University of Southern Queensland
Faculty of Engineering and Surveying

The Behavior of Hybrid Fiber Composite Beams

A dissertation submitted by

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ABSTRACT

Many road and rail structures that are currently in use throughout Australia are constructed out of timber. Due to the limited life of timber that is exposed to the elements, many of these structures are approaching the end of their design life and a suitable replacement for the timber members in these structures is needed. Due to the limitations of hardwood timber that is available an alternative solution needs to be developed.

The Fibre Composite Design and Development (FCDD) facility at the University of Southern Queensland (USQ) has developed one such alternative that involves the uses of sustainable Laminated Veneer Lumber (LVL), composites and steel reinforcing. This dissertation looks at these hybrid beams developed by the FCDD and aims to predict the behaviors associated with these beams.

Materials' testing was first conducted on the materials used in the hybrid beams to determine the individual material properties. Then Finite Element (FE) analysis software was used to model these hybrid beams to make predictions about their behavior. To access the accuracy of this form of behavior prediction a 4-meter test beam was made and tested so that the results could be compared to those in the predictions and the process of construction is described.

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Scott McDonald

Q11219460

Signature

Date

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Fibre composites are materials that are made by combining a fibre with a resin to produce a material that has considerably high strength with very lightweight. The aim of this project is to examine the behaviour of hybrid fibre composite beams. These hybrid beams adopt a combination of timber, composites, polymer concrete and reinforcing steel and have been developed by the Fibre Composite Design and Development (FCDD) facility at the University of Southern Queensland (USQ). They were developed as a means of providing a suitable and sustainable replacement material for the hardwood that is currently used in various structures throughout Australia. The purpose of these beams is to provide a material that will meet or exceed the properties of the hardwood that they are to replace while still maintaining the size restraints and comply with the heritage listing issues associated with these structures.

Originally the FCDD was approached by the Roads and Traffic Authority (RTA) of New South Wales (NSW) to develop a beam that could be used to replace the timber bridge beams that are found in several of their structures. The solution that was developed was based on a Laminated Veneer Lumber (LVL) beam with reinforcing provided by glass fibre reinforced polymer (GFRP) pultrusions and reinforcing steel. As early prototypes were developed changes were made to the design however the concept remained essentially the same and this project investigates methods of predicting the behaviour of these beams.

1.2 Overview of the Project

The main objectives of this project are to;

- undertake a literature review the previous research into the reinforcement of timber using composites,
- obtain design properties for the materials that are used in hybrid fibre composite beams through destructive materials testing,
- predict the behaviour of a hybrid test beam using finite element analysis, and
- construct and test a full scale beam to determine the accuracy of the predictions made through computer modelling.

This project aims only to investigate the behaviour of a hybrid beam under short-term loading and does not intend to investigate the effects of long-term loading or the durability of these beams. These are both areas into which further research may be undertaken.

1.3 Dissertation Overview

This dissertation covers all of the aims of the project and describes the work that was undertaken and the results and conclusions that were obtained. A literature review was conducted to determine what research had been done on the reinforcing of timber beams both by the FCDD and by other researchers. Materials' testing that was conducted on both the LVL and composite used in hybrid beams is described along with the results obtained from these tests. The process of computer modelling is also examined and the predictions about beam behaviour that came from these models also detailed. Test beam construction and the methods of construction are also described along with the testing of the completed test beam and associated results. Finally conclusions are drawn from the research that has been done and areas where further research may be undertaken are highlighted.

CHAPTER 2

PREVIOUS RESEARCH

2.1 Introduction

Previous research has been done on determining what effects reinforcing timber with different types of composites, and other materials, in different configurations both by the FCDD and by other research organizations. The following are brief summaries of some of the research that has been previously undertaken on this topic that is relevant to the scope of this project.

2.2 Alternative Hardwood Girders – An Innovation with Composites

This paper was written by the FCDD and looks at the development of a beam that can be used to substitute and replace the hardwood that is currently used in many different structures throughout Australia. It looks primarily at the development of a beam to be used as a replacement for the hardwood beams used in many road and rail bridges. The issues of heritage listing, sustainability, changes to loading codes and the development of an alternative ‘hybrid’ beam are all examined.

It was found that many of these timber structures are heritage listed and as a result of this, the options that were available for the refurbishment of the structures was limited. This heritage listing means that the appearance and materials within the structure need to be maintained close to the original condition.

There is also the issue of sustainability to consider. Environmental regulations have placed a limit on the availability of replacement materials. Typically old growth hardwood was used in these structures, with relatively large sections common, however as hardwood reserves are slowly dwindling and public pressure to preserve remaining reserves it is becoming increasingly difficult to find replacements of sufficient size and equal strength properties. As a result, authorities such as the Roads and Traffic Authority of NSW (RTA) and the Department of Main Roads Queensland (DMR) are looking for alternatives to use in their timber structures.

Changes to the codes that are used for the design of bridges was also an issue that was investigated. A new draft code was being developed to replace the Australian Bridge Design code of 1996 with revision to the loads that these structures are designed for. However neither of these two documents looks specifically at the design or evaluation of timber structures thus there is no standard approach to the design of these structures and each authority reverts to their own standard based on various standards. This lack of agreement on the required properties of a hardwood girder adds to the problem of developing an alternative.

As a result of all of these considerations the FCDD developed a hardwood alternative that was based on the concept of a hybrid beam. This beam used plantation softwood in the form of a ply or LVL, for the bulk of the beam with the addition of reinforcement modules to obtain the required strength and stiffness properties. The benefit of using ply or LVL was that the variability found in the timber was decreased and the properties of the material were more predictable. Reinforcing modules were used to give the beams more strength and better flexibility properties and bring these properties closer to those found in the hardwood that they are replacing. These reinforcing modules are a combination of steel reinforcing, polymer concrete and glass fibre reinforcing generally in the shape of a square hollow section in which the steel and polymer concrete are contained.

Test beams were developed and tested with results indicating that these hybrid beams were able to obtain strength and stiffness equivalent to or greater than hardwood, with a 3m-test beam achieving better properties than a characteristic F34 beam and a 6m-test beam achieving properties equivalent to a F27 characteristic beam. There was also evidence of a ductile failure mode with the 3m-test beam. As a result of the success of the test beams further beams were developed with a 7m span and an 18m span for use within the Rail Infrastructure Corporation of NSW (RIC). The beam for this project is based on a further development of this hybrid girder concept.

2.3 Hardwood Bridge Girders – A Standard Alternative

This paper also by the FCDD covers many of the same areas as the previous Alternative Hardwood Girders – An Innovation with Composites and further covers the issue of a lack of a standard to which these types of beams should meet.

One of the main issues investigated is that the new Australian Standard AS5100 Bridge Design does not specifically apply to timber bridges. It does cover the use of concrete and steel but not the incorporation of these materials into timber structures. The uses of timber, fibre composites or combinations of materials are also not covered in AS5100. The two main issues that are raised with regard to hardwood alternatives are 1) the compatibility of these alternatives with structural behaviour and 2) the compatibility of installation with in current bridges.

The issue of setting some targets for the structural requirements of alternative materials is also investigated and takes into account the lower variability of these engineered beams in respect to the hardwood beams currently used. For example AS1720 the timber standards state that to be given a certain strength 95% of specimens must be over that strength so as a result of the lower variation in strength of hybrid beams the average strength of a hybrid beam would be significantly lower than the average strength value of a hardwood beam of the same characteristic strength grade. The ductile failure mode experienced in hybrid alternative beams is also considered.

As a result of all of these issues three alternatives for classifications of alternative hardwood girders were proposed;

1) specification consistent with AS1720,
2) specification with regard to the average strength of old growth hardwood,
3) special specification where the specification is based on specific strength and stiffness requirements.

2.4 Flexural and Shear Strengthening of Timber Beams Using Fibre Reinforced Polymer Bars – An Experimental Investigation

Svecova and Eden (2004) experimented with glass fibre reinforced polymer (GFRP) dowels in various configurations for both shear and flexural reinforcement similar to the steel reinforcement that is found in concrete beams. Their aim was to investigate the effect that this type or reinforcement would have on the strength of 300mm x 100mm x 2000mm Douglas Fir timber beams.

They divided their test beams into two groups with half containing shear dowels only and the rest containing both shear dowels and flexural reinforcement. The shear dowel only group consisted of beams with; steel dowels only in the shear zones at the end of the beam at 150mm cts, GFRP dowels in the shear zones at 150mm cts, GFRP dowels for the entire length at 150mm cts and GFRP dowels for the entire length at 300mm cts. These shear dowels, 225mm long with a 16mm diameter, were placed vertically in drilled holes in the centre of the cross section and held in place using an epoxy resin. The shear and flexural reinforcement group contained beams with; GFRP in the shear zones at 150mm cts with flexural reinforcement, GFRP in the shear zones at 300mm cts with flexural reinforcement, GFRP for the entire length at 150mm cts with flexural reinforcement and GFRP for the entire length at 300mm cts with flexural reinforcement. The flexural reinforcement was a 5mm diameter bar and was contained in small groves cut in the sides of the beams 275mm from the top edge and held in place using epoxy resin.

Results from these test indicated a 33% increase in the Modulus of Rapture (MOR) for the beams with shear reinforcement only and a 47-52% increase in the MOR for the beams with both shear and flexural reinforcement. They also found that the steel does not bond as well as the GFRP dowels and that a dowel spacing equal to the depth of the beam (300mm) was equally effective as the 150mm spacing. Providing shear and flexural reinforcement also produce a compressive failure of the beam with large deflections as the failure load was approached and that the variability in strength that is normally associated with timber was reduced with the addition of reinforcement.

2.5 Strengthening Timber Bridge Beams Using Carbon Fibre

Buell and Saadatmanesh (2005) investigate the effects of wrapping Douglas Fir bridge beams with carbon fibre in various ways. Their aim was to determine what effects this would have on the strength of the beams and also which method of wrapping provided the greatest increase in strength. They used timber stringers from an actual two-lane bridge in Yuma County Arizona. The bridge had an overall span of 9.1m and this resulted in the test specimens having dimensions of 203mm wide x 483mm deep x 9.1m long.

A bi-directional carbon fabric was used for the reinforcing in this project and an epoxy matrix was applied to the beam prior to wrapping the beam with a two-part epoxy applied to the fabric before and after wrapping. In addition to the fibre wraps laminates were also applied to 3 of the test specimens for additional reinforcement.

The testing of the beam was preformed using a 4 point bending test with the loading span varied according to the property being tested (shear or bending). There were 6 specimens used for the flexure tests being;

- a control beam,
- a beam wrapped in the longitudinal direction where the tension, two side faces and some of the compression face were covered,
- a beam wrapped perpendicular to the longitudinal direction with 7 pieces of fabric,
- a beam with no wrapping but two laminates on the bottom face,
- a beam with longitudinal wrapping and two laminates on the tension face, and
- a beam with longitudinal wrapping and laminates where the laminates were spaced from the bottom of the beam so as to completely utilize the strength of the fibres.

After the testing they found that there was an increase in the stiffness of the beams of between 5% and 27%, the ultimate bending strength was increased by between 40% and 53%, there was an increase in ductility of between 28% to 51% and there were no catastrophic failures of any of the wrapped beams, shear strength was increased, beams wrapped longitudinally performed better than those wrapped perpendicularly and the addition of carbon laminates to the bottom face did not significantly contribute to strength and stiffness.

There were also 4 beams used as shear testing specimens and the configuration of the reinforcement was;

- two control beams,
- a beam with longitudinal wrapping, and
- a beam wrapped perpendicular to the length of the beam.

As a result of the shear tests it was found that there was an increase in shear strength of up to 68%, wrapping beams resulted in a deflection ductility increase of between 29% and 45% and one piece of carbon wrapping appeared to perform better than perpendicular wrapping.

2.6 The Use of FRP Composites in Enhancing the Structural Behaviour of Timber Beams

In 2003 Gilfillan, Gilbert and Patrick also conducted research into the effects that reinforcing laminated Sitka Spruce beams with fibre-reinforced polymers would have. In this research they used glue laminated (glulam) beams made from Sitka Spruce with the standard laminate size being 70mm x 30mm and test beams with spans of 2,3,4 and 6m with 4,5,10 and 10 laminates per beam respectively. Two beams made of LVL were also produced to compare the Sitka Spruce to a more uniformly behaving material and both carbon and glass FRP's were used along with reinforcing steel as the reinforcing materials.

The FRP reinforcement used came in the form of pultruded strips with the carbon strips being 1.2mm thick and the glass strips being 3.3mm thick. In total 5 different reinforcing layouts were used these being;

- no reinforcement control beams,
- strips attached to the tension face of the beam,
- strips attached to the tension and compression faces,
- strips attached to the tension and compression faces with the strips in the compression face being embedded vertically into grooves cut in the face, and
- steel tension reinforcing positioned in a groove in the bottom face of the beam.

For the beam with the steel reinforcement and the beam where the FRP strips are embedded in the compression face an epoxy resin was used to hold the reinforcing in position. Again the testing was done using 4-point bending tests with loads being applied at one-third span positions.

Several conclusions were drawn from this experiment these being.

- Beams made from Sitka Spruce are suitable for reinforcement.
- The elastic behaviour of beams with tension and both tension and compression reinforcement was predictable.
- Limited time-dependent investigations have indicated that creep deflection is reduced.
- The ultimate load of all of the reinforced beams was increased and the addition of tension reinforcement induced a ductile compressive type of failure in the beams.

CHAPTER 3

MATERIALS TESTING

3.1 Introduction

In order to create accurate computer models, destructive testing was conducted on the various materials that are used in the construction of the hybrid beam. From these tests it is possible to place values such as tensile strength and modulus of elasticity, into the computer models that were developed to accurately predict the behaviour of the hybrid beam. These tests were carried out on the GFRP from which the pultrusions are made and also on the LVL. The tests undertaken on the composites were;

- tensile strength
- compressive strength
- flexural strength
- V-notch shear
- cross tensile strength
- inter-laminar shear, and
- fibre fraction.

and the LVL tests were;

- flexural strength,
- tensile strength, and
- shear strength.

Results of all of the testing are summarized in Table 3.1 and Table 3.2 on p29 with full testing reports in Appendix B.

3.2 Composite Testing

3.2.1 Pultrusion Manufacturing Process

The glass fibre pultrusions used in this project are a commercially available material manufactured by Pacific Composites. The pultrusions come in the form of a 50 x 50 x 5 square hollow section (SHS) in 12m lengths. Most of the fibres are arranged so that they run along the length of the material however some layers consist of a mat of continuous fibre filament. These layers are provided in the material to give some circumferential reinforcement to the section. The pieces that were used for testing were cut directly from pultrusions delivered in the same batch as those used in the test beam. The test pieces were cut so that bulk of the fibres ran along the long side of the test piece and between 7 and 10 pieces were cut for each test.

3.2.2 Tensile Test

The tensile testing was conducted following ISO 527 part 4 Plastics – Determination of Tensile Properties. The aim of this test is to determine the tensile strength and also the modulus of elasticity for the material. Specimen size for this standard was 300mm x 25mm x 5mm and the test was performed on an MTS 810 machine. This is a computer-controlled machine that is capable of applying a 100kN force in either tension or compression. It also records data from the testing process electronically and can interpret this data to display various properties along with load and deflection in real time during the test.

In this test the specimen was placed in the testing machine and a tensile force was applied to the test piece at a controlled rate of 2mm/minute until a tensile failure was achieved. In total 10 pieces were tested with all specimens displaying an acceptable failure mode. Figure 3.1 below shows a tensile testing specimen after the test has been completed.

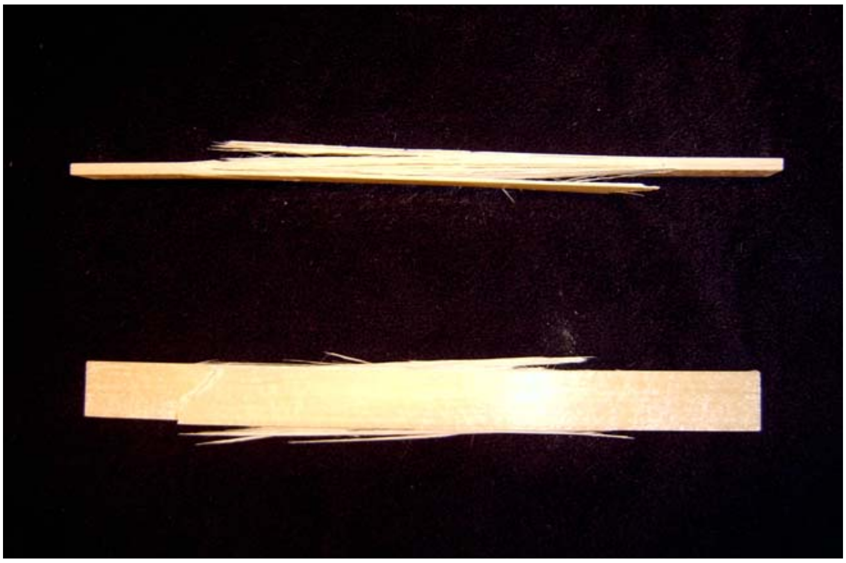


Figure 3.1. Tensile testing specimen after testing.

During the test the load is recorded by the computer, and the Peak Stress and Modulus of Elasticity is calculated. The Peak Stress is calculated using the following equation;

$$\text{Peak Stress} = \frac{\text{Peak Load}}{\text{Cross sectional Area}}$$

and the Modulus of Elasticity is calculated using;

$$\text{Modulus of Elasticity (E)} = \frac{\Delta\sigma}{\Delta\varepsilon}$$

where; $\Delta\sigma$ = change in stress

$\Delta\varepsilon$ = change in strain

(these two values are calculated of the linear portion of the Stress vs. Strain graph)

All of the tension tests performed produced an acceptable failure mode and from the results the average peak stress at failure was found to be 471.91MPa and the average Modulus of Elasticity = 32 238MPa.

3.2.3 Compression Test

The compression tests were also conducted on the MTS 810 testing machine and followed ISO 14126 Fibre-Reinforced Plastic Composites – Determination of Compressive Properties in the In-Plane Direction. The specimen size for this test was 112mm x 12.5mm x 5mm and the aim was to determine the compressive strength of the material. In total 7 specimens were loaded at a rate of 1mm/minute. The specimen was placed in the machine and a compressive force was applied to the test piece until a compressive failure was achieved. To ensure that the failure is a compressive failure, not buckling failure only 20mm of the specimen is unrestrained by the grips of the test fixture. Figure 3.2 below shows a failed compression test specimen.

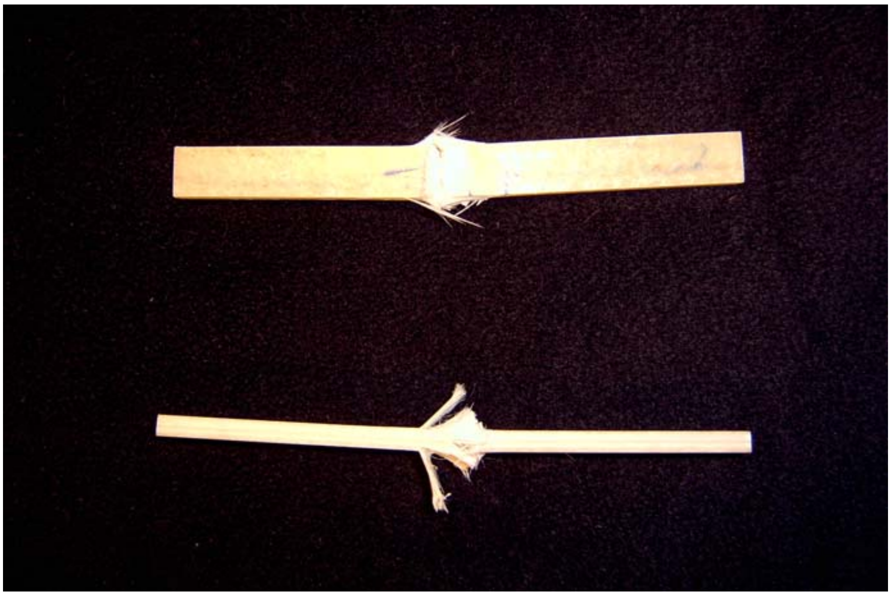


Figure 3.2 Compression test specimen.

The load was also recorded during the test by the computer and the Peak Stress again calculated using;

$$\text{Peak Stress} = \frac{\text{Peak Load}}{\text{Cross sectional Area}}$$

All of the compression test pieces failed in an appropriate manner and results from the above equation produced an average peak stress at failure of 733.78Mpa.

3.2.4 Flexural Test

A 200mm x 15mm x 5mm specimen was used for this test and the standard followed was ISO 14125 Fibre-Reinforced Plastic Composites – Determination of Flexural Properties. The purpose of this test is to determine the flexural strength and flexural modulus of the material. This test was conducted on a MTS Alliance RT/10 machine and involved failing the specimen using a 4-point bending test (see figure 3.3).

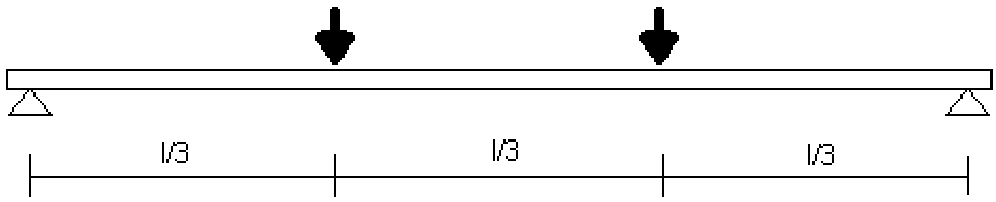


Figure 3.3 Four point bending test.

The MTS Alliance machine records data during the test and displays properties along with load and deflection in real time. A total of ten specimens were tested using a controlled deflection loading rate of 2mm/minute.

Again the load was measured and recorded during the test by the computer and the peak flexural stress calculated using;

$$\text{Peak Flexural Stress} = \frac{F\,L}{b\,h^2}$$

where; F = load (N)

L = span (mm)

h = thickness of specimen (mm)

b = width of specimen (mm).

and flexural modulus using

$$\text{Flexural Modulus} = \frac{0.21\,L^3}{b\,h^3}\,(\Delta F/\Delta s)$$

where; L = span (mm)

b = width of specimen (mm)

h = thickness of specimen (mm)

ΔF = the difference in load F” and F’ at s” and s’ respectively

Δs = the difference in deflection between s" and s'

(s" and s' correspond to deflections at strain values of 0.0005 and 0.0025)

The failure mode in all test pieces was acceptable with a tensile fracture in the outermost tension layer being observed. This resulted in an average Peak Flexural Stress of 509.24MPa and an average Flexural Modulus of 19 251MPa.

3.2.5 V-Notch Shear Test

The V-notch shear test is a test on a 76mm x 20mm x 5 mm specimen to which a shear force is applied. Two notches that are cut in the test piece are used to initiate the shear failure in the required region. These notches reduce the width of the specimen to 12mm and the method of conducting this test is outlined in ASTM D 5379 Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method. Figure 3.4 shows a typical test specimen and the loads applied to it.

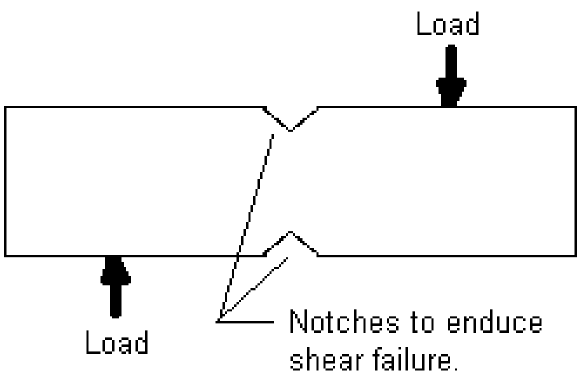


Figure 3.4 V-notch shear specimen.

A total of 8 test specimens were used for this test and the loading was applied through a controlled deflection of 2mm/minute. The computer recorded the load during the test and the shear stress at failure is calculated using;

$$\text{Peak Shear Stress} = \frac{\text{Peak Load}}{\text{Area at notch}}$$

Shear failure at the notch was achieved in all of the test pieces and the above equation produced an average Peak Shear Stress of 82.64MPa.

3.2.6 Inter-laminar Shear Test

The aim of the inter-laminar shear test is to create a shear failure between the fibre layers of the material. This is achieved by testing a 50mm x 10mm x 5mm test piece in 3 point bending. The standard for this test is ISO 14130 Fibre-Reinforced Plastic Composites – Determination of Apparent Inter-laminar Shear Strength by Short – Beam Method. A total of 10 tests were conducted and during each test the load was recorded and from this the shear stress at failure determined using the following formula.

$$\text{Apparent inter-laminar shear strength} = \frac{3\,F}{4\,bh}$$

where; F = Load (N)

b = width of specimen (mm)

h = thickness of specimen (mm).

Each test piece failed through inter-laminar shearing and as a result the average apparent inter-laminar shear strength for the material was found to be 37.40MPa

3.2.7 Fibre Fraction Test

ISO 1172 Textile-Glass-Reinforced Plastics – Prepregs, Moulding Compounds and Laminates – Determination of the Textile Glass and Mineral-Filler Content – Calcination Methods is the standard that this test followed and the aim of this test is to determine the percentage of fibres in the sample by weight. To do this the sample is placed in an oven at a temperature of 575°C resulting in the resin in the material to be vaporized leaving only the fibres from which the percentage of fibres is calculated using;

$$\text{Fibre Fraction} = \frac{\text{Mass of Calcinated Sample}}{\text{Mass of Initial Specimen}}$$

Each of these samples initially weighed approx. 6g and total of 3 specimens were tested resulting in an average Fibre Fraction of 69.14%.

3.2.8 Cross-Tensile Strength Test

The final test on the composites was a cross-tensile test. This test involved cutting a section from the pultrusion and then testing the specimen to determine the force required to create a tensile failure (see figure 3.5).

Figure 3.5 Cross tensile specimen during test.

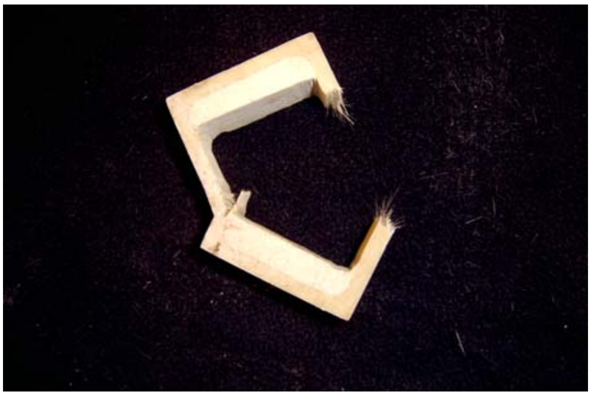


Figure 3.6 Specimen after cross tensile test.

Figure 3.6 shows a test specimen after the test and also shows the small amount of polymer concrete that was placed in the top and bottom of the test piece to help achieve the desired failure mode. A total of 5 tests were conducted each using a controlled loading rate of 2mm/minute. The load was recorded by the computer and from this the cross tensile strength is determined by;

$$\text{Cross-tensile Peak Stress} = \frac{\text{Peak Load}}{\text{Area}}$$

The failure mode in all five test specimens was acceptable and this resulted in an average Cross Tensile Shear Strength value of 66.02MPa.

3.3 LVL Testing

3.3.1 LVL Manufacturing Process

LVL or Laminated Veneer Lumber is a manufactured timber product similar to plywood that is made by bonding together lamina of material to build up a panel. Unlike plywood the grain of each laminate is orientated in the same direction. The LVL used for this project is manufactured by Norwood and the sheets are approximately 2400mm long, 1200mm wide and 27mm thick when delivered. The main benefit of this material is that the variability that is normally encountered with the use of timber is reduced. Having the plies all orientated in the same direction results in better performance in certain orientations than plywood and it is generally made from a more sustainable source than hardwood.

3.3.2 Flexure Test

The flexure test for the LVL was done using a 4-point bending test with the same loading configuration as that shown in figure 3.7.

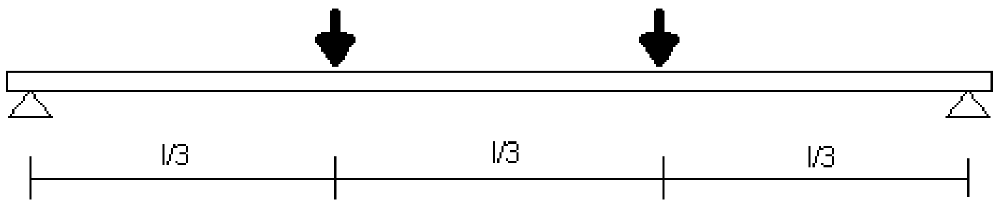


Figure3.7 Load configuration for 4-point bending test.

The test followed AS 2098.9 Methods of Test for Veneer and Plywood Method 9: Procedures for In-Grade Testing of Structural Plywood Clause 7.2. The test specimen was 1300mm x 300mm x 26mm in size, and there were 8 specimens tested with the load manually applied by the machine operator so that the duration of the test was between 3 – 5 minutes. The LVL flexure testing was not conducted on a computer controlled testing machine and this meant that more time had to be taken to set up and conduct each test. During the test, deflection readings were read from 2 dial gauges for a number of specified loads from 0 to 5000N at increments of 200N, then the dial gauges were removed and the test continued until a flexural failure was achieved. From this data the Modulus of Rapture (MOR) and Modulus of Elasticity (E) were calculated using the following equations;

$$\text{Modulus of Rapture (MOR)} = \frac{P_{max} \times L}{6 \times Z_{par}}$$

where: P_{max} = Maximum load (N)

L = Test span (mm)

Z_{par} = Section Modulus (mm^3) $= \frac{I_{par}}{y}$

I_{par} = Second moment of area (mm^4)

y = distance from neutral axis to outer most veneer (mm)

and

$$\text{Modulus of Elasticity (E)} = \frac{23 \times L^3}{1296 \times I_{par}} \times (P / \Delta)$$

where; L = Test span (mm)

(P / Δ) = Gradient of load-deflection curve

I_{par} = Second moment of area (mm^4)

A total of 8 specimens were tested with all except one displaying a tensile failure. The specimen that did not fail was still included in the average values as it was determined that had the test been continued any further a failure would have been achieved at a load only marginally higher than the load that was achieved. The results from this test gave a MOR of 77.2MPa and a Modulus of Elasticity of 14 913MPa.

3.3.3 Tensile Test

The test specimens were 800mm long x 65mm wide x 26mm thick for the LVL tensile tests and a total 5 specimens were tested. These sizes were slightly different to the sizes given in AS 2098.9 Methods of Test for Veneer and Plywood Method 9: Procedures for In-Grade Testing of Structural Plywood Clause 7.3 with the standard specifying a test specimen size of 1950mm long by 150mm wide, however a specimen of this size would not fit in the MTS 810 testing machine (figure 3.8).A total of 8 specimens were tested and a loading rate of 2mm/minute was applied until failure.

Test fixtures had to be manufactured to hold the test specimens and connect them to the testing machine (figure 3.9) and consisted of welded plates that the test specimen was bolted between with an additional plate that was held in the grips of the testing machine and attached to the clamping plates via a pin. Staff in the USQ workshop made these clamps and drawings for these can be found in appendix C.

Figure 3.8
Tension test piece in MTS machine. testing

Figure 3.9
Clamp attaching test piece to machine.

The computer recorded the load during the test and the tensile stress at failure is calculated using;

$$\text{Peak Stress} = \frac{\text{Peak Load}}{\text{Cross sectional Area}}$$

Of the 8 specimens tested only 5 produced a failure mode that was considered acceptable. Problems that occurred due to slippage of the specimens in the clamps due to insufficient pressure and also issues with breakage of the bolts that were used to fix the clamps to the specimens resulted in the tests for 3 of the specimens producing unusable data. From the 5 tests that produced accurate results an average tensile strength of 38.77MPa was calculated.

3.3.4 Shear Panel Test

Grips and support blocks had to be made to allow the test pieces to fit into the machine. Again the USQ workshop staff made these grips and fitting blocks and the drawing for these pieces can be found in appendix C. The test followed the standard AS2098.9 Methods of Test for Veneer and Plywood Method 9: Procedures for In-Grade Testing of Structural Plywood Clause 7.4 with a 250mm x 85mm x 32mm specimen and the aim was to achieve a shear failure of the test piece (see figure 3.10).

Figure 3.10 Shear failure of test piece through boltholes.

The load during the test was recorded on the computer and the panel shear strength was calculated using;

$$\text{Panel Shear Strength} = \frac{\text{Peak Load}}{\text{Shear Area}}$$

There were some issues during this test with most of the specimens failing through the boltholes (figure 3.10). This resulted in a shear strength of 3.98MPa, however, if the area of the boltholes is excluded from the calculations a shear strength of 4.74MPa results. Table 3.2 summarises values of the panel shear strength and the values in brackets indicate the panel shear strength with the area of the boltholes removed from the calculations.

A draft standard specifies that the metal clamps used in the test should be glued to the specimen, not bolted as they are in AS 2098.9. This would remove the issues that were experienced during the tests with failure occurring through the boltholes.

3.4 Results

A summary of the results of the composite testing, and the LVL testing are shown in tables 3.1 and 3.2 respectively. These results are the average values from each test, and are also the values used in the computer models.

Table 3.1
Composite testing results summary

TEST	PROPERTY OF INTREST	RESULT (average)
Tensile Strength	Peak stress Modulus of Elasticity (E)	471.91 MPa 32 238 MPa
Compressive Strength	Peak stress	733.78 MPa
Flexural Strength	Peak flexural stress Flexural Modulus	509.24 MPa 19 251 MPa
V-notch Shear	Peak shear stress	82.64 MPa
Cross-tensile Strength	Peak stress	66.02 MPa
Inter-laminar Shear	Peak shear stress	37.40 MPa
Fibre Fraction	Glass content	69.14 %

Table 3.2
LVL testing results summary.

TEST	PROPERTY OF INTREST	RESULT (average)
Flexural Strength	Modulus of Rapture (MOR) Modulus of Elasticity (E)	77.2 MPa 14913 MPa
Tensile Strength	Tensile stress	38.77 MPa
Shear	Panel shear (PS)	3.98 MPa (4.74 MPa)

3.5 Conclusions

The results for the properties of the composite tests that were conducted matched the results that were expected from previous testing and all of the tests that were conducted produced values that remained constant for each specimen tested in each test.

Issues were found in the LVL testing however. It was expected that the flexural strength (MOR) and the tensile strength would produce similar results as the failure mode in a flexural failure is predominately tensile failure in the tension zone, however, as table 3.2 shows, this was not the case. It is believed that this may be due to the orientation of the material within the testing machine during the flexural test. The orientation of the plies in the flexure test that was conducted were horizontal, however, the orientation of the plies in the test beam were vertical. To overcome this a test piece where the plies are orientated vertically would have to be constructed. There were also some problems associated with the orientations specified by other standards used with these standards often requiring an orientation that did not match the orientation that the LVL would have in the beam thus producing results that may not be entirely accurate. Developing modified testing procedures based on the standard defined procedure could rectify this. Further investigation into the new draft LVL testing code may also produce testing procedures that may give more accurate results.

It was also discovered that the Shear Modulus, that would be required for computer modelling, was not accounted for in the standard followed for the testing. For this reason a value provided by an LVL manufacture of 660MPa was used for the shear strength in the computer modelling.

CHAPTER 4

COMPUTER MODELING AND PREDICTIONS

4.1 Introduction

In recent years, Finite Element (FE) Analysis has been applied to many areas of the engineering profession; including fluid dynamics, structural analysis, electrostatics and heat flow. In this project FE Analysis software was used to help make predictions about the behaviour of the beam. To do this computer models of the beam were constructed, and the information that was gathered from the materials testing was used to define the individual properties of each material within the beam to improve the accuracy of the models. Several different models were made to determine the effects that the addition of each different material had on the strength and stiffness of the beam. Non-linear analysis was also used to more accurately model the non-elastic behaviour of the beam as the steel yields.

4.2 What is Finite Element Analysis

Finite element analysis is a numerical method of determining the behaviour of a structure, fluid or material. It works by dividing the material, in this case the beam, into a number of smaller pieces. This results in a set of equations being developed that can be solved using linear algebra. The finite element analysis method is used to provide accurate approximations to the solutions of complex problems.

FE analysis involves sometimes hundreds or thousands of equations that need to be solved and it is for this reason that FE analysis has only been generally accepted since computers have been available to perform these calculations. The nature of the FE process means that it only gives approximations to the behaviours of the structure and the accuracy of these approximations is directly related to the size and number of elements that are used. Basically the smaller the elements the more elements there are and the greater the accuracy of the model.

There are three basic element families used in FE analysis, these being beams, plates and bricks and various properties are assigned to each of these elements. All three of these basic elements are used in the models for the hybrid beam.

4.3 Modelling

Strand7 was the finite element analysis software used for the modelling, with a number of different models developed to determine what effect the addition of each material would have on the behaviour of the beam. These models included;

- a beam that was entirely LVL,
- a beam that consisted of glass fibre pultrusions and LVL,
- a beam that consisted of LVL and polymer concrete filled pultrusions,
- a beam that consisted of LVL, polymer concrete filled pultrusions and reinforcing steel,
- a beam that closely matched the test beam with pultrusions, polymer concrete, steel and glass laminate panels, and
- a ‘cracked’ beam

The nature of FE software means that the entire beam does not have to be modelled. In the case of the models used for this project only half of the length was modelled, with restraints applied to the model to make it behave as if it were a full model. The major benefit of this is that the solve time for the model is reduced as the number of elements is halved. This ‘cutting down’ of the model can be performed over any plane of symmetry that exists within the model.

All three of the basic element families; bricks, beams and plates were used in the computer models in this project. The reinforcing steel and prestressing strand were modelled using beam elements, the LVL and polymer concrete as brick elements and the pultrusions and laminate panels using plate elements. For the models where the laminates were included it is possible to define these plates as laminates within the model. This allowed the laminate panels to be modelled in the same way that they are constructed and to define the fibre directions in each laminate layer to match the fibres in the laminates. By default Strand7 displays each property type as a different colour, this can be seen in the screen shots later in this chapter.

4.3.1 The LVL Only Model

This model was made entirely of bricks, with properties of LVL obtained from the material testing detailed in Chapter 3. This model was included to provide a comparison between a pure LVL beam and the full hybrid beam and also as a means of verifying the results with hand calculations. Figure 4.1 shows the model as it appears in Strand7 before solving.

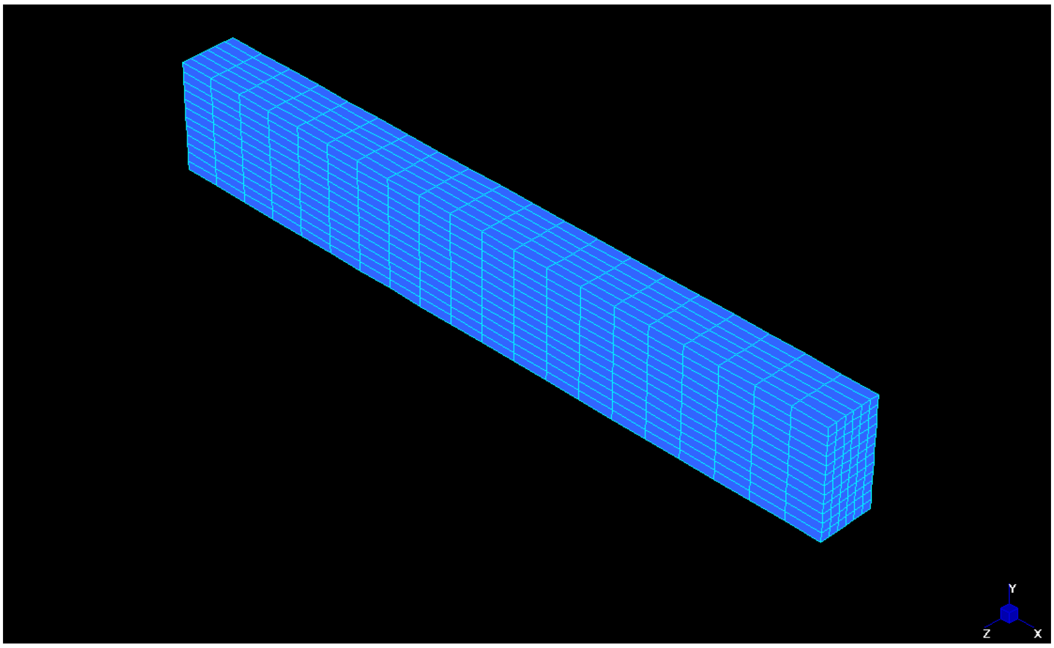


Figure 4.1 LVL beam as it appears in Strand7.

Figure 4.1 shows the LVL beam made entirely of bricks with each brick having dimensions of 100mm in the X direction, 35mm in the Y direction and 25-27mm in the Z direction (note the axis system is shown at the bottom right of the figure). The blocks in the centre of the beam are only 25mm in the Z direction, this is so that the 50mm width of the pultrusion can be easily accommodated in later models.

After the model had been built, the loads and restraints were applied. The first restraint applied was the support reaction and this involved fixing the displacement in the Y direction of the nodes on the bottom edge of the beam 100mm from the end. The restraints applied to the beam to do this were fixing of its displacement in the X and Z directions and allowing no rotation about any axis, these restraints are typical of all of the models produced and can be seen in figure 4.2.

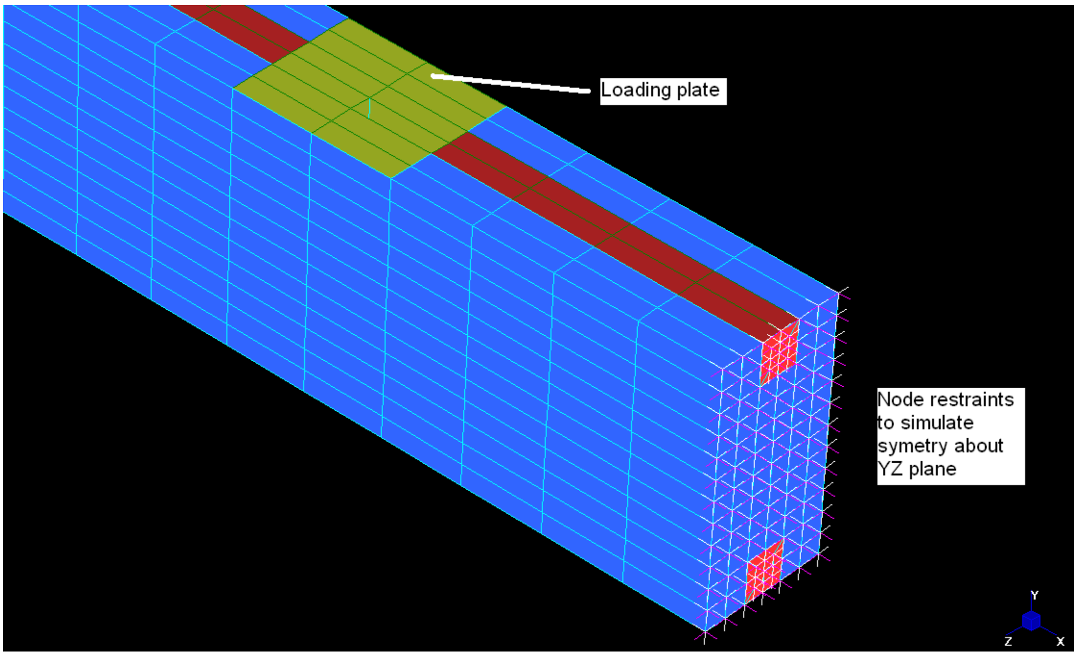


Figure 4.2 Node restraints and loading plate.

After the restraints had been applied a load was applied to the model. This load was applied as a nodal load however if this load had been placed directly on the beam it would cause a considerable amount of localized stress around the area that the load is applied. For this reason a steel plate was placed on top of the beam to more evenly distribute the load to the beam, as is done in the test. This loading plate was given a bending thickness of 25mm, the same as the loading plate used on the test beam, but was given a membrane thickness of 0.5mm so that the plate would not locally strengthen the beam too much. A load of 100kN was then applied to the beam and the model was solved using a linear solution method. This produced the following figure 4.3.

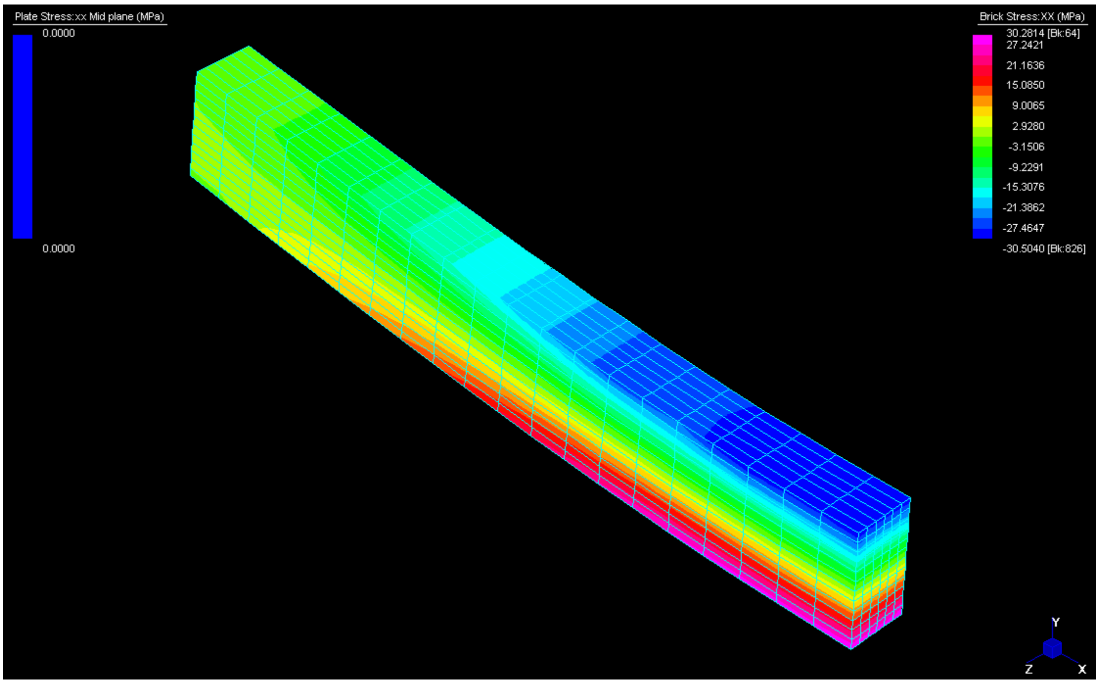


Figure 4.3 LVL only beam stress @100kN

As figure 4.3 shows Strand7 graphically displays results as a coloured contour. This type of display is the most user friendly and easy to interpret however results can be displayed in various ways. The two main results that were used for this project were stress and displacement and both are displayed using a graphical colour contour in strand7. Table 4.1 is a summary of the results from the computer model.

Table 4.1 Summary of results for LVL beam.

Quantity	Value
Brick Stress +	30.28 MPa
-	30.5 MPa
Centre span displacement	19.55mm
Solve time	5 seconds

A check was then carried out on the deflection to verify the results produced by strand7. To do this the following formula was used;

$$\text{Deflection (mm)} = \frac{P(L_o - L_i)(2L_o^2 + 2L_oL_i - L_i^2)}{96\ EI}$$

where Lo = Test span

Li = Load span

P = Total load/ 2

E = Modulus of Elasticity

I = Second Moment of Area.

This resulted in a deflection of 19.54mm for a beam made entirely of LVL, confirming that the 19.55mm deflection calculated by Strand7 is accurate. The full spreadsheet calculation can be found in appendix D

4.3.2 LVL and Pultrusions Model

This model contained LVL and the Glass Fibre Pultrusions. For this model both bricks and plates were used, bricks for the LVL and plates for the pultrusions. When defining the properties of the plates the data from the material testing was used, and it was also necessary to specify the thickness of the plates. For all of the models in this project the thickness of the pultrusion plates was equal to the actual thickness of the pultrusions, 5mm. Figure 3.2 shows the model before solving and it is possible to see the LVL as bricks and the plates that make up the pultrusions placed in the spaces where bricks were removed.

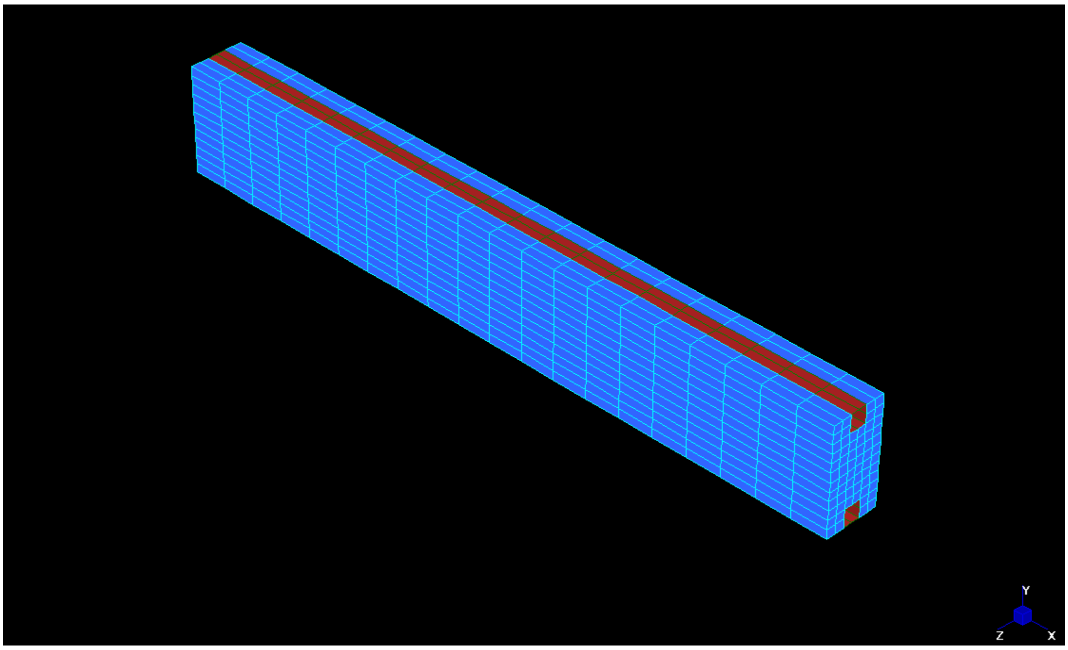


Figure 4.4 Strand 7 model of LVL beam with pultrusions.

The loading method for this model was the same as that used for the LVL only model with a steel plate through which the load was applied being used. Restraints were imposed and then a 100kN force was applied. The model was then solved using a linear solution method. Figure 4.5 shows the contour diagram for the stresses in the beam.

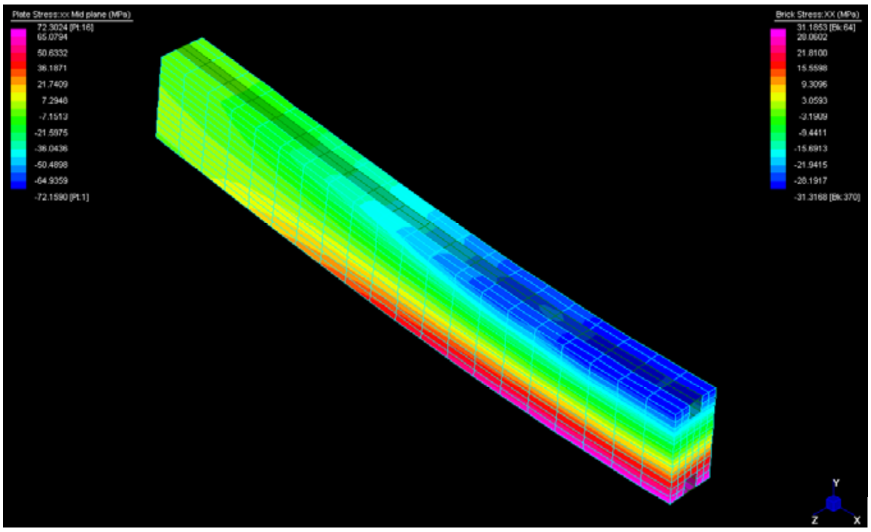


Figure 4.5 LVL and Pultrusion beam stress at 100kN.

The display has a legend that shows the stress value that corresponds to each colour and there is a legend for the plate stress (top right of figure 4.5) and a legend for brick stress (top left of figure 4.5). Table 4.2 gives a summery of the results produced from this model.

Table 4.2 Summary of results for LVL and pultrusion beam

Quantity	Value
Brick Stress + -	31.18 MPa 31.31 MPa
Plate Stress + -	72.3 MPa 72.16 MPa
Deflection	20.05mm
Solve time	5 seconds

As table 4.2 shows there is a slight increase in both brick stress and deflection. A check on the deflection was performed using a spreadsheet that was capable of calculating the EI value for the entire beam using the following formula;

$$\text{Overall EI} = \sum E(I + Ad^2)$$

where; E = modulus of elasticity of material (MPa)

I = second moment of area of each section (mm^4)

A = area of the material (mm^2)

d = distance of materials centroid to the neutral axis (mm)

$$\text{Neutral Axis depth} = \frac{\sum EAy}{\sum EA}$$

where; E = modulus of elasticity of material (MPa)

A = area of the material (mm^2)

y = distance of material centroid from beam (mm)

This EI value could then be placed in the deflection formula used in section 4.3.1 and a deflection =20.52mm was calculated confirming that the computer model is accurate. The full spreadsheet can be found in appendix D.

4.3.3 LVL, Pultrusions and Polymer Concrete Model

The natural progression from the previous model was to fill the hollow glass fibre pultrusions with a polymer concrete material. Testing on this material was not undertaken in this project so property values from previous tests by the FCDD were used.

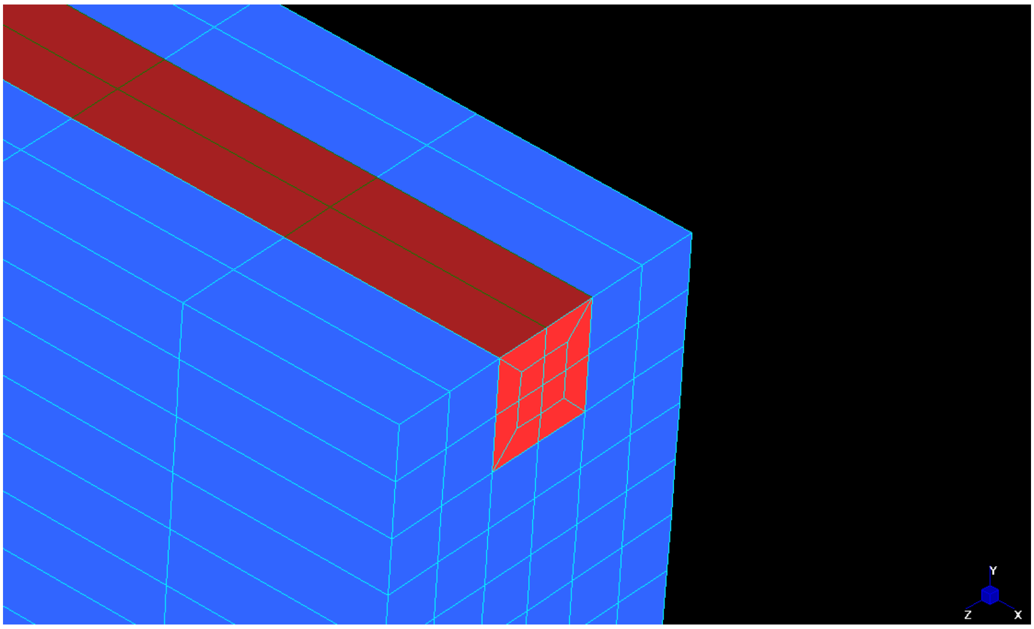


Figure 4.6 Close up end view of beam with polymer concrete filled pultrusions

Figure 4.6 shows a close up of the end of the model where the LVL and polymer concrete bricks can be seen along with the pultrusion plates. It also shows the different mesh used in the polymer concrete with both square and trapezoidal bricks present, these shape bricks are required to provide a continuous mesh because if there are nodes (not shown in figure 3.3 above but present at the corner of each block or plate) that are present but not connecting elements errors will be encountered during the solving process. The polymer concrete bricks were divided like this so that the three reinforcing steel bars and the four stressing strands could be easily placed in future models. Dividing a mesh like this is quite a simple task in Strand 7 as it has several different built in commands for grading plates and bricks.

A 100kN load was applied through a simulated loading plate and restraints applied to simulate the support at one end and the second half of the beam at the other and a linear solve method used to produce the following stress distribution (figure 4.7).

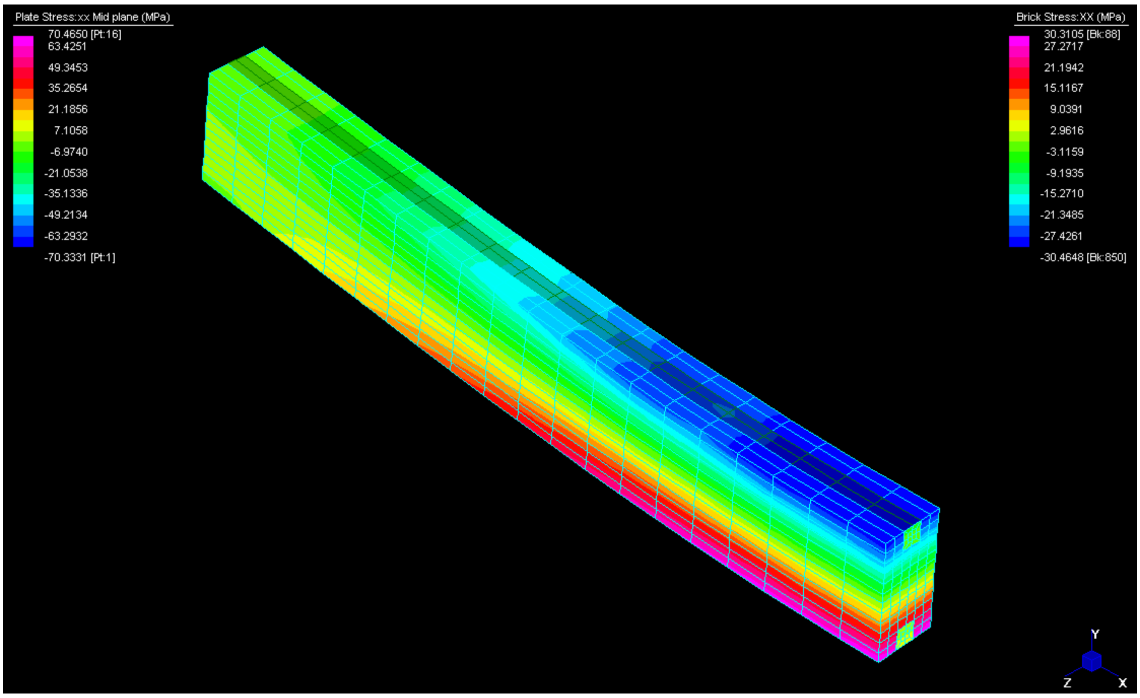


Figure 4.7 LVL, Pultrusion and Polymer Concrete beam stress at 100kN

Figure 4.7 shows the Strand7 output of the stress contours and table 4.3 has a summary of the results produced.

Table 4.3 Summary of results for LVL, pultrusion and polymer concrete model

Quantity	Result
Brick Stress + -	30.31 MPa 30.46 MPa
Plate Stress + -	70.47 MPa 70.33 MPa
Deflection	19.5mm
Solve time	9 seconds

A check of the results was not conducted using the spreadsheet for this model, as the spreadsheet does not allow for the polymer concrete. Although the polymer concrete is not included in the spreadsheet check the values for deflection produced by the spreadsheet are still accurate enough to be used as a check due to the stiffness of the polymer concrete being low, resulting in it having little effect on the stiffness of the beam. This is confirmed by the deflection only being decreased by 0.55mm when the polymer concrete is included in the models.

4.3.4 LVL, Pultrusions, Polymer Concrete and Steel Model

This was the first of the models that actually resembled how the test beam would behave. It is a relatively simple extension of the previous model with only the addition of beams where the reinforcing bars and stressing strands are located in the beam (figure 4.8).

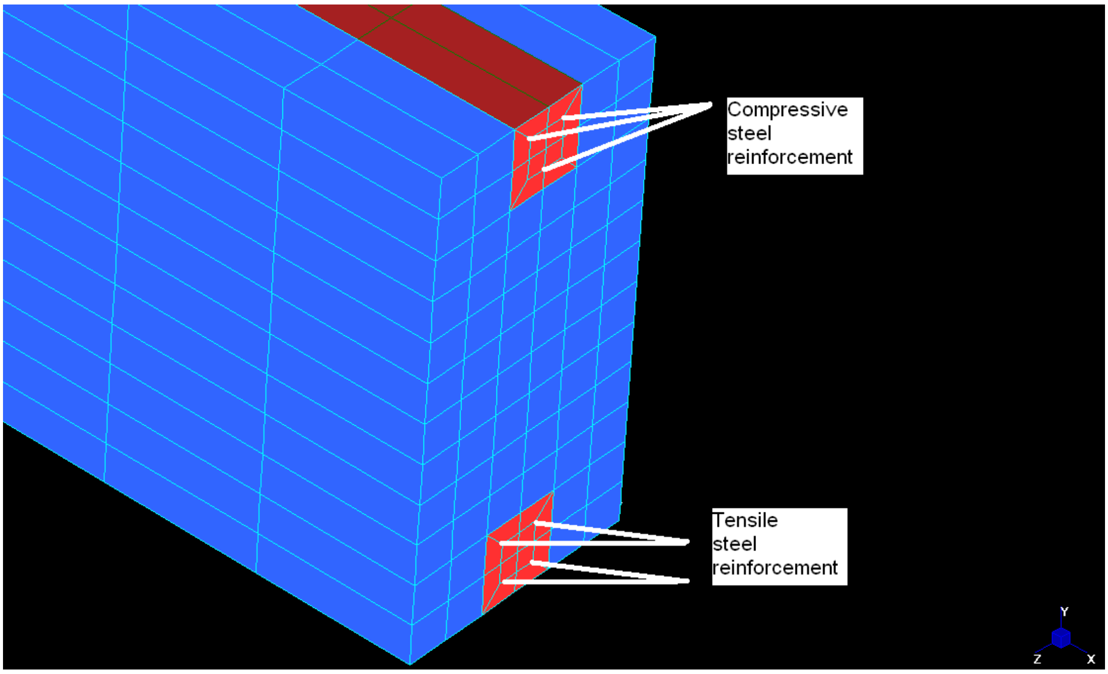


Figure 4.8 End view of model showing location of steel beams.

In Strand 7 the beams appear only as lines defining each different property with a different colour. The properties of the beam are defined in the program, in this case three 16mm diameter N500 reinforcing bars for the compression steel reinforcing and four 15.2mm diameter super-strand stressing strand for the tensile reinforcement. The stressing strand is used due to his higher capacity in tension then reinforcing bar, however, the strand is not actually prestressed in the beam.

Restraints were then applied to the model and a 100kN load applied through a simulated loading plate producing the stress contour shown in figure 4.9.

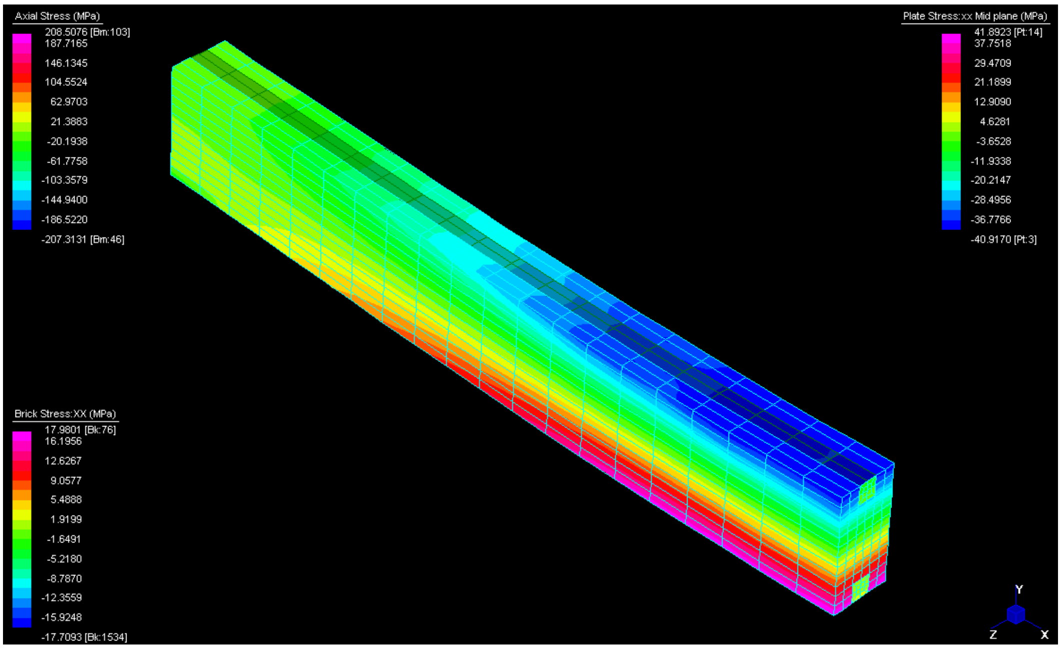


Figure 4.9 Full Beam stress at 100kN

As figure 4.9 shows with the inclusion of the reinforcing steel another legend is shown for the axial stress in the beam elements. A summary of the results is included in table 4.4.

Table 4.4 Summary of Results for full beam model

Quantity	Value
Brick Stress +	17.98 MPa
-	17.71 MPa
Plate Stress +	41.98 MPa
-	40.92 MPa
Axial Beam Stress +	208.51 MPa
-	207.31 MPa
Displacement	11.62mm
Solve time	9 seconds

The spreadsheet described in section 4.3.2 was then used to confirm the results by checking the deflection. This spreadsheet produced a deflection value = 11.77mm confirming that the computer model was accurate and the full spreadsheet can be found in appendix D.

4.3.5 Full Model with Laminates

The only part of the beam that was not modelled in the previous model was the glass fibre laminates that run the full depth of the beam either side of the pultrusions. It is possible to define laminates in Strand 7 and this function was used to model the laminates for this beam. The first step was to define the properties of each different ply of the laminate for both thickness and properties. So that the model would not encounter any problems both the glass for one layer of a laminate and the pultrusion were defined as plies. The next step was to build up the laminate in layers to produce the same laminate as is found in the beam and to do this 3 different laminates were made (figure 4.10). The bricks have been removed from the figure and only the plates (which are the element that the laminates are displayed as) are visible.

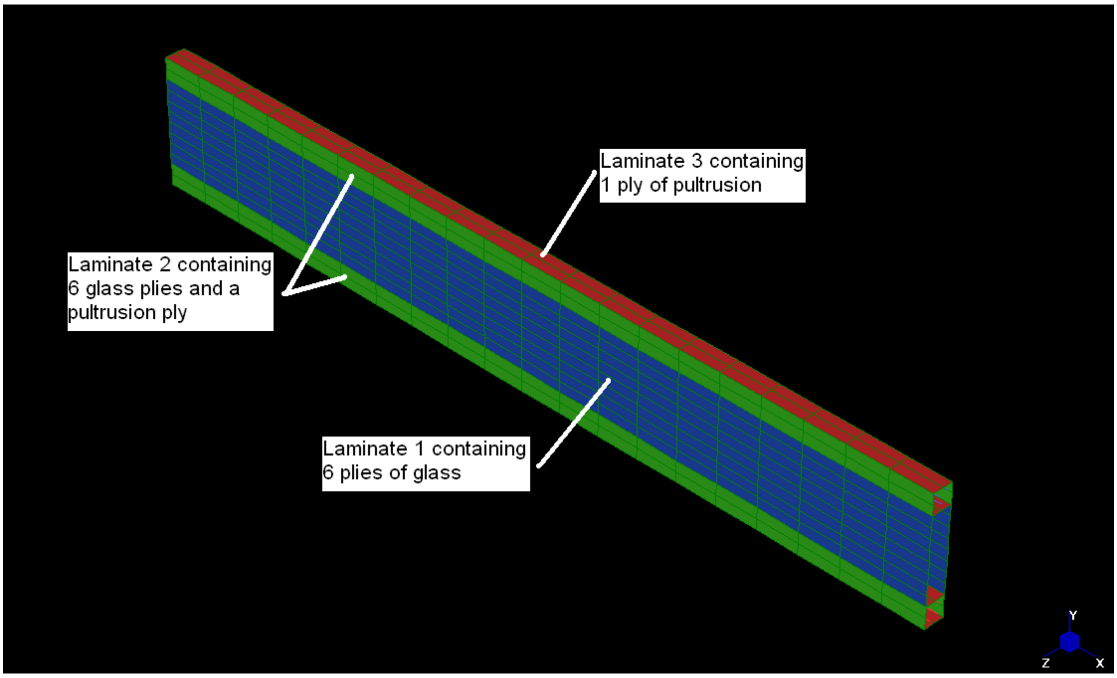


Figure 4.10 Three different laminates in computer model

The first simply consisted of the glass layers and consisted of 6 plies, six were required because the glass used in the test beam was double bias meaning that there were fibres running at +45^{o} in one direction and also another layer at -45^{o} as shown in figure 4.11.

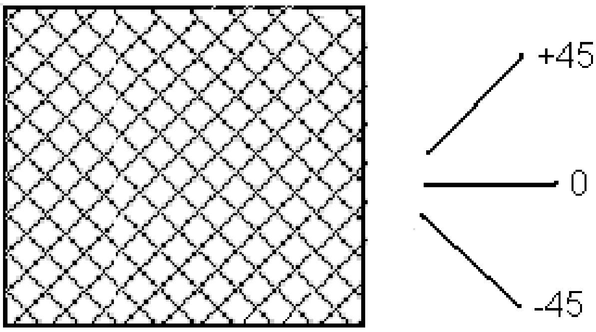


Figure 4.11 Orientation of fibres in double bias

The second laminate contained the same six glass layers as the first and also had an additional layer for the pultrusion (figure 4.12).

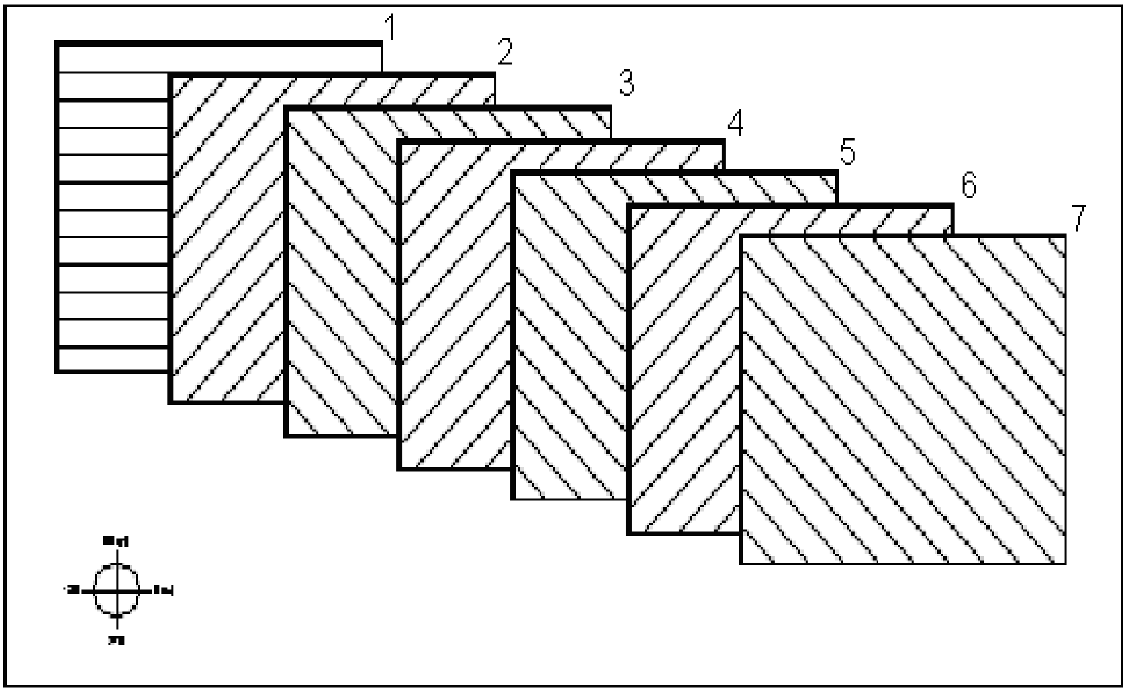


Figure 4.12 Plies making up laminate containing glass panel and pultrusion with lines showing direction of fibres

Figure 4.12 shows how the laminate was constructed in Strand 7 with ply 1 being the pultrusion and sheets 2 – 7 being the plies that make up the glass panel and it also shows the orientation of the fibres in each ply. This laminate was used where the glass laminate met the pultrusion. A laminate that only consisted of plies 2-6 was used in the centre of the beam, and the final laminate that only consisted of ply 1 was used for the top and bottom faces of each pultrusion as indicated in figure 4.12.

Node restraints and a 100kN load applied through a simulated loading plate were then placed in the model and this produced the stress contour shown in figure 4.13 and the results shown in table 4.5.

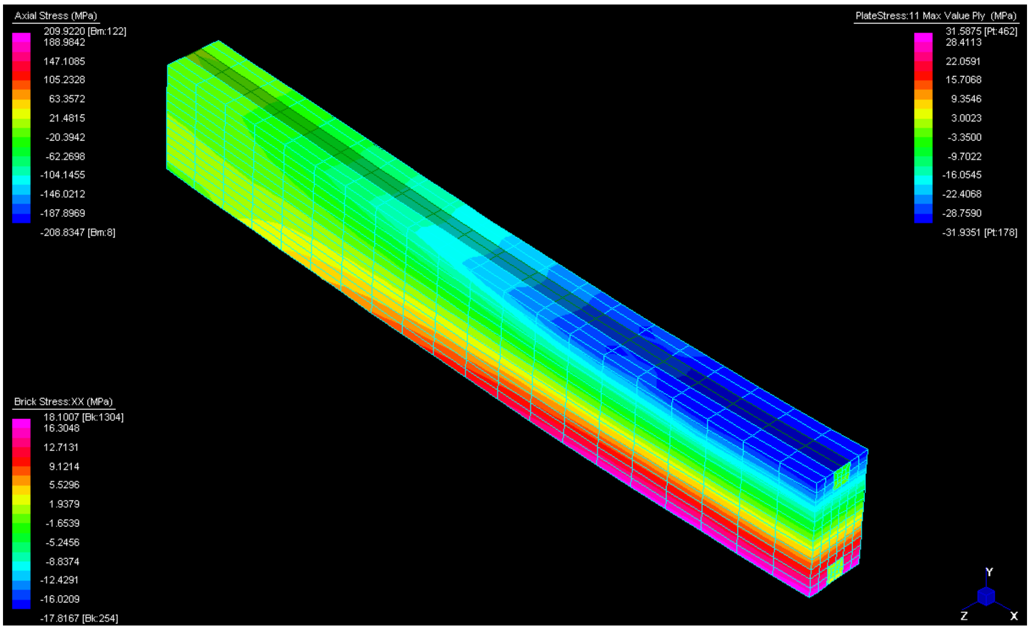


Figure 4.13 Full Beam with Laminates stress at 100kN

Table 4.5 Summary of results for full beam with laminates

Quantity	Value
Brick Stress +	18.72 MPa
-	19.42 MPa
Plate (Laminate) Stress +	31.59 MPa
-	31.94 MPa
Axial Beam Stress +	210 MPa
-	208.81 MPa
Displacement	11.79mm
Solve Time	11 seconds

4.3.6 Fine Mesh and Non-Linear Model

Another model was also made from the model described in section 4.3.5 that had a finer mesh as a sensitivity analysis. In this model every brick, plate and beam was divided, each brick into eight bricks, each plate into four plates and each beam into two beams. In the original model there were 1760 bricks, 652 plates and 140 beams and in the model with the finer mesh there were 14 080 bricks, 2584 plates and 280 beams. This fine mesh model was also used for the non-linear solving process. This model formed the basis of the predictions for the behaviour of the test beam.

For the non-linear analysis an enforced deflection method was used to provide results. To ensure that the results the properties of the LVL were also changed from isotropic to orthotropic so that shear deformation would be included in the analysis. To perform the enforced deflection non-linear analysis a small beam was placed on a loading plate in the same position as the point load had been placed in previous models. The solver then calculated the load that was required to displace this beam a predetermined amount and the stress that were produced in the beam by the load.

Two separate non-linear analyses were conducted, one simulating the beam as it behaves up to LVL cracking and a second that would simulate the behaviour after the LVL had cracked. To perform the analysis that simulated the behaviour after cracking small bricks 5mm in the X direction were added to the end of the beam then from slightly above the neutral axis to the bottom of the beam these bricks were deleted to simulate a crack in the LVL at centre span.

Linear solve times for this model were increased over the other models due to the increased number of elements with the solve time for this model being 10 times that of its equivalent model with the course mesh. Non-linear analysis solve times were greatly increased, due to the fact the model has to be solved numerous times to obtain a result.

4.4 Test Beam Predictions

Using results from the computer modelling and materials testing it was possible to make some predictions about the behaviour of the test beam. These predictions included load vs. deflection behaviour before and after cracking, loads at which the compression steel would yield and loads that would cause cracking of the LVL.

The first predictions were based on the linear models. From the values of axial stress in the steel and the brick stress in the LVL bricks it was possible to predict some load values that the steel would yield at and the LVL would begin to crack.

The steel yielding was calculated using;

$$\text{Steel yield load} = \frac{\text{yield stress}}{\sigma \text{ at } 100\text{kN}} \times 100\text{kN}$$

This resulted in a predicted yielding load of 240kN and a similar formula was used for the calculation of the LVL cracking load;

$$\text{LVL cracking} = \frac{\text{MOR}}{\sigma \text{ at } 100\text{kN}} \times 100\text{kN}$$

This resulted in a predicted cracking load of 411kN. However, it was thought that this value might be high due to the issues that were experienced during the LVL flexural tests with large variations between the results obtained for the MOR and the value obtained from the tensile test. Replacing the value for MOR in the above equation with the value obtained from the tension tests results in a cracking load of 200kN. It was expected that the actual cracking would occur somewhere between these two values.

The results of the load deflection relationship of the two non-linear models are shown in figure 4.14 along with the solution that is produced when the LVL is modelled with isotropic properties. It can be seen that the difference between isotropic and orthotropic LVL properties is large and that the cracked section has a lower stiffness than the un-cracked section. It was predicted that the load deflection relationship of the test beam would be a combination of both the cracked and un-cracked predictions, with the relationship initially following the un-cracked plot up until cracking occurred in the LVL, at which point the relationship would jump from the un-cracked, to the cracked prediction. Yielding of the compression steel can also be seen in figure 4.14 where the gradient of each plot changes direction.

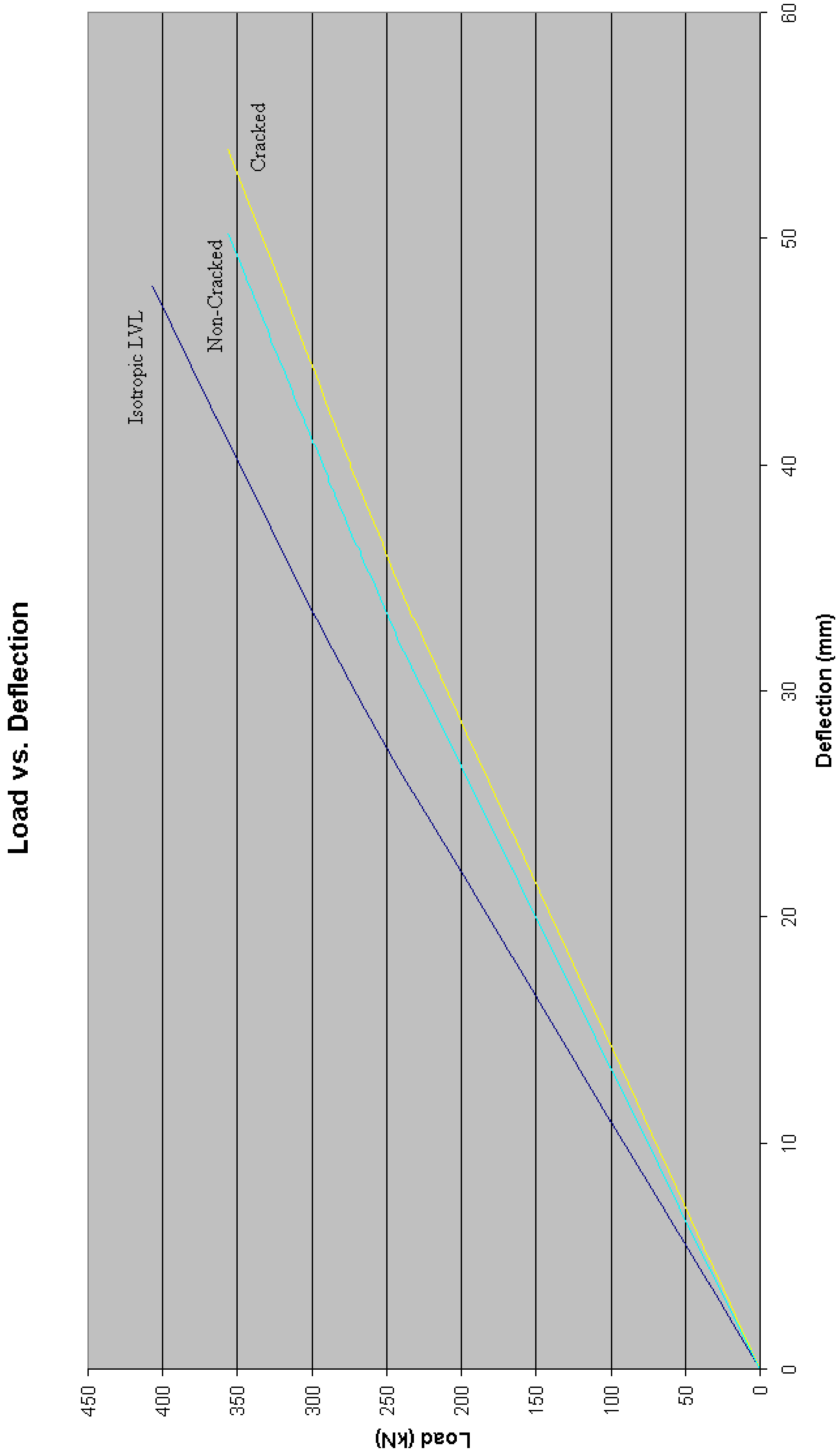


Figure 4.14 Load vs. deflection predictions

CHAPTER 5

BEAM CONSTRUCTION

5.1 Introduction

Making a hybrid beam involves a considerable amount of planning before the commencement of construction to ensure that all materials are available and ready when they are required. Once the overall dimensions of the test beam for this project had been determined drawings had to be made showing the materials to be used, dimensions of the beam, scarf details and the allowable tolerances (these drawings can be found in Appendix C). After these details had been determined construction of the beam could commence with the basic series of events being;

- preparation of the reinforcing modules,
- laminate manufacturing,
- LVL preparation,
- gluing of the side sections,
- gluing of the centre section,
- gluing all sections together, and
- sanding and attaching of the strain gauges.

5.2 Reinforcement Modules

5.2.1 Materials

The materials used in the construction of the test beam included; glass fibre pultrusions, N16 steel reinforcing bars, 15.2mm prestressing strand and polymer concrete. The two reinforcing modules are both manufactured using the same process with one containing 3 reinforcing bars (the top or compression module) and the other containing 4 prestressing strands (the bottom or tension module).

The purpose for using the prestressing strand is that earlier tests show that this material was able to perform better in tension, with a tensile strength of 1500MPa compared to 500MPa for reinforcing bars. It was also found previously that despite the high tensile strength of the stressing strand when the strands were placed in compression (even if they were confined by polymer concrete) they tended to fray apart under relatively low loads so solid reinforcing bars are used for the compression modules.

5.2.2 Manufacturing

The process of manufacturing the reinforcing modules involves cutting the glass fibre pultrusions to the desired length, in this case two, 4m lengths, and then one side of the section is carefully cut out leaving a channel type section. This is done to allow the reinforcing bars or prestressing strands to be placed in the pultrusions.

After the pultrusions have been cut the steel can then be placed in them in the required configuration. The steel bars are stopped 100mm from the end of the module to ensure an adequate protection is present to prevent water infiltration.

Small supports are used to hold the steel and are spaced at 500mm centres to prevent it from touching the sides of the pultrusion and also to prevent each bar or strand from touching each other. It is necessary to prevent the bars from touching as much as possible to prevent the spread of any corrosion and if there is corrosion it will be limited to only one bar or strand decreasing the effects. At first difficulty was experienced with getting the tensioning strands to stay in position within the pultrusion. This was due to the strand being delivered rolled up however the use of the supports can overcome this problem.

Once the steel is in place and the proper spacing is achieved within the pultrusion it is then filled with polymer concrete and the section of pultrusion that was cut to allow access is replaced. The polymer concrete is a mixture of resin with a filler agent and it firmly holds the bars and strands in place and also provides another layer of protection that aids in preventing corrosion of the steel. The polymer concrete in the compression module also has a small amount of pigment added so that it is clearly discernable which module is the compression and which is the tension after the modules are completed. The polymer concrete is then allowed to set and then cleaned up by sanding before it is ready to be used in the beam.

5.3 Laminates

Two glass fibre laminate panels also had to be made so that they could be positioned either side of the centre section (see figure 5.1). The purpose of these laminates is to prevent a brittle failure mode occurring in the beam. This brittle failure was experienced in early developments of this type of beam and was attributed to very high loads being transferred to a small area of the reinforcing modules when cracking occurred in the LVL. The addition of a laminate panel was then included in beams to help distribute this load and prevent brittle failure.

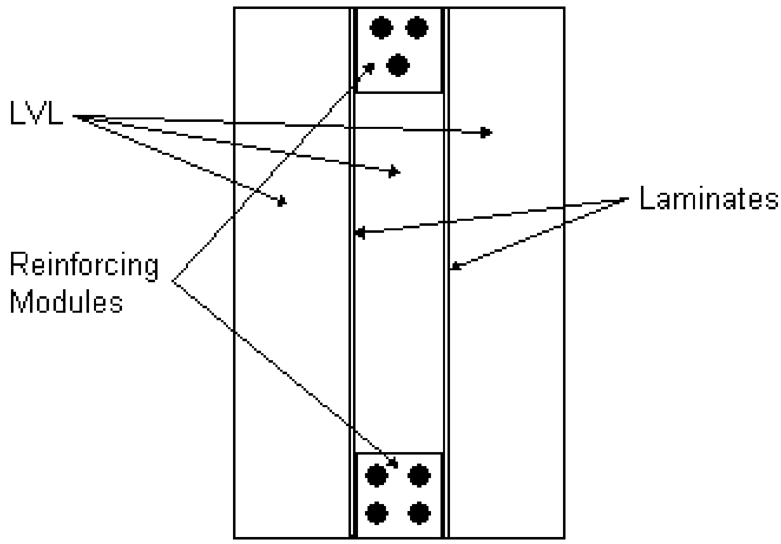


Figure 5.1 Beam section showing laminates and reinforcing modules.

The laminates for the test beam were made from three layers of MX4500 double bias. MX4500 double bias is a glass fibre fabric in which the fibres are orientated at $\pm 45^{o}$. Three strips of the double bias are cut from a roll for each panel, each strip being slightly over the 4m length and 300mm width required. A resin mixture is then made and a layer of this resin is placed on a table. The first layer of double bias is then placed on this resin layer and care is taken to ensure that the fabric is completely covered with resin (figure 5.2).

Figure 5.2 Resin coating of fabric in laminate panels.

This process is then repeated until the required number of layers, in this case 3, is achieved. To ensure that full curing of the laminates was achieved the two completed panels were post-cured in an oven overnight.

5.4 LVL Preparation

The LVL used in the test beam came from the manufacturer in sheets approximately 2400mm x 1200mm x 27mm and the ends of each sheet are cut with a 1 in 6 scarf and these scarf’s are used to join boards in the beam. Initially these sheets are cut along their length at a width equal to the depth of the beam (300mm) and also to a width that is required to make the section in between the two reinforcing modules (see figure 5.3). After enough LVL had been cut it has to again be cut to create the two ends of the beams. In order to ensure that there were no weak spots within the beam it is necessary to ensure that the scarf joins of the LVL are spread evenly along the length of the beam (see drawings in appendix C for scarf layout).

After all of the LVL had been cut the beam was laid out to ensure that all of the cuts matched those in the drawings and small holes were drilled in the joins of the

LVL and between layers to allow for the use of small dowels to hold the boards in position during the gluing process.

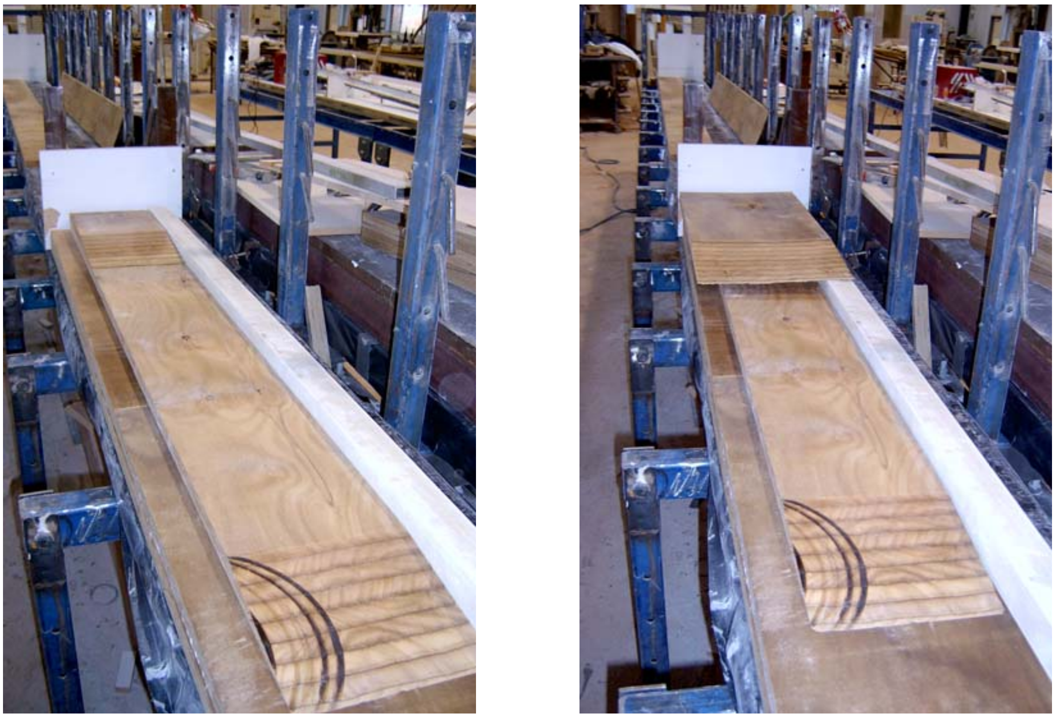


Figure 5.3 Showing scarf positioning in beam before gluing.

5.5 Gluing the Beam

5.5.1 Glue Used

The glue used for this project was a two-part glue that is manufactured by Huntsman. The two parts need to be mixed thoroughly to ensure that the maximum strength can be achieved and care is taken when applying the glue to the surfaces to ensure that it is a consistent colour with no areas that are not mixed that would produce weak spots within the beams (figure 5.4).

Figure 5.4 Glue after it has been spread on the LVL.

5.5.2 Method

The beam is basically glued as three separate sections that are then glued together to produce the final beam. These three sections are the two side sections that include the full depth LVL and the laminates and the centre section that includes the two reinforcing modules and the LVL in between them.

The first glue up for the test beam was the two side sections with both of these sections being glued at the same time. The first step was to lay down one of the outside faces of the beam and glue the scarfs for that layer. The joins were then held in place using small wooden dowels placed in the holes that were drilled earlier. Wood dowels are used so that they will not interfere with any future drilling or cutting of the beam. After the first layer of LVL is in place the top face is covered with glue (figure 5.5) and the second layer is positioned again using dowels to hold the joins in position and also to keep the two layers in the same position relative to each other.

Figure 5.5 Glue being spread between LVL layers.

Another glue line is then placed on top of the second layer of LVL and then the laminate is positioned. A layer of greaseproof paper is then put on top of the laminate and the process is then repeated for the other side section on top of the first section. This is done to make the clamping process easier as both sections can be clamped with the same clamps. A final layer of greaseproof paper is placed over the top of the two sections and weights are placed on top that are the clamped to ensure a proper spread of the glue throughout all of the glue lines (see figure 5.6). It is also beneficial to remove as much of the squeeze out glue as possible while it is still wet as this saves on sanding once the glue has set.

Figure 5.6
Photo showing two side sections separated by greaseproof paper with weight and clamps in place.

The centre section of the beam is made separately from the two side sections. This is because this section requires pressure from two directions while it is being glued. The first step in manufacturing this section is to glue the internal LVL strips together using the same method used on the outer sections. After the LVL is glued the reinforcing modules are then attached to the sides and after all of the glue lines have been completed it is necessary to apply a clamping force from both directions to ensure a good bond between all of the materials (figures 5.7 and 5.8 below shows the gluing of the centre section).

Figure 5.7
Clamps applied to entire length during gluing of centre section.

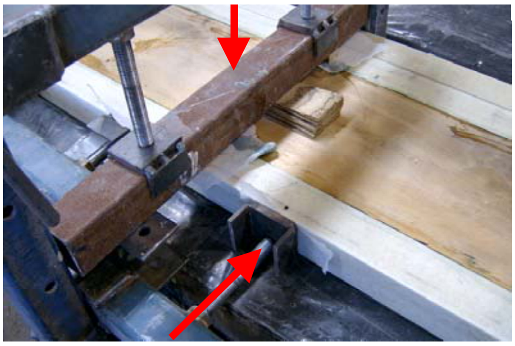


Figure 5.8
Close up view of clamping in two directions.

After the three separate sections had been glued, allowed to set and cleaned up by sanding, it was then possible to glue the three separate sections together to form the final beam. This process is similar to that used to glue up the side sections with one side section being laid on the jig, followed by a glue line on which the centre section is placed, then another glue line and finally the second side section. Care must be taken to ensure that each section is square with the others and after the glue lines are finished weights are again applied with addition clamping force applied from the jig. It is at this stage that the centre section can be manipulated using additional side clamping. This is done to ensure that the 2mm gap is maintained around the edges of the centre section as shown in the drawings (Appendix C). This gap is used so that sanding of the final beam can be completed if necessary without the loss of any of the pultrusion material. After the final gluing was finished excess squeeze out glue that could not be removed while still wet is sanded off and the beam was ready for testing after an additional week to allow the glue to achieve its maximum strength.

In the full size beams that are constructed by the FCDD, that this beam was base on, it is interesting to note that the reinforcing modules do not travel the full length of the beam. This is done because the LVL has enough capacity to handle the shear forces encountered and also to leave areas that are easy to cut and drill during installation without damaging the reinforcing modules.

5.6 Conclusions

The manufacture of hybrid beams is a labour and time intensive process. To improve this several things could be done to lower construction times and reduce labour. The LVL that is used could be manufactured to the full length of the beam thus eliminating the need for scarfs and the join of individual boards along the length of the beam. The module manufacture could be made into a continuous process whereby reinforcing modules are manufactured and stockpiled so that they could be used whenever necessary not made individually for each beam that is required. Alterations to the way that the pultrusions are delivered by the manufacturer could also aid in construction times. If the pultrusions could be delivered as a channel section along with a matching top (figure 5.9) there would be no need to cut them so that the steel and polymer concrete could be positioned.

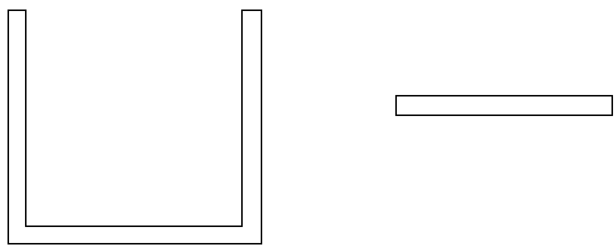


Figure 5.9 Pre-cut pultrusion sections

Changes such as these to the current manufacturing process would reduce construction time therefore reducing the cost of hybrid beams.

CHAPTER 6

TESTING AND RESULTS

6.1 Testing

A 4-point bending test (figure 6.1) was conducting with a test span of 3800mm and a loading span of 1000mm, with the final dimensions of the beam being 300mm deep x 165mm wide.

Figure 6.1 Test beam prior to testing.

The test was conducted using a controlled head displacement rate of 25mm/minute and the loading was continued straight through from the start of the test until the final failure. Strain gauges were attached to the compression pultrusion, tension pultrusion and in the shear zone of the LVL. A string pot and was also used to measure deflection throughout the test. Data from the strain gauges, string pot and load cell were recorded electronically for the duration of the test with ten data points being recorded every second. The total duration of the test was around 20 – 25 minutes, which resulted in a considerable amount of data at the completion of the test however it is desirable to have a close spacing between data points as anything that happens unexpectedly or very quickly during the test will be captured.

6.2 Results

During the test data was recorded electronically and graph below (figure 6.2) shows a plot of the load vs. the deflection.

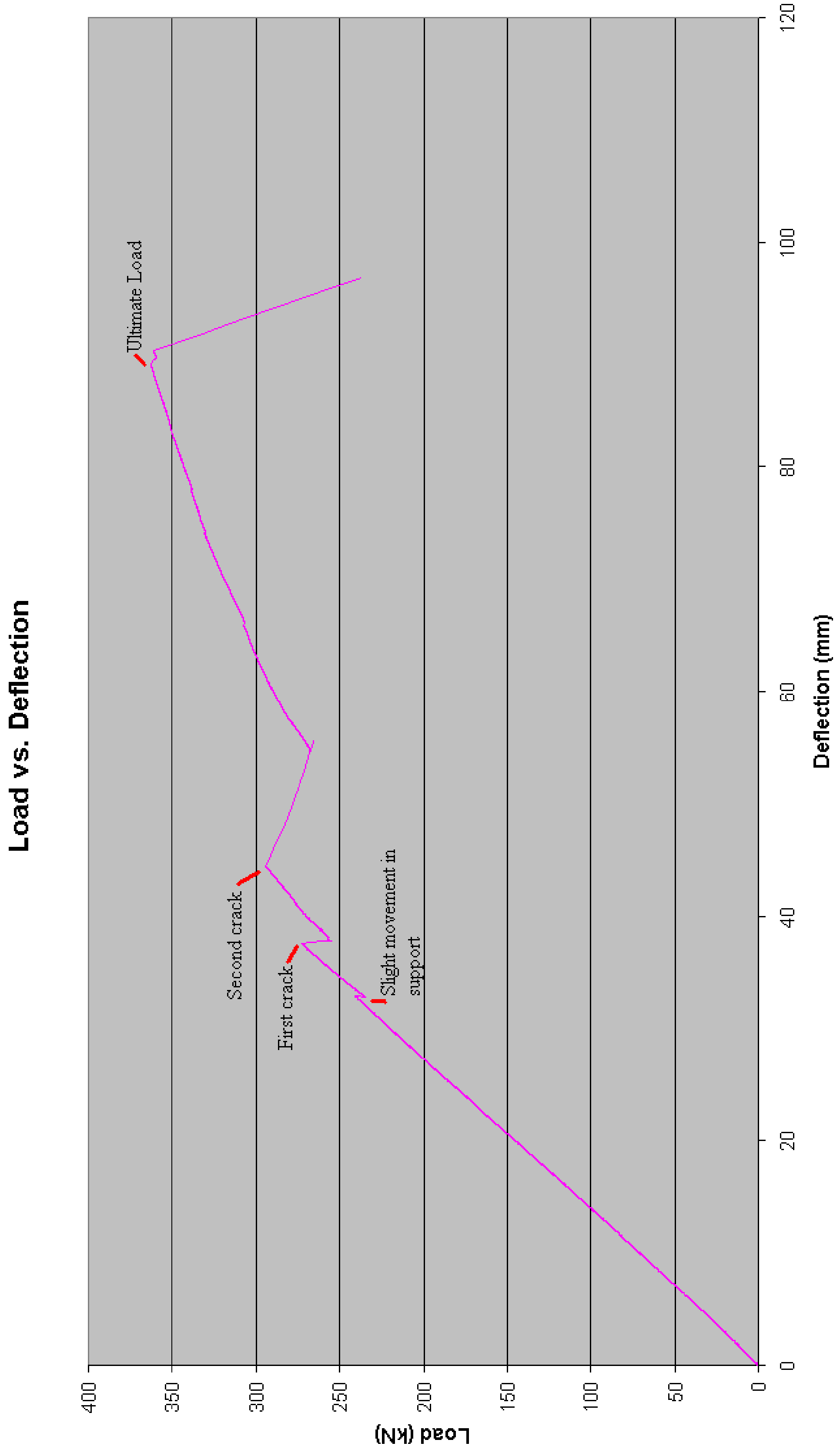
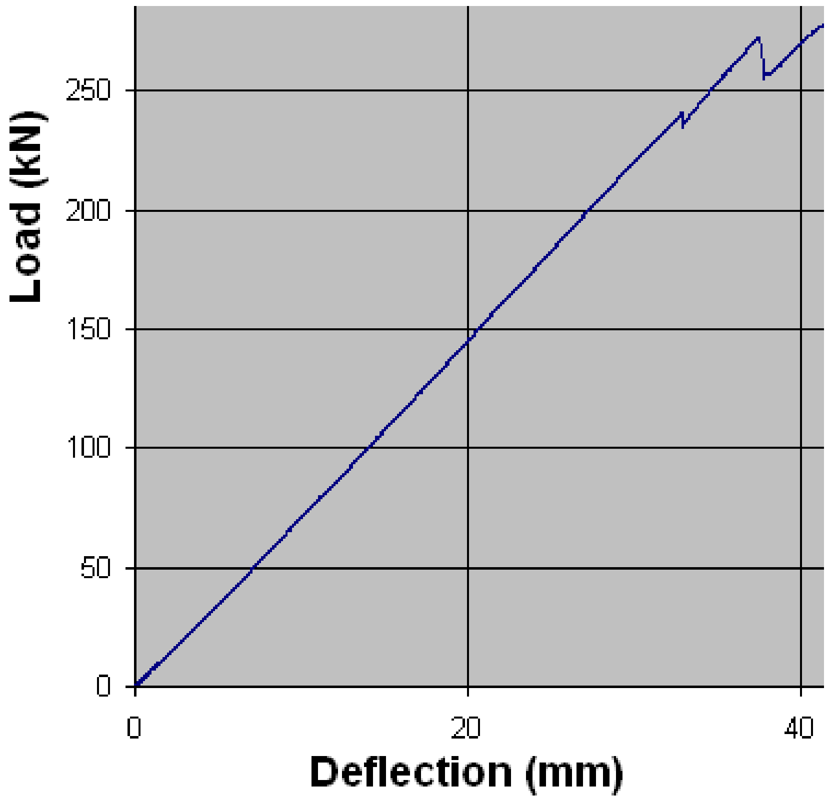


Figure 6.2 Load vs. Deflection Plot.

The main points of interest in this graph are;

- the linear portion at the beginning up to the first major crack in the LVL,
- the slight curve developing in the graph after the first crack but prior to the second crack,
- the change in the slope of the graph after the recovery from the second crack and the curve of the graph in this region,
- and the ultimate load achieved and a comparison of this to the loads where cracking of the LVL occurred.

6.2.1 Up to The First Crack



It can bee seen that at the beginning of the test the relationship between the load and the deflection of the beam was linear. This linear relationship continued at a rate of approximately 7.5kN/mm (P/δ) up until the first crack appeared in the LVL at approximately 275kN (figure 6.3). This can then be converted to an equivalent Modulus of Elasticity (E) value for comparison to other materials using the following formula;

$$\delta = \frac{P(L_o - L_i)(2L_o^2 - L_i^2 + 2L_oL_i)}{96\ EI}$$

from this formula an equivalent E value can be calculated using;

$$E = \frac{P}{\delta}\ \frac{(L_o - L_i)(2L_o^2 - L_i^2 + 2L_oL_i)}{96\ I}$$

where; P = load (N)

L_o = distance between supports (mm)

L_i = loading span (mm)

E = modulus of elasticity (MPa)

I = second moment of area = $\frac{bd^3}{12}$

$$= 7500 \times \frac{(3800-1000)(2 \times 3800^2 - 1000^2 + 2 \times 3800 \times 1000)}{96 \times 355\ 500\ 000}$$

$$= 21\ 832 \text{ MPa}$$

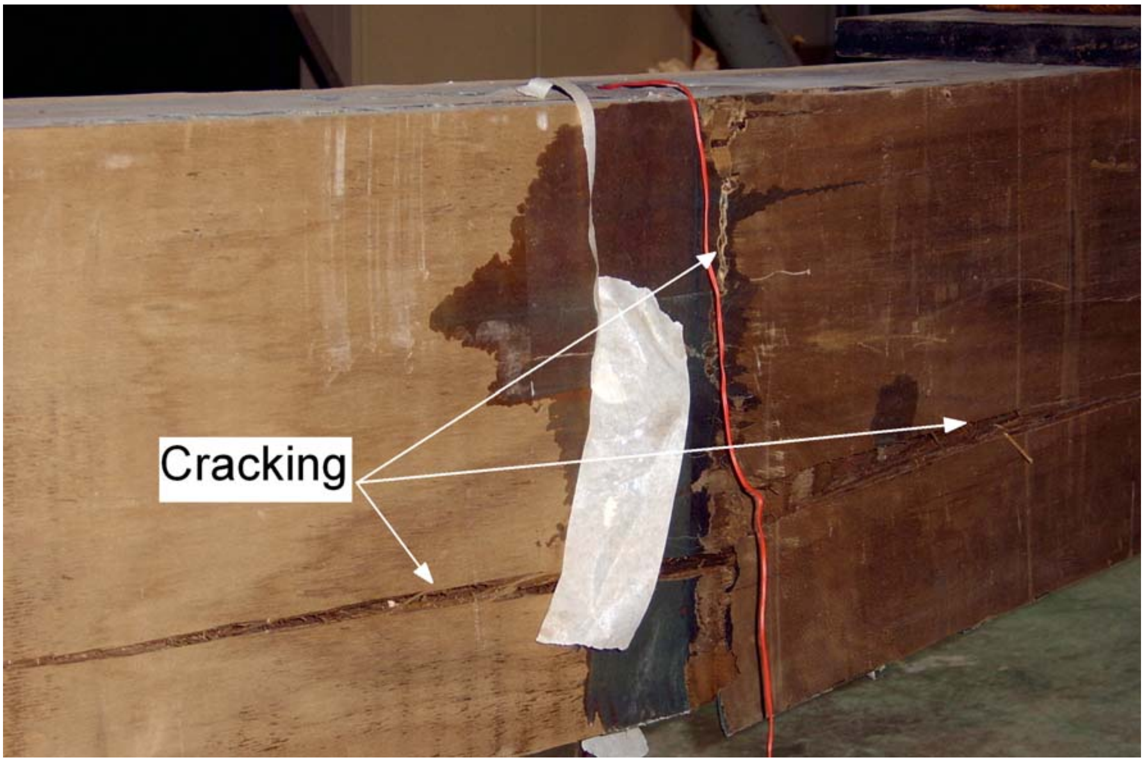


Figure 6.3 First cracking of LVL.

As can be seen in figure 6.3 the cracking that occurred in the LVL is quite pronounced and gives a good indication that a considerable amount of force had been applied to the beam. It can also be seen that the join in the outside layer of LVL that was present almost exactly at centre span also aided in the crack propagation up the beam. It should also be noted that the small decrease in load in the linear section of the graph at approx 240kN was due to some movement in the supports during the test, not any movement or failure within in the beam itself.

6.2.2 Between Cracks

Immediately after the first LVL cracking occurred there was a significant drop in the load of approximately 17kN. After this crack further load was applied to the beam and as the graph shows slope of the graph was fairly close to that of the first section prior to the crack, however it can be seen that the graph is starting to move away from the linear relationship between load and deflection. This is a result of the compression steel in the top reinforcing module beginning to yield, which can be seen in the Strain vs. Moment plot figure 6.4.

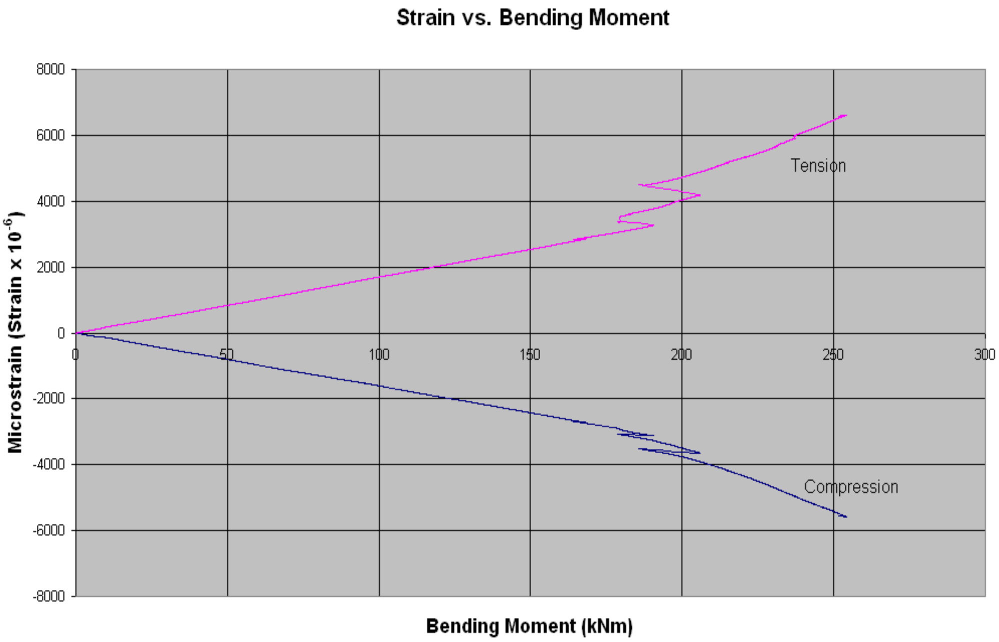


Figure 6.4 Strain vs. Bending Moment

It was predicted from the computer modelling that this yielding would occur at approximately 240kN, and yielding of the steel in the test beam can be seen at approx 250kN. This continued up to a load of approx 295kN at which point there was another significant crack in the LVL on the opposite side of the beam (figure 6.5) that again was a very prominent crack. After this second crack the deflection values recorded were not accurate due to the LVL moving where the string pot was attached relative to the rest of the beam due to the crack (figure 6.5).

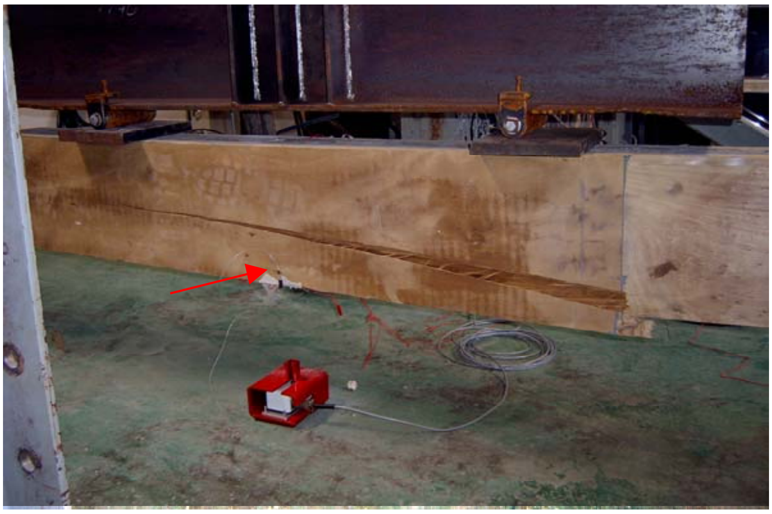


Figure 6.5 Second crack in LVL

6.2.3 After LVL Cracking

After the LVL had cracked the change in the slope is quite noticeable as the deflection increased for progressively less and less load. A ductile failure was occurring as the compression steel continued to yield. This type of failure is quite desirable, as the large deflections that are experienced under high loads would give a clear indication that the beam is being overloaded. This load deflection relationship continued up to the ultimate load of 360kN at which point ultimate failure occurred.

6.2.4 Ultimate Failure

When the final failure of the beam was reached there was a massive failure within the tension pultrusion at which point the beam was no longer able to take any significant amount of load. This failure occurred as a result of a one of the layers in the outer surface of the tension pultrusion being torn apart.

Figure 6.6 Failure of tension module.

The above photo (figure 6.6) shows the tension pultrusion after the final failure. The module was still intact however it was no longer bonded to the laminate panels and therefore was unable to be effective in carrying loads. Figure 6.7 shows how the failure of the bond between the pultrusion and the other materials resulted in the movement of the module within the beam.

Figure 6.7 Movement of tension pultrusion within beam.

6.3 Pultrusion Behaviour

The strain gauges that were place on the pultrusions were used to see how the pultrusions were behaving during the test and compare this behaviour with that predicted. From the strain gauge data that was recorded during the test it was possible to produce a graph of Strain vs. Bending Moment, with;

$$\text{Bending Moment (kNm)} = \frac{\text{Load (Support span – Load span)}}{4}$$

This gave the following graph.

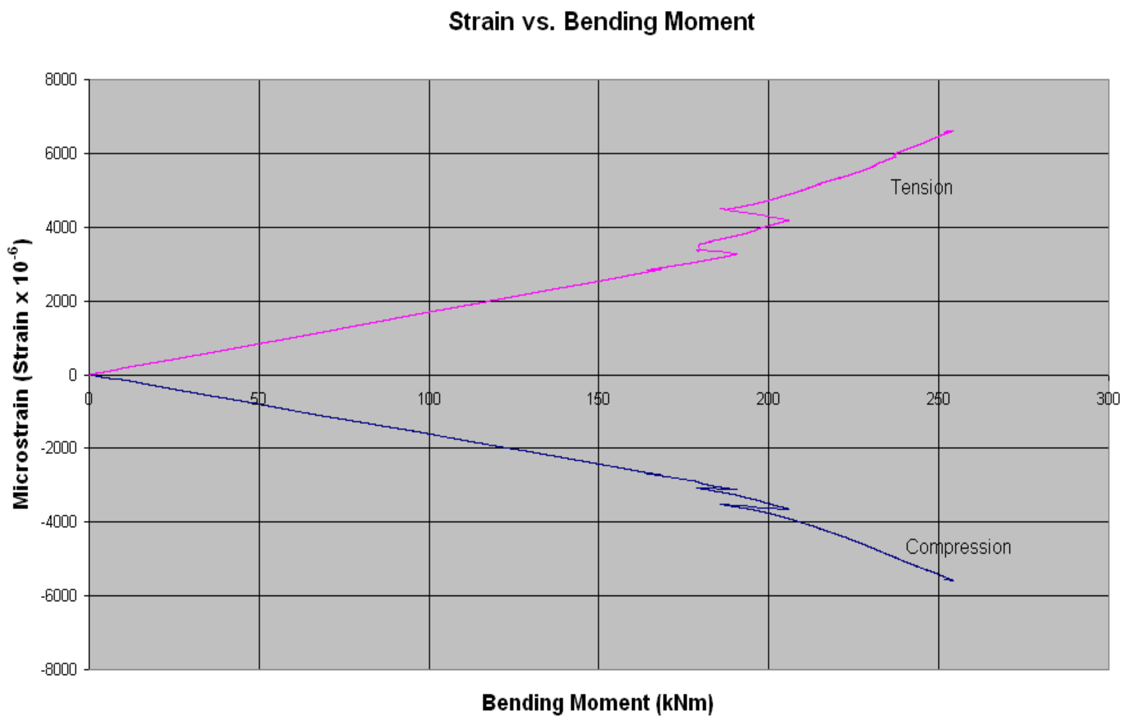


Figure 6.8 Strain vs Bending Moment Plot

As this graph shows the relations ship between strain and bending moment is linear up until the first cracks occur in the LVL. After the point where the LVL cracks there is quite a large increase in strain for relatively little increase in bending moment. This is due to the reinforcing modules having to ‘catch’ the load that was being carried by the LVL, the extent of this cracking through the beam can be seen in figure 6.9.

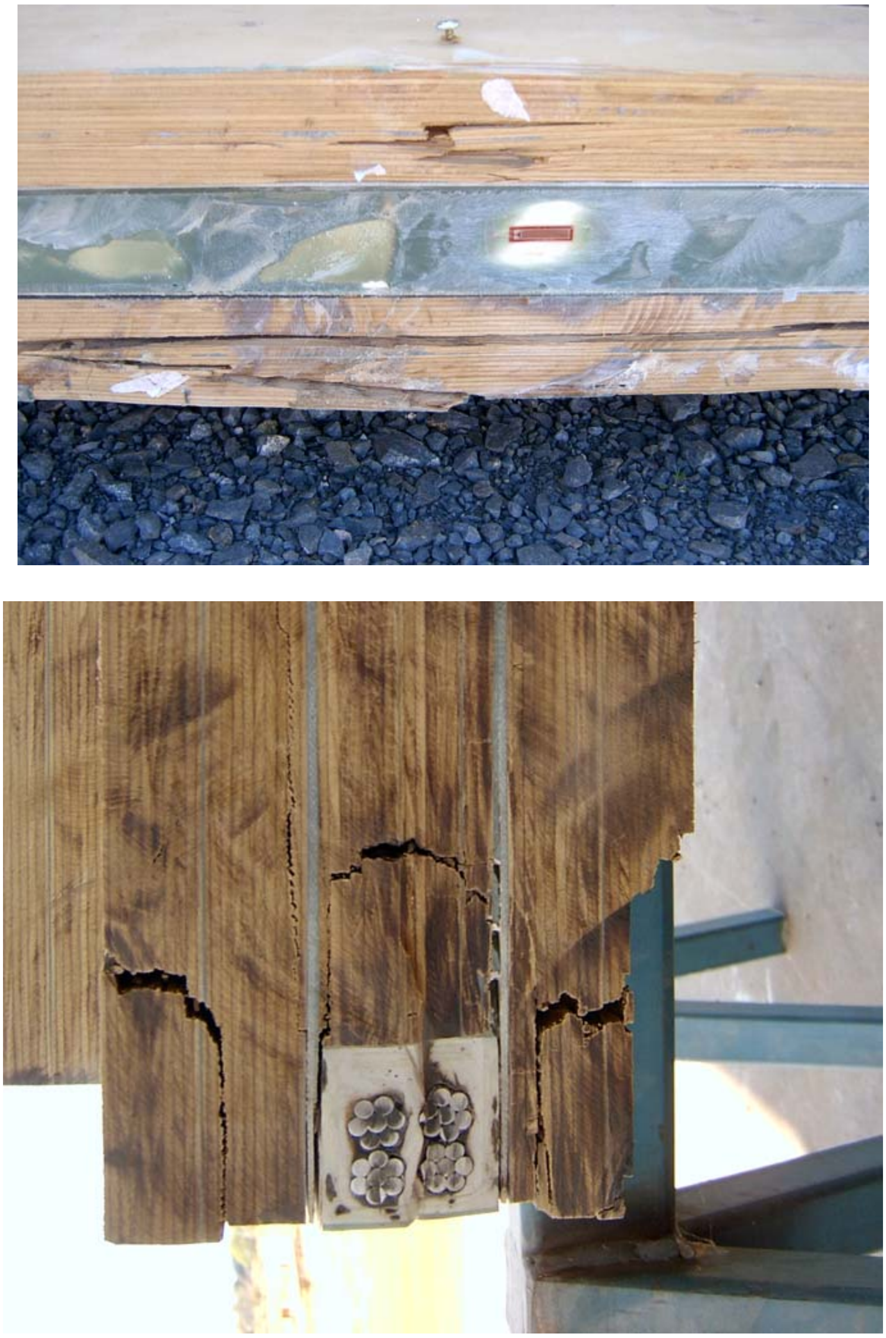


Figure 6.9 Extent of LVL cracking through beam section

Once cracking of the LVL had occurred the load that was being carried to these sections had to be transferred to the reinforcing modules. Due to the extensive cracking occurring around centre span of the beam where the strain gauges were located this resulted in noticeable change in the gradient of both the compression and tension lines in the graph (figure 6.8).

From the strain gauge data a graph of the relationship of Stress vs. Load was produced to see the relationship between the stress in the top and bottom reinforcing modules throughout the test with the stress being calculated using the following formula;

$$\text{Stress (MPa)} = \frac{E}{\varepsilon}$$

where; E = Modulus of elasticity (MPa)

(E value obtained from the flexural testing = 32 238 MPa)

ε = Strain

This produced the following graph.

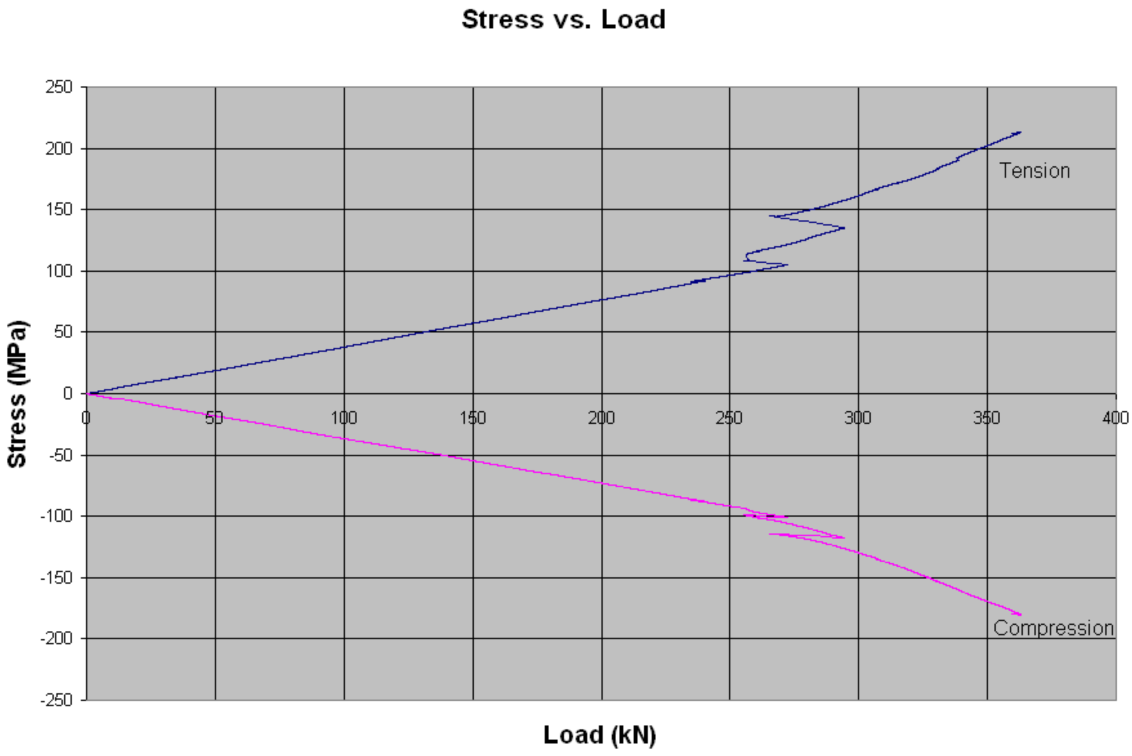


Figure 6.10 Stress vs. Load plot.

Again this graph shows that at the point where the outer layers of LVL crack and the load at the cracks is transferred to the reinforcing modules of the beam there is a considerable increase in the stress in both the compression and tension modules.

These graphs are essentially the same shape because of the linear relationship between load and bending moment, and strain and stress.

6.4 Comparison of Results

From the data recorded during the tests it is possible to compare the results achieved from the test beam to those calculated using computer modelling. The graph below (figure 6.11) shows a plot of the predicted and actual Load vs. Deflection curves.

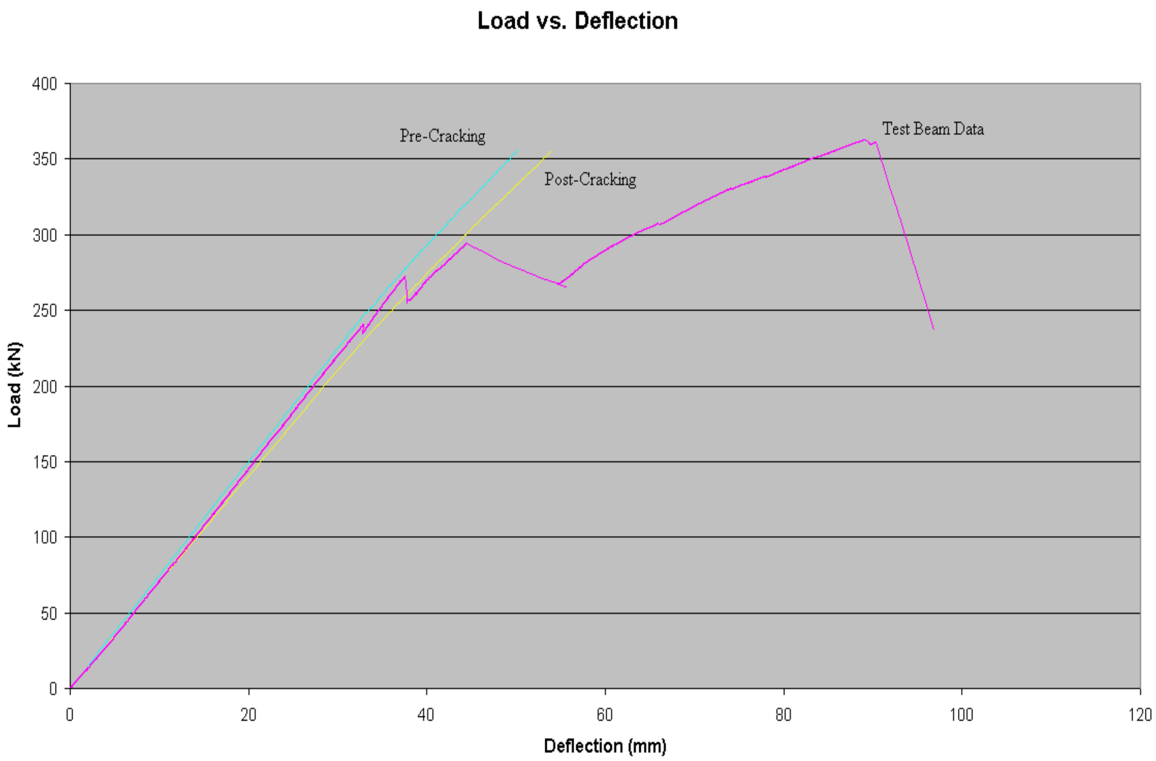


Figure 6.11 Comparison of predicted and test beam results.

As figure 6.11 shows the predicted pre-cracking and measured results vary slightly during the linear phase of the load/deflection relationship. This is also confirmed by the comparison between the predicted E value and the equivalent E value.

Predicted E value = 24 742MPa

(Calculated by dividing the EI value used in the computer modelling check by the formula for calculating I for a solid section = $bd^3/12$). It should be noted that this E value does not take into account the effects of shear bending therefore it is higher than the E value predicted by the orthotropic models, which are approx. equivilant to that of an F34 hardwood beam (21 500Mpa) as can be seen in figure 6.12.

Equivalent E value = 21 832 MPa.

After the first crack occurs it can be seen that the test beam data drops down to the match the predictions for the post-cracking behaviour and both plots start to move away from the linear relationship between load and deflection experienced during the initial stages as the compression steel begins to yield. Due to the inaccuracy of the deflection data that was recorded after the second crack the predictions that were made are only accurate up until this second crack occurred.

From these values a comparison can also be made (over the linear section of the load/deflection relationship) between the test beam and other beams with the same section size that are made from different timber grades. Figure 6.12 shows the comparison of the test beam with the finite element predictions and also a solid F27 and solid F34 grade hardwood beam.

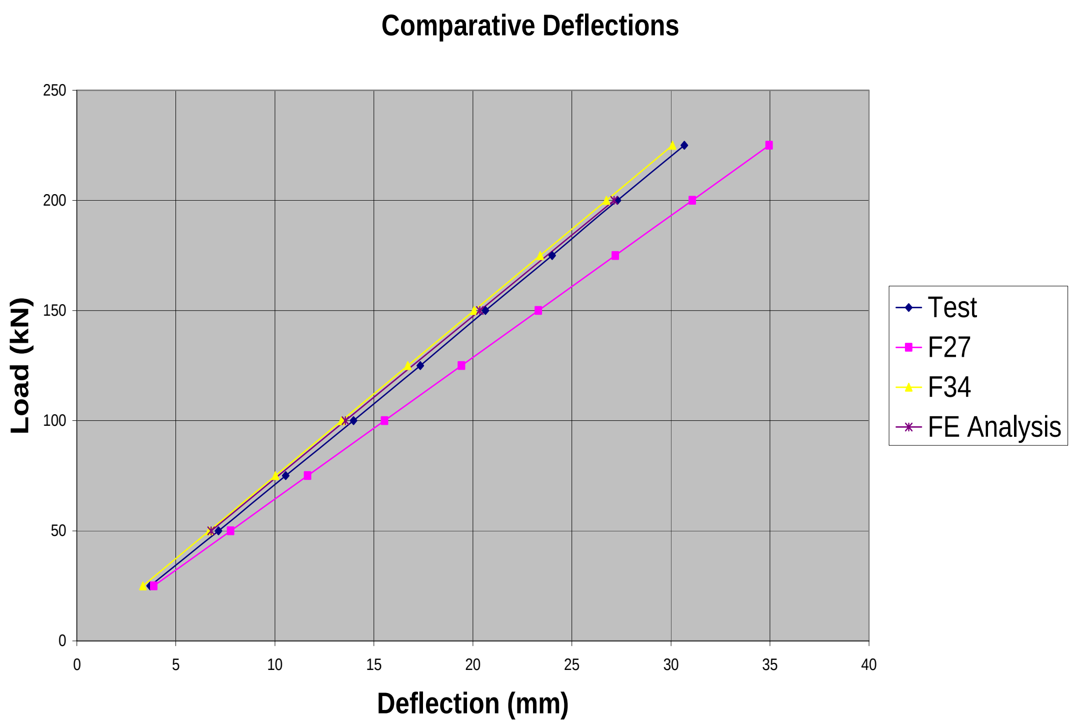


Figure 6.12 Comparative Load/Deflection relationship

As figure 6.12 shows the load/deflection or stiffness of the hybrid test beam was comparable to that of a solid hardwood beam of F34 grading. This is the highest stress grade of timber classified by the standard AS 1720.1 Timber Structures, and has a Modulus of Elasticity = 21 500MPa. These results from the test beam indicate that this type of beam is capable of reproducing the stiffness and strength of a hardwood beam of comparable size.

CHAPTER 7

CONCLUSIONS

AND FURTHER WORK

7.1 Conclusions

This project has looked at the concept of a hybrid fibre composite beam and the behaviour, construction and testing of such a beam. As a result of the work completed several conclusions could be drawn about hybrid beams, their properties and behaviours and the accuracy to which these properties and behaviours could be predicted and modelled. These conclusions include;

- The stiffness that was achieved from the test beam and also from the computer modelling was high enough to make hybrid beams a viable alternative to hardwood bridge girders.

- There was good evidence of a ductile type of failure mode.

- It appeared with the test beam that there were no issues associated with the type of glue or method used in construction of the beam.

- This type of hybrid beam can produce a suitable alternative to hardwood beams of similar size.

- Finite Element analysis is a suitable tool for predicting the behaviour of this hybrid type of construction.

- More extensive materials testing may be required to more accurately create computer models.

7.1.1 Stiffness

Results from both the computer modelling and associated checks and from the actual test beam indicate hybrid beams can achieve a very high level of stiffness. This is reflected in the results obtained that indicate a stiffness of the beam that very closely matches that of a F34 grade hardwood beam of the same dimensions. F34 is the highest strength grade of timber currently classified by the Australian Standard AS 1170 and with supplies of old growth hardwood on a steady decline the chances of finding a solid hardwood beam of similar dimensions to the test beam in this project with a F34 strength grade is low.

This high stiffness is predominantly due to the inclusion of the reinforcing steel in the reinforcing modules. This is clearly reflected in the various computer models that show what effect each component has on the deflection of the beam. These models show that under a 100kN load the deflection is greatly reduced from around 20mm to less than 12mm, a considerable decrease. The use of this reinforcing steel also has another advantage in the ductile failure mode that is produced as a result of its use.

7.1.2 Ductile Failure

It is generally accepted that a ductile failure mode is quite desirable as the increased deflections that are experienced under higher loading conditions can give a good indication that a failure may be immanent. This ductile failure was also desired in these hybrid beams and evidence from the test beam indicated that ductile failure modes could be expected.

The ductile failure within this beam occurred as a result of the compression steel yielding and this yielding can clearly be seen in the Load vs. Deflection curve that was produced from the testing results. This graph indicated a good linear relationship between load and deflection in the early elastic stages of the graph up to a load where yielding began to occur in the reinforcing steel in the compression module. After yielding occurred there was a gradual change in the gradient of the load/deflection curve that resulted in greater deflections over a given load range than those experienced in the elastic section of the graph.

This type of ductile failure mode is very desirable as it can give a good indication of an impending failure. Another benefit of this beam is that quite prominent cracking of the LVL occurs at a load that is considerably lower that the ultimate capacity of the section. This too was reflected in the test beam with the first cracks of the LVL occurring at a bending moment that was approximately three quarters of the maximum bending moment (in the case at a load 80kN lower). This cracking is also a good indication that the beam has been overloaded however the fact that there is still a good amount of capacity means that a failure will not occur immediately allowing for measures to be taken to prevent such a failure.

7.1.3 Construction Method

Inspection of the beam after the testing indicated that there were no failures occurring as a result of weak glue lines. This indicates that this form of construction of the beam where the section is effectively built up in a number of layers is appropriate. Although there was some evidence of the bond between the glue and the laminate panel coming apart (figure 7.1) this was most probably as a result of the cracking of the LVL and the energy release at failure rather than the cause of the failure.

Figure 7.1 Break in bond between laminate and LVL.

7.1.4 Suitable Alternative

The data and results obtained from computer modelling and testing of the 4-metre test beam in this project indicate that this type of hybrid beam can produce a suitable alternative to hardwood. This would have to be further investigated however to determine the long term creep behaviour and problems that may result from durability issues over a longer period of time, however the time limitations of this project limited this type of research from being undertaken.

7.1.5 Adequacy of Finite Element Models

When compared to the results obtained from the test beam it was found that the predicted results obtained from the FE models gave a good representation of the actual results provided the LVL was modelled as an orthotropic material. With further refinement to the models and more accurate materials testing data the accuracy of these models could be further increased.

It was found that the FE models quite accurately predict the behaviours that were observed in the elastic stage. FE models were also able to quite accurately predict the load at which the compression steel would yield and also produced an accurate representation of the behaviour after the initial cracking up to the second crack. Results for the behaviour after the second crack are less accurate due to the errors in the deflection data from the test. Repositioning of the point where the deflection measuring device was attached to the beam could rectify this problem in future tests. Despite this it is still believed that FE analysis is suitable and accurate for use in this type of application.

7.1.6 Materials Testing

The testing that was conducted on the GFRP material was found to be quite adequate in providing properties and data for the computer models. However, issues were found with the results obtained for the LVL testing. Although all of the LVL tests were conducted to, or as closely as possible to, the relevant standards it was found that in some cases the results obtained seemed different to those that were expected.

An example of this is the difference between the Modulus of Rapture (MOR) that was obtained from the flexural tests and the tensile strength that was obtained from the tension tests. As the major failure mode that occurs in a flexural failure is tensile failure in the tension zone of the specimen it was expected that the two values of MOR and tensile strength would be fairly similar. Table 7.1 shows the difference between the tensile strength and the MOR (or flexural strength for the GFRP) for both the LVL and the GFRP.

Tensile Strength	MOR (flexural strength)	% MOR of Tensile Strength
LVL 38.77MPa	LVL 77.2MPa	200%
GFRP 471.91MPa	GFRP 509.24MPa	108%

Table 7.1 Comparison of Tensile Strength to MOR

As table 7.1 shows the MOR for LVL is almost double the tensile strength of the LVL where as the two corresponding values for GFRP are very similar. It is believed that this variation may be due to the orientation of the test specimen in the flexural test. The orientation specified in the standard test is for each ply in the test specimen to be orientated horizontal, however, this is not how the plies are orientated within the beam. In the beam these plies are orientated vertically and it is believe that if the test were to be conducted with this ply orientation that the results would be more useful and provided more accurate predictions of LVL cracking loads.

Refinements also have to be made to the shear testing of the LVL so that an accurate shear modulus can be obtained. This is a vital property in the computer modelling and slight variations in this value can result in predictions that are inaccurate.

7.2 Opportunities for Further Research

From the results and conclusions drawn from this research project several areas where further research could be undertaken have been found.

Long-term durability of the materials could be investigated more thoroughly to determine what durability problems may occur from the use of LVL and the other materials that are used in this type of hybrid beam. Generally plywood and LVL are not used in outdoor applications and investigations could be conducted into the best treatment process that would be applicable to different situations. This research could look at issues of waterproofing and the prevention of attack from insects as well as the suitability of this type of beam to various climates such as low temperatures and high humidity’s.

Another area that exists for further research to be conducted is the behaviour of this type of beam under more long term and repetitive loading situations that would be experienced in a structure. The creep behaviour of these beams could be investigated along with any possible issues that may arise from fatigue.

Finally investigations could be preformed into finding suitable alternatives for the LVL in these hybrid beams. The use of composite panels is one possibility for this that may reduce the problems of durability. This could result in a lighter beam that would still be able to produce the same performance with a higher durability.

Further research into any of these areas would be quite interesting and may lead to new developments that change the way composites and hybrid structures are viewed.

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APPENDIX A

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Scott McDonald

TOPIC: BEHAVIOR OF HYBRID FIBRE COMPOSITE BEAMS

SUPERVISORS: Craig Cattell
Tim Feldt

SPONSORSHIP: Faculty of Engineering, USQ

ENROLMENT: ENG 4111 – S1, D, 2005;
ENG 4112 – S2, D, 2005

PROJECT AIM: This project aims to examine the behavior of hybrid fibre composite, timber beams by testing the properties of the materials used and using finite element computer software to model the behaviors.

PROGRAMME: **ISSUE A, 18th March 2005**

1. Research the available background information on the use of fibre composite materials in the strengthening of timber beams and the materials used.

2. Materials testing of the materials that are used in hybrid beams to determine strength properties.

3. Use results from materials testing to create and analyze finite element model of a hybrid beam under different loading conditions.

4. Testing of a complete hybrid beam.

As time permits

5. Investigation into the effects of the different code defined loads on hybrid beams.

AGREED:

.________________ (Student) .__________________,
(Supervisors)

.___/ ___/ ___   ___/ ___/ ___   ___/ ___/ ___.

APPENDIX B

TENSILE TESTING REPORT

ISO 527-4/2/2: 1993 Plastics – Determination of Tensile Properties

Test Date:	**Test Method:**	**Operator:**
16-Mar-05	FCDD Laminate Tensile Test - Dual Ext - Normal Tension (ISO 527).msm	Wayne Crowell

Sample Information:

(A) Client Name:	FCDD
(B) Mailing Address:	USQ
(C) Mailing Address:	Toowomba
(D) Mailing Address:	Qld 4350
(E) Attn:	Scott
(F) Phone:	
(G) Fax:	
(H) Client Job ID:	50 x 50 x 5 Pacific Composites Pultrusion
(I) STS Job Number:	STS-05-035-T
(J) Specimen Orientation:	0 Degrees
(K) Sample Description:	Laminate Test Panel
(L) Layup Sequence:	As Per Details Supplied by Client
(M) Principle Dimensions:	50 x 50 x 5 Pultrusion
(N) Method of Manufacture:	Details Not Supplied by Client
(O) Laminate Cure Schedule:	Details Not Supplied by Client
(P) Test Room Conditions:	21°C, 65% RH
(Q) Conditioning Temp. & RH:	23°C, 50% RH Constant for 24 Hours
(R) Clamping Pressure (MPa):	8
(S) Testing Speed (mm/min):	2.0
(T) Specimen Prep. Method:	Specimens cut by diamond coated cutting wheel, edges sanded smooth & defect free.

Test Equipment Details:

Test Machine:	MTS 810 Material Test System
Location:	Z104 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	10/02/2005
Expiration Date:	10/02/2006
Strain Measurement Device:	MTS Extensometer Model No. 632.85F-14
Extensometer Calibration Date:	26/08/2004
Load Cell Calibration Date:	10/02/2005
Expiration Date:	10/02/2006

Specimen Results:

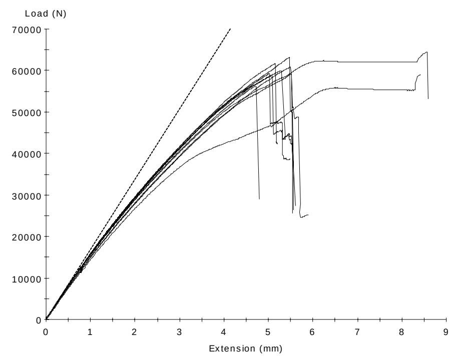
Specimen #	Thickness1 mm	Thickness 2 mm	Thickness 3 mm	Width 1 mm	Width 2 mm	Width 3 mm	Avg Thick mm	Avg Width mm	Area mm^2
1	5.30	5.31	5.33	23.96	23.99	23.99	5.31	23.98	127.41
2	5.20	5.20	5.17	25.35	25.35	25.36	5.19	25.35	131.58
3	4.96	4.92	4.95	24.48	24.50	24.42	4.94	24.47	120.95
4	4.93	4.95	4.94	24.87	24.83	24.87	4.94	24.86	122.79
5	5.34	5.25	5.20	24.90	24.86	24.88	5.26	24.88	130.95
6	5.17	5.17	5.13	25.36	25.32	25.29	5.16	25.32	130.58
7	5.39	5.36	5.40	24.85	24.88	24.88	5.38	24.87	133.88
8	4.79	4.80	4.77	24.70	24.71	24.75	4.79	24.72	118.33
9	5.21	5.26	5.29	24.88	24.94	24.90	5.25	24.91	130.84
10	5.27	5.20	5.19	25.10	25.12	25.13	5.22	25.12	131.11
Mean	**5.16**	**5.14**	**5.14**	**24.84**	**24.85**	**24.85**	**5.14**	**24.85**	**127.84**
Std Dev	**0.20**	**0.19**	**0.20**	**0.41**	**0.40**	**0.40**	**0.19**	**0.40**	**5.28**

Specimen Results:

Specimen #	Peak Load N	Peak Stress MPa	Modulus of Elasticity MPa
1	59073	463.63	30267
2	59321	450.83	32005
3	59136	488.94	33301
4	56178	457.51	33962
5	64542	492.87	30908
6	63200	483.98	32075
7	59969	447.92	30977
8	60841	514.18	33807
9	61645	471.14	32716
10	58745	448.06	32358
Mean	**60265**	**471.91**	**32238**
Std Dev	**2400**	**22.43**	**1253**

Specimen Comments:

Specimen #	Failure Status
1	Acceptable
2	Acceptable
3	Acceptable
4	Acceptable
5	Acceptable
6	Acceptable
7	Acceptable
8	Acceptable
9	Acceptable
10	Acceptable



Load vs Extension Plot

COMPRESSION TESTING REPORT

ISO 14126: 1999 Fibre-Reinforced Plastic Composites – Determination of Compressive Properties in the In-Plane Direction

Test Date:	**Test Method:**	**Operator:**
17-Mar-05	FCDD - Laminate Compression (ISO 14126).msm	Wayne Crowell

Sample Information:

(A) Client Name:	FCDD
(B) Mailing Address:	USQ
(C) Mailing Address:	Toowoomba
(D) Mailing Address:	Qld 4350
(E) Attn:	Scott
(F) Phone:	
(G) Fax:	
(H) Client Job ID:	50 x 50 x 5 Pacific Composites Pultrusion
(I) STS Job Number:	STS-05-035-C
(J) Specimen Orientation:	0 Degrees
(K) Sample Description:	Laminate Test Panel
(L) Layup Sequence:	As Per Details Supplied by Client
(M) Method of Manufacture:	Details not Supplied by Client
(N) Nom. Specimen Dimensions (mm):	140 x 12.5 x 5
(O) Specimen Gauge Length:	12
(P) Laminate Pretreatment:	Details not Supplied by Client
(Q) Test Room Conditions:	22°C, 82% RH
(R) Conditioning Temp. & RH:	23°C, 50% RH Constant for 24 Hours
(S) Testing Speed (mm/min):	1
(T) Specimen Prep. Method:	Specimens cut by diamond coated cutting wheel, edges sanded smooth & defect free

Test Equipment Details:

Test Machine:	MTS 810 Material Test System
Location:	Z104 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	12/02/2004
Expiration Date:	12/02/2005
Strain Measurement Device:	MTS Extensometer Model No. 632.29F-30
Strain Calibration Date:	13/02/2004
Expiration Date:	13/02/2005
Load Cell Calibration Date:	12/02/2004
Expiration Date:	12/02/2005
Compression Test Fixture:	End Load, Side Support
Serial Number:	ISO 14126-01

Specimen Results:

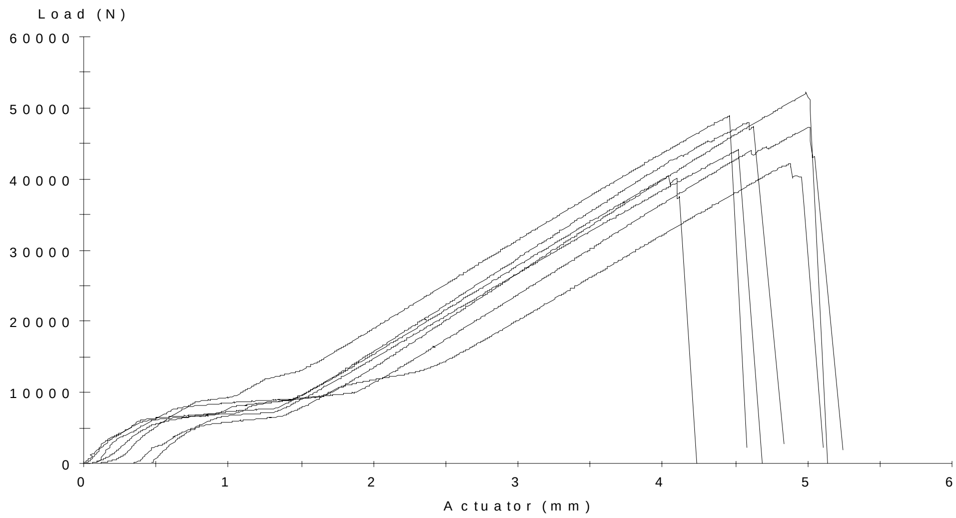
Specimen #	Width1 mm	Width2 mm	Width3 mm	Thick1 mm	Thick2 mm	Thick3 mm	Average Thickness mm	Average Width mm	Area mm^2
1	12.31	12.37	12.35	4.88	4.90	4.94	4.91	12.34	60.56
2	12.32	12.32	12.32	5.07	5.00	5.02	5.03	12.32	61.97
3	12.33	12.39	12.41	5.23	5.24	5.23	5.23	12.38	64.77
4	12.29	12.38	12.42	5.44	5.41	5.45	5.43	12.36	67.17
5	12.52	12.50	12.62	4.87	4.86	4.87	4.87	12.55	61.06
6	12.38	12.35	12.38	4.74	4.75	4.79	4.76	12.37	58.88
7	12.46	12.38	12.28	5.34	5.36	5.32	5.34	12.37	66.07
Mean	**12.37**	**12.38**	**12.40**	**5.08**	**5.07**	**5.09**	**5.08**	**12.38**	**62.93**
Std Dev	**0.09**	**0.06**	**0.11**	**0.26**	**0.26**	**0.25**	**0.26**	**0.07**	**3.10**

Specimen Results:

Specimen #	Peak Load N	Peak Stress MPa	Elongat-ion at Peak mm						
1	44208	729.93	3.75						
2	48001	774.60	5.81						
3	40397	623.70	4.63						
4	52152	776.38	4.99						
5	47306	774.74	5.02						
6	42214	716.94	4.57						
7	48906	740.18	4.47						
Mean	**46169**	**733.78**	**4.75**						
Std Dev	**4098**	**54.18**	**0.63**						

Specimen Comments:

Specimen #	Failure Mode
1	Through Thickness Shear
2	Through Thickness Shear
3	Through Thickness Shear
4	Through Thickness Shear
5	Through Thickness Shear
6	Through Thickness Shear
7	Through Thickness Shear



Stress vs Strain Plot

FLEXURE TESTING REPORT

ISO 14125:1998(E)/Method A/Class II

Fibre-Reinforced Plastic Composites - Determination of Flexural Properties

Test Date:	**Test Method:**	**Operator:**
16/03/2005	STS - Laminate Flexure (ISO 14125).msm	Wayne Crowell

Sample Information:

(A) Client Name:	FCDD
(B) Mailing Address:	USQ
(C) Mailing Address:	Toowoomba
(D) Mailing Address:	Qld 4350
(E) Attn:	Scott
(F) Phone:	
(G) Fax:	
(H) Client Job ID:	50 x 50 x 5 Pacific Composites Pultrusion
(I) STS Job Number:	STS-05-035(0)-F
(J) Layup Sequence:	As Per Details Supplied by Client
(K) Test Orientation:	0 Degrees
(L) Sample Description:	Laminate Test Panel
(M) Laminate Cure Schedule:	Details Not Supplied by Client
(N) Conditioning Temp. & Humidity:	23°C, 50% RH Constant for 24 Hours
(O) Test Room Conditions:	21°C, 65% RH
(P) Nominal Specimen Dimensions (mm):	200 x 15
(Q) Nominal Span (mm):	81
(R) Test Speed (mm/min):	2.0
(S) Surface in Compression:	Mould Side
(T) Cushion Material:	Not Used
(U) Specimen Preparation Method:	Specimens cut by diamond coated cutting wheel, edges sanded smooth & defect free.
(V) Equations Used:	ISO 14125: 1998(E) Clause 10.1

Test Equipment Details:

Test Machine:	MTS Alliance RT/10
Location:	Z126 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	08/06/2004
Expiration Date:	08/06/2005
Strain Measurement Device:	Axial Displacement of Crosshead
Strain Calibration Date:	08/06/2004
Expiration Date:	08/06/2005
Load Cell Calibration Date:	08/06/2004
Expiration Date:	08/06/2005

Specimen Results:

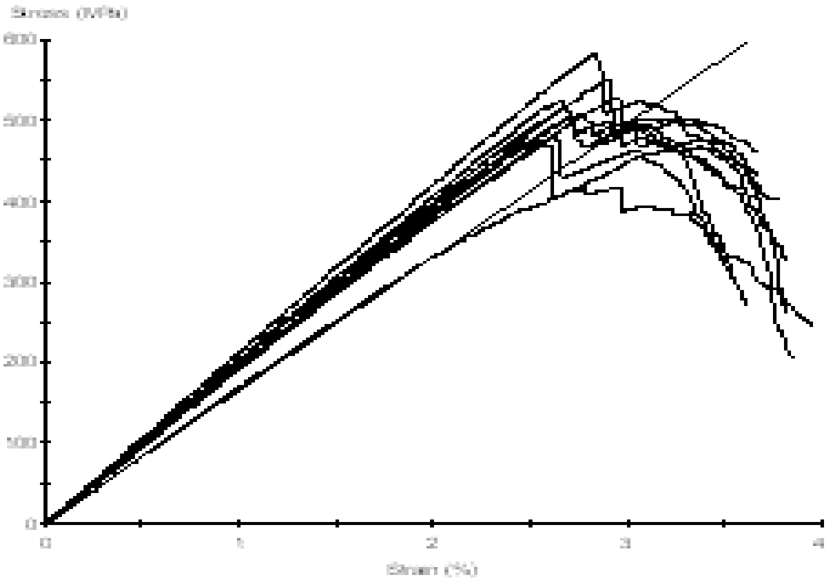
Specimen #	Thickness 1 mm	Thickness 2 mm	Thickness 3 mm	Width 1 mm	Width 2 mm	Width 3 mm	Average Width mm	Average Thickness mm	Peak Load N
1	5.09	5.09	5.09	14.93	14.90	15.09	14.97	5.09	1760
2	4.90	4.92	4.93	15.02	14.95	14.80	14.92	4.92	1561
3	4.93	4.86	4.94	15.15	15.27	15.30	15.24	4.91	1537
4	4.95	4.99	4.95	14.92	14.94	14.93	14.93	4.96	1765
5	5.26	5.27	5.23	15.04	15.06	15.10	15.07	5.25	1632
6	5.10	5.01	5.07	14.85	14.87	15.00	14.91	5.06	1583
7	5.11	5.15	5.13	15.21	15.14	15.21	15.19	5.13	1741
8	5.18	5.15	5.15	15.09	14.89	14.83	14.94	5.16	1698
9	5.04	5.14	5.11	15.07	14.86	14.84	14.92	5.10	1528
10	5.36	5.32	5.39	15.15	15.09	15.21	15.15	5.36	1490
Mean	**5.09**	**5.09**	**5.10**	**15.04**	**15.00**	**15.03**	**15.02**	**5.09**	**1629**
Std Dev	**0.15**	**0.15**	**0.14**	**0.12**	**0.14**	**0.18**	**0.13**	**0.14**	**104**

Specimen Results:

Specimen #	Peak Flexural Stress MPa	Deflection at Peak mm	Strain at Peak %	Flexural Modulus MPa
1	551.12	6.26	2.91	18579
2	525.68	5.92	2.66	20249
3	508.32	6.18	2.77	18599
4	582.98	6.25	2.84	21085
5	476.76	7.14	3.43	19447
6	504.08	5.84	2.70	18929
7	529.25	6.29	2.95	19001
8	518.86	5.71	2.69	20145
9	478.81	5.62	2.62	19853
10	416.55	6.03	2.95	16621
Mean	**509.24**	**6.12**	**2.85**	**19251**
Std Dev	**45.41**	**0.43**	**0.24**	**1226**

Specimen Comments:

Specimen #	Failure Mode
1	Tensile Fracture at Outermost Layer
2	Tensile Fracture at Outermost Layer
3	Tensile Fracture at Outermost Layer
4	Tensile Fracture at Outermost Layer
5	Tensile Fracture at Outermost Layer
6	Tensile Fracture at Outermost Layer
7	Tensile Fracture at Outermost Layer
8	Tensile Fracture at Outermost Layer
9	Tensile Fracture at Outermost Layer
10	Tensile Fracture at Outermost Layer



Stress vs Strain Plot

V-NOTCH SHEAR TESTING REPORT

ASTM D 5379

Test Date:	Test Method:	Operator:
23/03/2005	STS - Laminate Shear (ASTM D5379).msm	Wayne Crowell

Sample Information:

(A) Client Name:	FCDD
(B) Mailing Address:	USQ
(C) Mailing Address:	Toowoomba
(D) Mailing Address:	Qld 4350
(E) Attn:	Scott
(F) Phone:	-
(G) Fax:	-
(H) Client Job ID:	50 x 50 x 5 Pacific Composites Pultrusion
(I) STS Job Number:	STS-05-035-S
(J) Layup Sequence:	As Per Details Supplied by Client
(K) Sample Description:	Pultrusion Sample
(L) Test Orientation:	0 Degrees
(M) Laminate Fabrication Details:	Details Not Supplied by Client
(N) Average Ply Thickness:	Details Not Supplied by Client
(O) Test Speed (mm/min):	2.0
(P) Test Room Conditions:	21°C, 65% RH
(Q) Conditioning Temp. & Humidity:	23°C, 50% RH Constant for 24 Hours
(R) Coupon Cutting Method:	Blanks cut by diamond coated cutting wheel, notch machined by diamond coated notch cutter
(S) Sampling Method:	Representative Sample

Test Equipment Details:

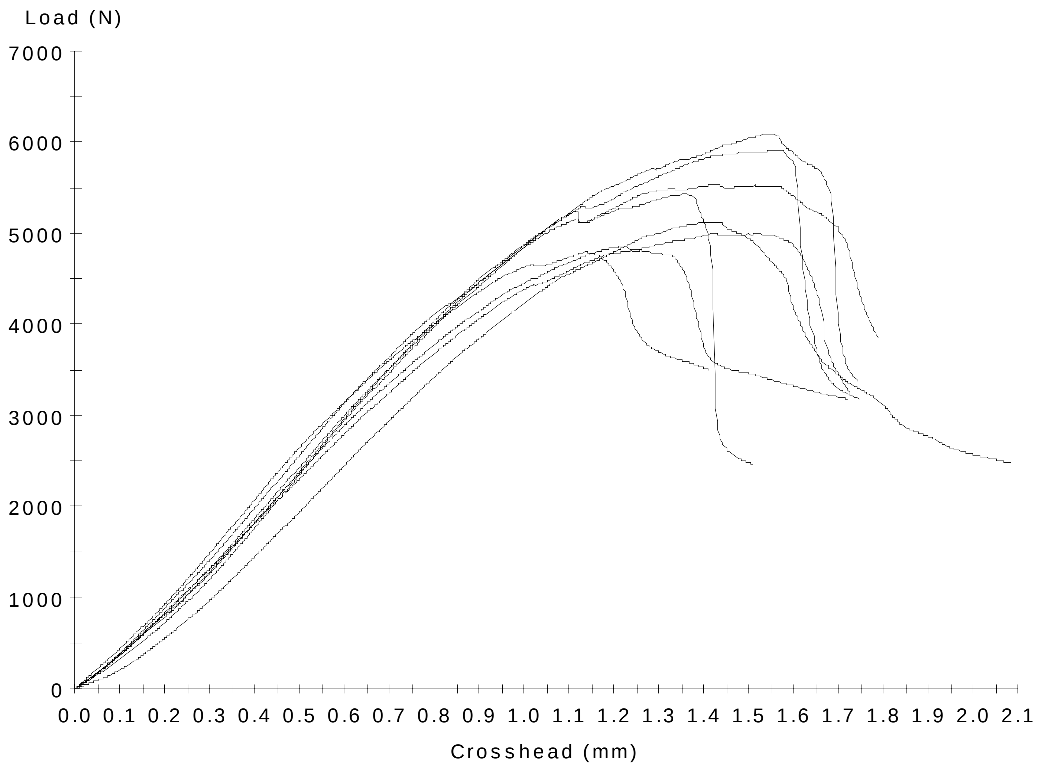
Test Machine:	MTS Alliance RT/10
Location:	Z126 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	08/06/2004
Expiration Date:	08/06/2005
Strain Measurement Device:	Axial Displacement of Crosshead
Strain Calibration Date:	08/06/2004
Expiration Date:	08/06/2005
Load Cell Calibration Date:	08/06/2004
Expiration Date:	08/06/2005

Specimen Results:

Specimen #	Notch Height mm	Notch Width mm	Deflection at Peak mm	Peak Load N	Peak Shear Stress MPa				
1	12.31	4.80	1.14	4795	81.15				
2	12.49	4.89	1.22	4860	79.58				
3	12.40	5.40	1.56	5910	88.27				
4	12.68	5.07	1.36	5425	84.39				
5	12.70	5.41	1.55	6088	88.61				
6	12.78	5.01	1.42	4996	78.02				
7	12.81	5.01	1.41	5120	79.77				
8	12.56	5.42	1.43	5536	81.32				
Mean	**12.59**	**5.13**	**1.39**	**5341**	**82.64**				
Std Dev	**0.18**	**0.25**	**0.15**	**482**	**4.02**				

Specimen Comments:

Specimen #	**Failure Mode**
1	Shear failure, near notch
2	Shear failure, near notch
3	Shear failure, near notch
4	Shear failure, near notch
5	Shear failure, near notch
6	Shear failure, near notch
7	Shear failure, near notch
8	Shear failure, near notch



Stress vs Strain Plot

INTERLAMINAR SHEAR TESTING REPORT

Test Date:	Test Method:	Operator:
17/03/2005	STS - Inter Lam Shear (ISO 14130).msm	Wayne Crowell

Sample Information:

(A) Client Name:	FCDD
(B) Mailing Address:	USQ
(C) Mailing Address:	Toowoomba
(D) Mailing Address:	Qld 4350
(E) Attn:	Scott
(F) Phone:	
(G) Fax:	
(H) Client Job ID:	50 x 50 x 5 Pacific Composites Pultrusion
(I) STS Job Number:	STS-05-035-ILS
(J) Layup Sequence:	As Per Details Supplied by Client
(K) Test Orientation:	0 Degrees
(L) Sample Description:	Laminate Test Panel
(M) Laminate Cure Schedule:	Details Not Supplied by Client
(N) Conditioning Temp. & Humidity:	23°C, 50% RH Constant for 24 Hours
(O) Test Room Conditions:	21°C, 65% RH
(P) Nominal Specimen Dimensions (mm):	50 x 20
(Q) Radius of Loading Member:	5mm
(R) Radius of Supports:	2mm
(S) Nominal Span (mm):	25
(T) Test Speed (mm/min):	1.0
(U) Surface in Compression:	Mould Side
(V) Specimen Preparation Method:	Specimens cut by diamond coated cutting wheel, edges sanded smooth & defect free.

Test Equipment Details:

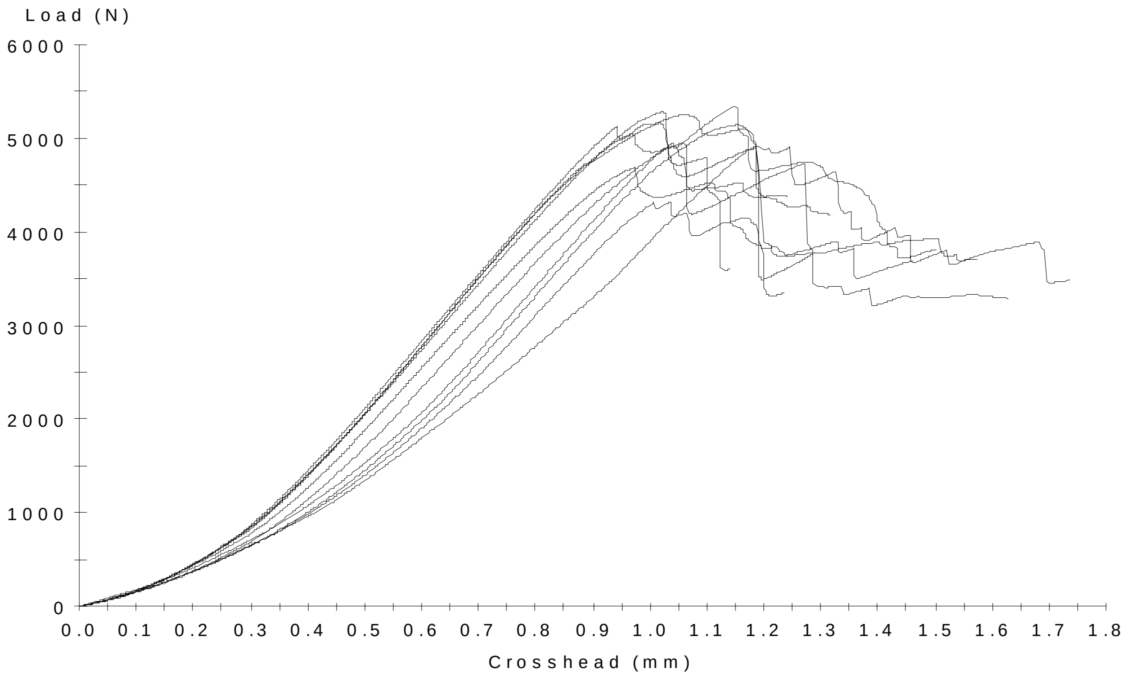
Test Machine:	MTS Alliance RT/10
Location:	Z126 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	08/06/2004
Expiration Date:	08/06/2005
Strain Measurement Device:	Axial Displacement of Crosshead
Strain Calibration Date:	08/06/2004
Expiration Date:	08/06/2005
Load Cell Calibration Date:	08/06/2004
Expiration Date:	08/06/2005

Specimen Results:

Specimen #	Average Width mm	Average Thickness mm	Peak Load N	Shear Stress @ Failure MPa
1	20.02	4.88	4913	37.72
2	19.91	5.06	4318	32.15
3	20.04	4.94	5144	38.97
4	19.93	5.19	5338	38.71
5	20.09	4.87	4946	37.92
6	20.13	4.86	5278	40.46
7	19.90	5.18	5249	38.19
8	19.90	5.06	4684	34.89
9	20.13	5.25	5046	35.81
10	20.18	4.89	5160	39.22
Mean	**20.02**	**5.02**	**5008**	**37.40**
Std Dev	**0.11**	**0.15**	**312**	**2.46**

Specimen Comments:

Specimen #	Failure Mode
1	Interlaminar Shear
2	Interlaminar Shear
3	Interlaminar Shear
4	Interlaminar Shear
5	Interlaminar Shear
6	Interlaminar Shear
7	Interlaminar Shear
8	Interlaminar Shear
9	Interlaminar Shear
10	Interlaminar Shear



Stress vs Strain Plot

FIBRE FRACTION TEST REPORT

Test Standard ISO 1172: 1996 (E)

Determination of textile-glass and mineral-filler content – Calcination method A

Sample Information

Client Name:	FCDD
Mailing Address:	USQ
Mailing Address:	Toowoomba
Mailing Address:	Qld
Attn:	Scott
Phone:	-
Fax:	-
STS Job Number:	STS-05-035-G
Client Job Id:	50 x 50 x 5 Pacific Composites Pultrusion
Sampling Method:	Representative Sample
Sample Description:	Pultrusion
Specimen Conditioning:	23°C + 50% RH Constant for 24 Hours
Approximate Specimen Mass (g):	6
Test Date:	3/22/2005
Calcination Temperature:	575°C ± 20°C
Testing Technician:	Wayne Crowell

Test Equipment Details

Furnace Details:	Ceramic Engineering, SN. K013
Location:	P6 Research Facility, Faculty of Engineering & Surveying, USQ
Balance Details:	Mettler Toledo, Model AS204-S SNR. 1120272299
Location:	Z104 Test Laboratory, Faculty of Engineering & Surveying, USQ

Specimen Results

Specimen Number	Dry Crucible Mass (g)	Initial Dry Mass: Crucible & Specimen (g)	Final Calcinated Mass: Crucible & Specimen (g)	Glass Content (%)
1	23.1644	28.9515	27.2123	69.95
2	22.6431	28.2491	26.5273	69.29
3	20.5895	26.5461	24.6510	68.18
Average				**69.14**
Std. Deviation				**0.89**

CROSS-TENSILE TESTING REPORT

Test Date:	**Test Method:**	**Operator:**
29-May-02	FCDD - Tensile Test - Pultrusion.msm	Wayne Crowell

Sample Information:

(A) Company Name:	FCDD
(B) Mailing Address:	USQ
(C) Mailing Address:	Toowoomba
(D) Mailing Address:	Qld 4350
(E) Attn:	Scott McDonald
(F) Phone:	2548
(G) Fax:	2110
(H) Client Job ID:	50x50x5 Pultrusion
(I) USQ Job Number:	STS-05-035(90)-T
(J) Specimen Orientation:	90°
(K) Sample Description:	Pultrusion
(L) Testing Room Temp. & RH:	23°C, 65% RH
(M) Conditioning Temp. & RH:	23°C, 50% RH Constant for 48 Hours
(N) Testing Speed (mm/min):	2.00

Test Equipment Details:

Test Machine:	MTS 810 Material Test System
Location:	Z104 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	12/05/2005
Expiration Date:	12/05/2006
Load Cell Calibration Date:	12/02/2005
Expiration Date:	12/02/2006

Specimen Results:

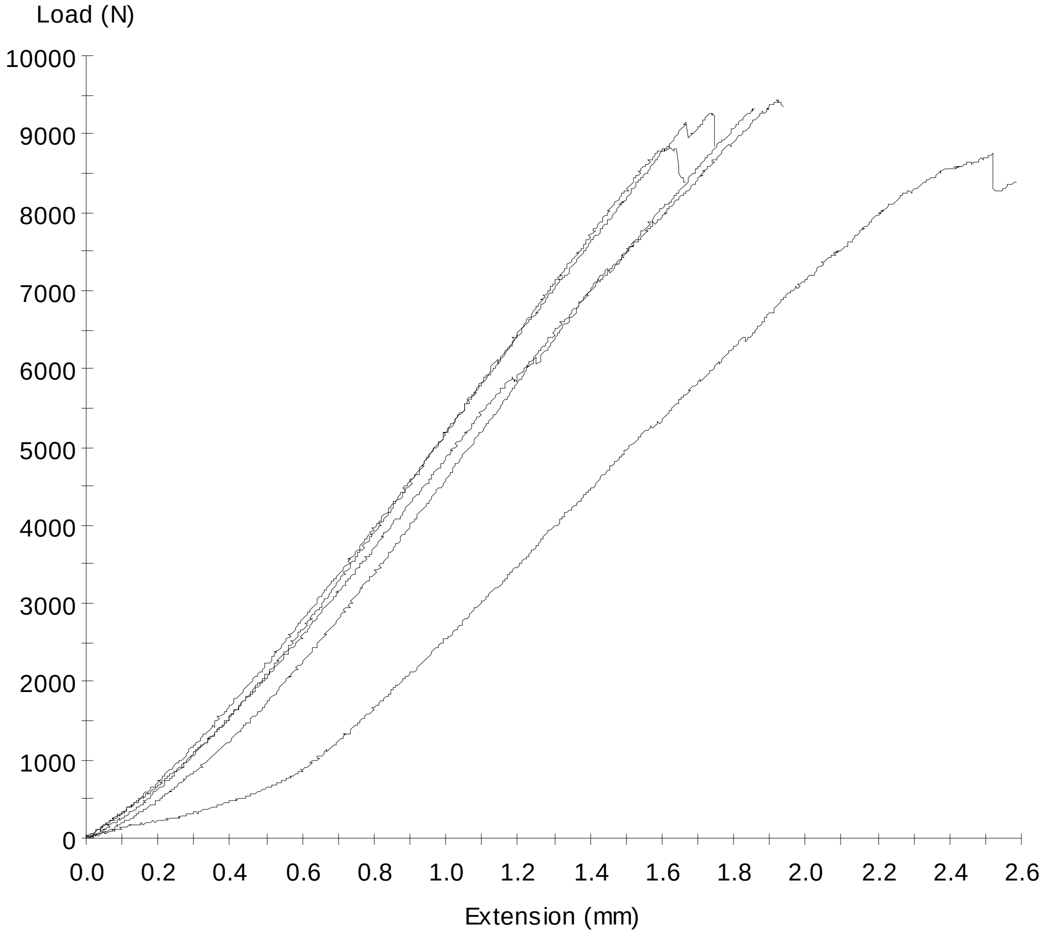
Specimen #	Avg Thick mm	Avg Width mm	Area mm^2
1	5.72	25.44	145.52
2	5.15	25.58	131.74
3	5.34	27.97	149.36
4	5.15	26.06	134.21
5	5.14	25.52	131.17
Mean	**5.30**	**26.11**	**138.40**
Std Dev	**0.25**	**1.06**	**8.44**

Specimen Results:

Specimen #	Peak Load N	Peak Cross Break Stress MPa
1	9432	64.81
2	8826	67.00
3	9274	62.09
4	9330	69.52
5	8743	66.66
Mean	**9121**	**66.02**
Std Dev	**313**	**2.76**

Specimen Comments:

Specimen #	Failure Status
1	Acceptable
2	Acceptable
3	Acceptable
4	Acceptable
5	Acceptable

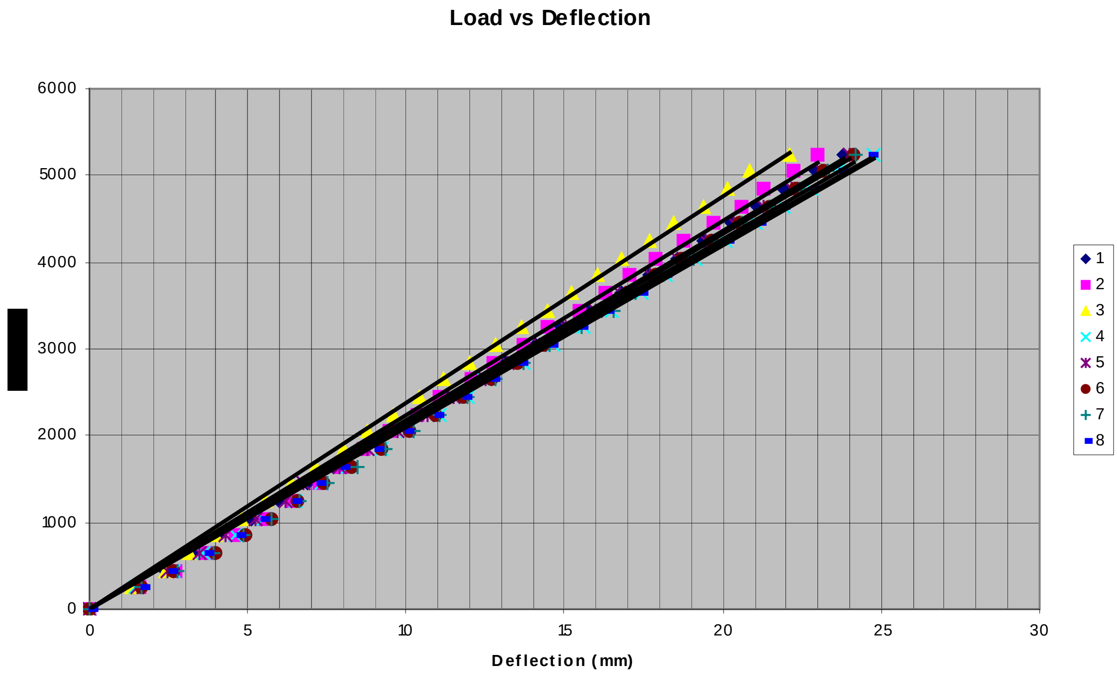


Load vs Extension Plot

Timber Flexure Test

DIAL GUAGE READINGS

	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7	7	8	8	8	Actual
Load	Left	Right	Average	Left	Right	Average	Left	Right	Average	Left	Right	Average	Left	Right	Average	Left	Right	Average	Left	Right	Average	Left	Right	Average	Load
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	136	140	1.38	160	160	1.60	130	132	1.31	145	147	1.46	155	147	1.51	165	167	1.66	164	164	1.64	165	163	1.64	243
200	0	240	2.40	270	275	2.73	240	235	2.38	255	280	2.68	240	250	2.45	250	285	2.68	260	290	2.75	280	220	2.50	443
400	0	325	3.25	370	365	3.68	310	325	3.18	340	375	3.58	340	350	3.45	400	400	4.00	400	385	3.93	340	390	3.65	643
600	400	425	4.13	470	450	4.60	390	400	3.95	440	480	4.60	420	440	4.30	490	490	4.90	490	480	4.85	440	500	4.70	843
800	500	520	5.10	570	538	5.54	470	485	4.78	530	570	5.50	510	535	5.23	570	585	5.78	575	570	5.73	510	580	5.45	1043
1000	590	610	6.00	650	620	6.35	550	565	5.58	630	670	6.50	610	625	6.18	650	660	6.55	665	660	6.63	610	675	6.43	1243
1200	680	695	6.88	750	700	7.25	630	645	6.38	710	755	7.33	640	710	6.75	730	750	7.40	755	750	7.53	680	755	7.18	1443
1400	765	780	7.73	800	790	7.95	710	720	7.15	800	835	8.18	780	795	7.88	820	840	8.30	850	840	8.45	750	845	7.98	1643
1600	845	865	8.55	0	865	8.65	790	810	8.00	900	940	9.20	880	875	8.78	910	930	9.20	935	935	9.35	860	940	9.00	1843
1800	930	960	9.45	0	950	9.50	870	890	8.80	990	1020	10.05	970	970	9.70	1000	1020	10.10	1015	1025	10.20	960	1040	10.00	2043
2000	1020	1055	10.38	0	1035	10.35	955	960	9.58	1090	1115	11.03	1070	1065	10.68	1080	1110	10.95	1110	1105	11.08	1050	1130	10.90	2243
2200	1120	1145	11.33	1090	1120	11.05	1040	1050	10.45	1180	1205	11.93	1155	1150	11.53	1165	1195	11.80	1195	1195	11.95	1140	1220	11.80	2443
2400	1210	1235	12.23	0	1205	12.05	1110	1120	11.15	1200	1290	12.45	1265	1240	12.53	1250	1285	12.68	1280	1285	12.83	1230	1310	12.70	2643
2600	1310	1320	13.15	1260	1290	12.75	1200	1200	12.00	1360	1385	13.73	1325	1320	13.23	1330	1370	13.50	1370	1370	13.70	1320	1400	13.60	2843
2800	0	1410	14.10	1360	1380	13.70	1285	1280	12.83	1450	1480	14.65	1425	1415	14.20	1420	1450	14.35	1450	1455	14.53	1410	1490	14.50	3043
3000	1480	1500	14.90	1420	1470	14.45	1370	1360	13.65	1550	1565	15.58	1500	1500	15.00	1505	1540	15.23	1565	1540	15.53	1500	1590	15.45	3243
3200	1560	1590	15.75	0	1550	15.50	1450	1440	14.45	1640	1660	16.50	1600	1590	15.95	1595	1630	16.13	1645	1660	16.53	1590	1675	16.33	3443
3400	0	1680	16.80	0	1630	16.30	1530	1520	15.25	1730	1750	17.40	1680	1670	16.75	1680	1720	17.00	1710	1740	17.25	1700	1770	17.35	3643
3600	0	1770	17.70	0	1705	17.05	1610	1595	16.03	1810	1830	18.20	1770	1765	17.68	1770	1810	17.90	1820	1805	18.13	1770	1855	18.13	3843
3800	0	1855	18.55	0	1790	17.90	1690	1675	16.83	1900	1925	19.13	1860	1855	18.58	1850	1895	18.73	1895	1915	19.05	1800	1990	18.95	4043
4000	1940	1940	19.40	0	1875	18.75	1780	1760	17.70	2000	2020	20.10	1950	1945	19.48	1940	1985	19.63	1960	1985	19.73	1920	2100	20.10	4243
4200	2020	2030	20.25	0	1970	19.70	1850	1840	18.45	2090	2110	21.00	2040	2030	20.35	2030	2080	20.55	2060	2060	20.60	2050	2170	21.10	4443
4400	0	2110	21.10	0	2060	20.60	1950	1925	19.38	2185	2200	21.93	2130	2125	21.28	2120	2170	21.45	2140	2155	21.48	2130	2240	21.85	4643
4600	2180	2200	21.90	2120	2140	21.30	2030	2000	20.15	2270	2285	22.78	2225	2210	22.18	2210	2255	22.33	2240	2245	22.43	2230	2330	22.80	4843
4800	0	2295	22.95	0	2225	22.25	2110	2060	20.85	2350	2380	23.65	2320	2300	23.10	2290	2340	23.15	2325	2340	23.33	2320	2420	23.70	5043
5000	0	2380	23.80	0	2300	23.00	2280	2140	22.10	2480	2470	24.75	2410	2395	24.03	2400	2430	24.15	2415	2420	24.18	2430	2500	24.65	5243



Width (mm)	Thickness (mm)	Length (mm)	Weight (kg)	Density (kg/m^3)	Test Span (mm)
299	26	1356	5.725	543.089	1190
299	26	1346.5	5.735	547.876	1190
299	26	1335	5.686	547.874	1190
298	26	1332.5	5.605	542.899	1190
298.5	26	1324	5.564	541.479	1190
298	26	1319	5.624	550.314	1190
298.5	26	1315	5.581	546.850	1190
298.5	26	1316	5.542	542.616	1190
298.6	26.0	1330.5	5.6	545.4	1190.0

Gradient (N/mm)	Max Load (kN)	MOR (MPa)	Modulus (MPa)
217.4	13.493	79.4	14845.5
223.2	14.543	85.6	15243.2
238.1	10.843	63.8	16259.4
212.8	13.493	79.7	14578.4
216.5	14.543	85.8	14806.0
216.5	13.093	77.3	14830.9
210.1	13.143	77.5	14370.6
210.1	11.643	68.7	14370.6
218.1	13.1	77.2	14913.1

TENSILE TESTING REPORT

Test Date:	**Test Method:**	**Operator:**
5/05/2005	FCDD - Tensile Test - Laminates (ISO 527).msm	Wayne Crowell

Sample Information:

(A) Company Name:	Fibre Composites Design & Development
(B) Mailing Address:	USQ
(C) Mailing Address:	Toowoomba
(D) Mailing Address:	Qld 4350
(E) Attn:	Scott McDonald
(F) Phone:	07 46312548
(G) Fax:	07 46312110
(H) Client Job ID:	LVL Sample
(I) STS Job Number:	STS-05-041-T
(J) Specimen Orientation:	0°
(K) Sample Description:	32mm LVL
(L) Layup Sequence:	N/A
(M) Principle Dimensions:	800 x 60
(N) Method of Manufacture:	N/A
(O) Pretreatment:	N/A
(P) Test Room Conditions:	23°C, 65% RH
(Q) Conditioning Temp. & RH:	23°C, 50% RH Constant for 88 Hours
(R) Clamping Pressure (MPa):	15
(S) Testing Speed (mm/min):	2.00
(T) Specimen Prep. Method:	N/A

Test Equipment Details:

Test Machine:	MTS 810 Material Test System
Location:	Z104 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	12/02/2004
Expiration Date:	12/02/2005
Strain Measurement Device:	MTS Extensometer Model No. 632.29F-30
Strain Calibration Date:	13/02/2004
Expiration Date:	13/02/2005
Load Cell Calibration Date:	12/02/2004
Expiration Date:	12/02/2005

Specimen Results:

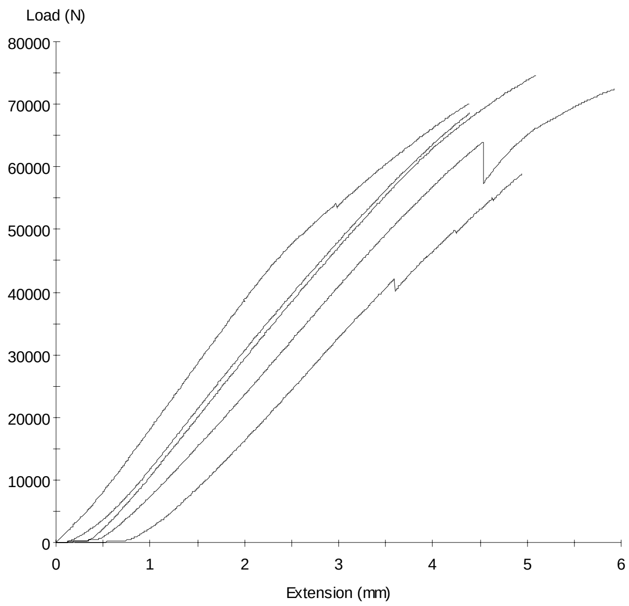
Specimen #	Thickness 1 mm	Thickness 2 mm	Thickness 3 mm	Width 1 mm	Width 2 mm	Width 3 mm	Avg Thick mm	Avg Width mm	Area mm^2
1	31.65	31.65	31.65	54.95	54.95	54.95	31.65	54.95	1739.17
2	31.04	31.04	31.04	55.79	55.79	55.79	31.04	55.79	1731.72
3	31.56	31.56	31.56	54.72	54.72	54.72	31.56	54.72	1726.96
4	31.96	31.96	31.96	57.97	57.97	57.97	31.96	57.97	1852.72
5	32.01	32.01	32.01	57.56	57.56	57.56	32.01	57.56	1842.50
Mean	**31.64**	**31.64**	**31.64**	**56.20**	**56.20**	**56.20**	**31.64**	**56.20**	**1778.61**
Std Dev	**0.39**	**0.39**	**0.39**	**1.49**	**1.49**	**1.49**	**0.39**	**1.49**	**63.24**

Specimen Results:

Specimen #	Peak Load N	Peak Stress MPa							
1	70139	40.33							
2	58913	34.02							
3	72419	41.93							
4	68596	37.02							
5	74671	40.53							
Mean	**68948**	**38.77**							
Std Dev	**6063**	**3.21**							

Specimen Comments:

Specimen #	Failure Status
1	Acceptable
2	Acceptable
3	Acceptable
4	Acceptable
5	Acceptable



Load vs Deflection Plot

SHEAR TESTING REPORT

AS/NZ 2098.9:1995
Methods of test for veneer and plywood
Method 9: Procedures for in-grade testing of structural plywood

Test Date:	**Test Method:**	**Operator:**
03-May-05	FCDD - LVL Shear Test (AS 2098).msm	Wayne Crowell

Sample Information:

(A) Client Name:	Fibre Composites Design & Development
(B) Address:	University of Southern Qld
(C) Address:	Toowoomba Qld 4350
(D) Attn:	Scott McDonald
(E) Phone:	07 46312548
(F) Fax:	07 46312110
(G) Client Job ID:	32mm LVL Test Panel
(H) STS Job Number:	STS-05-041-S
(I) Test Orientation:	0 Degrees
(J) Sample Description:	LVL Panel
(K) Test Room Conditions:	23°C, 65% RH
(L) Conditioning Temp. & Humidity:	23°C, 50% RH Constant for 24 Hours
(M) Nominal Specimen Dimensions:	250mm x 30mm
(N) Testing Speed (mm/min):	2.0

Test Equipment Details:

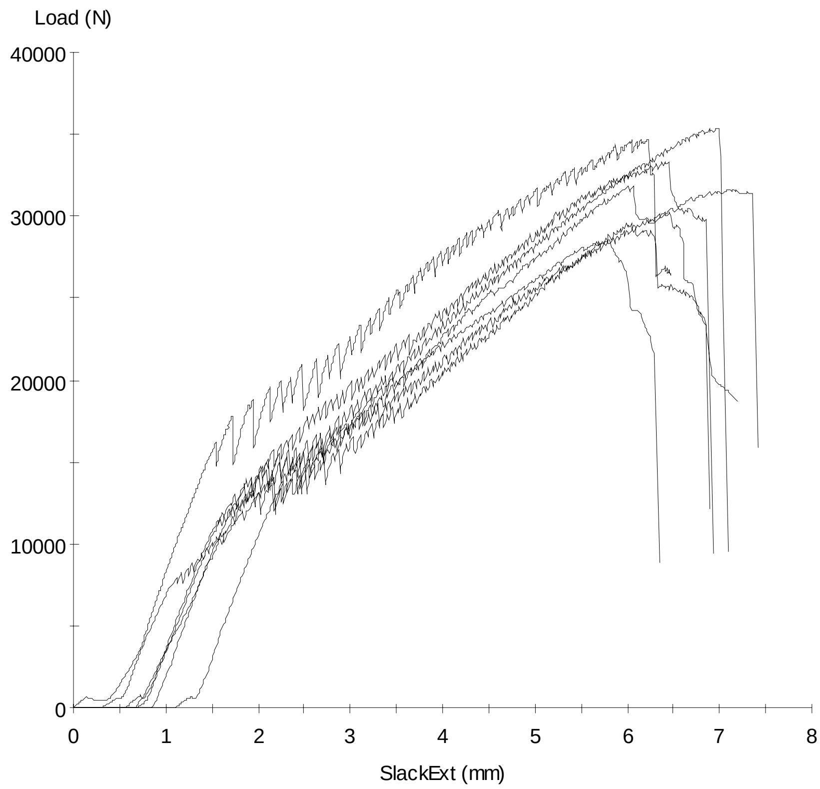
Test Machine:	MTS 810 Material Test System
Location:	Z104 Test Laboratory, Faculty of Engineering and Surveying, USQ
Accuracy Grading:	Grade A
Machine Calibration Date:	10/02/2005
Expiration Date:	10/02/2006
Strain Measurement Device:	Axial Displacement of Crosshead
Strain Calibration Date:	10/02/2005
Expiration Date:	10/02/2006
Load Cell Calibration Date:	10/02/2005
Expiration Date:	10/02/2006

Specimen Results:

Specimen #	Length mm	Thickness mm	Peak Load N	Panel Shear Strength MPa					
1	250.00	32.00	28563	3.57					
2	250.00	31.98	34720	4.34					
3	250.00	31.98	35333	4.42					
4	250.00	32.34	30260	3.74					
5	250.00	32.06	31801	3.97					
6	250.00	32.09	33349	4.16					
7	250.00	31.96	29551	3.70					
Mean	**250.00**	**32.06**	**31940**	**3.98**					
Std Dev	**0.00**	**0.13**	**2620**	**0.33**					

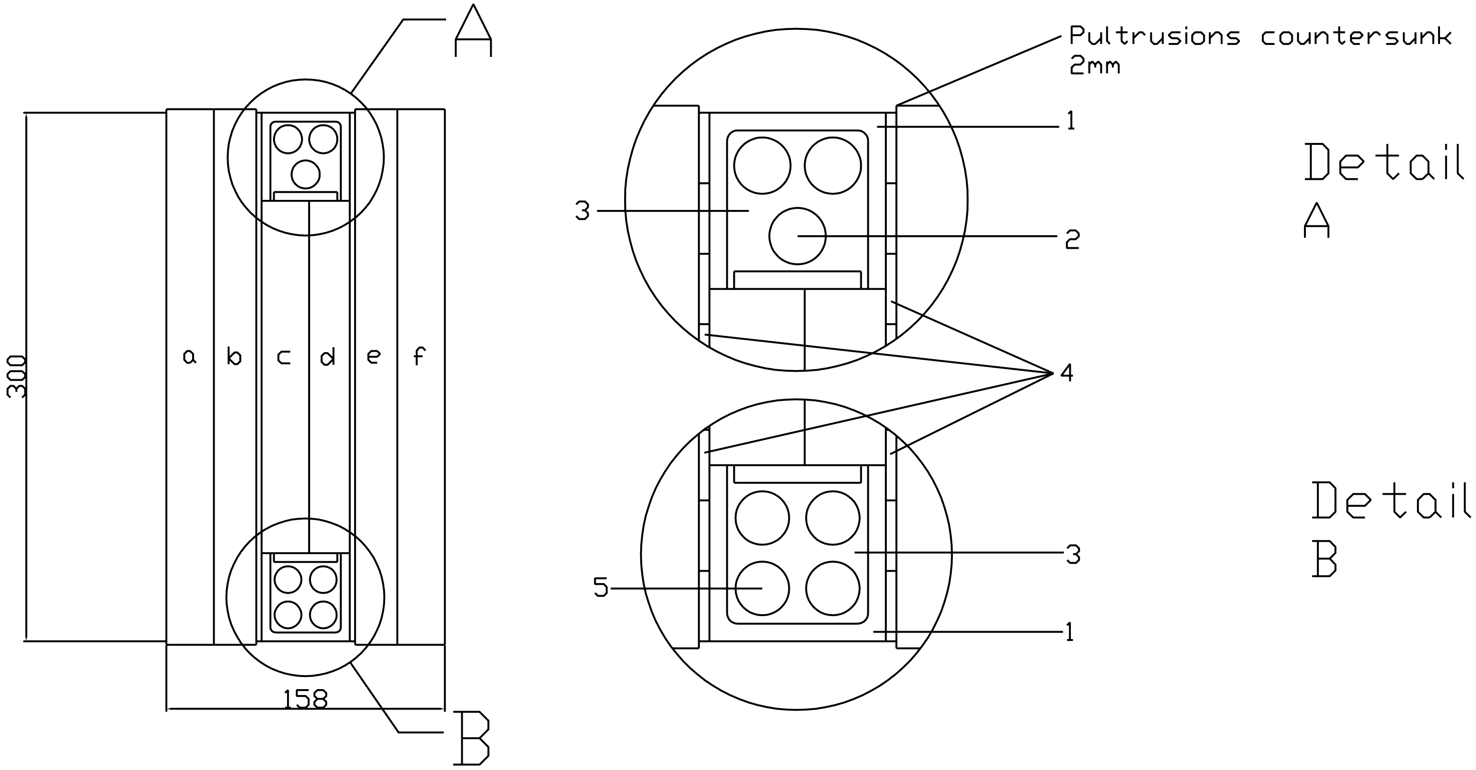
Specimen Comments:

Specimen #	Failure Status
1	Shear failure
2	Tearing around bolt holes
3	Tearing around bolt holes
4	Tearing around bolt holes
5	Tearing around bolt holes
6	Tearing around bolt holes
7	Tearing around bolt holes



Load vs Extension Plot

APPENDIX C



Item	Part	Description	Qty
1	Pultrusion	50*5 box tube	2
2	Rebar	N16 reinforcing	3
3	PFR	PFR	-
4	Laminate	3 layers MX4500 double bias epoxy	2
5	Strand	15.2mm stressing strand	4
6	LVL	27mm LVL	-

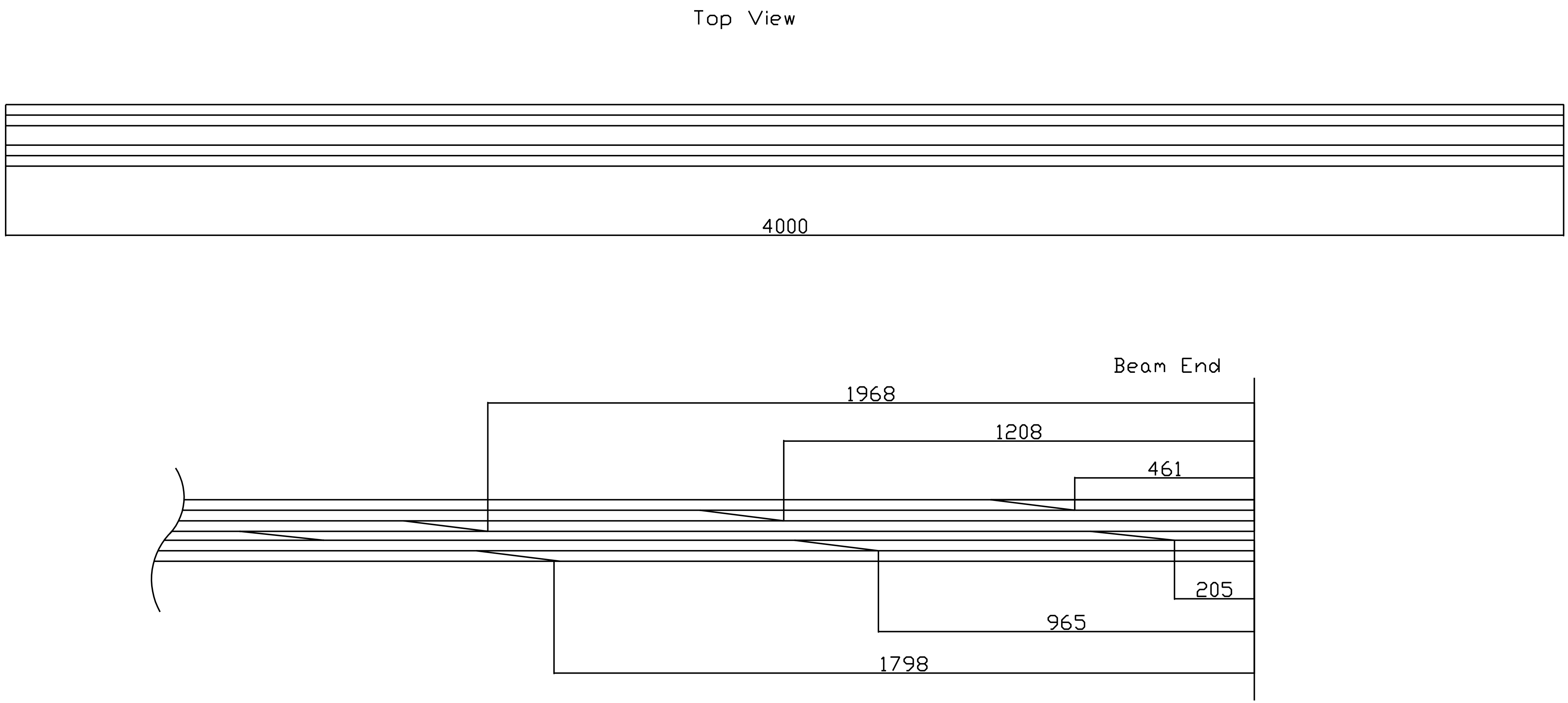
Overall Tollerance +/- 5mm

a,b,c,e,f 27mm thick

d 22mm thick

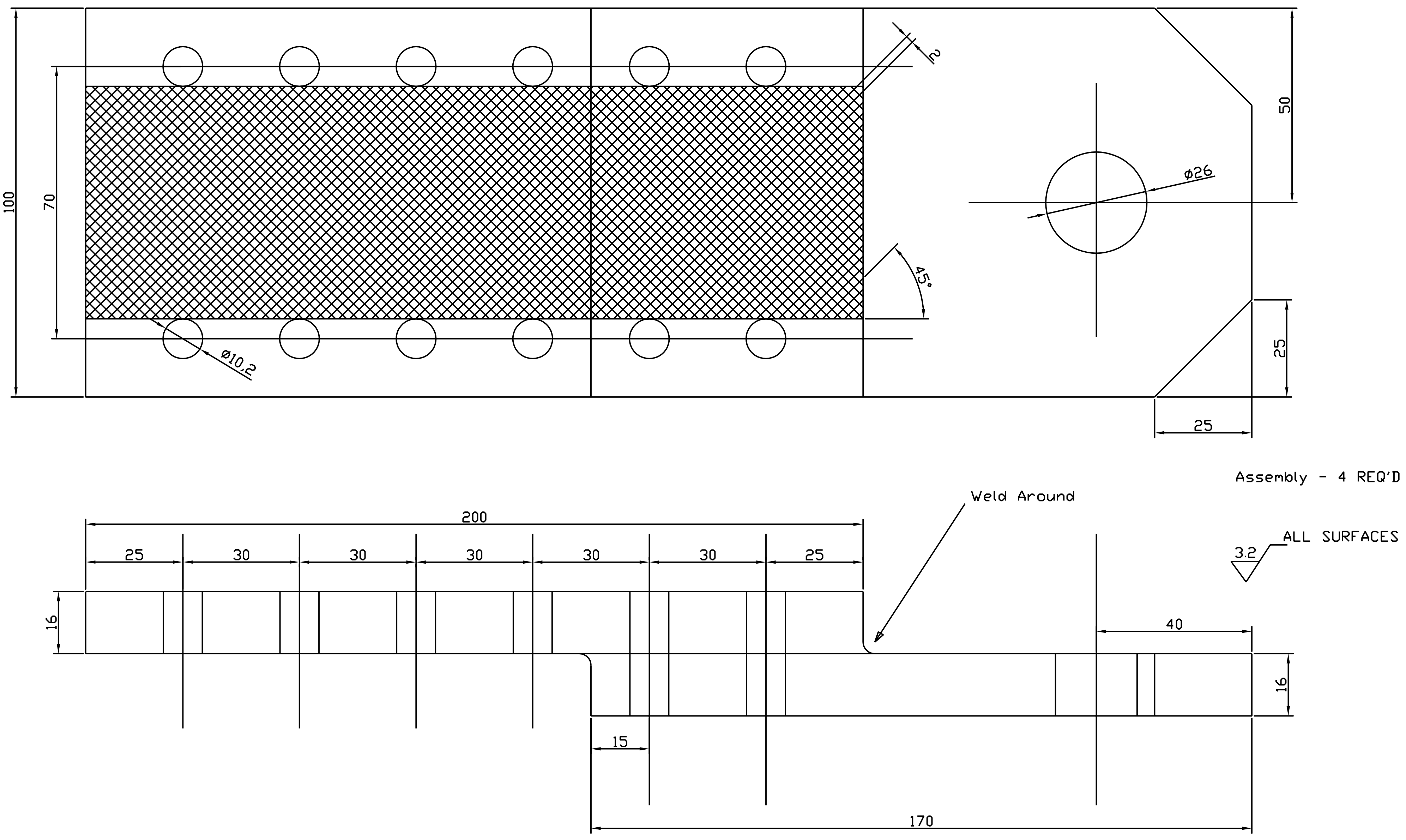
Beam Section Detail

Drawn : Scott McDonald



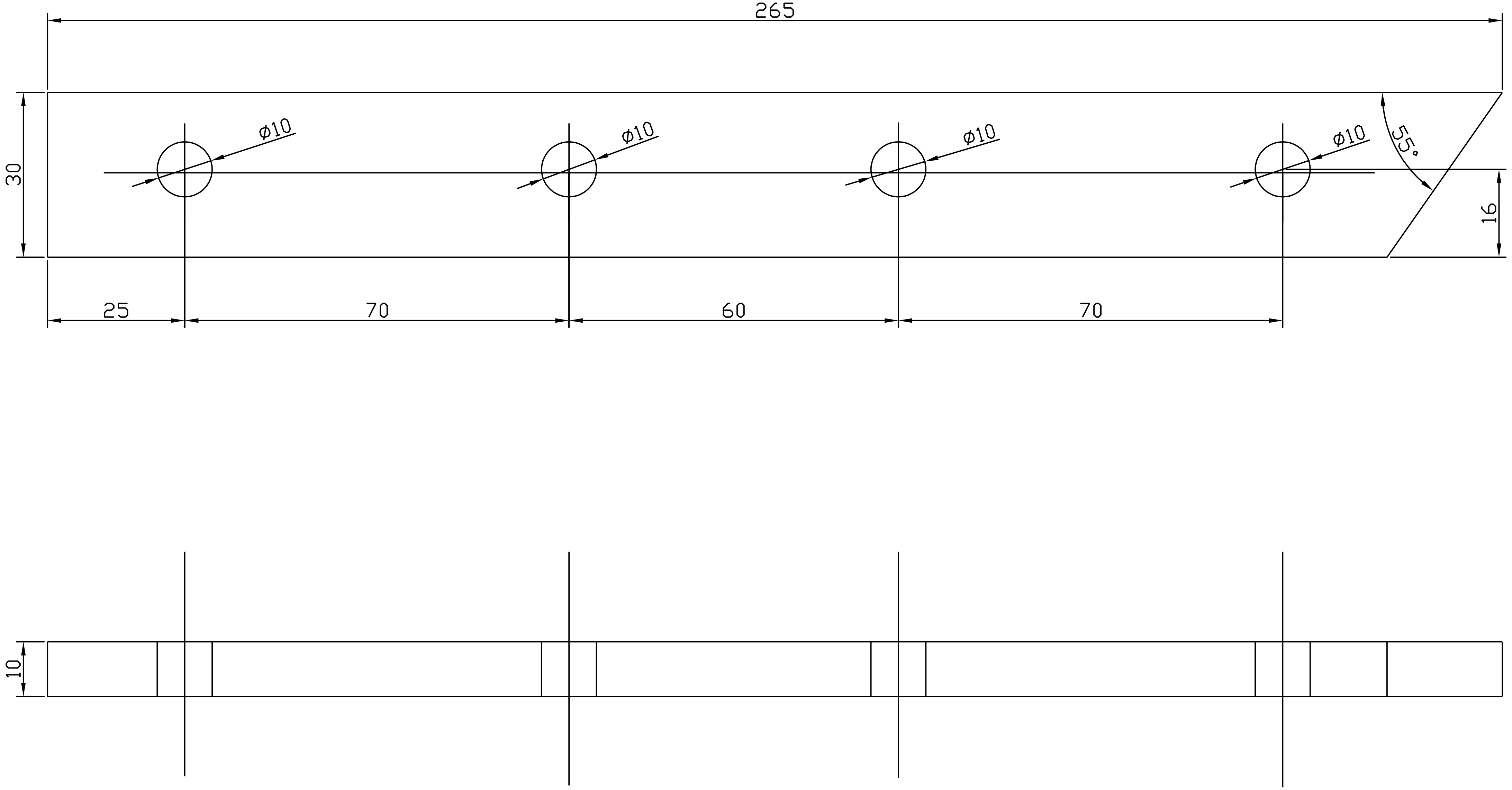
Beam Scarf Detail

Drawn : Scott McDonald

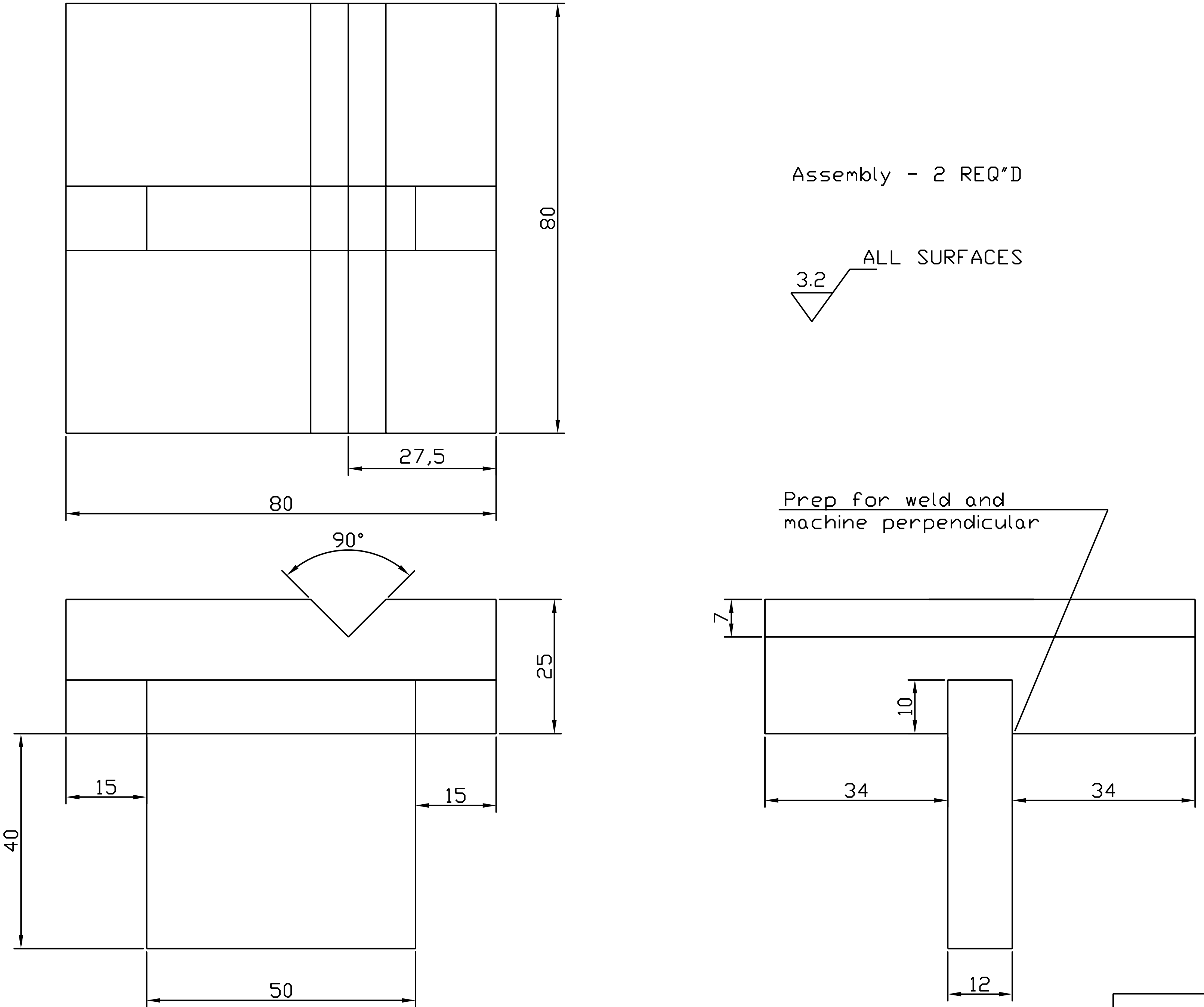


Tension Test Grip

Drawn : Scott McDonald



Panel Shear Grip
Drawn : Scott McDonald



Assembly - 2 REQ"D

3.2 ALL SURFACES

Prep for weld and machine perpendicular

Panel Shear Fitting

Drawn : Scott McDonald

APPENDIX D

LVL and Pultrusions Beam Spreadsheet Check

Enter Overall Dimensions	(mm)
Depth	300
Width	158

No. of Pultrusions in Top	1
No. of Pultrusions in Bottom	1

No. Of Steel Bars in Pultrusions	No.
Top Pultrusions Top Layer	0
Top Pultrusions Bottom Layer	0
Bottom Pultrusions Top Layer	0
Bottom Pultrusions Bottom Layers	0

Neutral Axis Depth (mm)	150

Material	Width	Depth	Diameter	Number	Area
Full Depth LVL	108	300		1	32400
LVL Between Pultrusions	50	200		1	10000
Top Pultrusions	50	50		1	900
Bottom Pultrusions	50	50		1	900
Top Steel Top Layer			16	0	0.00
Top Steel Bottom Layer			16	0	0.00
Bottom Steel Top Layer			15.2	0	0.00
Bottom Steel Bottom Layer			15.2	0	0.00

y	E	I	d	Ad^2	$E(I+Ad^2)$
150	14900	243000000	0	0	3.621E+12
150	14900	33333333	0	0	4.967E+11
275	32200	307500	125	14062500	4.627E+11
25	32200	307500	-125	14062500	4.627E+11
285	200000	0.00	135	0	0.000E+00
265	200000	0.00	115	0	0.000E+00
35	195000	0.00	-115	0	0.000E+00
15	195000	0.00	-135	0	0.000E+00

EI	5.04279E+12

Beam Span (mm)	3800
Distance Between Loads (mm)	1000
Load (kN)	100
Deflection (mm)	20.52

Full Beam Spreadsheet Check

Enter Overall Dimensions	(mm)
Depth	300
Width	158

No. of Pultrusions in Top	1
No. of Pultrusions in Bottom	1

No. Of Steel Bars in Pultrusions	No.
Top Pultrusions Top Layer	2
Top Pultrusions Bottom Layer	1
Bottom Pultrusions Top Layer	2
Bottom Pultrusions Bottom Layers	2

Neutral Axis Depth (mm)	151.6697

Material	Width	Depth	Diameter	Number	Area
Full Depth LVL	108	300		1	32400
LVL Between Pultrusions	50	200		1	10000
Top Pultrusions	50	50		1	900
Bottom Pultrusions	50	50		1	900
Top Steel Top Layer			16	2	402.12
Top Steel Bottom Layer			16	1	201.06
Bottom Steel Top Layer			15.2	2	286.00
Bottom Steel Bottom Layer			15.2	2	286.00

y	E	I	d	Ad^2	$E(I+Ad^2)$
150	14900	243000000	-1.6697	90325.19	3.622E+12
150	14900	33333333	-1.6697	27878.14	4.971E+11
275	32200	307500	123.33	13689332	4.507E+11
25	32200	307500	-126.67	14440686	4.749E+11
285	200000	6433.98	133.33	7148546	1.431E+12
265	200000	3216.99	113.33	2582392	5.171E+11
35	195000	5240.52	-116.67	3892979	7.602E+11
15	195000	5240.52	-136.67	5342080	1.043E+12

EI	8.79572E+12

Beam Span (mm)	3800
Distance Between Loads (mm)	1000
Load (kN)	100
Deflection (mm)	11.77