 75 (d). The complete rupture of the back face was observed at 20g and appeared to reduce the delaminated area along the boundary edge.

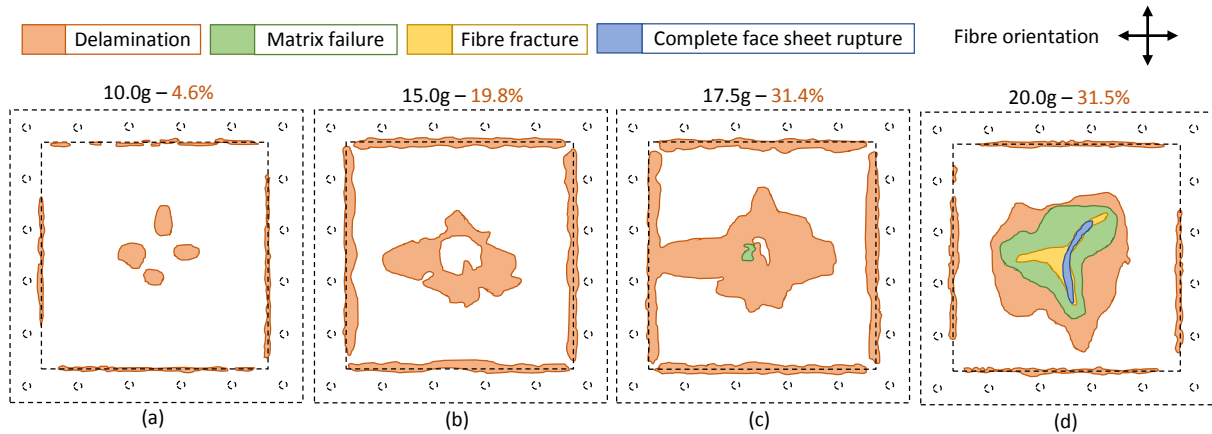


Figure 75: Rendered failure modes of the back face sheet of the flat FRP sandwich panels subjected to: (a) 10.0g, (b) 15.0g, (c) 17.5g, (d) 20.0g

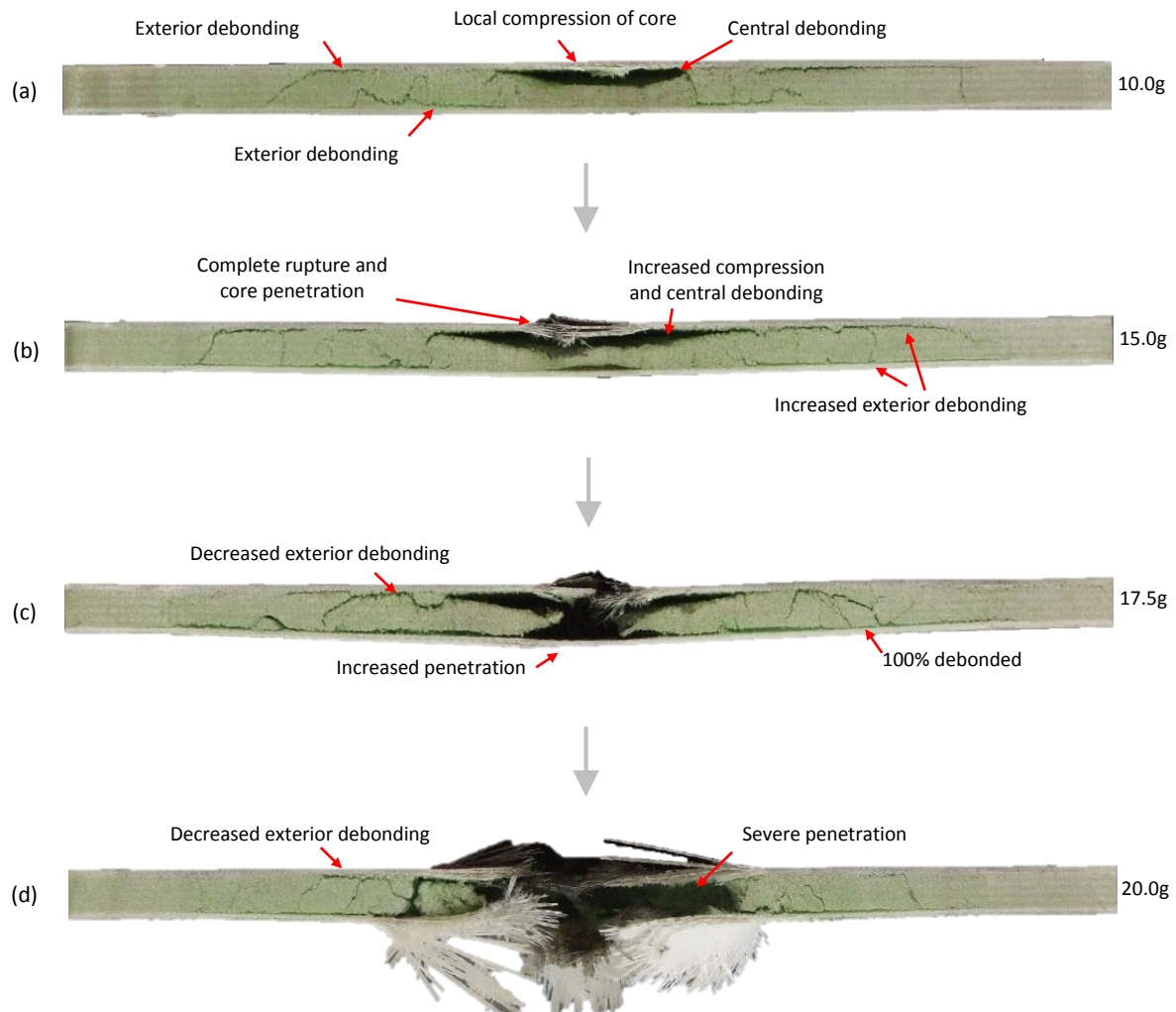


Figure 76: Photographs of the midpoint cross section of the flat FRP sandwich panels subjected to a charge mass of: (a) 10.0g, (b) 15.0g, (c) 17.5g, (d) 20.0g, illustrating the failure progression through the thickness of the panel

6.2.1.3 Debonded Lengths

Figure 77, with Table 20 illustrates a bar graph of the debonded lengths of the front and back interfaces of the flat FRP sandwich panels for increasing charge mass. The debonded length of the front interface initially increased with increasing charge mass, reaching a peak of 87% at 15g. Above 15g, the debonded length of the front interface decreased as charge mass was increased to 20g. The debonded length of the back interface also initially increased with increasing charge mass until the whole back face was debonded at 17.5g and 20g.

Charge mass (g)	% Debonded Length	
	Front	Back
10.0	56.6	54.0
15.0	87.0	75.3
17.5	57.7	100.0
20.0	55.0	100.0

Table 20: Percentage debonded lengths of the front and back interfaces of the flat FRP sandwich panels

The initial debonded length of the front interface was a result of the central and exterior debonding, as seen in Figure 76 (a). The increase at 15g resulted from an increase in both regions and indicated an increase in local and global response of the panel. The decrease of front interface was observed at a charge mass of 17.5g and was a result in the decrease of the exterior debonding, as seen in Figure 76 (c). This suggested, with respect to debonded lengths, a reduction in global response of the front face sheet. This decrease occurred after the complete rupture of the front face sheet and penetration of the core was observed. The debonded length of the back interface however continued to rise and indicated that after complete rupture of the front face sheet and penetration of the core occurred, the global response of the back face sheet increased.

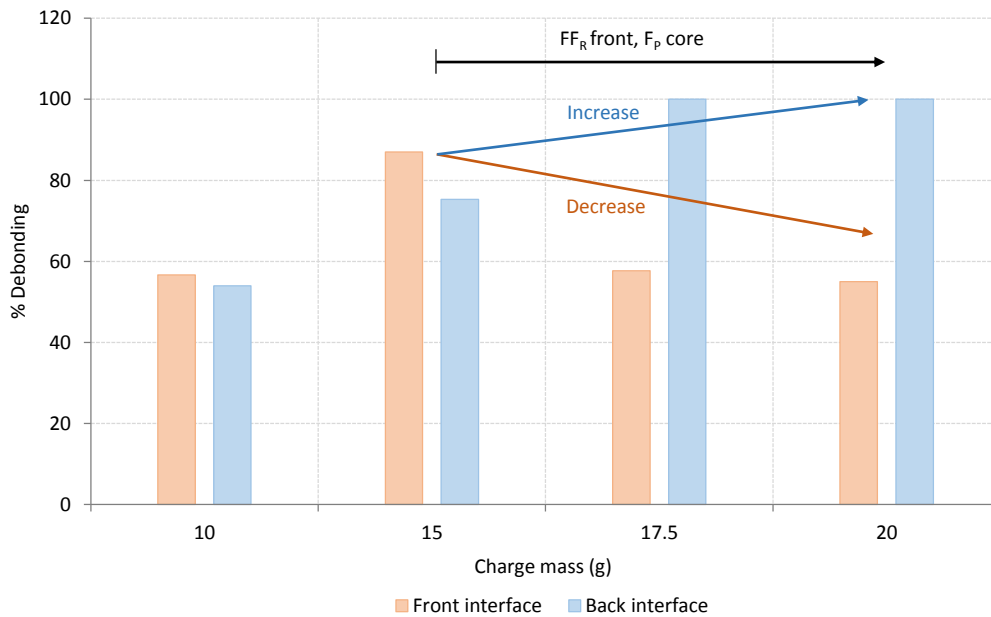


Figure 77: Percentage debonded lengths of the front and back interfaces of the flat FRP sandwich panels

6.2.2 Influence of Curvature

The section to follow elaborates on the response of the 1000mm and 500mm curved panels to charge mass range of 10g to 22.5g and 10g to 27.5g respectively. The influence of curvature to the FRP sandwich panels are discussed and compared with respect to the comparable failure modes.

It should be noted that the 500mm curved sandwich panel subjected to a charge mass of 15g was removed from the comparable data. Investigation of the cross sectional area indicated the asymmetric loading of the panel as shown in Figure 78.

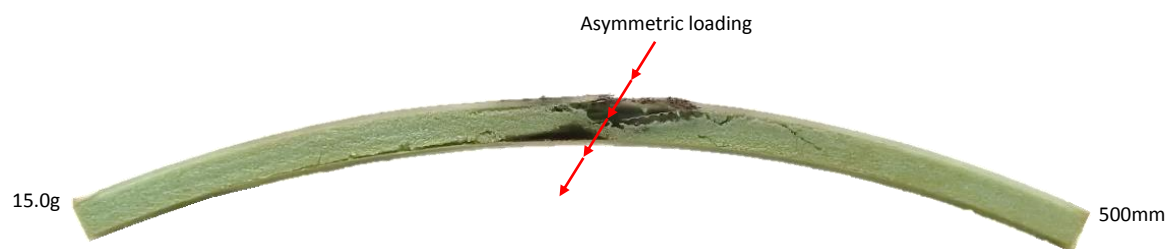


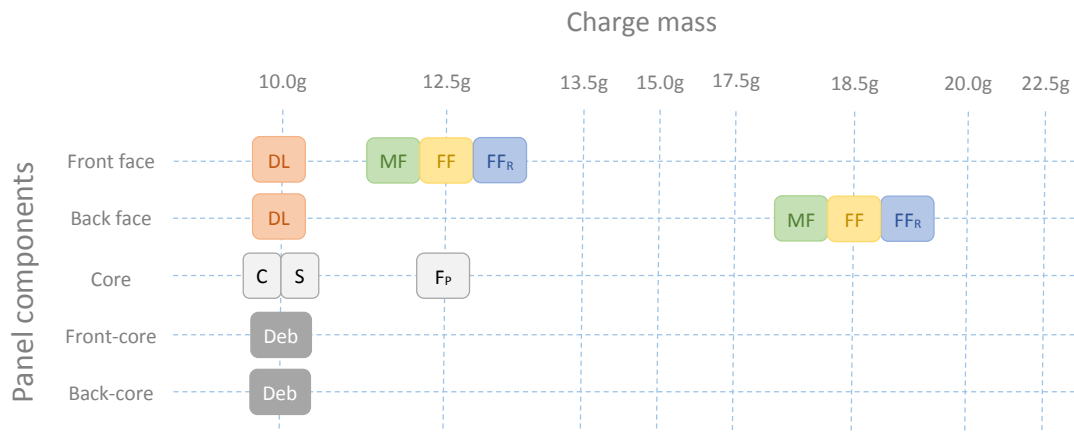
Figure 78: Removed 500mm curved FRP sandwich panel due to asymmetric loading

6.2.2.1 Failure Mode Initiation Chart

A similar behaviour to that of the flat panels was observed for the 1000mm and 500mm curved panels where the failure modes were concentrated on the front face sheet and core material. Increasing charge mass resulted in load transfer and hence damage to the back face sheet.

1000mm Curved Panels

The failure mode initiation chart for the 1000mm curved FRP sandwich panels is illustrated in Figure 79. The initial charge mass of 10g resulted in delamination observed on the front and back face sheets. Compression and shear cracks were observed on the core material and debonding was observed at the front and back interfaces. A 12.5g charge mass resulted in matrix failure, fibre fracture and complete rupture of the front face sheet and fragmentation penetrating the core material. No new failure modes were evident in the 13.5-17.5g tests and a charge mass of 18.5g resulted in matrix failure, fibre fracture and complete rupture of the back face sheet. Similar failure modes were observed in the tests up to 22.5g, with no additional failure modes present.

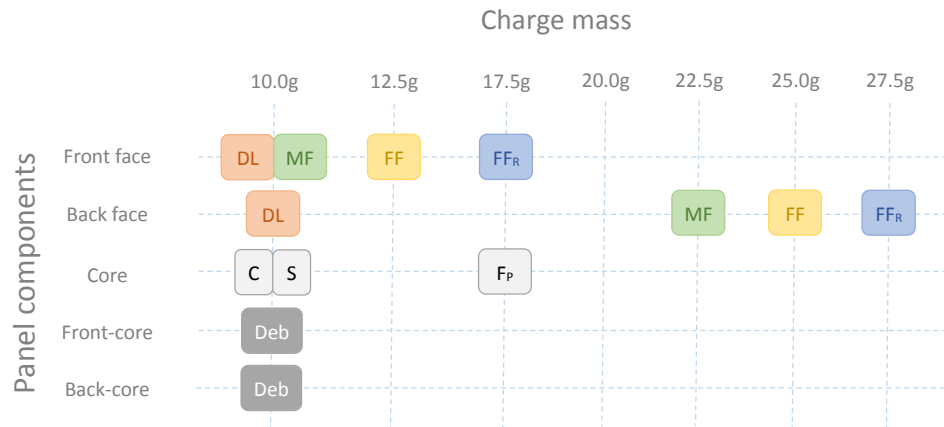


DL – Delamination, MF – Matrix failure, FF – Fibre fracture, FF_R – complete face sheet rupture
 C – compression, S – shear failure, F – fragmentation, F_P – fragmentation penetrating through core
 Deb – Debonding

Figure 79: Failure mode initiation chart of the 1000mm curved FRP sandwich panels for increasing charge mass

500mm Curved Panels

The failure mode initiation chart for the 500mm curved FRP sandwich panels is illustrated in Figure 80. The initial charge mass of 10.0g resulted in delamination and matrix failure on the front face sheet. Delamination was observed on the back face sheet along with compression and shear cracks on the core material. Debonding was observed at the front and back interfaces. At 12.5g fibre fracture was observed on front face sheet. At 15.0g, complete rupture of the front face sheet and fragmentation penetrating through the core material were present and matrix failure was observed on the back face sheet. A charge mass of 17.5g resulted in the complete rupture of the front face sheet and fragmentation penetrating the core material. No new failure modes were observed in the 20g test however, at 22.5g resulted in matrix failure observed on the back face sheet. Charge masses of 25g and 27.5g resulted in fibre fracture and complete rupture of the back face sheet respectively.



DL – Delamination, MF – Matrix failure, FF – Fibre fracture, FFR – Complete face sheet rupture
 C – Compression, S – Shear failure, F – Fragmentation, F_p – Fragmentation penetrating through core
 Deb – Debonding

Figure 80: Failure mode initiation chart of the 500mm curved FRP sandwich panels for increasing charge mass

6.2.2.2 Delaminated Area of the Front Face Sheet

1000mm Curved Panels

The percentage delaminated areas of the front face sheets for the 1000mm curved panels are listed in Table 21. The delaminated area was initially observed at 5.7% and gradually increased over the charge mass range to 10.8% at 22.5g. Four rendered images of charge masses 10g, 13.5g, 17.5g and 22.5g are illustrated in Figure 81.

Charge Mass (g)	Delaminated Area (%)
10.0	5.7
12.5	6.7
13.5	7.3
15.0	8.5
17.5	8.5
18.5	8.5
20.0	10.7
22.5	10.8

Table 21: Percentage of delaminated areas of the front face sheets of the 1000mm curved FRP sandwich panels

At 10g, the delaminated area was initially observed in the central region of the panel and resulted in a delaminated area of 5.7%, as seen in Figure 81 (a). This was approximately half of the flat panel of 11.6%.

Increasing the charge mass resulted in similar response to the flat panels where the progression of delamination was observed in the direction of the fibre orientation, as seen in Figure 81 (b). The increase in delaminated area observed was still less than the flat panels with delaminated area at 15g approximately half that of the flat panels.

A different response of the 1000mm curved front face sheet was observed with the complete rupture of the front face sheet. Initially the increase in delamination was similar to the flat panels, where it spread across central region for increasing charge masses, as seen in Figure 81 (b) and (c). This however, differed for higher charge masses between 18.5g to 22.5g. At these charge masses, the complete rupture of the front face sheet propagated into the exterior region and was predominantly observed perpendicular to the axis of curvature, resulting in delaminated areas in these regions. This is seen Figure 81 (d) for 22.5g and illustrated in photograph in Figure 83 (a).

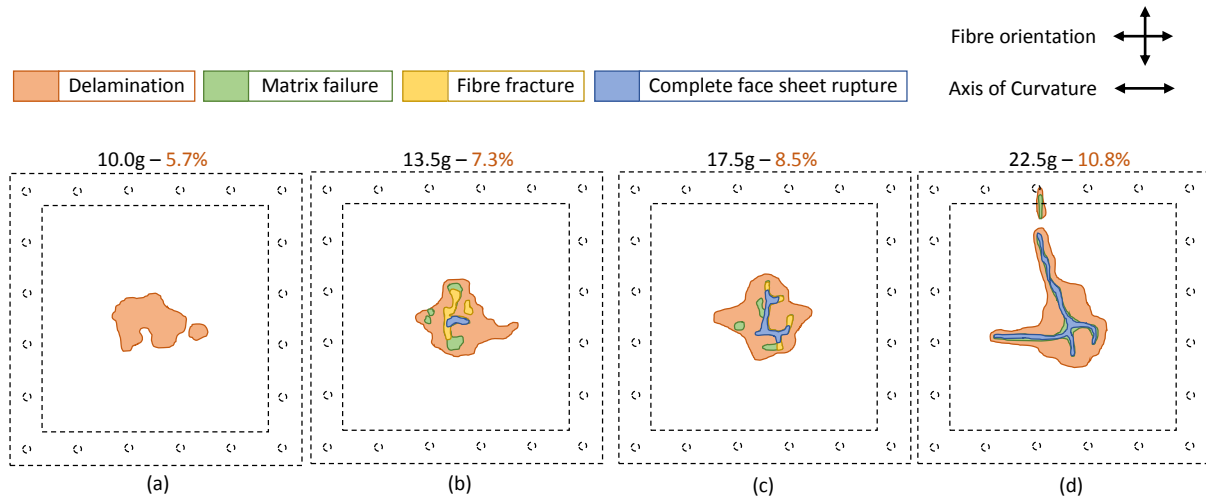


Figure 81: Rendered failure modes of the front face sheet of the 1000mm curved FRP sandwich panels subjected to: (a) 10.0g, (b) 13.5g, (c) 17.5g, (d) 22.5g

500mm Curved Panels

The percentage delaminated areas of the front face sheets for the 500mm curved panels are listed in Table 22. Delamination was initially observed at 2.6% and gradually increased over the charge mass range to 17.7% at 27.5g. Four rendered images of charge masses 10g, 17.5g, 22.5g and 27.5g are illustrated in Figure 82.

Charge Mass (g)	Delaminated Area (%)
10.0	2.6
12.5	5.2
17.5	8.1
20.0	10.9
22.5	14.2
25.0	12.5
27.5	17.7

Table 22: Percentage of delaminated areas of the front face sheets of the 500mm curved FRP sandwich panels

At 10g, the delaminated area was initially only observed in the central region at 2.6%. This was less than the delaminated area of the flat and 1000mm curved panels, as seen in Figure 82 (a).

As with the 1000mm curved panels, an increase in charge mass resulted in an increase in delamination and extended into the exterior region in the direction of the fibre orientation. The increase at 17.5g in delaminated area was similar to the 1000mm curved panels at approximately 8% and approximately half of the flat panels.

As with the 1000mm curved panels, the delaminated area continued to increase with the complete rupture, propagating into the exterior region and coupling delaminated areas to it. The failure of the panel appeared predominantly perpendicular to the axis of curvature, as is illustrated for 27.5g in Figure 82 (d) and illustrated in Figure 83 (b).

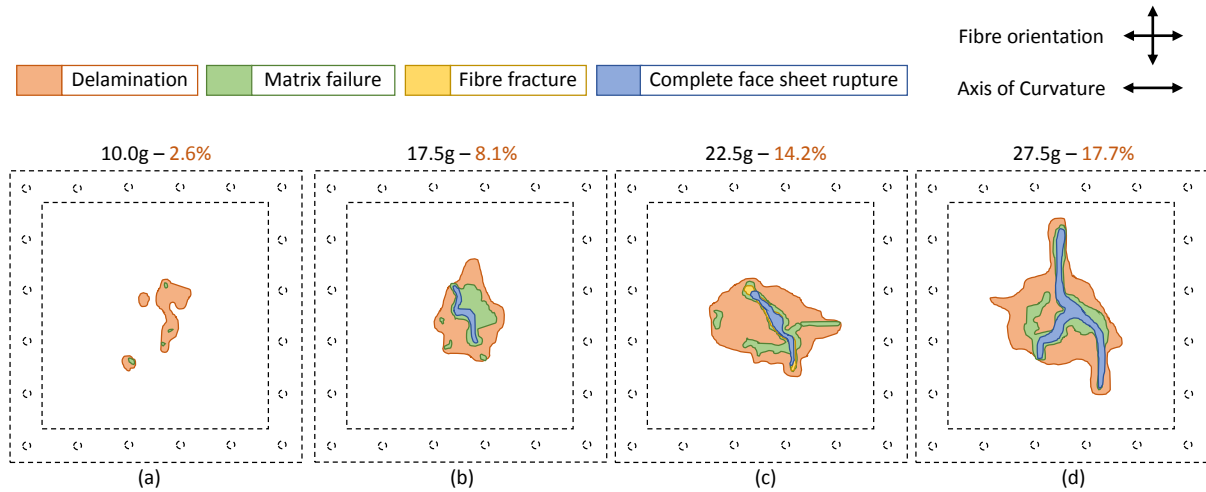


Figure 82: Rendered failure modes of the front face sheet of the 500mm curved FRP sandwich panels subjected to: (a) 10.0g, (b) 17.5g, (c) 22.5g, (d) 27.5g

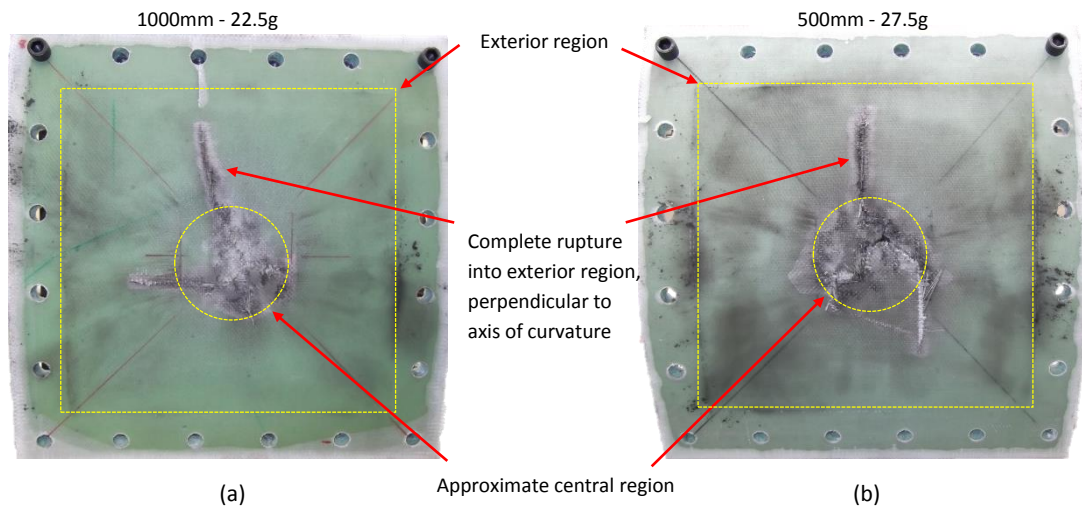


Figure 83: Photograph of the front face sheet of the curved FRP sandwich panels illustrating complete rupture propagation into exterior region for: (a) 1000mm, (b) 500mm

6.2.2.3 Delaminated Area of Back Face Sheet

The delaminated area of the back face sheets were separated into two ranges of charge masses, a lower range and higher range. These corresponded to the delaminated area observed predominately parallel the axis of curvature or perpendicular to the axis of curvature. The two ranges were different for the 1000mm and 500mm curved panels.

1000mm Curved Panels

The percentage delaminated areas of the back face sheets for the 1000mm curved panels are listed in Table 23. The lower charge mass range consisted of 10g to 17.5g and the higher of 18.5g to 22.5g. These ranges resulted in delaminated areas of 0.7% to 15.3% and 11.6% to 22.2%, respectively. The rendered images of the back face sheets are illustrated in Figure 84 for increasing charge mass and gave insight to the progression of the delaminated area.

Charge Mass (g)	Delaminated Area (%)
10.0	0.7
12.5	8.3
13.5	8.8
15.0	8.4
17.5	15.3
18.5	11.6
20.0	15.8
22.5	22.2

Table 23: Percentage of delaminated areas of the back face sheets of the 1000mm curved FRP sandwich panels

For the lower charge mass range, the initial delaminated area of 0.7% of the back face sheet was significantly lower than that of the flat panels, with no delamination observed in the central region of the panel. Small regions were observed along the boundary of the exterior region, on the axis of curvature, as seen in Figure 84 (a). An increase in charge mass to 12.5g, resulted in a large increase in delamination that was observed predominantly parallel to the axis of curvature. At 12.5g, the failure mode initiation chart showed the complete rupture of the front face sheet and penetration of the core material was observed and thus resulted in an increase in failure on the back face sheet. A small region of no delamination was observed in the centre of the panel, as observed with the flat panels and shown in Figure 84 (b). The midpoint cross section of the panel illustrates the compression of the central region of the core material, as seen in Figure 85 (b).

For the higher charge mass range, the initial delaminated area reduced to 11.6% from 15.3 % for 18.5g. This reduction was observed parallel to the axis of curvature. The complete rupture of the back face sheet was observed at 18.5g and spread across the central region into the exterior

region. The complete rupture was observed predominantly perpendicular to the axis of curvature coupled with a delaminated area, as seen in Figure 84 (c). Figure 84 (d) illustrates the severe rupture at 22.5g, where failure was predominantly perpendicular to the axis of curvature.

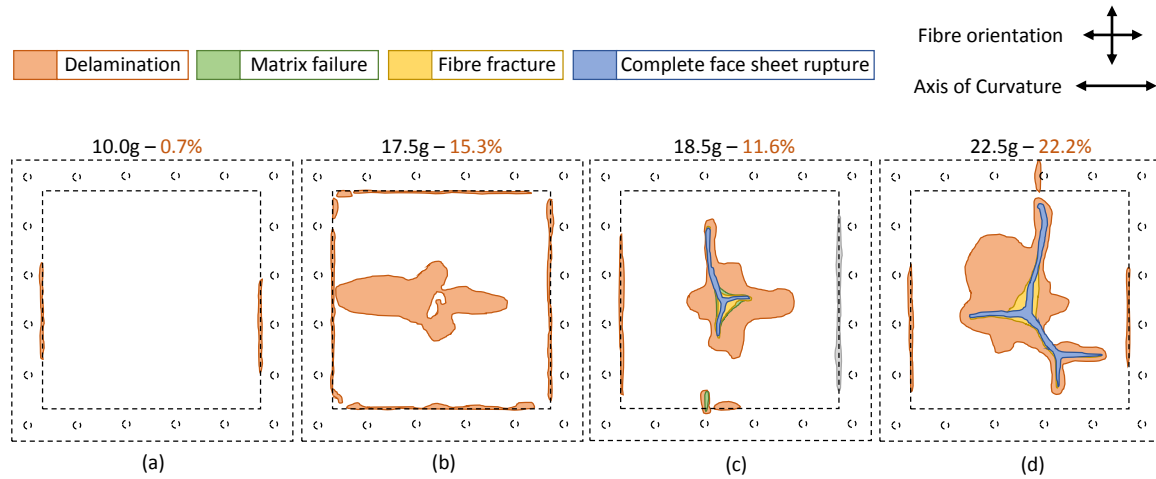


Figure 84: Rendered failure modes of the back face sheet of the 1000mm curved FRP sandwich panels subjected to: (a) 10.0g, (b) 17.5g, (c) 18.5g, (d) 22.5g

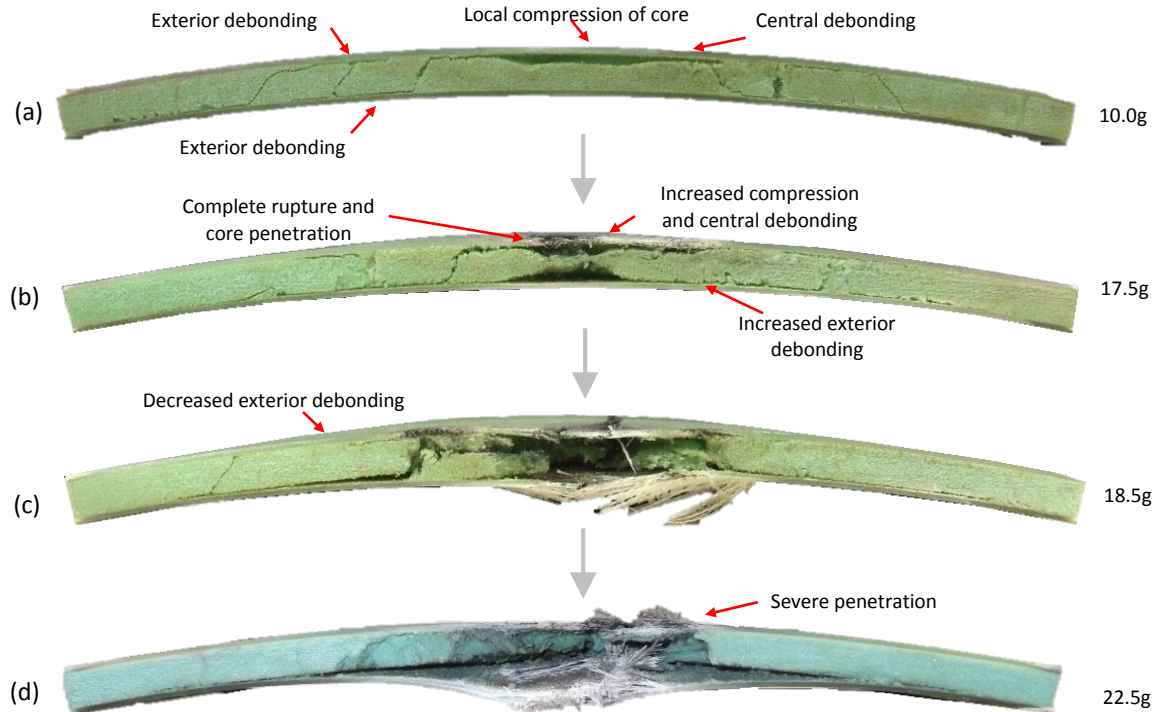


Figure 85: Photographs of the midpoint cross section of the 1000mm curved FRP sandwich panels subjected to: (a) 10g, (b) 17.5g, (c) 18.5g, (d) 22.5g

500mm Curved Panels

The percentage delaminated areas of the back face sheets for the 500mm curved panels are listed in Table 24. The lower and higher charge mass ranges were 10g to 20g and 22.5g to 27.5g respectively, and resulted in delaminated areas of 0.7% to 12.9% and 14.4% to 24.8%. The rendered images of the back face sheets are illustrated in Figure 86 for increasing charge mass and gave insight to the progression of the delaminated areas.

Charge Mass (g)	Delaminated Area (%)
10.0	0.7
12.5	0.7
17.5	11.0
20.0	12.9
22.5	14.4
25.0	19.7
27.5	24.8

Table 24: Percentage of delaminated areas of the back face sheets of the 500mm curved FRP sandwich panels

For the lower charge mass range, the initial delaminated area of back face sheet at 10g was 0.7%. This was identical to the 1000mm curved panels and was significantly lower than that of the flat panels. Small regions were observed along the boundary of the exterior region on the axis of curvature, as seen in Figure 86 (a). An increase in charge to 17.5g resulted in a large increase in delaminated area that was observed predominantly parallel the axis of curvature, with no delamination observed in centre of the panel. The failure mode initiation chart shows the complete rupture of the front face sheet and penetration of the core material was observed at 17.5g. This resulted in an increase in failure on the back face sheet, as observed with the flat and 1000mm curved panels. The midpoint cross section of the panel illustrated the compression of the central region of the core material and again suggested the reduction in load transfer to the back face sheet, as shown in Figure 86 (b).

The higher charge mass range began at 22.5g, as this charge mass represented the point where failure appeared to transition from parallel the axis of curvature to perpendicular to the axis of curvature, as seen in Figure 86 (c). The initial delaminated area was observed at 14.4% at 22.5g where the delaminated area reduced along the axis of the curvature and increase perpendicular to the axis of curvature, as with the 1000mm curved panels. The complete rupture of the back face sheet was only observed at 27.5g and spread across the central region into the exterior region. The complete rupture was observed predominantly perpendicular to the axis of curvature, along with the delaminated area as seen in Figure 86 (d).

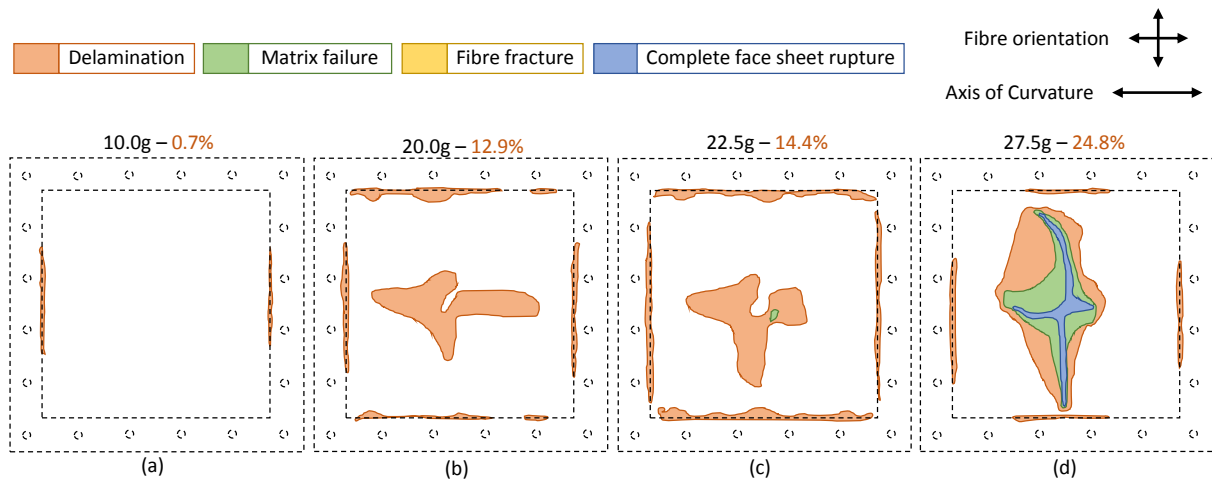


Figure 86: Rendered failure modes of the back face sheet of the 500mm curved FRP sandwich panels subjected to: (a) 10.0g, (b) 20.0g, (c) 22.5g, (d) 27.5g

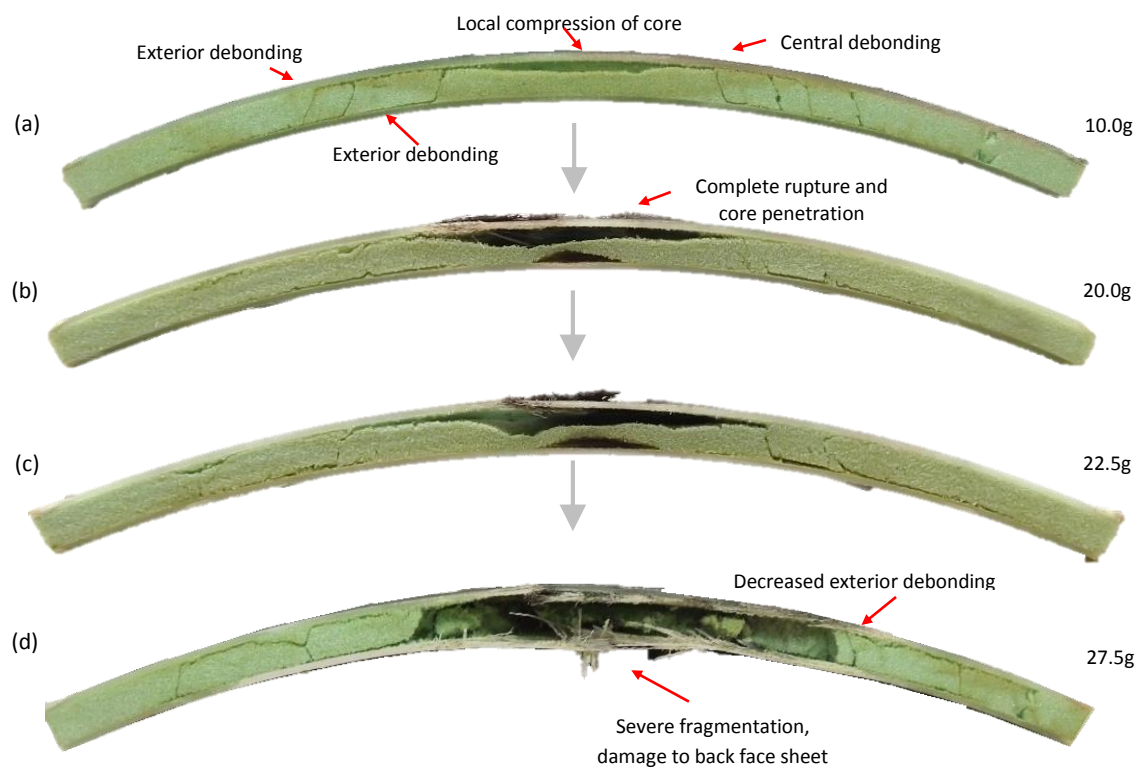


Figure 87: Photographs of the midpoint cross section of the 500mm curved sandwich panels subjected to (a) 10g, (b) 17.5g, (c) 22.5g, (d) 27.5g

6.3.2.6 Debonded lengths

1000mm curved panels

The debonded lengths of the front and back interfaces of the 1000mm curved panels are shown in Table 25 and Figure 88. The debonded length of the front interface was increased with increasing charge mass from 57.3% at 10g to a peak of 90.1% at 15g. Above 15g, the debonded length of the front interface decreased with increasing charge mass to 31.5% for 22.5g. The debonded length of the back interface was 44.4% at 10g and increased to 100% for charge masses greater than 15g. At 17.5g the debonded length of the back interface exceeded that of the front.

Charge mass (g)	% Debonding	
	Front	Back
10.0	57.3	44.4
12.5	61.9	78.3
13.5	84.1	64.4
15.0	90.1	57.6
17.5	61.3	100.0
18.5	36.4	100.0
20.0	34.8	100.0
22.5	31.5	100.0

Table 25: Percentage debonding of the front and back interfaces of the 1000mm curved FRP sandwich panels

The debonded lengths of the front and back interfaces occurred in a similar pattern to that of the flat panels. The debonded length of the front interface was observed in the central and exterior region. The increase in charge mass resulted in an increase in both regions and indicated increase in the local and global response of the front face sheet. The increase in charge mass from 15g to 17.5g resulted in a decrease in debonded length at the front interface from 90.1% to 61.3% and was a resulted of a decrease in the exterior region. The back interface at this charge mass jumped from 57.6% to 100% and exceeded the debonded length of the front interface. For comparable charge masses the debonded lengths were higher on front interface and lower on the back for 1000mm.

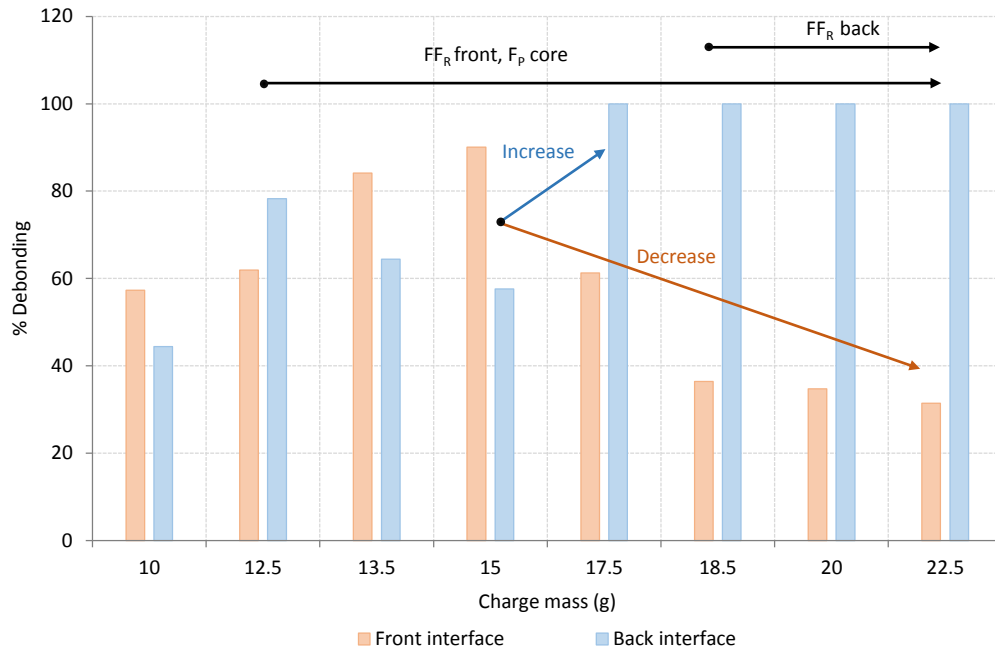


Figure 88: Percentage debonding of the front and back interfaces of the 1000mm curved FRP sandwich panels

500mm curved panels

The debonded length of the front and back interfaces of the 500mm curved are shown in Table 26 and Figure 89. The debonded length progression of the 500mm curved panels occurred differently to the flat and 1000mm curved panels. A similar behaviour was observed where the debonding at the front interface dropped and the debonding at the back interface exceeded it. However, this trend was observed at a much higher charge mass while the debonding at the front interface was still relatively large. The cross over charge mass occurred at 27.5g where complete rupture of the back face sheet was observed. The complete rupture of the front face sheet and penetration of the core material was observed at 17.5g.

Charge mass (g)	% Debonding	
	Front	Back
10.0	63.9	53.9
12.5	34.4	46.7
17.5	72.5	57.0
20.0	100.0	78.5
22.5	94.1	70.3
25	100.0	76.4
27.5	87.2	100.0

Table 26: Percentage debonding of the front and back interfaces of the 500mm curved FRP sandwich panels

The debonded length of the 500mm curved panels showed little similarity to the flat and 1000mm curved panels. A slight similarity was observed where the trend of the front interface showing a greater debonded length than the back and the back interface slowly increasing to the point where it was greater than that of the front. However for the flat and 1000mm curved panels this cross over occurred close to the charge mass where complete rupture of the front face sheet and penetration of the core material occurred. This was not the case for the 500mm curved panels. The complete rupture of the front face sheet and penetration of the core material occurred at a charge mass of 17.5g and the cross over point appeared to occur at a charge mass approximately 25g. This was closer to the complete rupture of the back face sheet. This suggests the failure of the 500mm curved panels in respect to debonded length failed in a different manner to that of the flat and 1000mm curved panels.

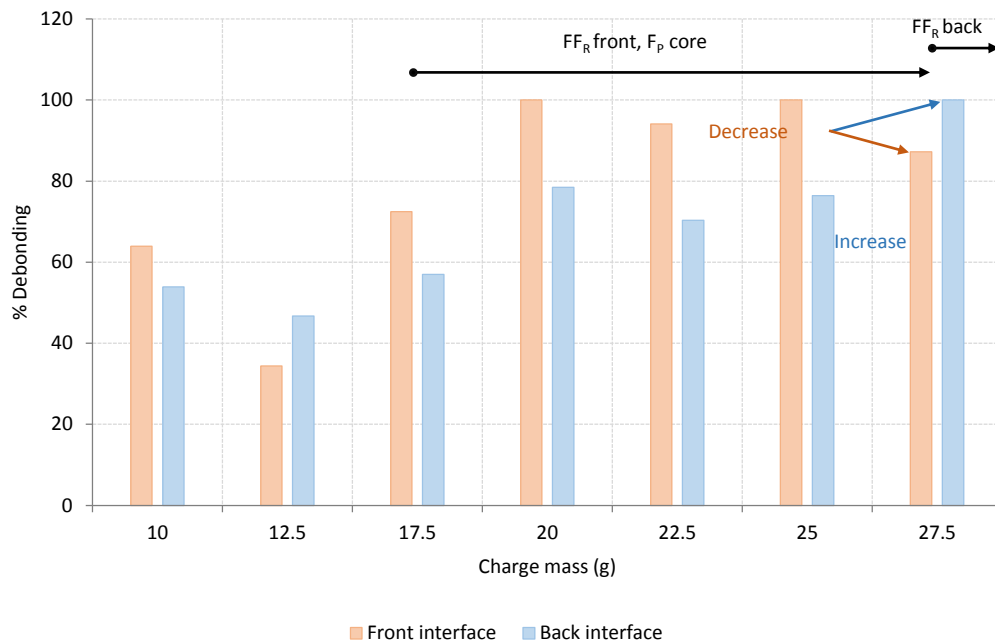


Figure 89: Percentage debonding of the front and back interfaces of the 1000mm curved FRP sandwich panels

6.3 Response of the Fibre Reinforced Polymer Laminate Panels to Blast Loading

Calculated impulses per charge mass, as seen in Table 17 (page 75), of the FRP laminate panels were plotted and are illustrated in Figure 90. Linear trend lines were inserted for the flat, 1000mm curved and 500mm curved panels for increasing charge mass. The gradient of the trend lines were 1.7, 1.3 and 1.2 respectively. The initial impulses were similar for all three panel types and the curved panels deviated from the flat panels for increasing charge mass. The gradient of the 1000mm and 500mm curved panels differed from the flat by approximately 24%, with the 500mm curved panels exhibiting lower transferred impulses than the 1000mm curved panels. As was case for the FRP sandwich panels, the flat panel tests exhibited the highest impulse transfer, while the introduction of curvature lowered the impulses.

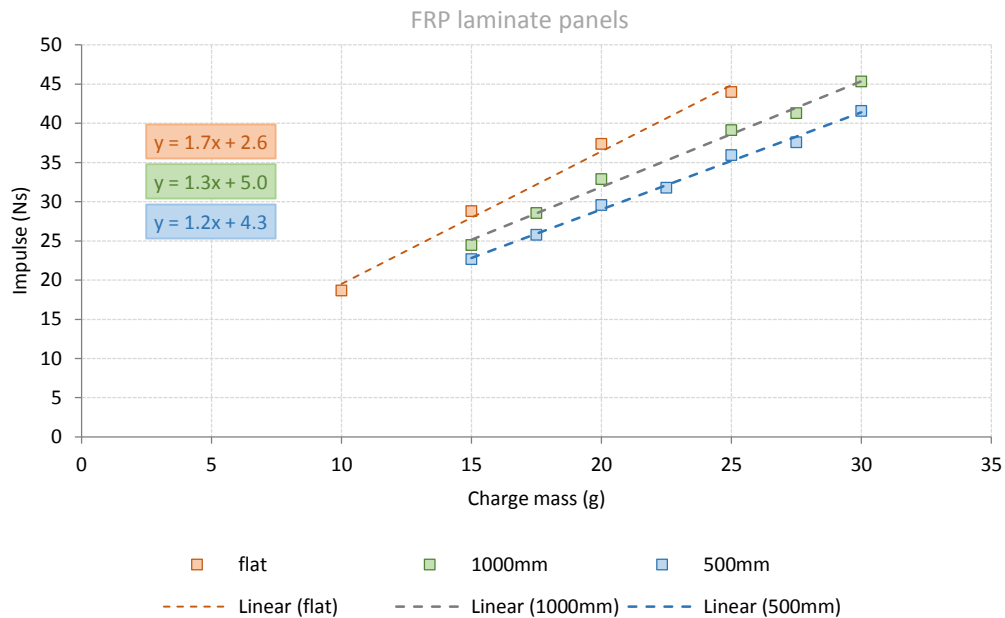


Figure 90: Graph illustrating the calculated impulse per charge mass for the flat, 1000mm curved and 500mm curved FRP sandwich panels

6.3.1 Flat panels

6.3.1.1 Failure Mode Initiation Chart

The failure mode initiation chart for the flat FRP laminate panels is illustrated in Figure 91. For an initial charge mass of 10g, delamination and matrix failure were observed and at 20.0g fibre fracture was observed.

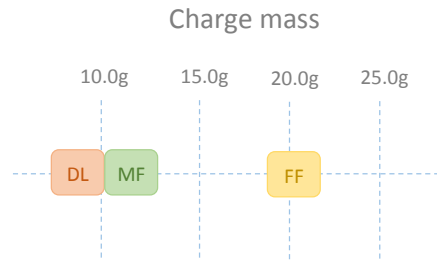


Figure 91: Failure mode initiation chart of the flat FRP laminate panels for increasing charge mass

6.3.1.1 Delaminated Area

The delaminated areas of the flat FRP laminate panels are shown in Table 27. The delaminated area was initially observed at 5.4% for 10g. This increased to approximately 60% for 15g, 20g and 25g. The rendered images of the panels are illustrated in Figure 92 for increasing charge mass and gave insight to the progression of the delaminated areas.

Charge mass (g)	Delaminated area (%)
10.0	5.4
15.0	60.8
20.0	53.7
25.0	67.8

Table 27: Percentage of delaminated areas of the flat FRP laminate panel

The delaminated area of 5.4% at 10g was concentrated in the central region of the panel with small regions observed along the boundary, as seen in Figure 92 (a). At 15g, a large increase in delaminated area of 60.8% was observed, where the delaminated area in the central region extended to the boundary of the exterior region. The increase in delaminated area in the exterior regions suggested a large global response of the panel. The delaminated area remained at this range for 20g and 25g where matrix failure and fibre fracture increased across the central region.

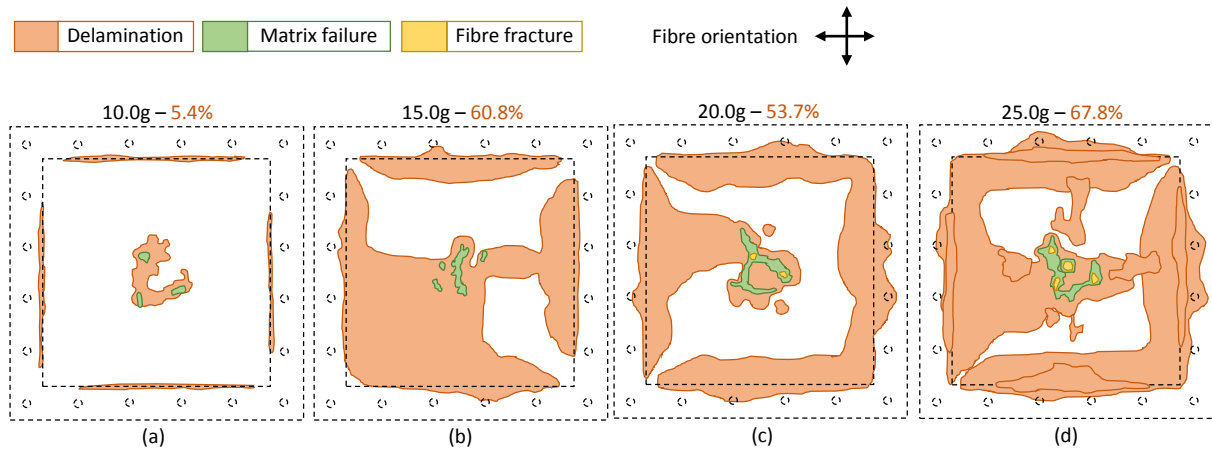


Figure 92: Rendered failure modes of the flat FRP laminate panels subjected to: (a) 10.0g, (b) 15.0g, (c) 20.0g, (d) 25.0g

6.3.2 Influence of curvature

The section to follow elaborates on the response of the 1000mm and 500mm curved FRP laminate panels subjected to a charge mass range of 10g to 27.5g and 10g to 30g respectively. The influence of curvature to the FRP laminate panels are discussed and compared with respect to the comparable failure modes.

6.3.2.1 Failure Mode Initiation Chart

1000mm Curved Panels

Figure 93 illustrated that a charge mass of 15g resulted in delamination and matrix failure and an increase to 17.5g resulted in fibre fracture observed. At 27.5g the complete rupture of the FRP laminate panel was observed.

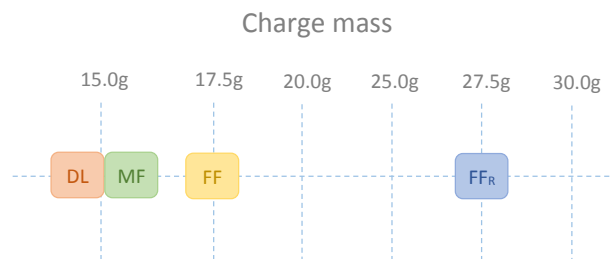


Figure 93: Failure mode initiation chart of the 1000mm curved FRP laminate panels for increasing charge mass

500mm Curved Panels

Figure 94 illustrates that an initial charge mass of 15g resulted in delamination, matrix failure and fibre fracture observed on the 500mm curved FRP laminate panels. A charge mass of 27.5g resulted in the complete rupture of the panel.

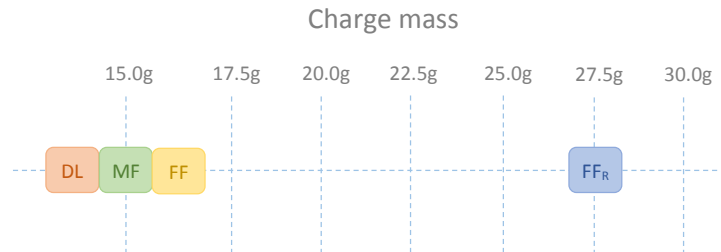


Figure 94: Failure mode initiation chart of the 500mm curved FRP laminate panels for increasing charge mass

6.3.2.2 Delaminated Area

1000mm curved panels

A list of the delaminated areas of the 1000mm curved FRP laminate panels are shown in Table 28. The delaminated area was observed in three groups. These were approximately 19% for 15g to 17.5g, approximately 70% for 20g to 25g and 49% for 27.5g to 30g. The rendered images of the panels are illustrated in Figure 95 for increasing charge mass and gave insight to the progression of the delaminated areas.

Charge mass (g)	Delaminated area (%)
15.0	21.5
17.5	17.9
20.0	62.3
25.0	76.6
27.5	53.2
30.0	44.5

Table 28: Percentage of delaminated areas of the 1000mm curved FRP laminate panel

The initial delaminated area of 19%, for 15g to 17.5g, was predominantly observed in the central region and along the boundary. The delaminated area was also observed parallel to the axis of curvature and suggested a more local response from the panel that extended into the exterior region.

An increase to 20g to 25g resulted in a large increase in delaminated area to 70%, where regions were observed from the central region to the boundary of the exterior region. This suggested

large global flexural response of the panel. This transition was also observed by Shukla et al [36] for curved panels (as discussed in section 2.7) and suggested the transition from indentation to flexural behaviour.

A further increase of 27.5g to 30g resulted in a decrease in delaminated area parallel to the axis of curvature. This charge mass range of 27.5g to 30g resulted in complete rupture of the panel in the central region.

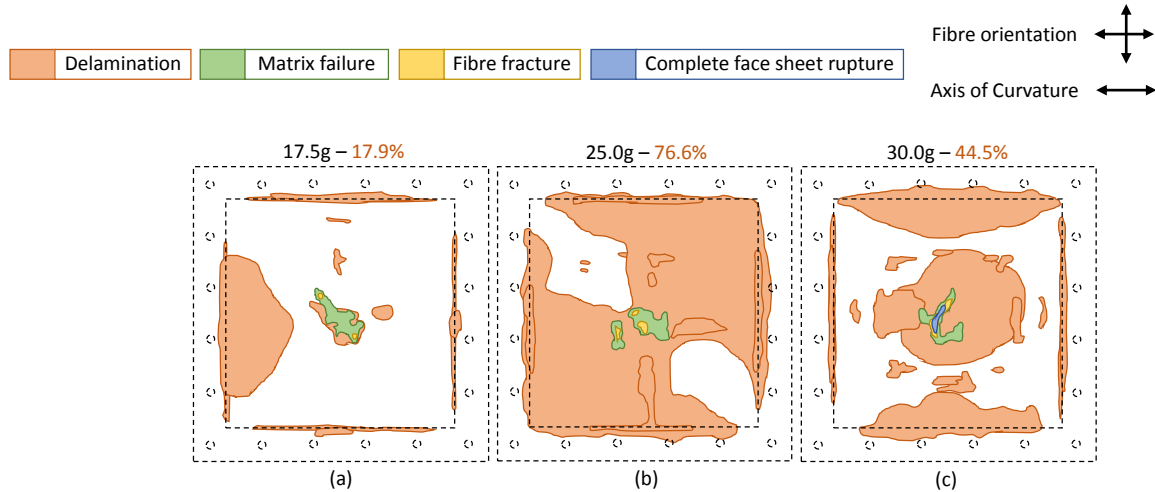


Figure 95: Frontal view of the rendered delamination of the 1000mm curved FRP laminate panels subjected to a charge mass of: (a) 17.5g, (b) 25.0g, (c) 30.0g

The failure of the panel originated on the back surface, as illustrated in Figure 96, as the area exhibiting matrix failure and fibre fracture was greater on the back surface than the front.

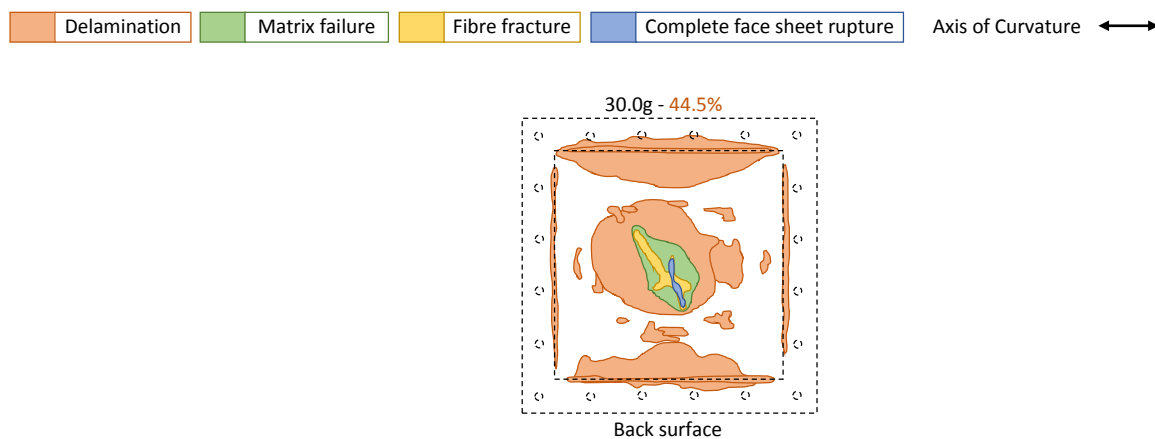


Figure 96: Rear view of a rendered 1000mm curved FRP laminate panel subjected to 30g

500mm curved panels

A list of the delaminated areas of the 500mm curved FRP laminate panels are shown in Table 29. At 15g and 25g, uncharacteristically small delaminated areas were observed. However, with the remaining delaminated areas a similar trend was observed to the 1000mm curved panels. The general trend was observed of increasing areas of delamination with increasing charge mass, namely from 16.3% at 17.5g and peaking at 65.7% for 22.5g. At 30g, the delaminated area decreased to 44.7%. The rendered images of the panels are illustrated in Figure 97 for increasing charge mass and gave insight to the progression of the delaminated areas.

Charge mass (g)	Delaminated area (%)
15.0	66.6
17.5	16.3
20.0	45.1
22.5	65.7
25.0	27.1
27.5	61.4
30.0	44.7

Table 29: Percentage of delaminated areas of the 500mm curved FRP laminate panel

The delaminated area of the 500mm curved panels showed a similar behaviour to the 1000mm curved panels. For 17.5g the delaminated area of 16.3% was observed in the central region that extended into the exterior region. This extension was observed parallel to the axis of curvature as with the 1000mm curved panels.

With an increase in charge mass to 22.5g, a peak delaminated area was observed of 65.7% and the delaminated area was observed within the central and exterior region. The matrix failure and fibre fracture increased in the central region. These illustrated an increased in local failure and global failure.

A further increase in charge mass resulted in a decrease in delaminated area as the local failure was severe enough to begin failure of the panel. The decrease was observed along the axis of the curvature.

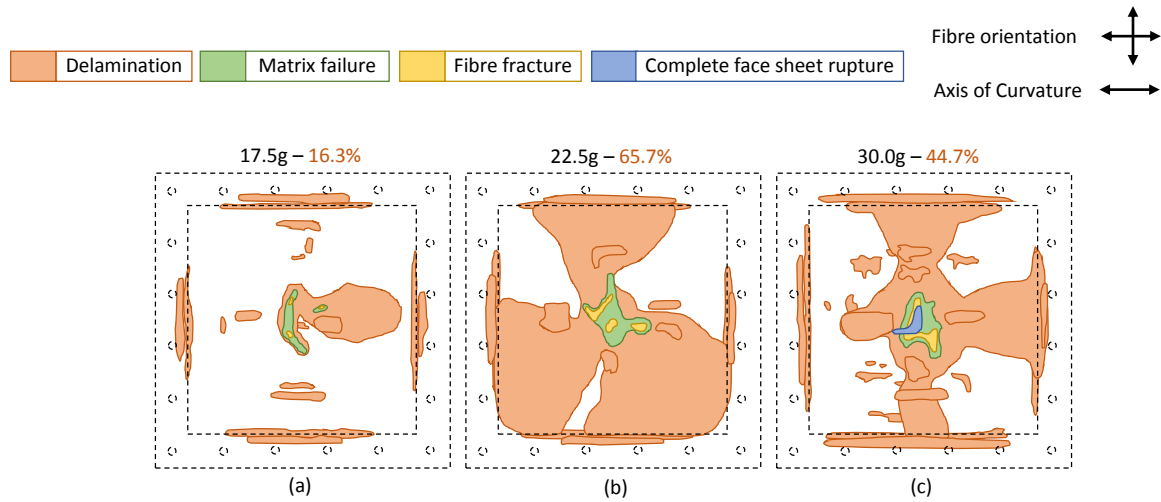


Figure 97: Selected 500mm curved FRP laminate panels subjected to: (a) 17.5g, (b) 22.5g, (c) 30.0g illustrating the rendered delamination progression

The fibre fracture was initially observed on the back surface of the 500mm curved FRP laminate panels, as with the flat and 1000mm curved panels. Once complete rupture of the panel was observed, the area of fibre fracture on the back surface of the panel was greater than on the front. Figure 97 (c) and Figure 98 illustrates this.

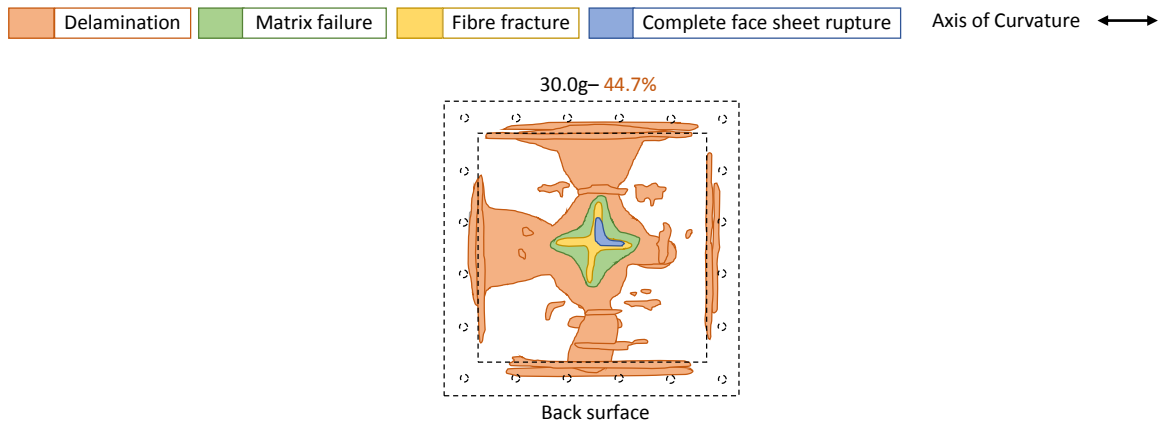


Figure 98: Rear view of 500mm curved FRP laminate panels subjected 30.0g illustrating the rendered matrix failure and fibre fracture on the back surface

6.4 Fibre Reinforced Sandwich and Laminate Panels

The progression of failure of the FRP sandwich and laminate panels was discussed in section 6.2 and 6.3. These illustrated that, for both panel types, a progression of failure that was initially localised in the central region of the panel and extended out into the exterior region for an increased charge mass. The central/local strength of the panel withstood the blast load of the lower charge masses and allowed the load to be transferred to the exterior region. Thus exhibiting local and global responses. Further increases in charge mass, resulted in failure of the fibre sheets and less load transferred to exterior region, where complete rupture of the central region of the panel occurred. The section to follow compares this threshold of the FRP sandwich and laminate panels for each radii.

6.4.1 Complete Rupture Threshold of the FRP Sandwich and Laminate Panels

As defined in section 5.2, the complete rupture of the FRP sandwich and laminate panels resulted when fibre fracture through the thickness of the face sheet of the FRP sandwich panels and through the thickness of the panel for the FRP laminate panels was observed. The threshold for the FRP sandwich panels was defined as the charge mass where complete rupture of the back face sheet was observed.

6.4.1.1 Flat Panels

The complete rupture of the flat FRP sandwich panels was observed at a charge mass of 20g. The charge mass range exposed to the flat FRP laminate panels was 10g, 15g, 20g and 25g, of which the worst failure observed was the slight appearance of fibre fracture on the back surface of the panel. This indicated that the flat FRP laminate panels outperformed the flat FRP laminate panels by at least 5g.

Panel Type	Threshold
Flat FRP sandwich	20g
Flat FRP laminate	>25g

Table 30: Complete rupture threshold for the flat FRP sandwich and laminate panels

6.4.1.2 1000mm Curved Panels

The complete rupture of the 1000mm curved FRP sandwich panels was observed at charge mass of 18.5g, similar to that of the flat FRP panels and suggests that no additional blast mitigation was observed for the slight increase in curvature.

The complete rupture of the 1000mm curved FRP laminate panels was observed at a charge mass of 27.5g. This was 9g greater than that of the 1000mm curved FRP sandwich panels.

Panel Type	Threshold
1000mm FRP sandwich	18.5g
1000mm FRP laminate	27.5g

Table 31: Complete rupture threshold for the 1000mm curved FRP sandwich and laminate panels

6.4.1.3 500mm Curved Panels

The complete rupture of the 500mm curved FRP sandwich panels was observed at a charge mass of 27.5g, 9g higher than that of the 1000mm curved FRP sandwich panels and 7.5g greater than the flat FRP sandwich panels. This indicated that the slight increase in curvature from flat to 1000mm resulted in no notable change in blast mitigation however, an increase to 500mm resulted in a significant increase in resistance to complete rupture of the back face sheet and hence blast mitigation.

The complete rupture of the 500mm curved FRP laminate panels was observed at a charge mass of 27.5g, identical to that of the 1000mm curved panels and one would assume very similar to that of the flat FRP laminate panels. This indicated that the increase in curvature for the FRP laminate panels offered no additional benefit to blast mitigation when comparing complete rupture of the panel. The complete rupture of the 500mm curved FRP laminate panel was also identical to the charge mass that resulted in complete rupture of the 500mm curved FRP sandwich panels. This illustrated that both panel types obtained identical blast thresholds when comparing complete rupture of the panel.

Panel Type	Threshold
500mm FRP sandwich	27.5g
500mm FRP laminate	27.5g

Table 32: Complete rupture threshold for the 500mm curved FRP sandwich and laminate panels

6.4.1.4 Severity of Rupture

The fibre fracture on the back surface of the 1000mm curved FRP laminate panels and complete rupture was less severe than that of the back face sheet of the FRP sandwich panels, as illustrated in Figure 99 (a) and (b). The propagation of the complete rupture for the 1000mm curved FRP sandwich panels extended further into the exterior region which was only observed in the central region for the FRP laminate panels. This indicated that the FRP laminate panels outperformed the FRP sandwich panels for the 1000mm radii.

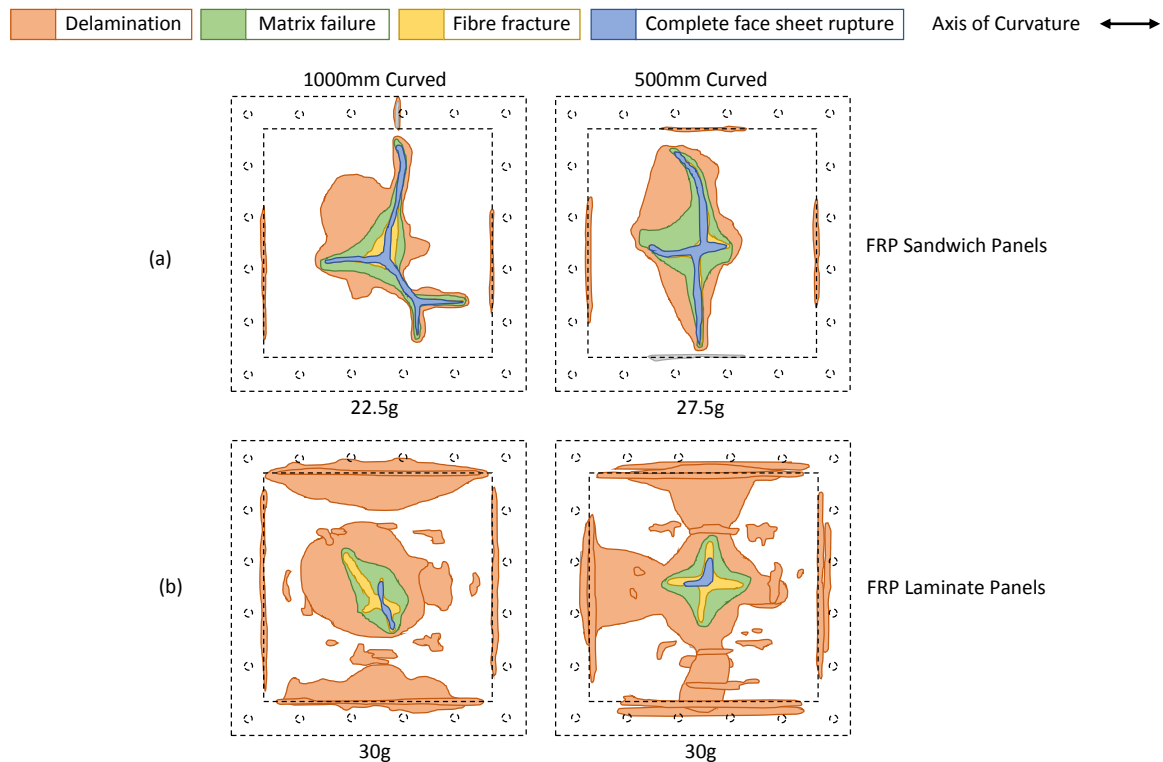


Figure 99: Complete rupture of the: (a) back face sheet of the 1000mm and 500mm curved FRP sandwich panels, (b) back surface of the 1000mm and 500mm curved FRP laminate panels

6.4.2 Calculated Impulse of the FRP Sandwich and Laminate Panels

The impulses per charge mass of the flat, 1000mm curved and 500mm curved panels are plotted in Figure 100, Figure 101 and Figure 102 respectively. Linear trend lines were inserted for the FRP sandwich and laminate panels. For increasing charge mass, the differences observed were negligible and indicated that the deformation occurred after loading, as expected for an impulsive load. This implies that the reduction in impulse transfer observed, for increasing curvature, was due to geometry re-directing the impulse loading rather than it being a function of panel configuration or material.

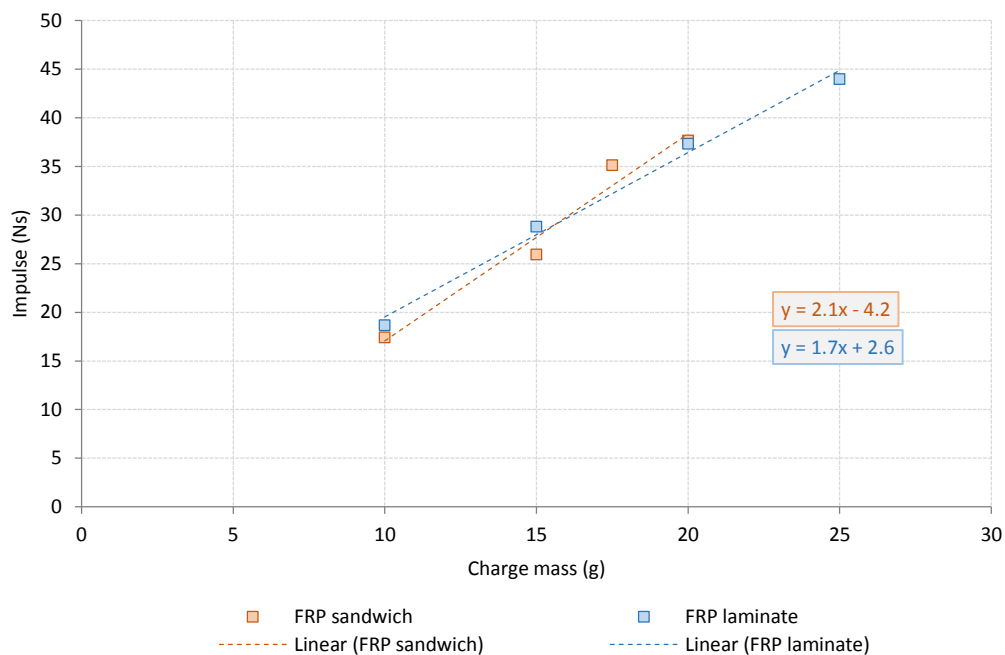


Figure 100: Graph illustrating the calculated impulse per charge mass for the flat FRP sandwich and laminate panels

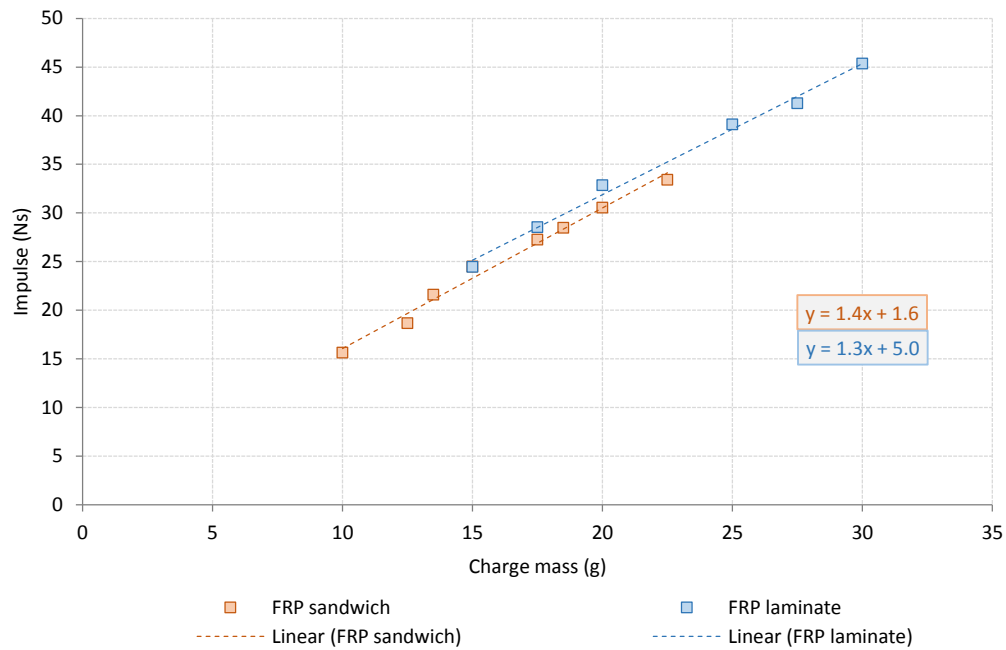


Figure 101: Graph illustrating the calculated impulse per charge mass for the 1000mm curved FRP sandwich and laminate panels

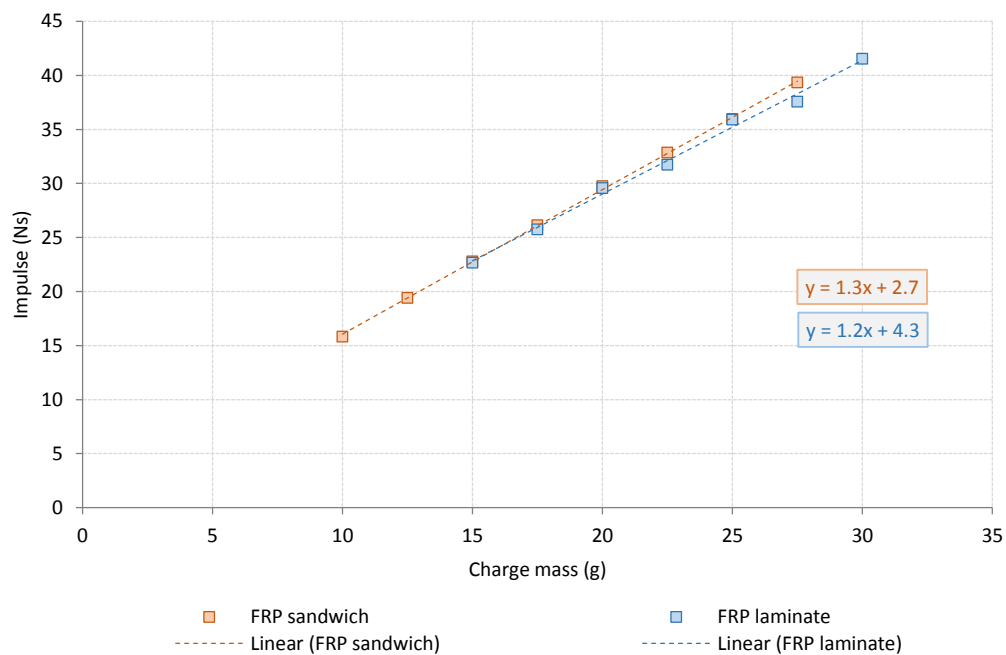


Figure 102: Graph illustrating the calculated impulse per charge mass for the 500mm curved FRP sandwich and laminate panels

Chapter 7

Conclusions

The section to follow lists the key conclusions discussed in chapter 6.

7.1 Material Characterisation of the FRP Sandwich and Laminate Panels

The results obtained from both quasi-static flexural tests of the FRP sandwich and laminate specimens showed good repeatability. The standard deviation from both quasi-static tests were 6% and 5% respectively, and hence validated the vacuum infusion manufacturing process used.

The FRP sandwich and laminate panels both failed by local compression under the central loading bar. The local compression of the core material reduced the load transfer to the bottom face sheet of the FRP sandwich panels. The resistance of the underlying layers of the FRP laminate panels resulted in the local compression leading to wrinkling of the top layers. The presence of the core material absorbed the local energy and reduced failure on the bottom face sheet. The substitution of the FRP sheets for a core material resulted in a significant increase in strength.

7.2 Response of the Fibre Reinforced Polymer Sandwich Panels to Blast Loading

Similar impulses were initially calculated at 10g for all three panel types, where minimal failure was observed. An increase in charge mass resulted in a steeper rise in impulse for the flat panels compared to the curved panels.

7.2.1 Failure Mode Initiation Chart

7.2.1.1 Flat Panels

The failure of the flat FRP sandwich panels was similar to that recorded in the literature where failure was initially concentrated on the front face sheet and core material. An increased charge mass lead to complete rupture of the front face sheet and penetration of the core material. This resulted in the blast load transferred to the back face sheet and eventually the complete rupture of the back face sheet. The charge mass difference between front and back face sheet rupture was 5g.

7.2.1.2 Influence of Curvature

A similar behaviour was observed on 1000mm and 500mm curved panels where failure was concentrated on the front face sheet and core material that progressed to the back face sheet with increasing charge mass.

The severity of the failure modes was initially less on the curved panels compared to the flat panels, namely no delamination was observed for 10g. The charge at which other failure modes were first observed was also larger than that of the flat panels. The charge mass difference between front and back face sheet rupture of the 1000mm and 500mm curved increased to 6g and 10g respectively.

7.2.2 Delaminated Area of the Front Face Sheet

7.2.2.1 Flat Panels

For increasing charge mass, the delaminated area was initially observed in the central and exterior regions, with the delaminated area in the exterior region in the direction of the fibre orientation. An increase in charge mass resulted in the increase in delaminated area in the exterior indicating an increase in global flexural response of the face sheet. Once complete rupture of the back face sheet occurred, a reduction in delaminated area in the exterior region of the front face sheet was observed.

7.2.2.2 Influence of Curvature

The delaminated areas of the 1000mm and 500mm curved panels were initially similar to the flat panels, with delamination observed in the central region and slight appearance in the exterior region. An increased charge mass resulted in slight increase in delamination in the exterior region in the direction of the fibre orientation. No reduction in delamination was observed for the 1000mm and 500mm curved panels. For charge masses 18.5g and 20g respectively, the complete face sheet rupture extended into the exterior region coupled with delaminated areas. This propagation was predominantly observed perpendicular to the axis of curvature for both curved panels.

7.2.3 Delaminated Area of the Back Face Sheet

7.2.3.1 Flat Panels

For increasing charge mass, the delaminated area was initially observed in the central region, predominantly in directions parallel to the fibre orientation. The compression of the core reduced the load transfer to the back face sheet and resulted in no delamination in the centre of the back face sheet. Once complete rupture of the front face sheet and penetration of the core occurred, a large increase in delaminated area of the back face sheet was observed. The complete rupture of the back face sheet resulted in a decrease in the delaminated area in the exterior region.

7.2.3.2 Influence of Curvature

The delaminated areas of the 1000mm and 500mm curved back face sheets were separated for the delaminated areas observed parallel and perpendicular to the axis of curvature. Lower charge mass ranges, namely 10g to 17.5g for the 1000mm curved panels and 10g to 20g for the 500mm curved panels, represented the delaminated area parallel to the axis of curvature. The higher charge mass ranges represented the delaminated areas perpendicular to the axis of curvature of 18.5g to 22.5g and 22.5g to 27.5g, respectively.

For the 1000mm and 500mm curved panels, the delaminated area was initially only observed along the clamped region, with no delamination in the central or exterior region. As with the flat panels, the complete rupture of the front face sheet and penetration of the core material resulted in large increases in delaminated area of the back face sheet. No decrease in delaminated area was observed.

7.2.4 Debonded Lengths

7.2.4.1 Flat Panels

For increasing charge mass, the debonded length at the front interface of the flat panels was initially observed in the central and exterior regions, that resulted from local and global responses of the panel. An increase in charge mass resulted in an increase in both regions. The debonded length at the back interface was initially observed only in the exterior region, with the compression of the core reducing local load to the back face sheet. After complete rupture of the front face sheet and penetration through the core, a reduction in the debonded length in the exterior region of the front interface was observed. At this charge mass the debonded length at the back interface increased significantly and exceeded that of the front. The debonded length at the front interface continued to decrease with increasing charge mass.

7.2.4.2 Influence of Curvature

The debonded lengths of the 1000mm curved panels occurred in an identical manner to that of the flat panels while the 500mm curved panels responded in a different manner. Similarities were observed with the debonded lengths of the 500mm curved panels where the debonded length at the front interface exceeded that of the back. An increased charge mass resulted in the debonded length at the back interface exceeding that of the front, as seen for the flat and curved panels.

7.3 Response of the Fibre Reinforced Polymer Laminate Panels to Blast Loading

A similar impulse was initially calculated for the flat and curved FRP laminate panels, where minimal damage was observed. For increasing charge mass, the gradient of the 1000mm and 500mm curved panels was similar however, the flat panels showed a slightly steeper response than the curved panels.

7.3.1 Failure Mode Initiation Chart

7.3.1.1 Flat Panels

For lower charge masses, delamination and matrix failure were initially observed and these increased until fibre fracture was observed for higher charge masses.

7.3.1.2 Influence of Curvature

There was no real influence from the introduction of a curved panel in terms of the initiation of failure modes. Delamination and matrix failure were initially observed and with an increased charge mass resulted in fibre fracture and complete rupture of the panel.

7.3.2 Delaminated Area

7.3.2.1 Flat Panels

For increasing charge mass, the delaminated area of the FRP laminate panels was initially observed in the central region and along clamped region. This revealed a local response of the panel. An increase in charge mass resulted in the delaminated area extending into the exterior region to the boundary. This revealed a more global response of the panel.

7.3.4.2 Influence of Curvature

The delaminated area of the curved panels was observed in three stages. This was initially the delaminated area observed in the central and exterior region, with the delaminated area in the exterior region observed along the axis of curvature. The second stage was the delaminated area increased largely in the exterior region and suggested large global response of the panels. Finally the delaminated area was observed in the central and exterior region, with the delaminated area

in the exterior observed predominately perpendicular to the axis of curvature and reduced along the axis of curvature.

7.4 Flat, 1000mm Curved and 500mm Curved Panels

7.4.1 Common Response

The response of flat, 1000mm curved and 500mm curved FRP sandwich and laminate panels was observed in three distinct stages. Initially a local and slight global response, an increased local and global response and finally an increased local response with a decreased global response. These were observed in the delaminated areas for the FRP sandwich and laminate panels, and in the debonded lengths for the FRP sandwich panels.

7.4.2 Complete Rupture Threshold

7.4.2.1 FRP Sandwich Panels

The complete rupture of the FRP sandwich panels was similar for the flat and 1000mm curved FRP sandwich panels at approximately 19g. The complete rupture of the 500mm curved panels was observed at 27.5g, a significant increase in complete rupture threshold.

7.4.2.2 FRP Laminate Panels

The complete rupture threshold for the flat (no rupture observed, only tested to 25g), 1000mm curved and 500mm curved FRP laminate panels was assumed identical. This was observed at 27.5g.

7.4.2.3 FRP Sandwich and Laminate Panels

The complete rupture threshold of the flat FRP laminate panels was at least 5g greater than the flat FRP sandwich panels.

The complete rupture threshold of the 1000mm curved FRP laminate panels was 9g greater than the 1000mm curved FRP sandwich panels.

The complete rupture threshold of the 500mm curved FRP laminate and sandwich panels was identical at 27.5g.

The failure of the back face sheet of the flat, 1000mm curved and 500m curved FRP sandwich panels was significantly worse than that of the FRP laminate panels.

Chapter 8

Recommendations

Based on the conclusions drawn, the following recommendations are listed.

8.1 Material Characterisation

- More detailed analysis of the failure of the FRP sandwich and laminate panels under quasi static conditions. High speed footage of the test procedure. Expand on failure of FRP sandwich panel components.

8.2 Blast Testing

- Further investigation to the repeatability of the initiation of the failure modes. Conduct a number of tests per charge mass.
- Reduce the increments between charge masses, especially where large amounts of failure are observed.
- Include charge masses less than 10g to expand on failure progression.
- Ensure equivalent charge mass ranges and increments for when comparing failure modes for different curvatures and materials.
- Due to the severe local failure of the front face sheet of the FRP sandwich panels, investigate the response of a FRP sandwich panel with a thicker front face than back face.

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Appendix A

Manufacturing Details

A1: Detailed layup

The layup of the FRP laminate and sandwich panels are shown in Figure 103 and Figure 104 respectively. Dimensions of constituent and consumable materials are shown.

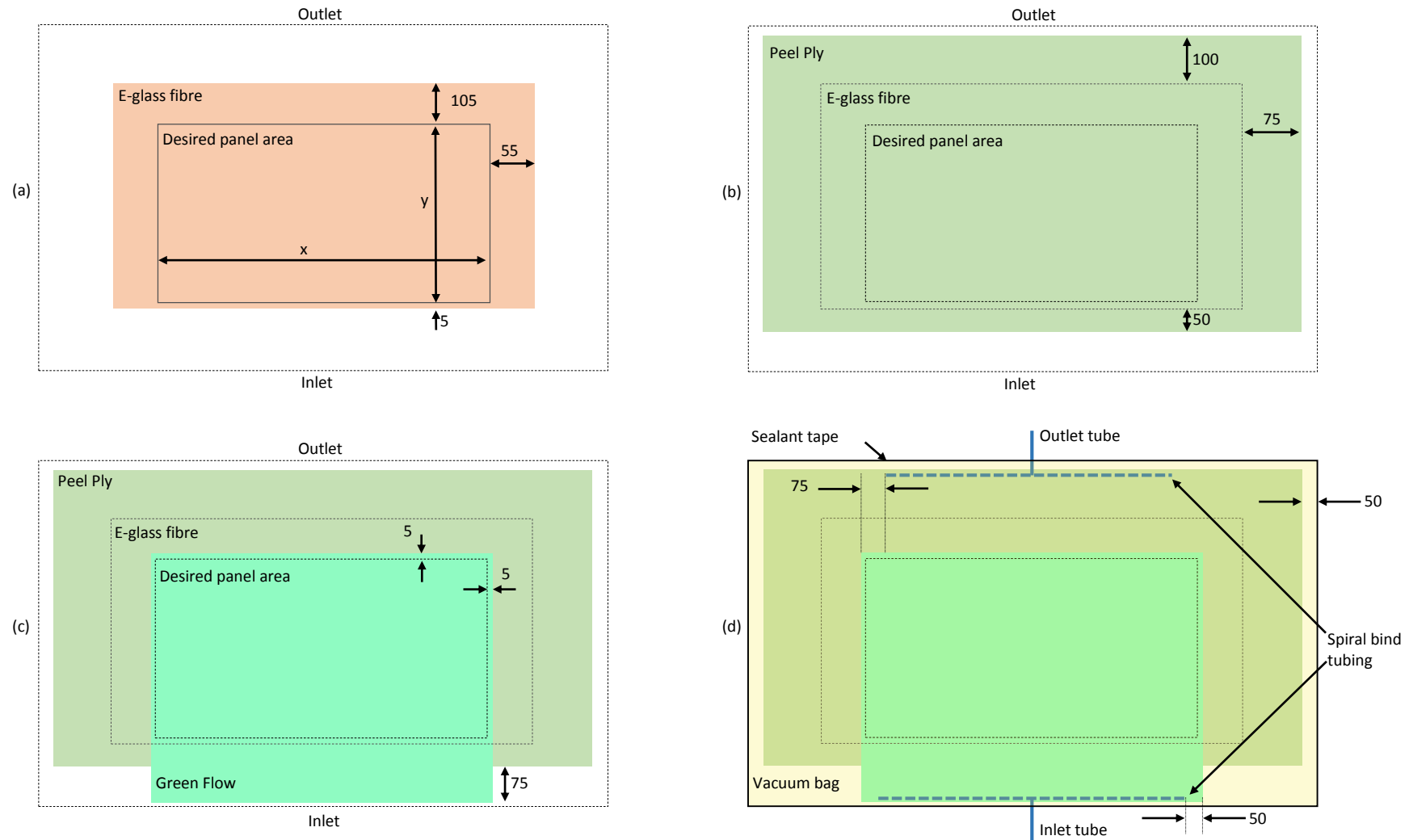


Figure 103: Layup for the FRP laminate panels: (a) glass fibre with desired area, (b) peel ply, (c) green flow, (d) tubing and vacuum bag

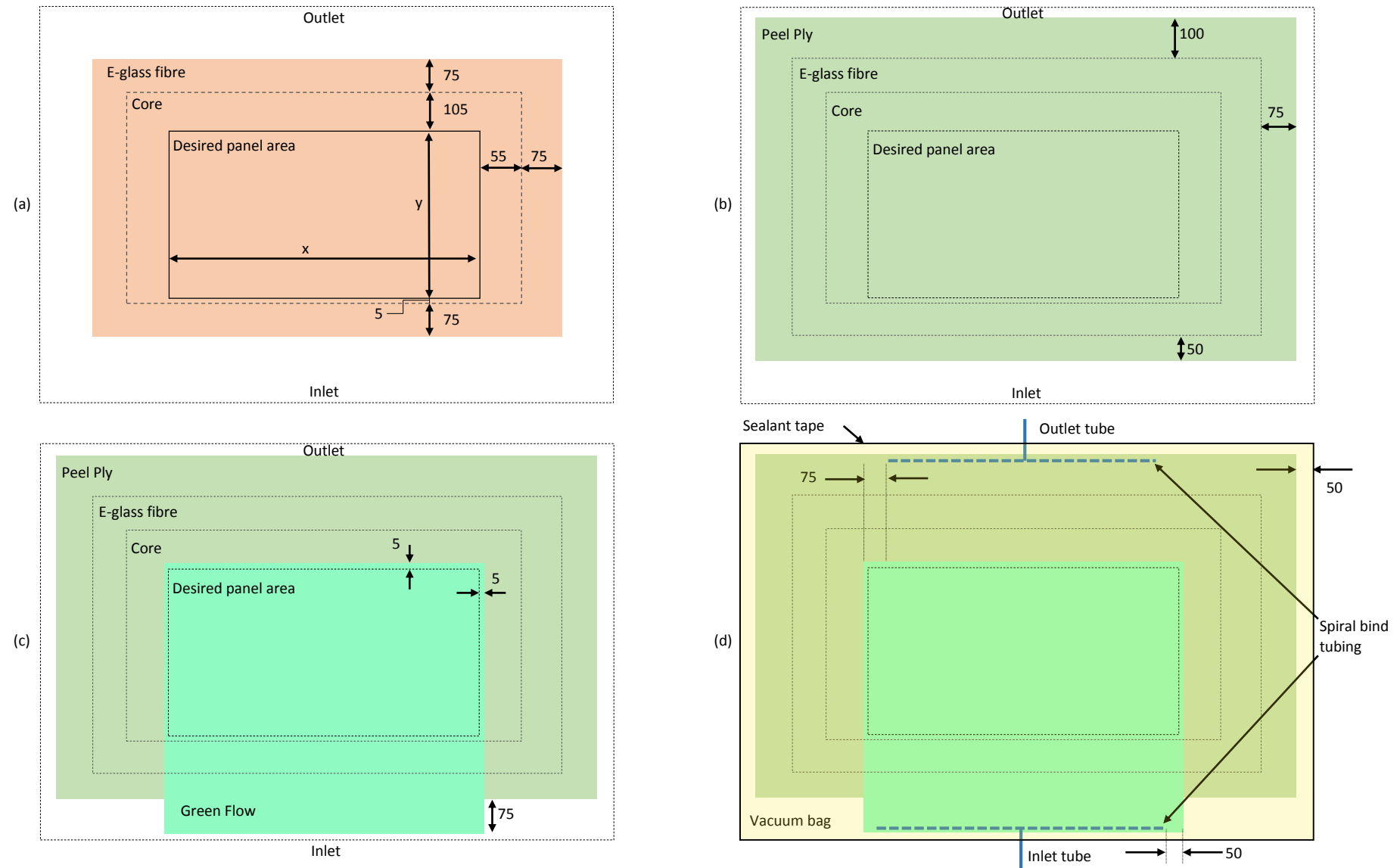


Figure 104: Layup for FRP sandwich panels: (a) glass fibre and core with desired area, (b) peel ply, (c) green flow, (d) tubing and vacuum bag

A2: Measurements of the manufactured FRP sandwich and laminate panels

The measurements of the manufactured panels are listed below. Measurements of the flat, 1000mm curved and 500mm curved FRP sandwich panel are listed in Table 33 to Table 37. Measurements of the flat, 1000mm curved and 500mm curved FRP laminate panels are listed in Table 38 to Table 42.

The areal density of the flat panels was calculated using lengths “x” and “y” where the curved panels were calculated using the flat length “x” and the arc length “s”. This is illustrated in Figure 105.

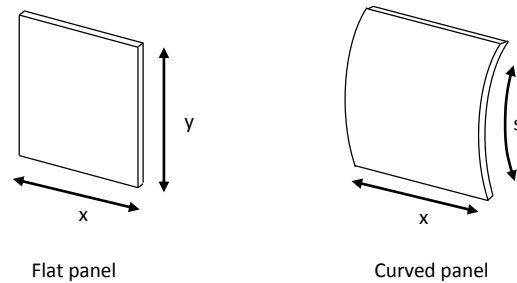


Figure 105: Aerial density measurement of the curved panels

Panel category	Panel #	Thickness (mm)				Length (mm)		Mass (g)	Areal density (g/m ²)
		Overall	Front face	Back face	Core	x	y		
Flat FRP	1a	18.7	2.3	2.4	14.0	403	403	1401	8626
Sandwich panels	1b	18.7	2.1	2.3	14.3	402	402	1386	8577
	1c	18.7	2.4	2.3	14.0	403	403	1404	8645
	1d	18.5	2.1	2.3	14.1	402	403	1393	8598
	1e	18.8	2.5	2.4	13.9	403	403	1405	8651
	1f	18.8	2.5	2.6	13.7	403	403	1390	8559
	1g	18.4	2.5	2.4	13.5	403	401	1376	8515
	mean	18.7	2.3	2.4	13.9	403	403	1394	8596
	Std dev.	0.14	0.17	0.10	0.24	0.5	0.7	9	46

Table 33: Measurements of the flat FRP sandwich manufacture

Panel category	Panel #	Thickness (mm)				Length (mm)		Mass (g)	Areal density (g/m ²)
		Overall	Front face	Back face	Core	x	s		
1000mm curved	1a	18.7	2.3	2.4	14.0	404	414	1427	8532
FRP sandwich panels	1b	18.9	2.6	2.5	13.8	401	411	1438	8725
	1c	18.9	2.5	2.2	14.2	404	413	1436	8606
	1d	18.8	2.4	2.4	14.0	401	413	1424	8598
	mean	18.8	2.5	2.4	14.0	403	413	1431	8615
	Std dev.	0.08	0.11	0.11	0.14	1.5	1.1	6	69

Table 34: Measurements of the first 1000mm curved FRP sandwich manufacture

Panel category	Panel #	Thickness (mm)				Length (mm)		Mass (g)	Areal density (g/m ²)
		Overall	Front face	Back face	Core	x	s		
1000mm curved	2a	18.3	2.3	2.3	13.7	400	411	1397	8498
FRP sandwich panels	2b	18.5	2.4	2.5	13.6	402	412	1412	8525
	2c	18.7	2.2	2.5	14.0	405	411	1422	8543
	2d	18.5	2.2	2.5	13.8	402	412	1417	8556
	mean	18.5	2.3	2.5	13.8	402	412	1412	8531
	Std dev.	0.14	0.08	0.09	0.15	1.8	0.5	9	22

Table 35: Measurements of the second 1000mm curved FRP sandwich manufacture

Panel category	Panel #	Thickness (mm)				Length (mm)		Mass (g)	Areal density (g/m ²)
		Overall	Front face	Back face	Core	x	s		
500mm curved	1a	18.9	2.6	2.8	13.5	398	435	1558	8999
FRP sandwich	1b	18.8	2.4	2.6	13.8	396	433	1522	9051
panels	1c	18.8	2.5	2.5	13.8	397	434	1533	8897
	1d	18.9	2.6	2.7	13.6	400	434	1540	8871
	mean	18.9	2.5	2.7	13.7	398	434	1546	8955
	Std dev.	0.05	0.08	0.11	0.13	1.5	0.7	13	73

Table 36: Measurements of the first 500mm curved FRP sandwich manufacture

Panel category	Panel #	Thickness (mm)				Length (mm)		Mass (g)	Areal density (g/m ²)
		Overall	Front face	Back face	Core	x	s		
500mm curved	2a	18.4	2.5	2.6	13.3	397	433	1440	8377
FRP sandwich	2b	18.4	2.5	2.4	13.5	396	432	1440	8418
panels	2c	18.3	2.5	2.3	13.5	397	433	1456	8470
	2d	18.4	2.4	2.5	13.5	397	431	1455	8503
	mean	18.4	2.5	2.5	13.5	397	432	1448	8442
	Std dev.	0.04	0.04	0.11	0.08	0.4	0.8	8	48

Table 37: Measurements of the second 500mm curved FRP sandwich manufacture

Panel category	Panel #	Thickness (mm)	Length (mm)		Mass (g)	Aerial Density (g/m ²)
			x	y		
Flat FRP laminate panels	1a	4.8	399	400	1365	8553
	1b	4.7	399	399	1356	8518
	1c	4.8	399	399	1348	8467
	1d	4.8	399	399	1347	8461
	1e	4.7	400	400	1342	8388
mean		4.8	399	399	1351	8477
		0.05	0.4	0.5	8	56

Table 38: Measurements of the flat FRP laminate manufacture

Panel category	Panel #	Thickness (mm)	Length (mm)		Mass (g)	Aerial Density (g/m ²)
			x	s		
1000mmcurved FRP laminate panels	1a	4.9	401	407	1426	8737
	1b	5.1	397	408	1418	8754
	1c	5.0	395	407	1407	8752
mean		5.0	398	407	1417	8748
		0.08	2.5	0.4	8	8

Table 39: Measurements of the first 1000mm curved FRP laminate manufacture

Panel category	Panel #	Thickness (mm)	Length (mm)		Mass (g)	Aerial Density (g/m ²)
			x	s		
1000mmcurved FRP laminate panels	2a	4.9	401	407	1387	8498
	2b	4.8	397	406	1371	8506
	2c	4.8	398	408	1374	8461
	2d	4.7	401	408	1377	8416
mean		4.8	399	407	1377	8470
		0.07	1.7	0.8	6	36

Table 40: Results from the 1000mm curved FCL panel manufacture 2

Panel category	Panel #	Thickness (mm)	Length (mm)		Mass (g)	Aerial Density (kg/m ²)
			x	s		
500mmcurved FRP laminate panels	1a	4.9	395	418	1369	8303
	1b	4.9	398	417	1382	8338
	1c	4.9	396	417	1372	8320
	1d	4.8	396	418	1372	8300
mean		4.9	396	418	1374	8315
		0.04	1.1	0.5	5	15

Table 41: Results from the 500mm curved FCL panel manufacture 1

Panel category	Panel #	Thickness (mm)	Length (mm)		Mass (kg)	Aerial Density (kg/m ²)
			x	s		
500mmcurved FRP laminate panels	2a	4.8	397	418	1367	8249
	2b	4.8	399	418	1375	8256
	2c	4.8	396	417	1366	8284
	2d	4.9	398	417	1380	8326
mean		4.8	398	418	1372	8279
		0.04	1.1	0.5	6	30

Table 42: Results from the 500mm curved FCL panel manufacture 2

Appendix B

Impulse Theory

B1: Impulse theory

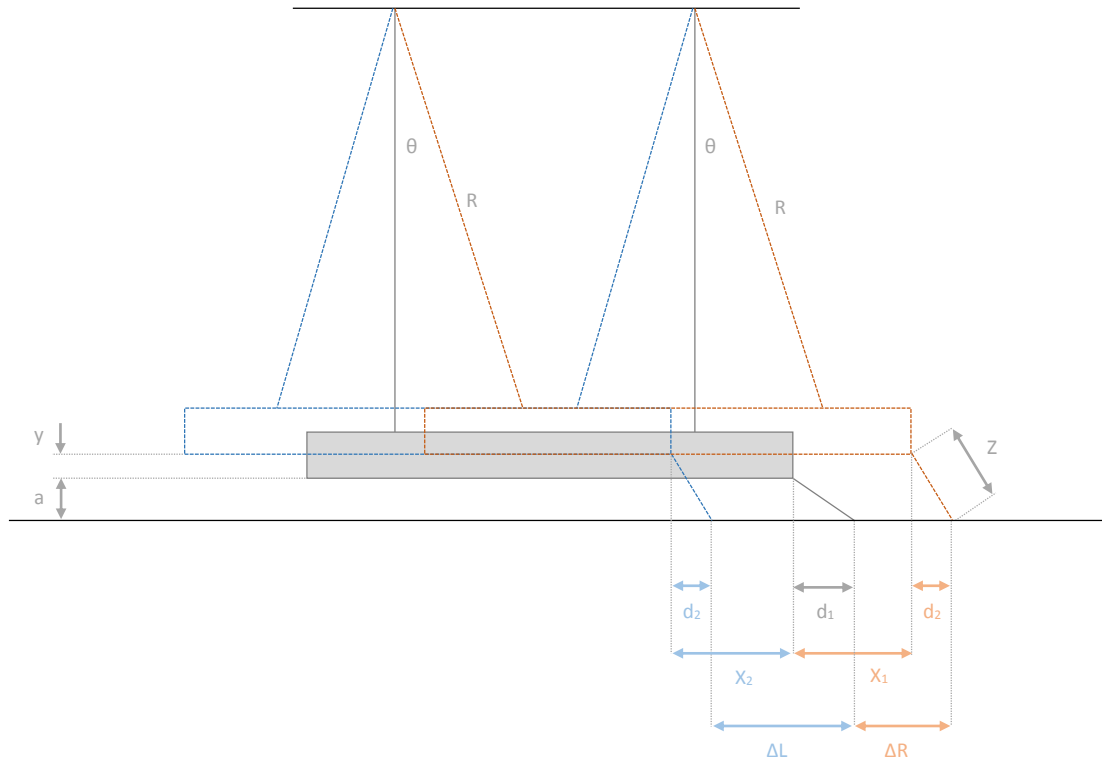


Figure 106: Schematic of the horizontal ballistic pendulum

The linearised equation of motion for a simple pendulum is

$$\ddot{X} + 2\beta\dot{X} + \omega_n^2 X = 0 \quad (\text{B1})$$

where

$$\beta = \frac{c}{2m_p} \quad (\text{B2})$$

and

$$\omega_n = \frac{2\pi}{T} \quad (\text{B2})$$

In Equations B1 and B2, β is the damping constant, C the damping coefficient, m_p the total mass of the pendulum (including front and back attachments) and T the natural period of the pendulum.

The solution to the second order differential equation of Equation B1 is

$$x = \frac{e^{-\beta t} x_0 \sin(\omega_d t)}{\omega_d} \quad (\text{B4})$$

where x_0 is the initial velocity of the pendulum and $\omega_d = \sqrt{\omega_n^2 - \beta^2}$

If x_1 is the maximum forward horizontal displacement of the pendulum occurring at time $t = \frac{T}{4}$ and x_2 is the maximum backward horizontal displacement of the pendulum occurring at time $t = \frac{3T}{4}$, then substituting into Equation B4 gives

$$x_1 = \frac{x_0 T}{2\pi} e^{(-\beta T/4)} \quad (\text{B5})$$

and

$$x_2 = \frac{x_0 T}{2\pi} e^{(-3\beta T/4)} \quad (\text{B6})$$

Solving for β in terms of x_1 and x_2 gives

$$\beta = \frac{2}{T} \ln\left(\frac{x_1}{x_2}\right) \quad (\text{B7})$$

and the initial velocity of the pendulum x_0 is found by substituting Equation B7 into Equation B5, giving

$$\dot{x}_0 = \frac{2\pi}{T} x_1 e^{(-\beta T/4)} \quad (\text{B8})$$

The impulse imparted to the pendulum is found by

$$I = m_p \dot{x}_0 \quad (\text{B9})$$

The natural period of the pendulum T is found by inducing movement of the pendulum and averaging the time taken for a number of oscillations. It should be noted, that owing to the geometry of the setup, the maximum forward ΔR and backward ΔL movements of the pen tip

do not correspond to the maximum forward x_1 and backward x_2 displacements of the pendulum. Consequently these must be related by taking into account the geometry of the pendulum.

The horizontal distance between the initial position of the pendulum and the tip of the pen is

$$d_1 = \sqrt{Z^2 - a^2} \quad (\text{B10})$$

and when the pendulum is at its maximum amplitude, this distance has been reduced to

$$d_2 = \sqrt{Z^2 - (a + y)^2} \quad (\text{B11})$$

It is reasonable to assume that the angle of oscillation of the pendulum θ is small, resulting in $x_1 = R\theta$ and $y = R\theta^2/2$ where R is the length of the wires from which the pendulum is hung. Combining these relationships gives

$$y = \frac{x_1^2}{2R} \quad (\text{B12})$$

which when substituted into Equation B11 results in

$$d_2 = \sqrt{Z^2 - \left(a + \frac{x_1^2}{2R}\right)^2} \quad (\text{B13})$$

From the geometry of Figure 106 it is clear that

$$x_1 = \Delta R + d_1 - d_2 \quad (\text{B14})$$

and

$$x_2 = \Delta L - d_1 + d_2 \quad (\text{B15})$$

Substituting for d_1 and d_2 gives

$$x_1 = \Delta R + \sqrt{Z^2 - a^2} - \sqrt{Z^2 - \left(a + \frac{x_1^2}{2R}\right)^2} \quad (\text{B16})$$

and

$$x_2 = \Delta L + \sqrt{Z^2 - a^2} + \sqrt{Z^2 - \left(a + \frac{x_1^2}{2R}\right)^2} \quad (\text{B17})$$

If ΔR , ΔL , Z , a and R are measured, then Equation B16 and B17 can be solved iteratively. The damping constant β can be calculated, followed by the initial velocity of the pendulum $\dot{x}_0$. Finally the impulse is found from Equation B9.

B2: Impulse Calculations

The maximum forward and backward movements of the pendulum and the impulses for tests carried out on the FRP sandwich and laminate panels are listed in Table 43 and Table 44.

Panel category	Charge mass (g)	Panel #	ΔR (mm)	ΔL (mm)	Impulse (Ns)
Flat FRP sandwich	10.0	1e	26	29	17.41
	15.0	1c	39	43	25.95
	15.0*	1b	40	44	26.58
	17.5	1g	54	57	35.13
	20.0	1f	57	62	37.66
1000 FRP sandwich	10.0	2a	25	25	15.64
	12.5	1d	29	30.5	18.67
	13.5	2b	36	33	21.60
	15.0	1a	40	38	24.48
	17.5	1c	46	41	27.26
	18.5	2c	45	46	28.47
	20.0	1b	48	49	30.53
	22.5	2d	51	55	33.39
500 FRP sandwich	10.0	1c	32	34	15.83
	12.5	2d	40	41	19.42
	15.0	1a	46	49	22.79
	17.5	1b	54	55	26.14
	20.0	1d	61	63	29.74
	22.5	2c	68	69	32.86
	25	2a	71	79	35.96
	27.5	2b	82	82	39.33

Table 43: Maximum forward and backward movements of the pendulum for tests carried out on the FRP sandwich panels

Panel category	Charge mass (g)	Panel #	ΔR (mm)	ΔL (mm)	Impulse (Ns)
Flat FRP laminate	10.0	1b	28	31	18.67
	15.0	1c	45	46	28.79
	20.0	2c	57	61	37.34
	25.0	1c	69	70	44.62
1000 FRP laminate	15.0	1b	49	53	24.47
	17.5	1c	59	60	28.54
	20.0	2c	66	71	32.86
	20.0*	1a	64	71	32.37
	25.0	2a	81	82	39.09
	27.5	2d	85	87	41.26
	30.0	2b	93	96	45.34
500 FRP laminate	15.0	1a	62	63	22.67
	17.5	2a	71	71	25.75
	20.0	1b	80	83	29.57
	22.5	2d	87	88	31.74
	22.5*	2b	93	90	33.17
	25.0	1c	95	103	35.91
	27.5	1d	102	105	37.55
	30.0	2c	113	116	41.54

Table 44: Maximum forward and backward movements of the pendulum for tests carried out on the FRP laminate panels

Appendix C

Calculating Delaminated Areas

C1: Validation

“Analyzing Digital Images” (freeware) was used to calculate the rendered delaminated areas of the FRP sandwich and laminate panels. The test area boundary and the delaminated area were saved as a “png file”, with the boundary highlighted in white and delaminated area in red, as shown in Figure 107 (b), with a grey background in order to observe the white boundary line.

The method used to calculate the delaminated areas is shown in Figure 108 (a) to (e) of the uploaded png file. The linear scale was inserted by placing a line over the image and assigning the test area width of 300mm, as shown in Figure 108 (a) and (b). Note the position of the “x” and “y” coordinates. The red pixel intensity was set to 100% and the image was masked, as shown in Figure 108 (c) and (d). A rectangular spatial analysis tool was used to calculate the area of the masked pixels, as seen in Figure 108 (e), note again the position of the “x” and “y” coordinates. The area masked pixels was calculated and compared to the test area. In this case the area was calculated as 7643mm², which is 8.5% of the total test area of 90000mm².

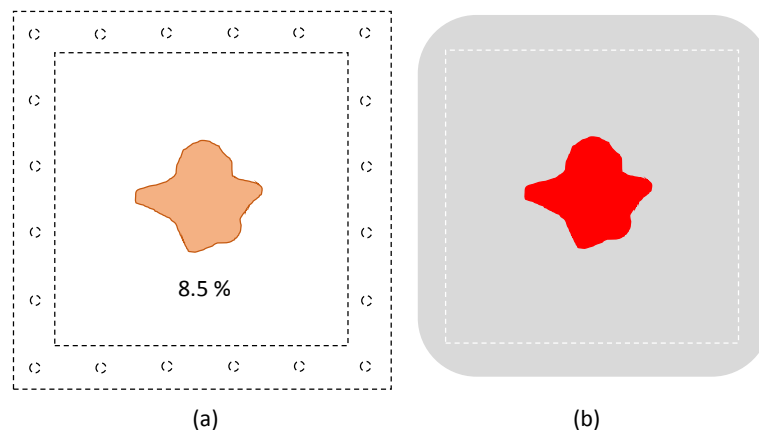
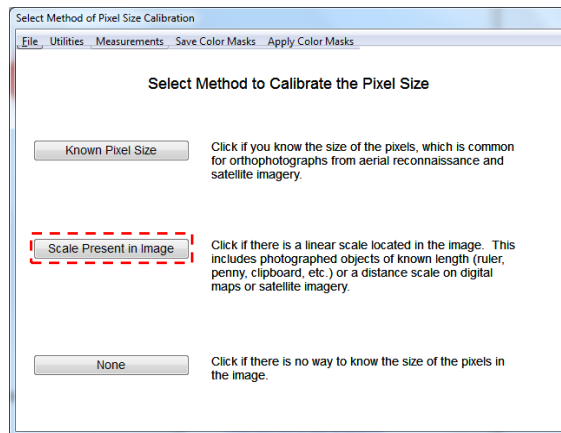
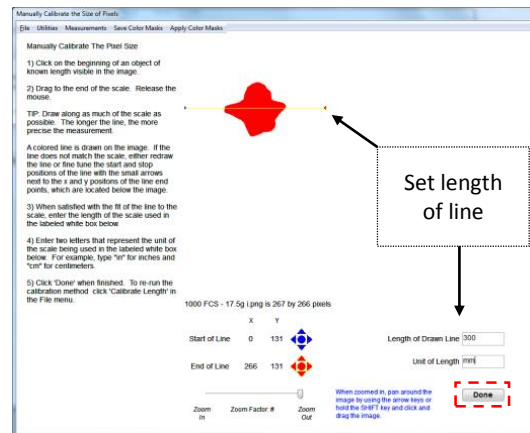


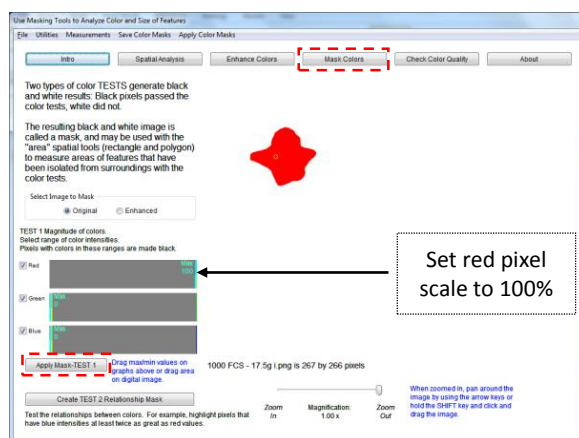
Figure 107: png file format for calculating the delaminated area: (a) rendered image, (b) saved png file used in “Analyzing Digital Images”



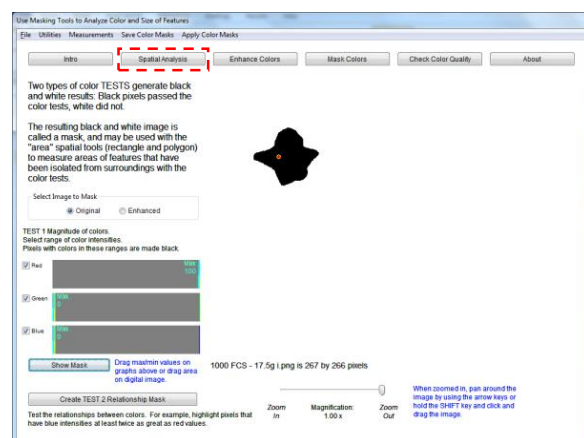
(a)



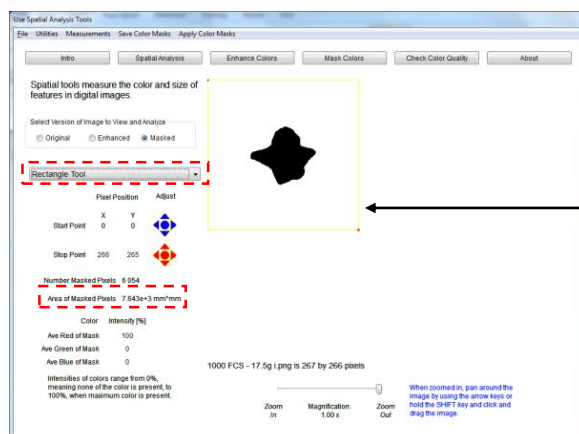
(b)



(c)



(d)



(e)

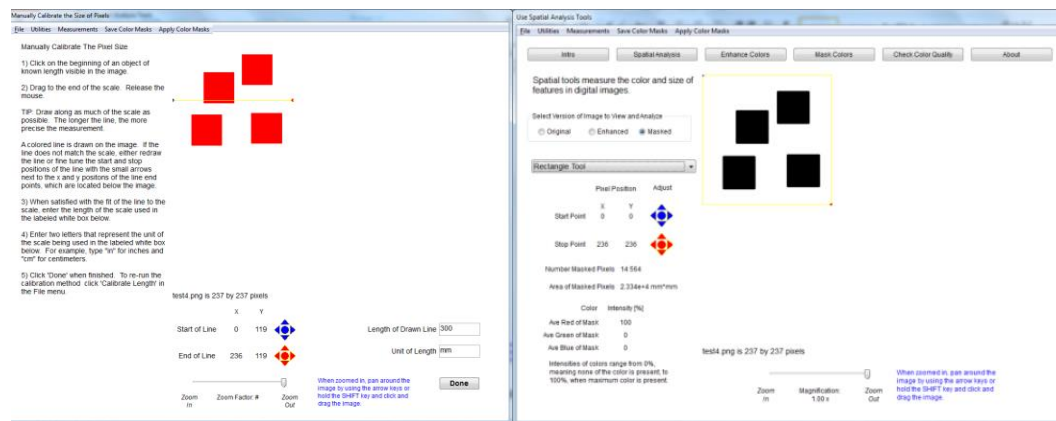
Figure 108: Method of calculating delaminated area

C2: Validation of calculated delaminated areas

This method was validated by calculating the area of known areas and comparing the two results. A number of examples are shown in Figure 109 and Figure 110.



Figure 109: Validation of the calculated delaminated areas: (a) 100% (b) 50%, (c) 25%



Actual area: 25%

Calculated area: 25.93%

Figure 110: Validation of the calculated delaminated areas continued: (d) 25%

Appendix D

Ethics Declaration

Appendix E

Design Drawings

EBE Faculty: Assessment of Ethics in Research Projects (Rev2)

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee; submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791).
NB: A copy of this signed form must be included with the thesis/dissertation/report when it is submitted for examination

This form must only be completed once the most recent revision EBE EIR Handbook has been read.

Name of Principal Researcher/Student: Gregory Sinclair Department: Mechanical Engineering BISRU

Preferred email address of the applicant: snagreg002@myuct.ac.za

If a Student: Degree: MSc Supervisor: Genevieve Langdon

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: Response of singly curved sandwich panels subjected to blast loading

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	☒ NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	☒ NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	☒ NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	☒ NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate. Ensure that you refer to the EIR Handbook to assist you in completing the documentation requirements for this form.

I hereby undertake to carry out my research in such a way that

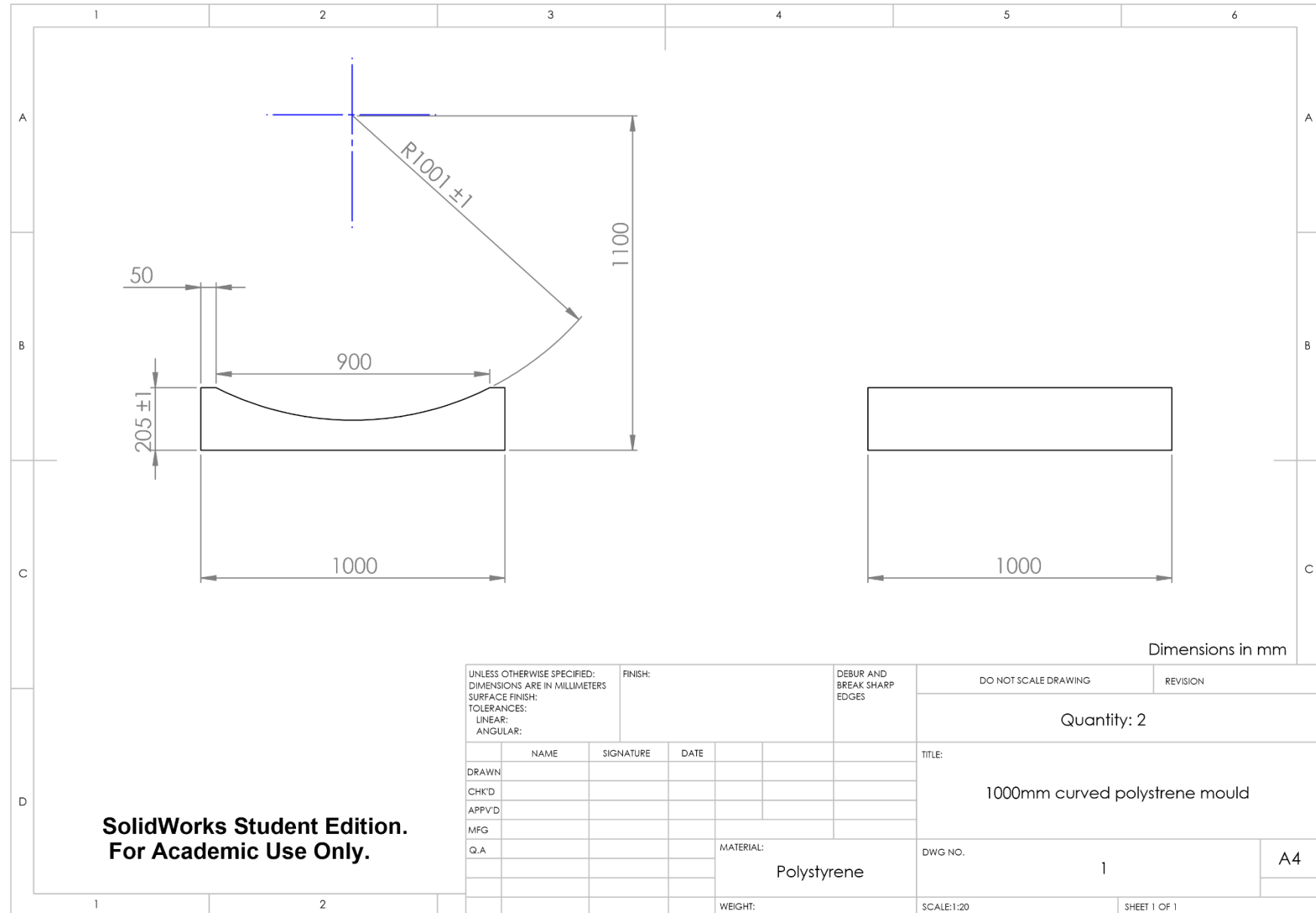
- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

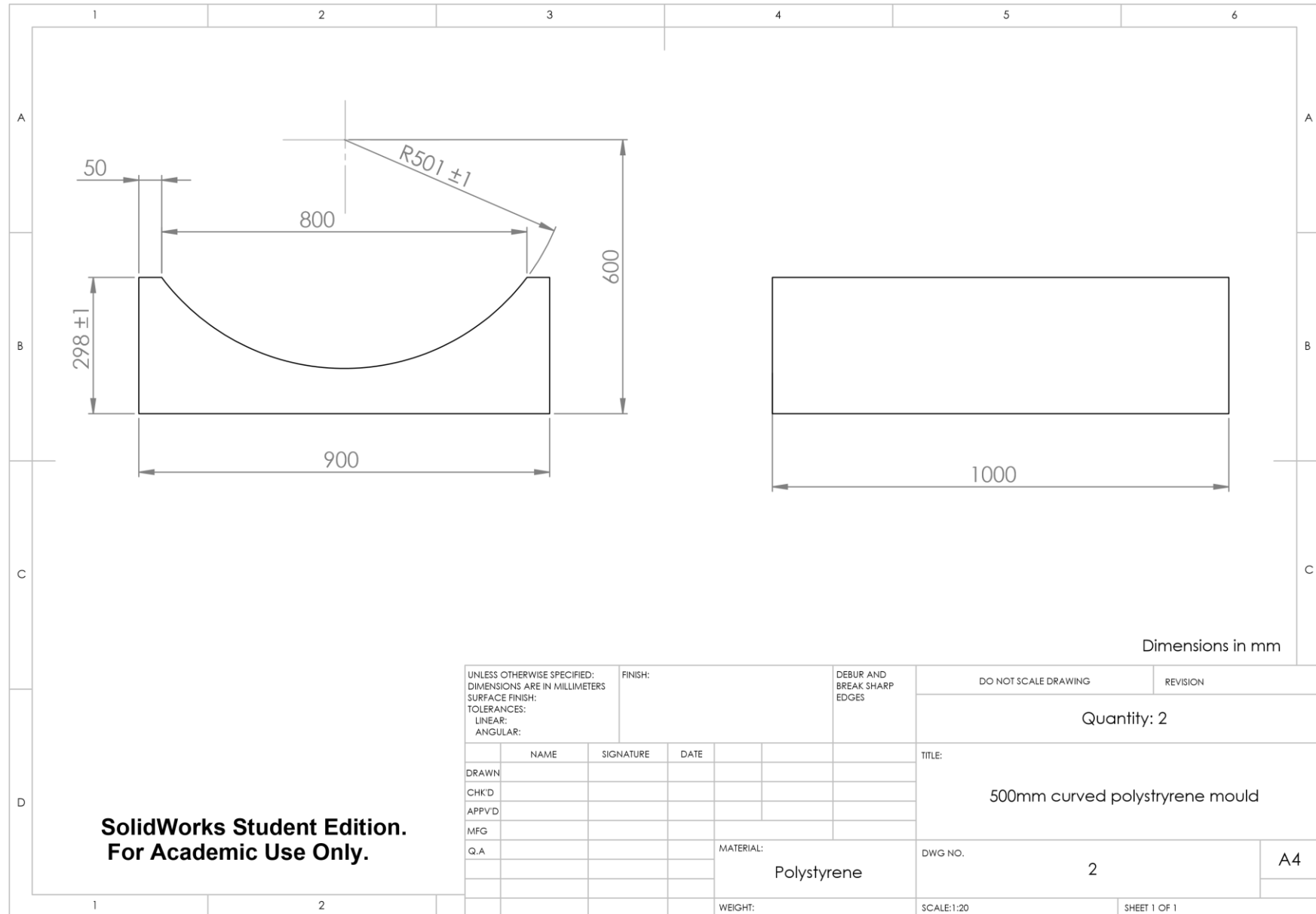
Signed by:

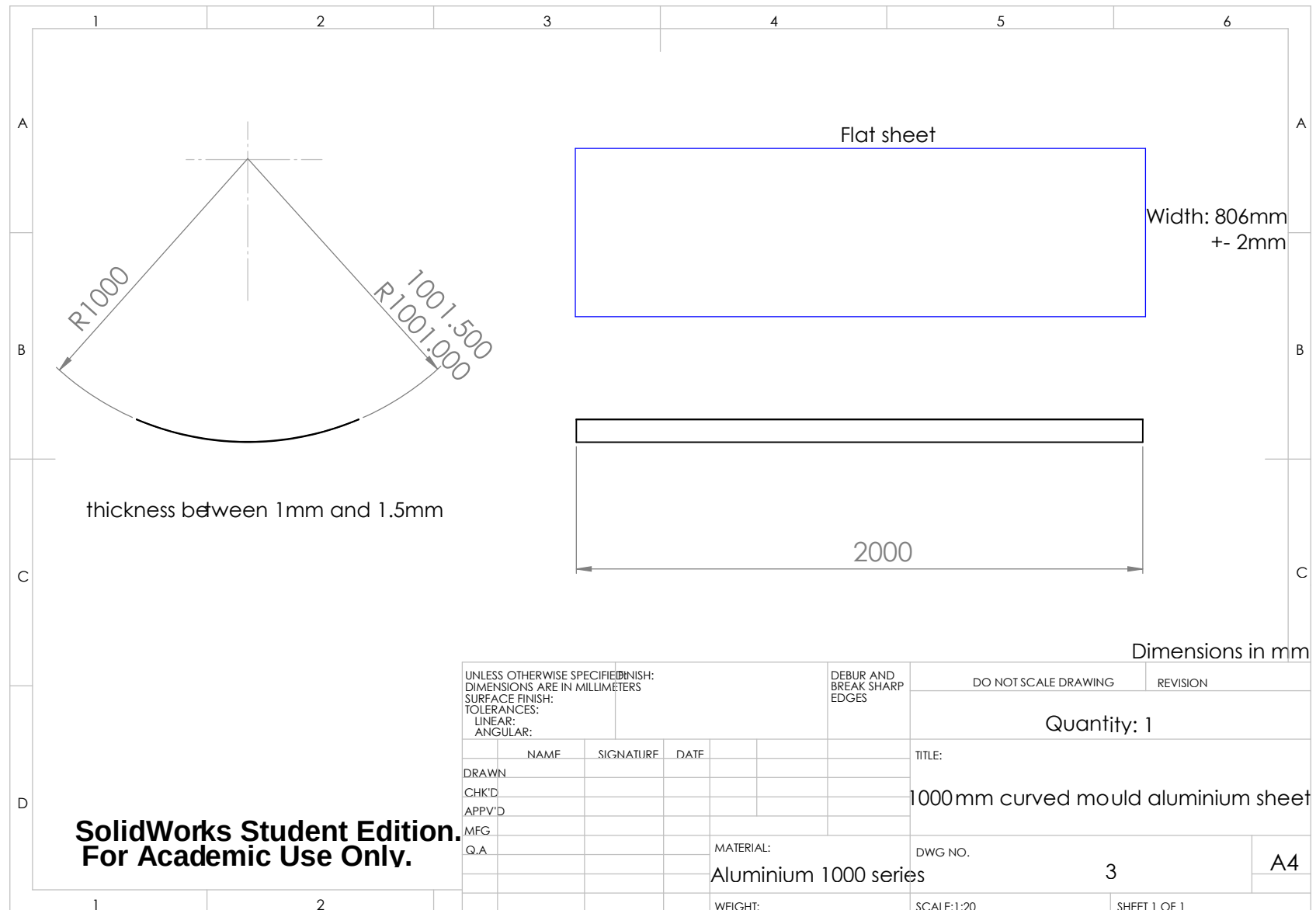
	Full name and signature	Date
Principal Researcher/Student:		<u>21/01/2013</u>

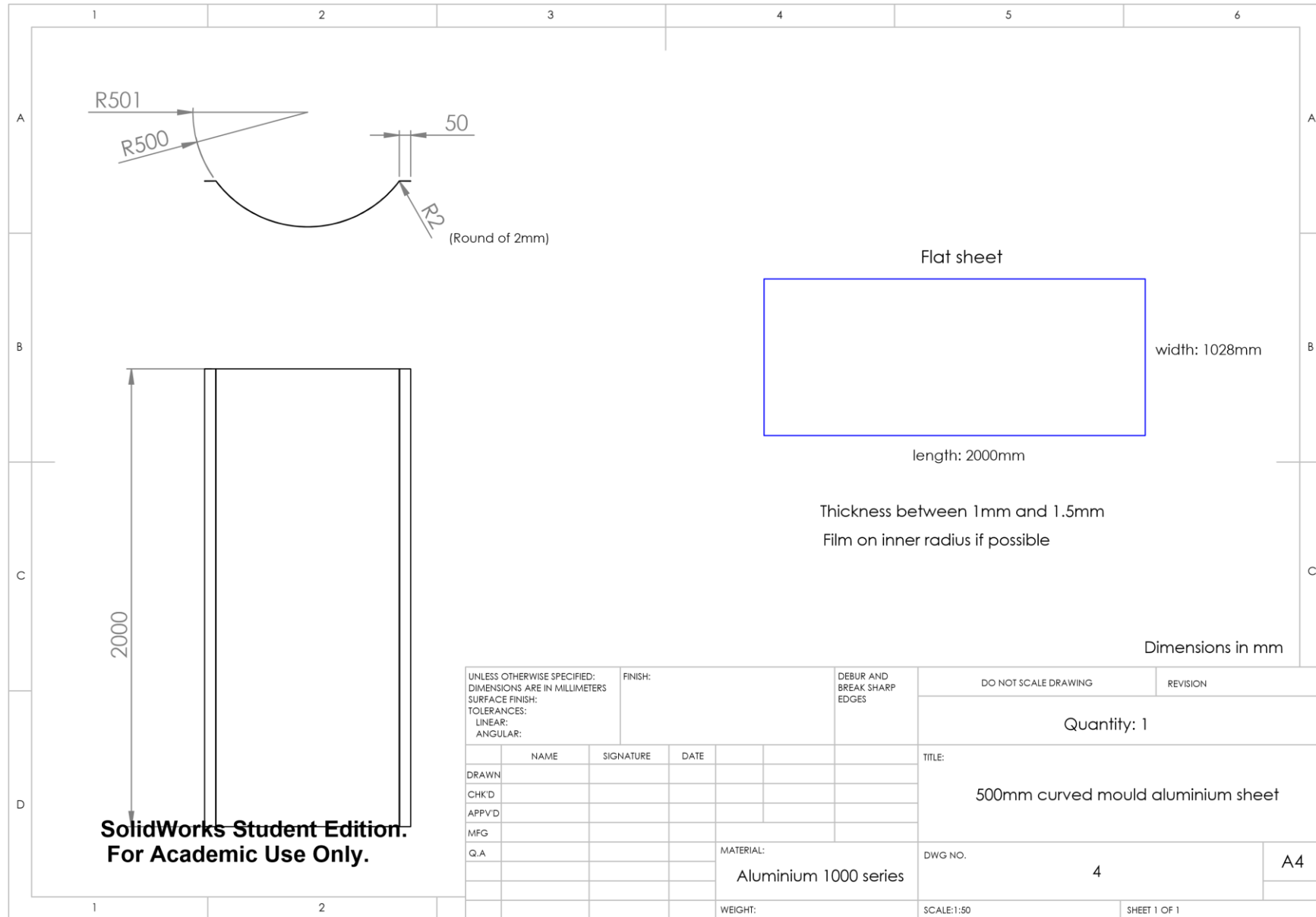
This application is approved by:

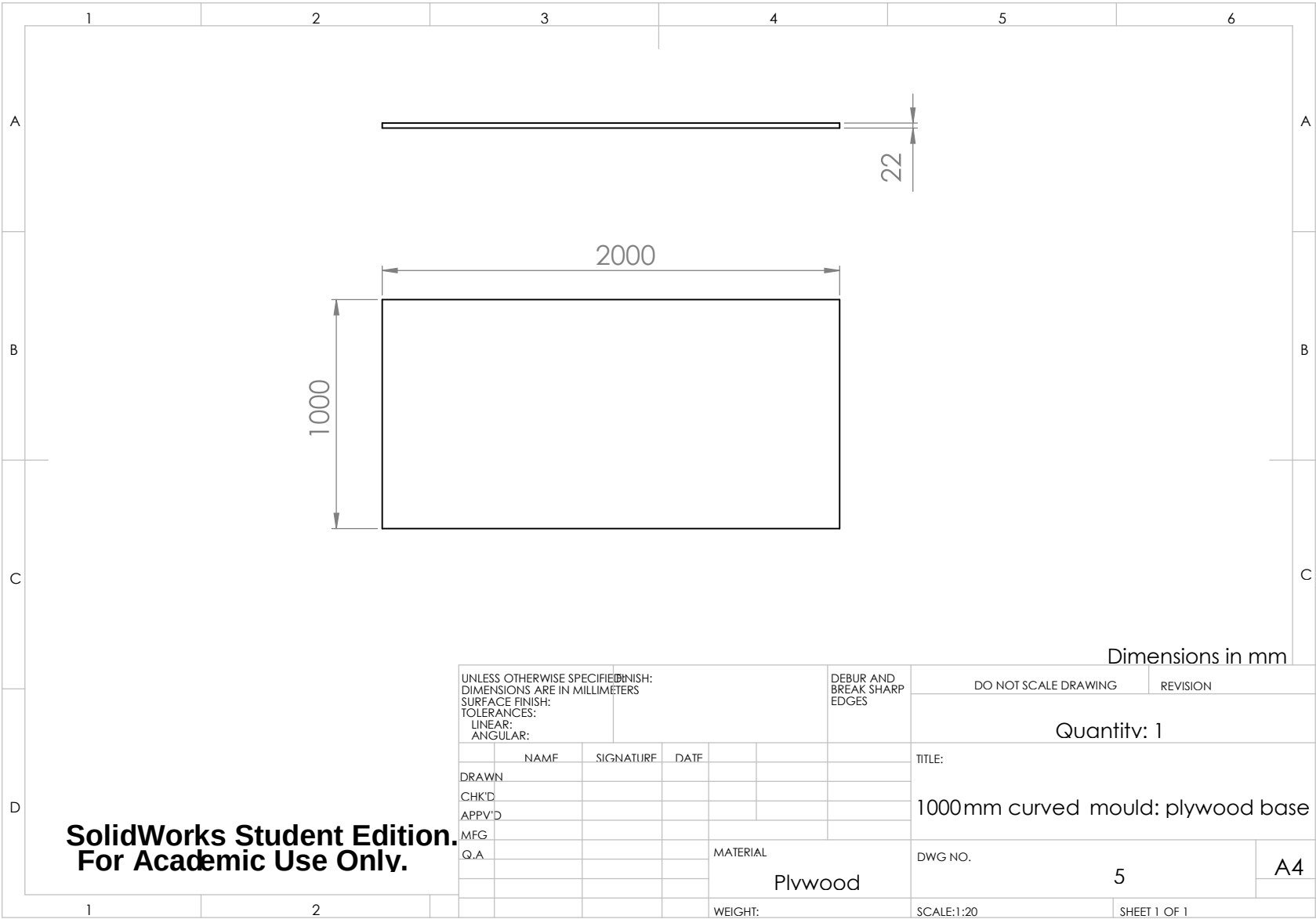
Supervisor (if applicable):	<u>Professor C Redelinghuys</u>	
HOD (or delegated nominee): <i>Final authority for all assessments with NO to all questions and for all undergraduate research.</i>	<u>Head of Department Department of Mechanical Engineering University of Cape Town</u>	<u>2013-01-13</u>
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		

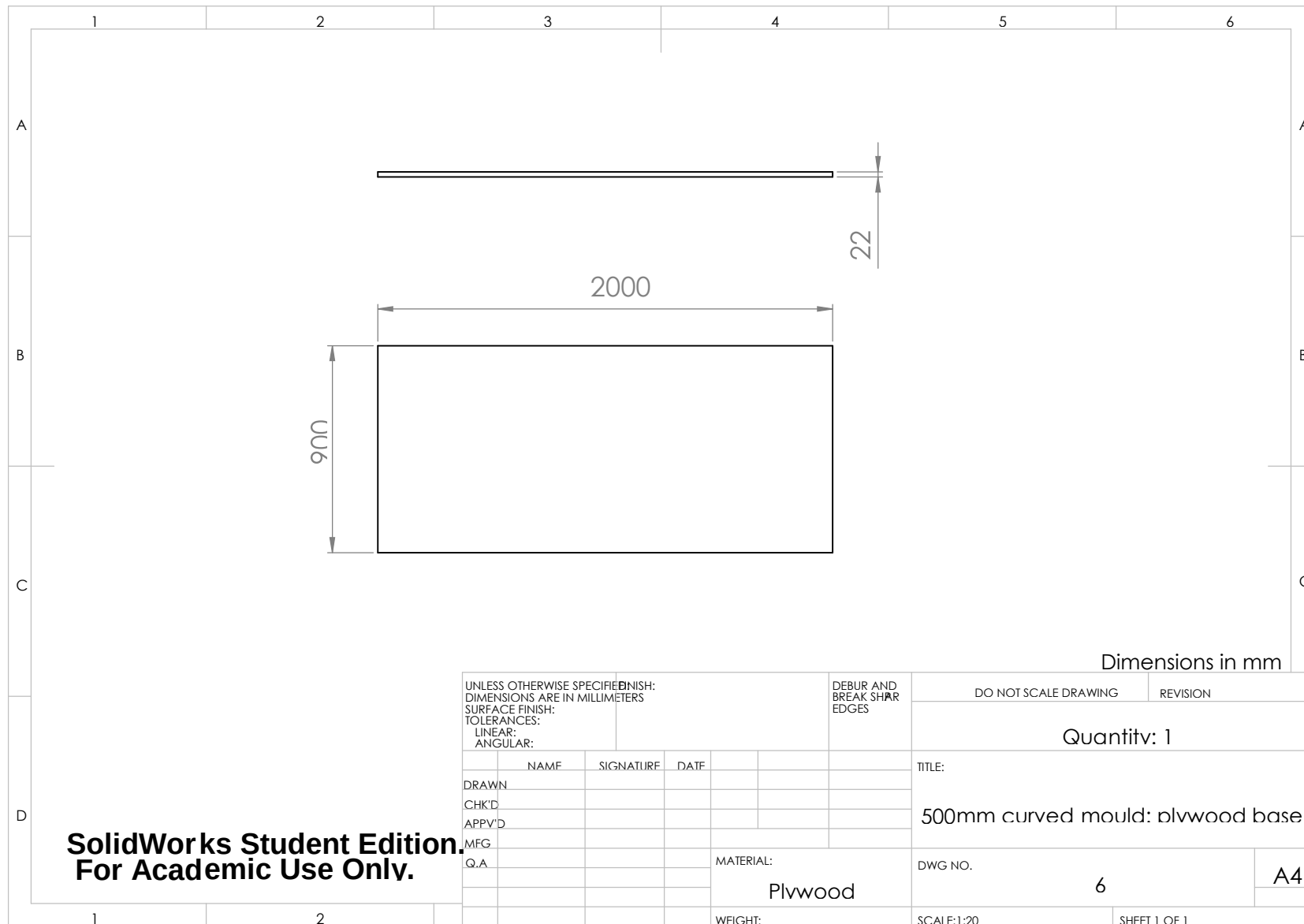


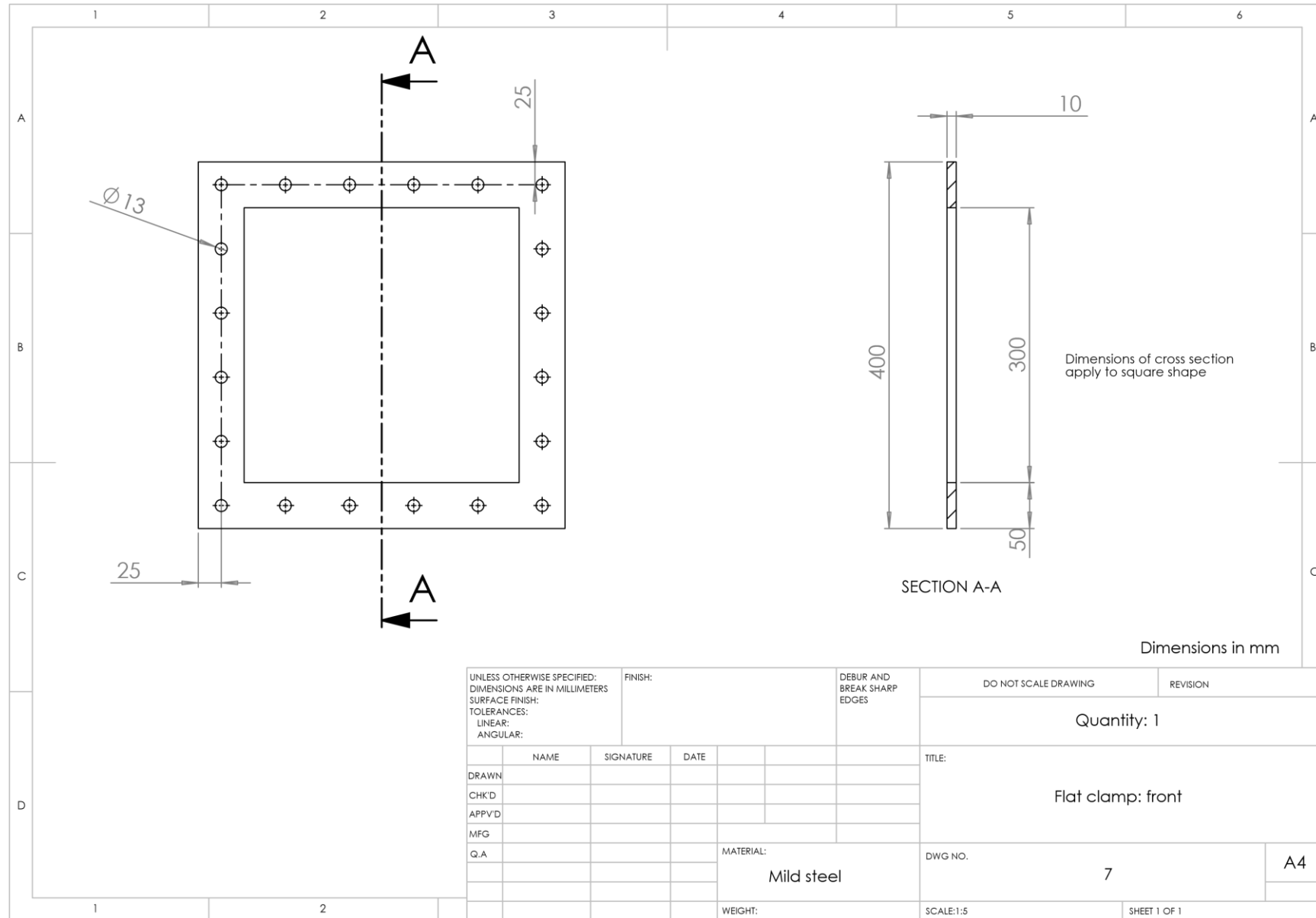


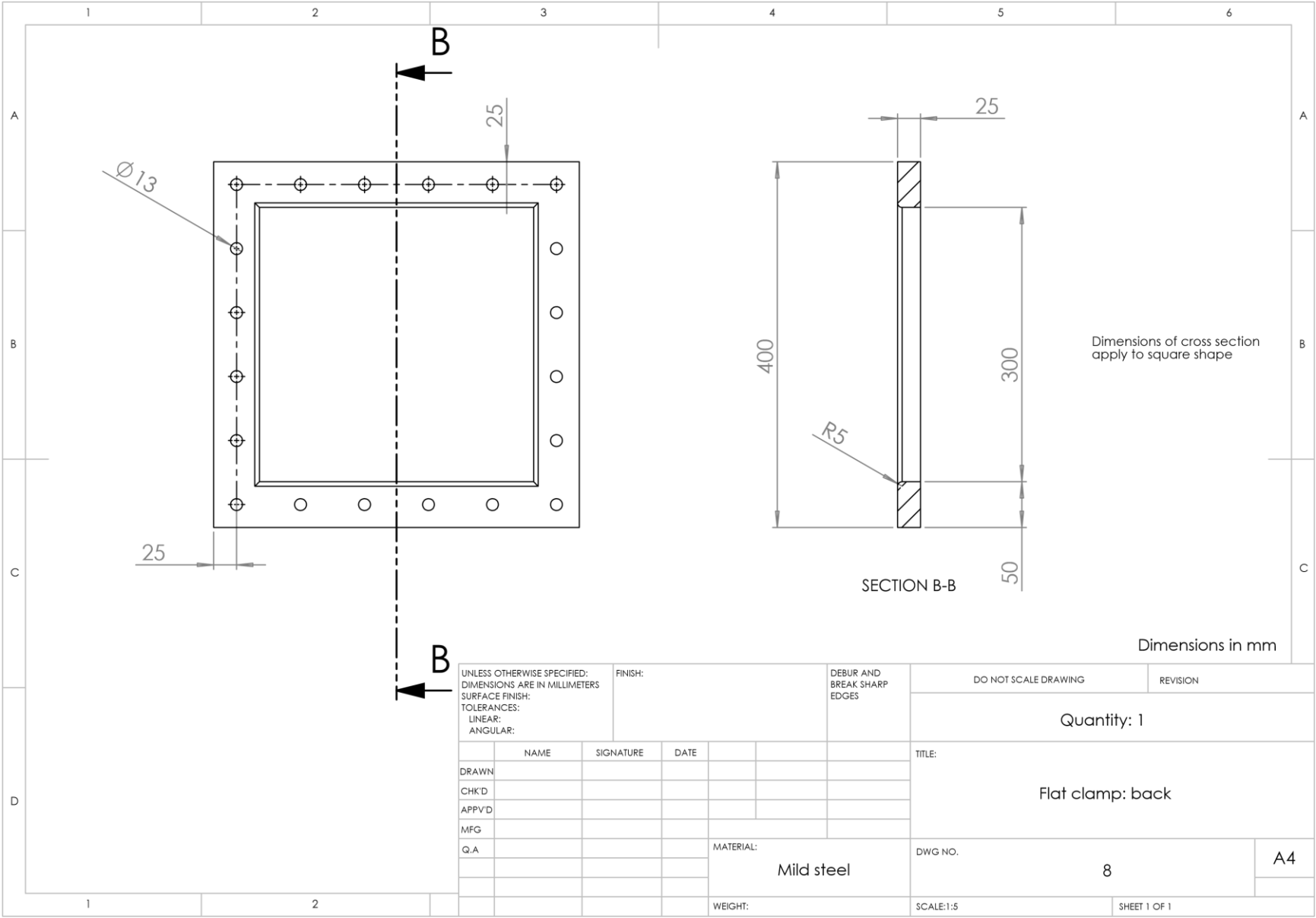


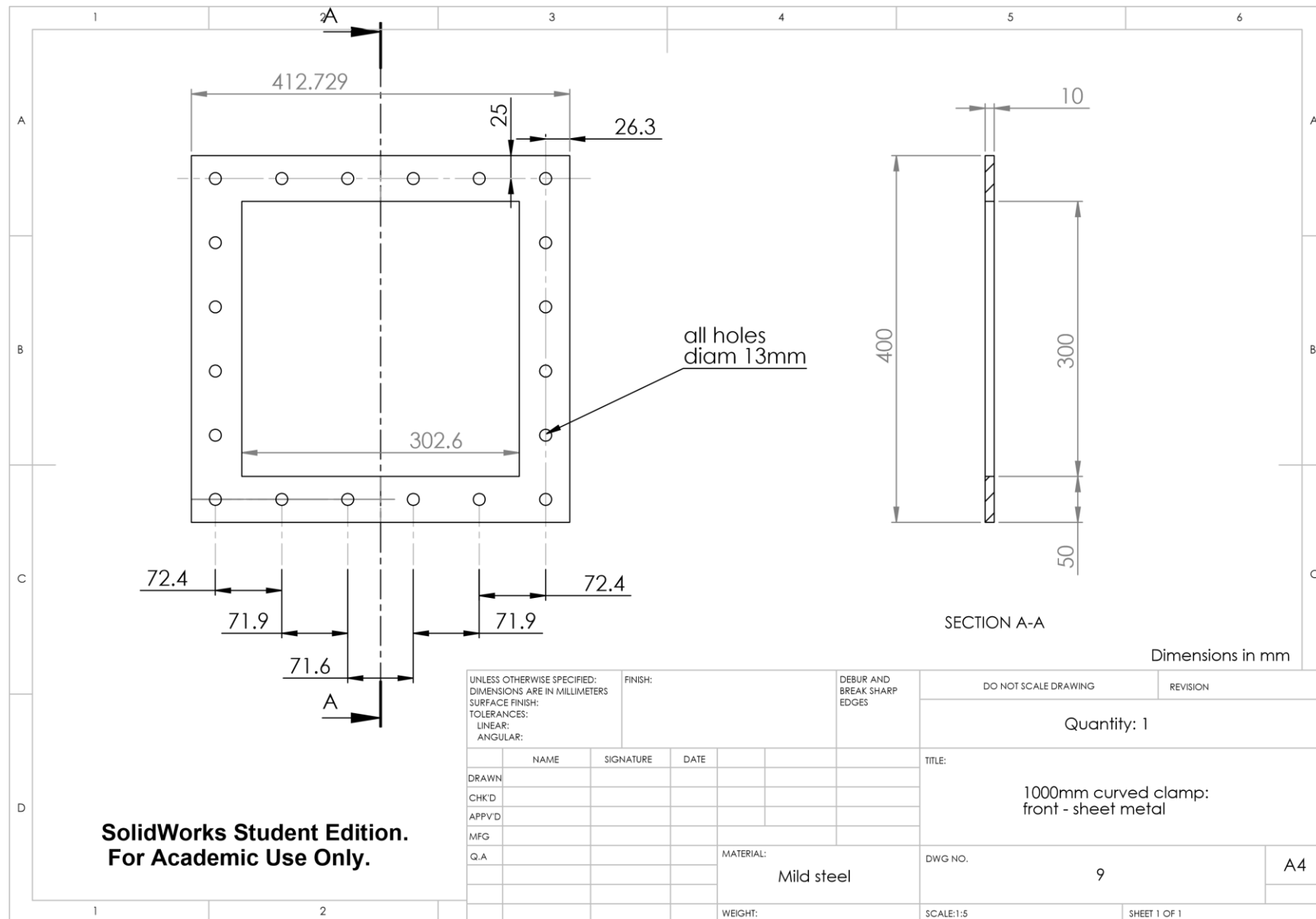


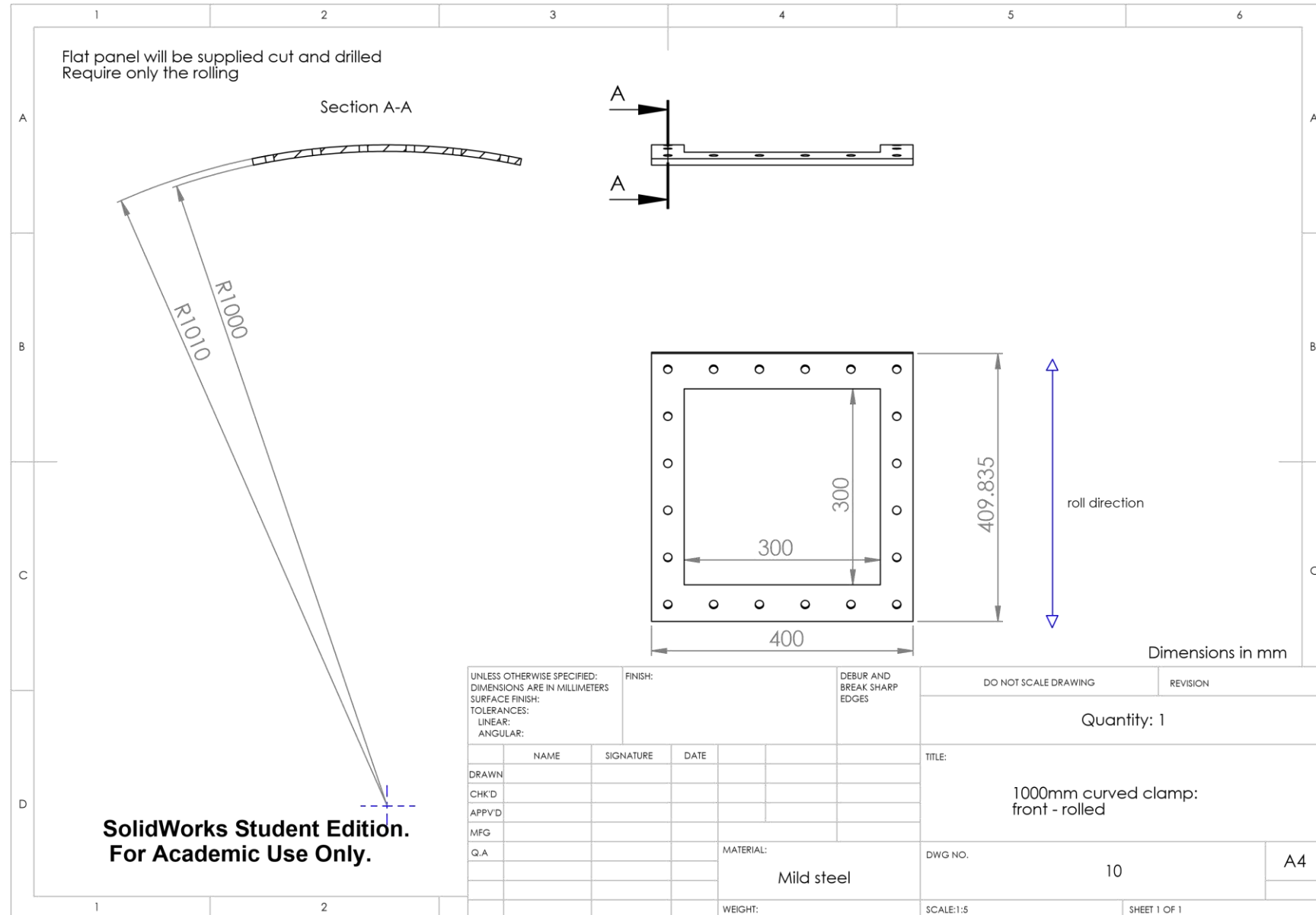


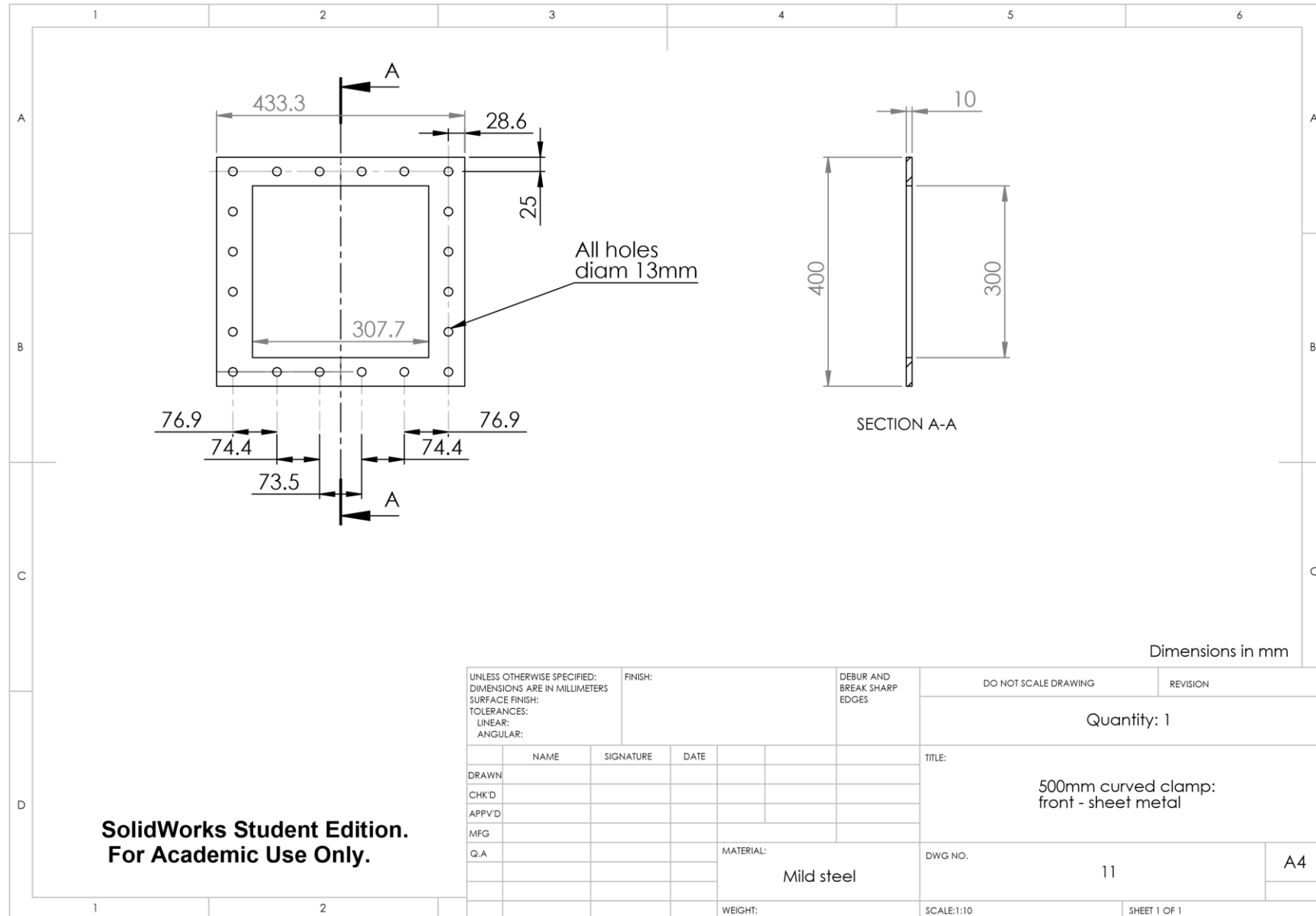


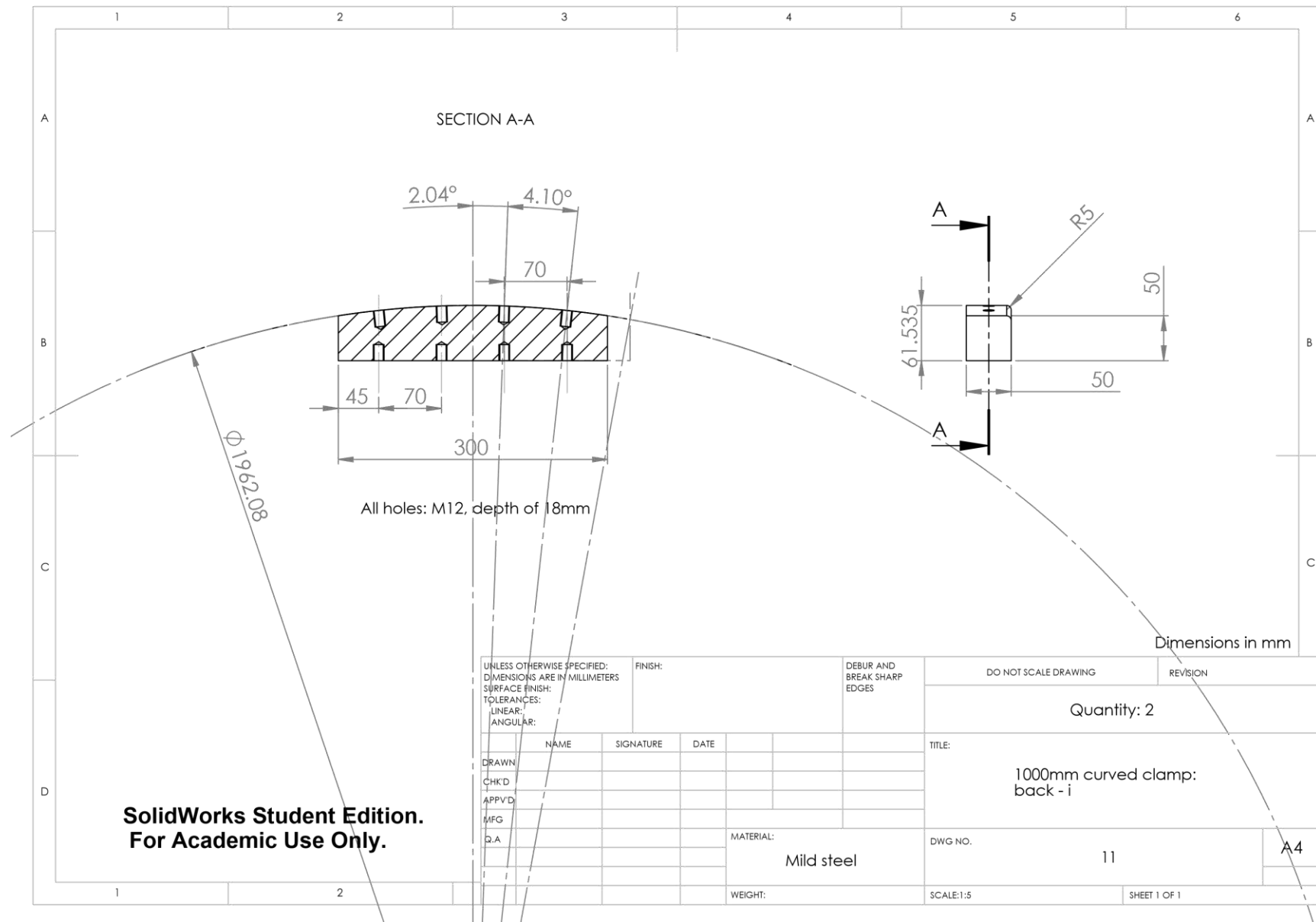


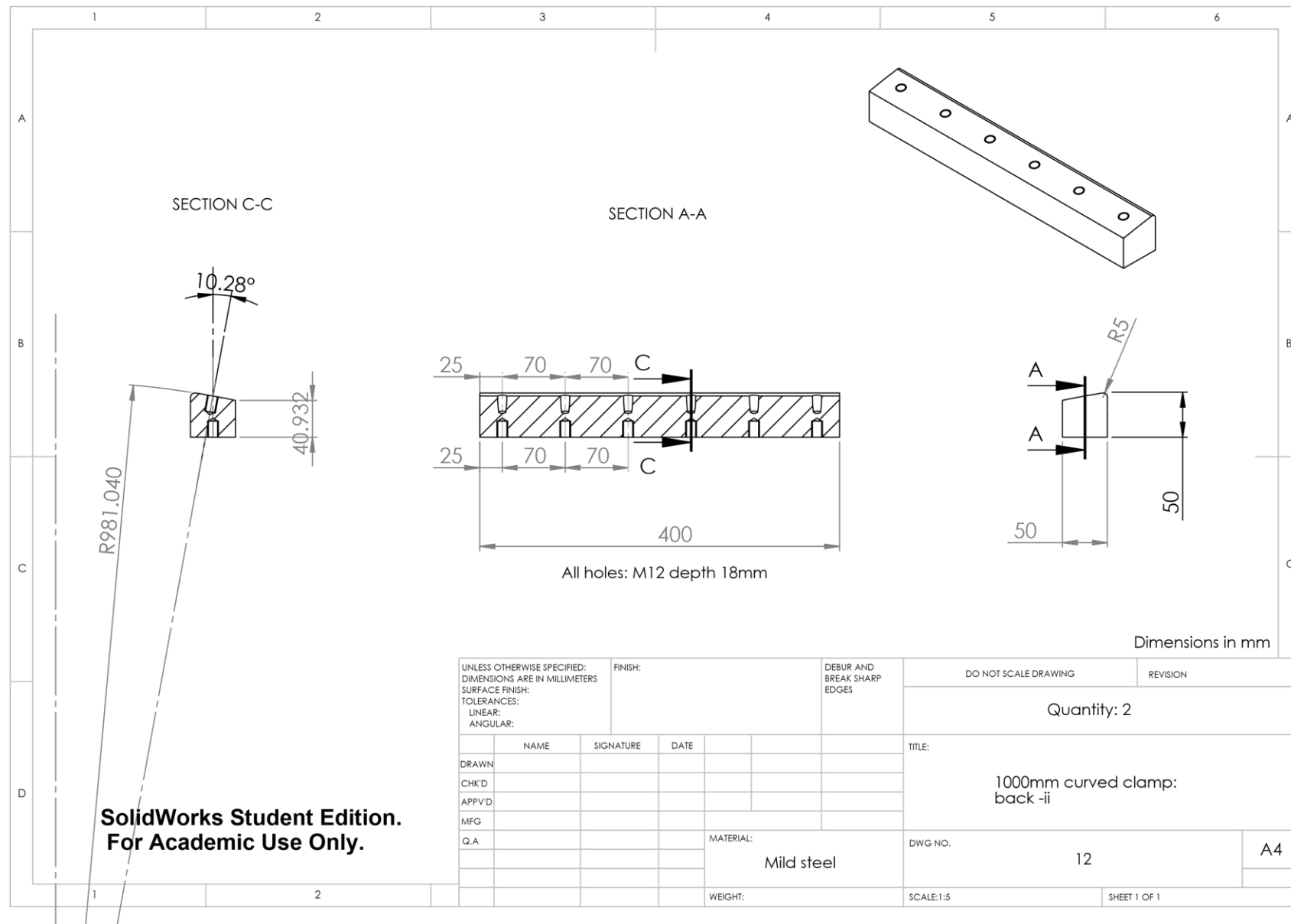


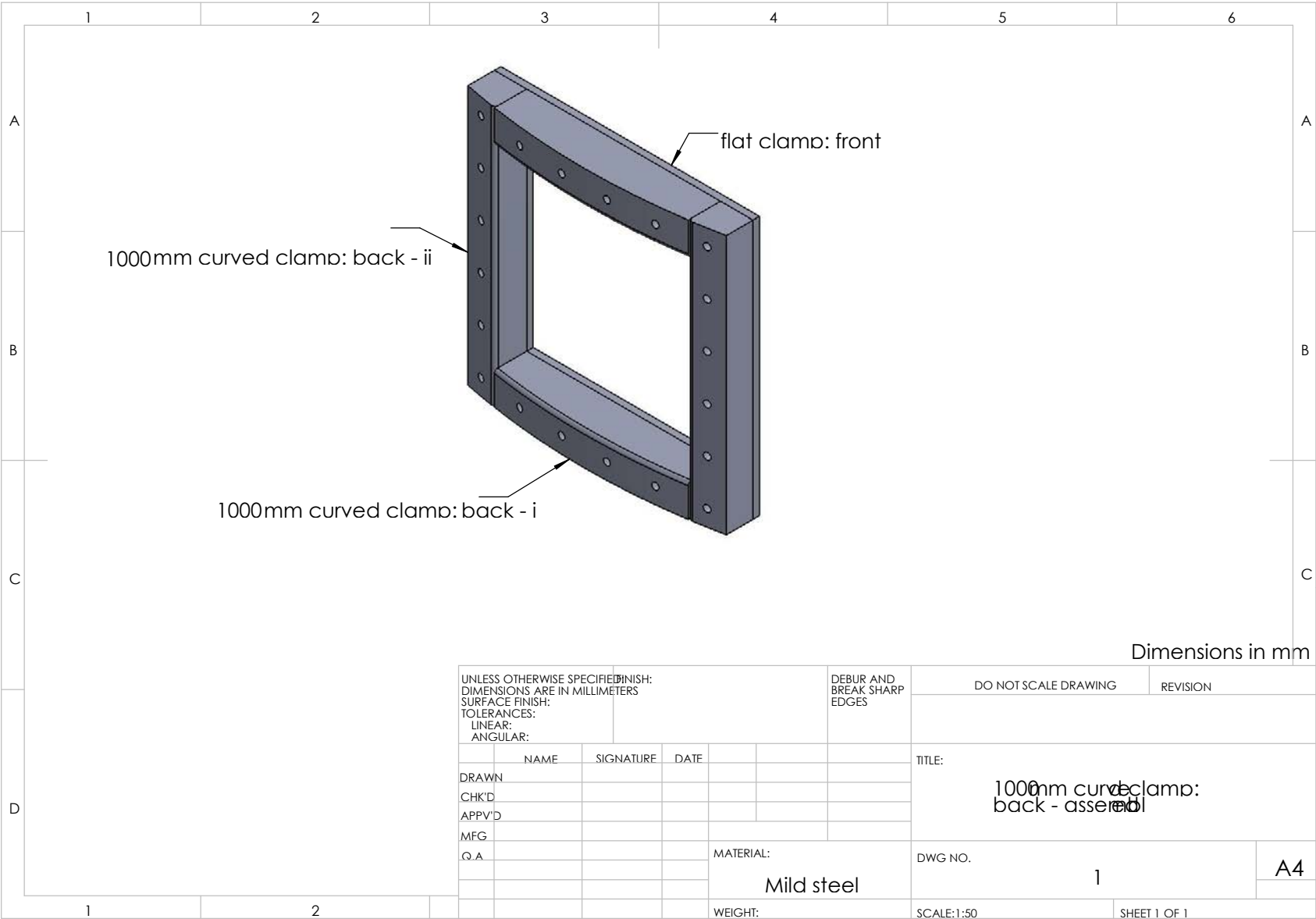


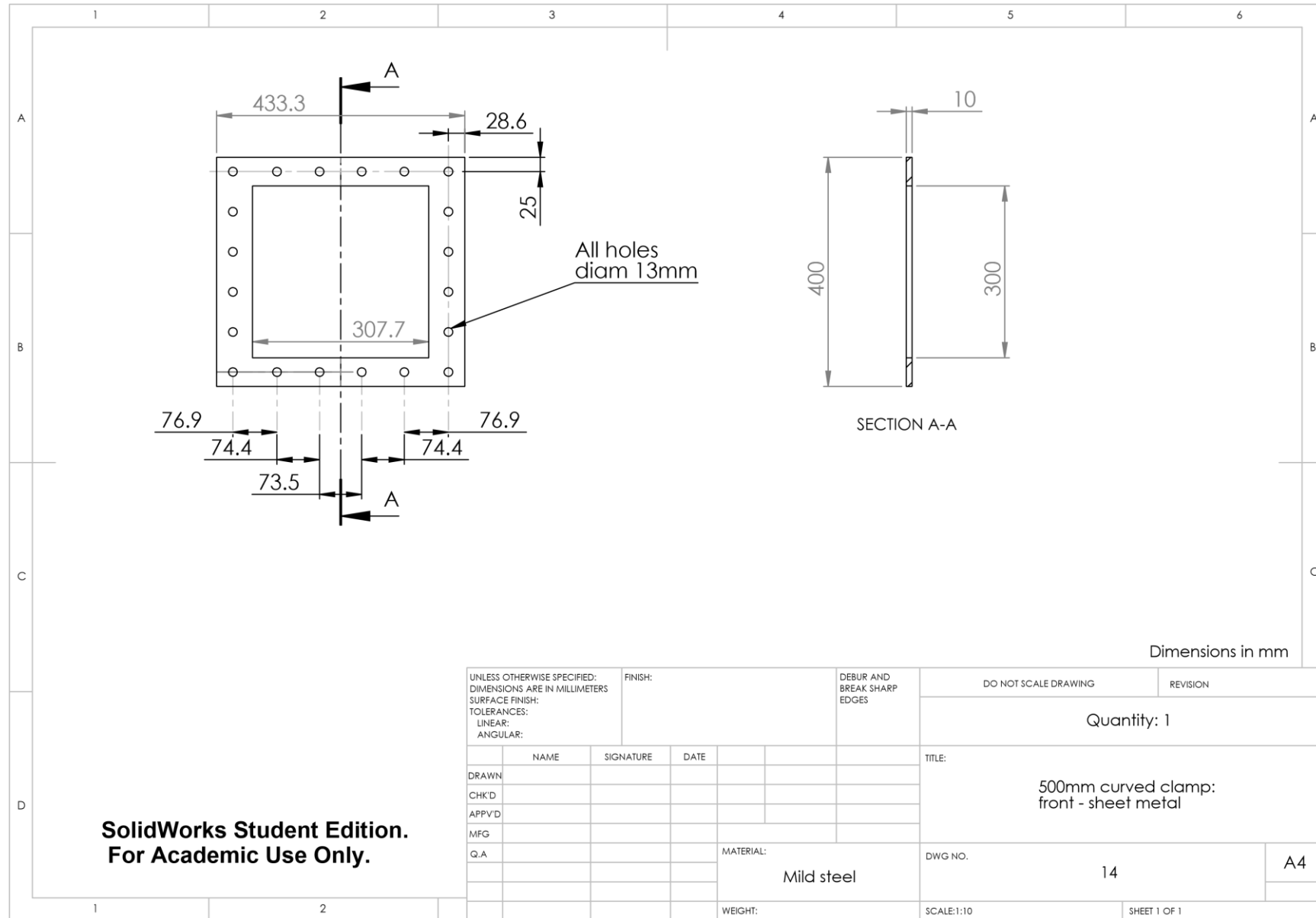


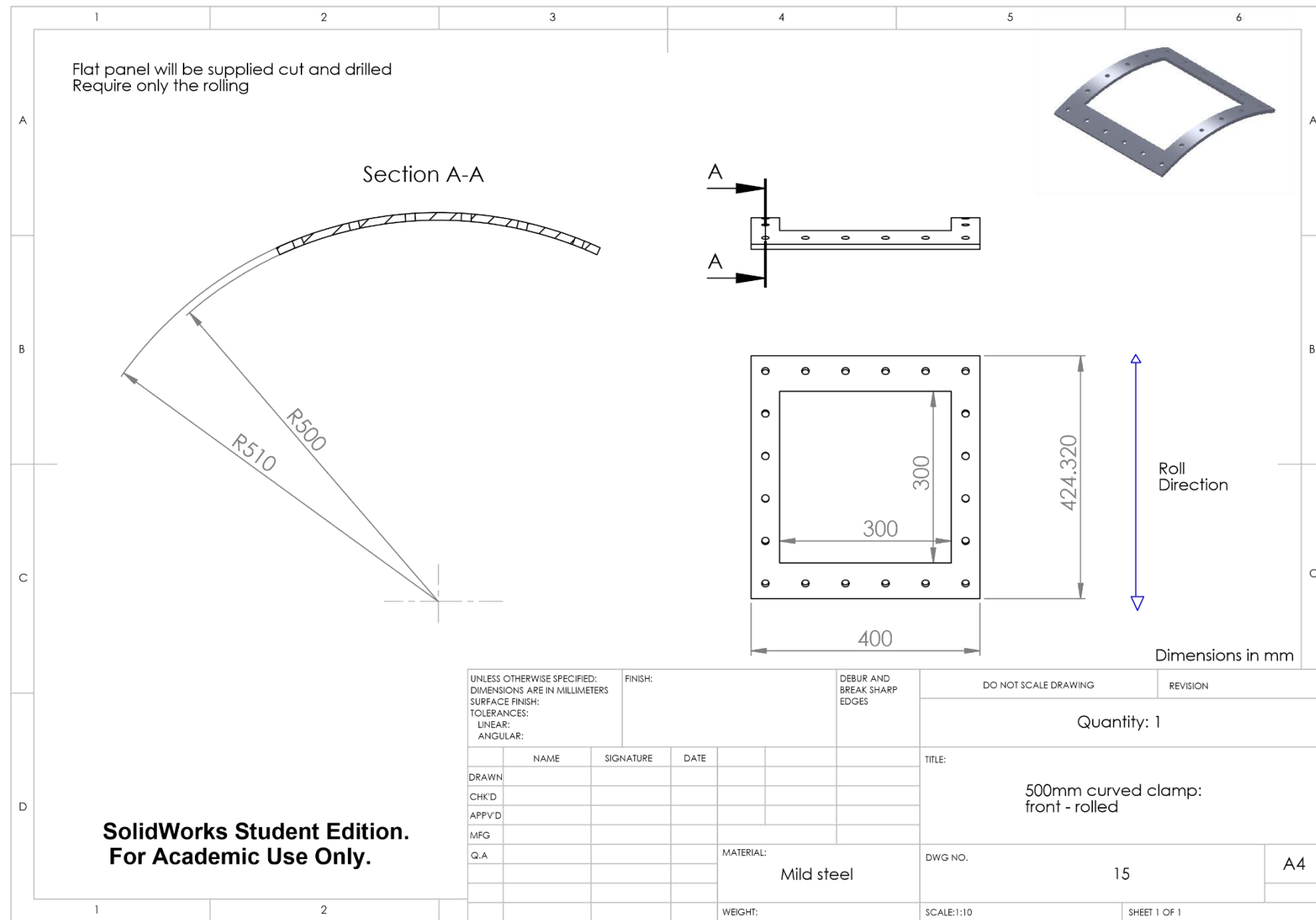


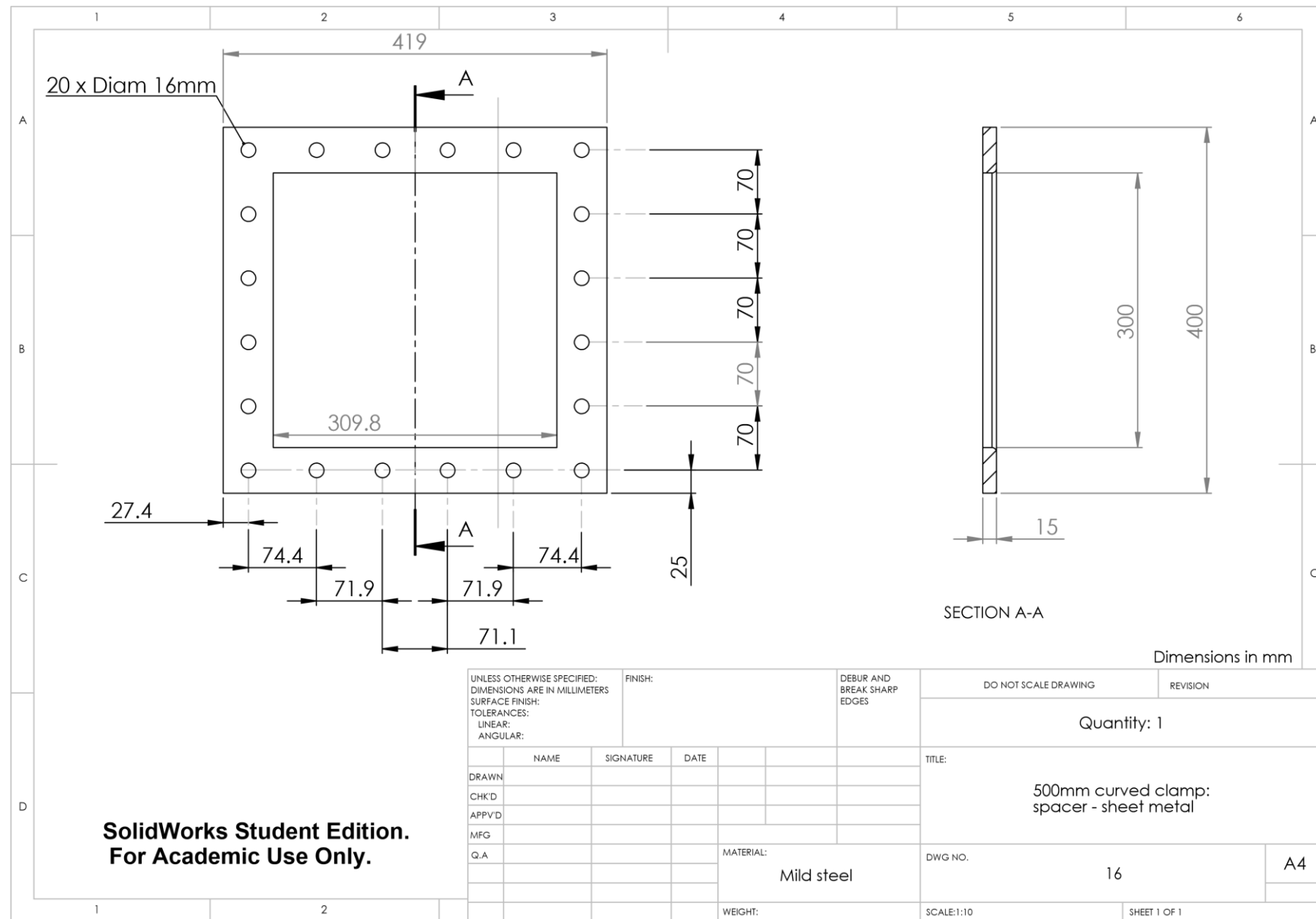


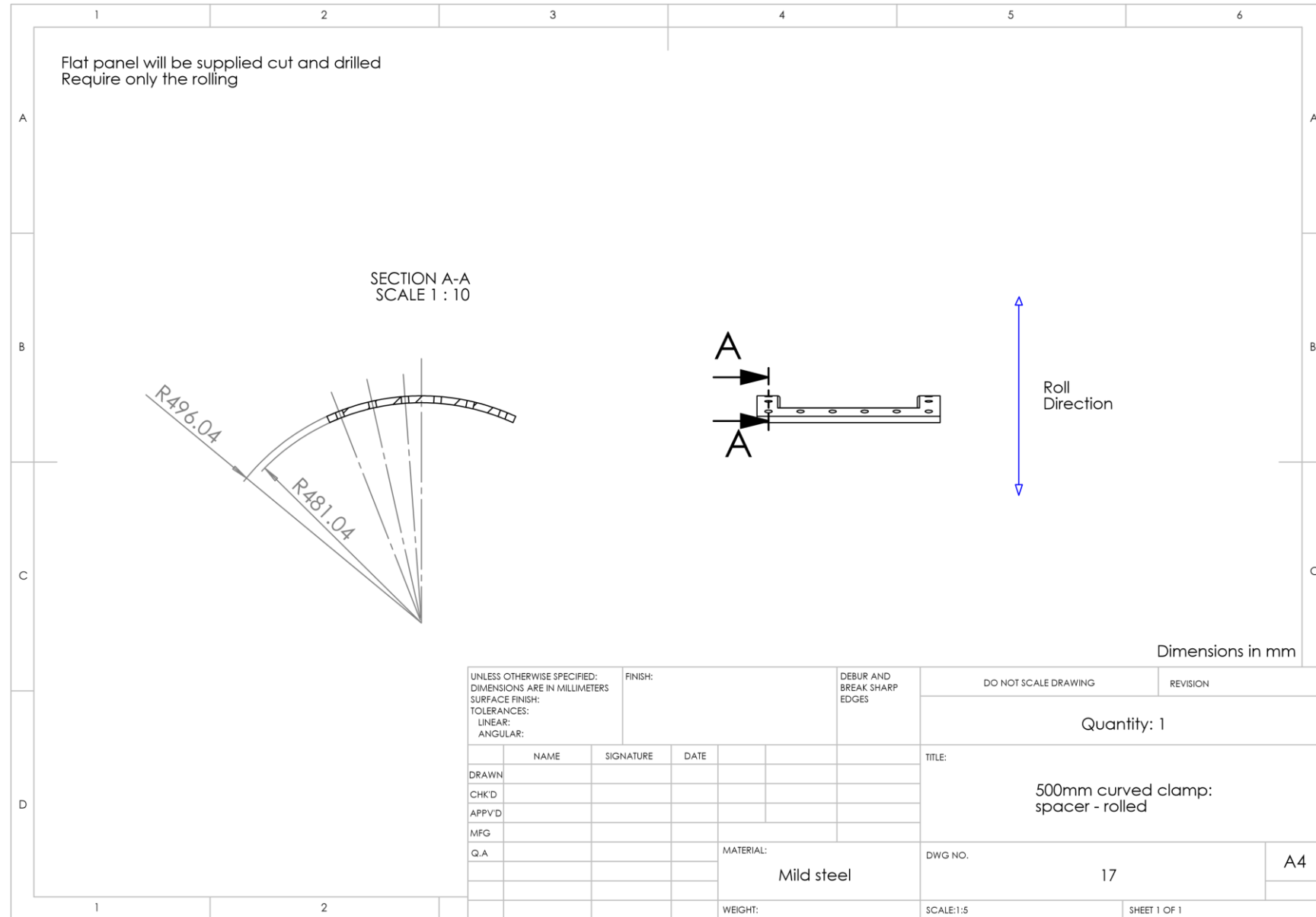


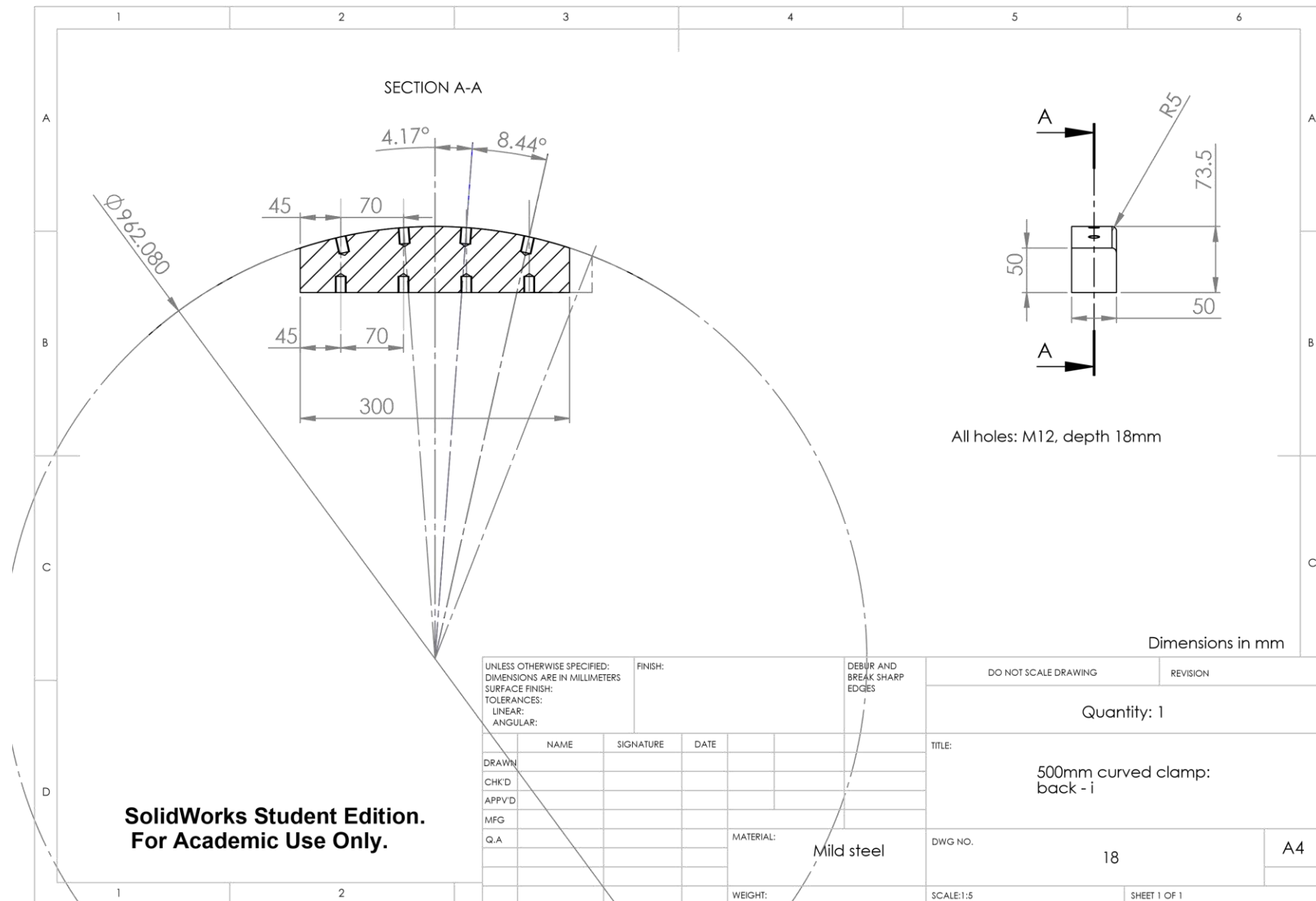


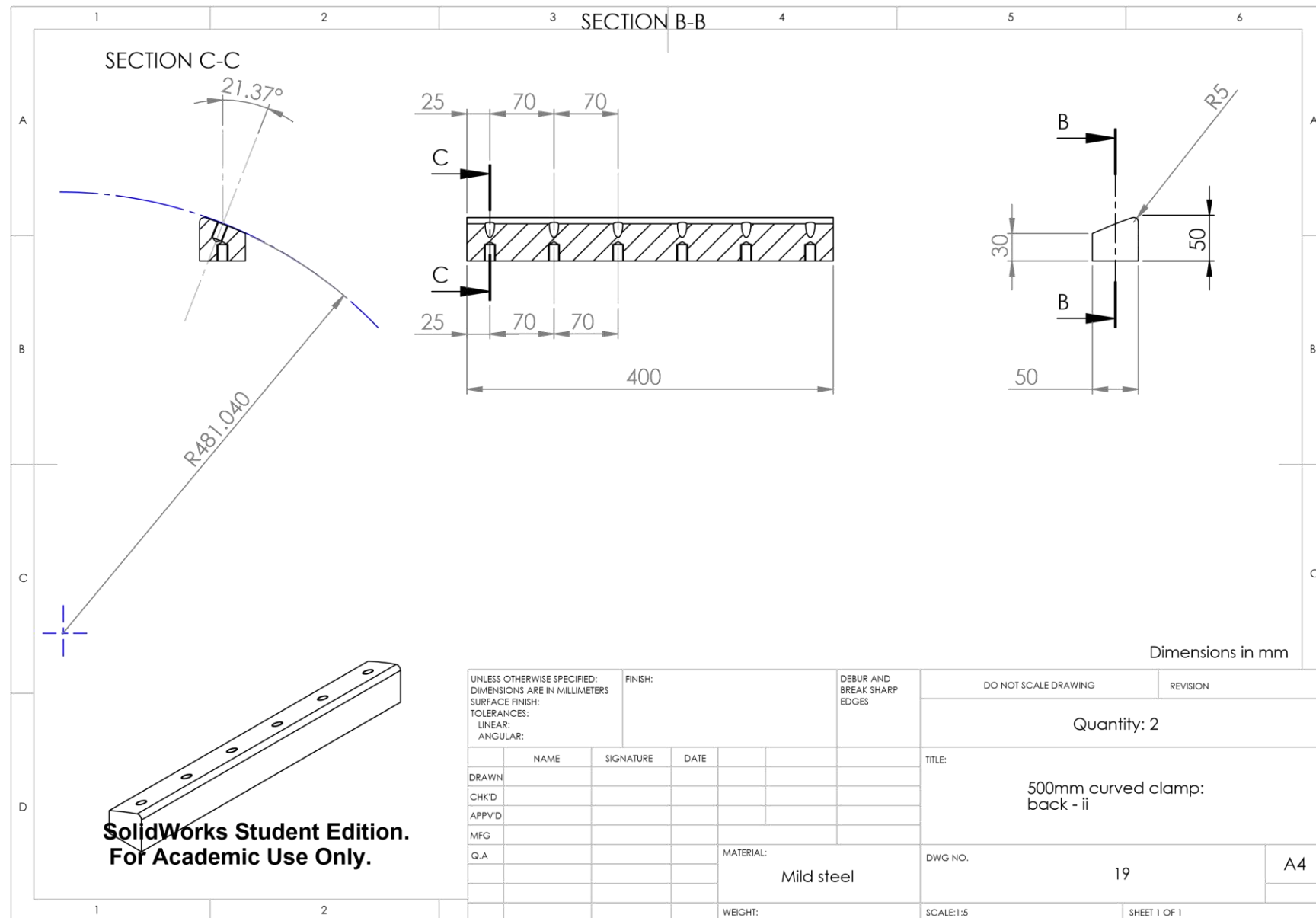


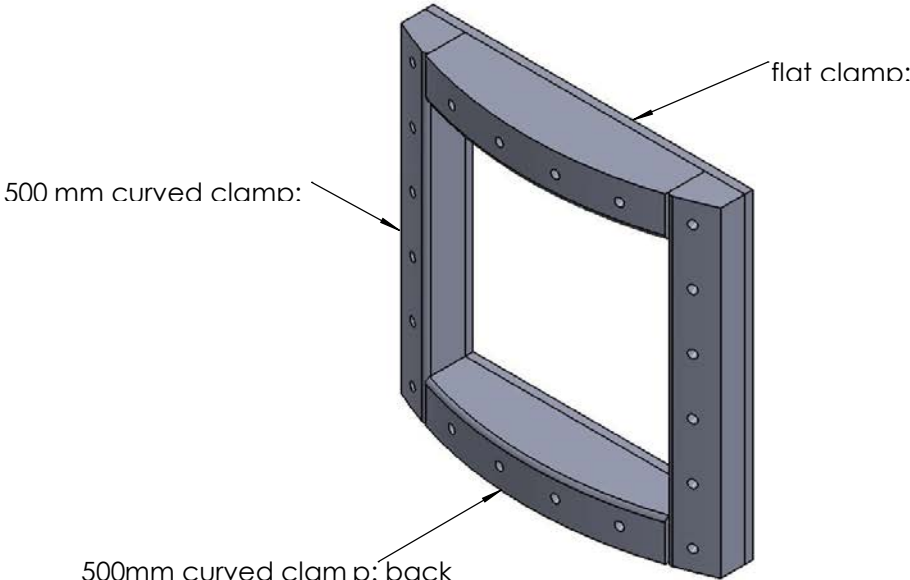










1	2	3	4	5	6
A					A
B					B
C					C
D					D
UNLESS OTHERWISE DIMENSIONS ARE IN SURFACE TOLERANCES: LINEAR: ANGULAR:		FINISH		DEBUR AND BREAK SHARP EDGES	
NAME DRAWN CHK APPV'D MFG Q.A.		SIGNATURE		DATE	
TITLE 500 mm curved clamp: back - assembled		MATERIAL: Mild		DWG NO. 2	
WEIGHT:		SCALE: 1:2		SHEET 1 OF	
1	2				