University of Southern Queensland

Faculty of Health, Engineering and Sciences

Thermally Insulated Structural Sandwich Panels for Roofing Applications

A dissertation submitted by

Mr. Aiden Michael Flannery

In fulfilment of the requirements of

Bachelor of Engineering (Civil)

October 2015

Abstract

The market for modular housing and infrastructure is growing remarkably quickly due to increasing costs of labour and the demand for energy efficient, long lasting buildings. The viability of using fibre composite sandwich panels for these applications formed the primary investigation of this research project. The flexural strength and thermal insulation were of main focus however fire resistance, cost effectiveness and lifespan were also investigated.

A literature review was conducted on the design methods, requirements and applications of fibre composite technology in the civil infrastructure industry. Based on these findings, the theoretical properties of the materials were than calculated and used to design a set of sample beams. The sample beams consisted of a rigid polyurethane core sandwiched between two fibreglass skins made from woven roving and chopped strand mat. The beams were tested in 3 point, 4 point, quarter-span and third-span bending. From the tests results, various material properties were calculated such as the core shear rigidity, core ultimate compressive stress, core ultimate shear stress and facing modulus. These mechanical properties along with the knowledge of failure modes gained throughout the testing period were used to redesign the sandwich panels. The final design was modelled in Creo Parametric with an FEA conducted using the Creo Simulation package.

Core crushing and skin delamination were the two most common failure modes observed during testing. The modulus of elasticity of the skins and shear rigidity of the core were calculated as 2797.5MPa and 2.4MPa respectively. The core ultimate compressive stress and shear stress were calculated as 0.3MPa and 0.34MPa respectively. The serviceability requirements governed the roofing panel design which resulted in a core thickness of 100mm and a thermal resistance (R) value of 5.75. The finite element analysis results confirmed the design satisfied the serviceability requirements with a variation of less than 10% when compared with the predicted values and physical testing data. A cost analysis revealed that the FRP sandwich panels were significantly more expensive than conventional roofing materials however key areas for design improvement and cost reductions have been identified.

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

Limitations of Use

Certification

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

I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

Aiden Michael Flannery

Student Number: 0061033162

____ _______________________

Student signature Date

Endorsement

Dr Sourish Banerjee

____ _______________________

Supervisor signature Date

Acknowledgements

This project would not have been possible if it weren't for the support and assistance that I received from others whilst undertaking the project and preparing the dissertation.

Firstly I would like to thank my friends and family for their support throughout my time studying at the University of Southern Queensland.

I would like acknowledge BAC and in particular Norman Watt for the supply of materials and continued support throughout this project.

I would also like to thank my supervisor, Dr Sourish Banerjee, for his guidance and Wayne Crowell from the Centre of Excellence in Engineered Fibre Composites for his assistance in the testing laboratories.

Table of Contents

Abstract iii

Limitations of Use iv

Certification v

Acknowledgements vi

Table of Contents vii

List of Figures xii

List of Tables xiv

Nomenclature and Acronyms xvi

Chapter 1. Introduction 1

1.1. Topic 1

1.2. Background 1

1.3. Aim and objectives 2

1.4. Justification of project 2

1.5. Design Concept 3

Chapter 2. Literature Review 7

2.1. Introduction 7

2.2. Fibre composites 7

2.2.1. History

2.2.2. Development and applications

2.3. Composite sandwich panels 12

2.3.1. Introduction

2.3.2. Fabrication

2.3.3. Development

2.3.4. Applications

2.3.5. Benefits

2.4. Flexural strength and deflection of sandwich panels..17

2.4.1. Strength of composites

2.4.2. Volume Fraction

2.4.3. Rule of mixtures

2.4.4. Micro-Cracking

2.4.5. Flexural rigidity

2.4.6. Bending stress

2.4.7. Deflection

2.4.8. Delamination

2.4.9. Wrinkling

2.4.10. Core shear failure

2.4.11. Crushing

2.4.12. Wide beams and effective width

2.5. Thermal insulation of sandwich panels...28

2.5.1. Thermal conductivity (**λ**)

2.5.2. Thermal resistance (R')

2.5.3. Thermal diffusivity (D)

2.6. Fire resistance..30

2.6.1. PU core

2.6.2. Fibreglass skins

2.7. Testing 31

2.7.1. Stiffness

2.7.2. Strength

Chapter 3. Methodology and Manufacture 35

3.1. Introduction..35

3.2. Design requirements 35

3.3. Initial design 35

3.4. Properties of materials 36

3.4.1. Introduction

3.4.2. Glass

3.4.3. Resin

3.4.4. Foam Cores

3.4.5. Theoretical properties

3.4.5.1. Volume fraction

3.4.5.2. Thickness of laminate

3.4.5.3. Composite density

3.4.5.4. Modulus of elasticity

3.4.5.5. Tensile strength

3.5. Manufacture 45

3.5.1. Materials

3.5.2. Procedure

3.6. Testing procedures 47

3.7. Modelling and final design 50

3.8. Resource requirements 50

Chapter 4. Results and Analysis 51

4.1. Introduction 51

4.2. Design loads 51

4.2.1. Dead load

4.2.2. Live load

4.2.3. Wind load

4.3. Serviceability limits 56

4.4. Thermal insulation requirements 57

4.5. Initial design 57

4.5.1. Flexural rigidity

4.5.2. Compressive strength

4.5.3. Shear strength

4.5.4. Bending moment

4.5.5. Thermal insulation

4.6. Testing 60

4.6.1. Test 1

4.6.2. Test 2

4.6.3. Test 3

4.6.4. Test 4

4.6.5. Test 5

4.6.6. Test 6

4.6.7. Testing summary

4.6.8. Stiffness

4.6.9. Strength

Chapter 5. Modelling and final design 73

5.1. Parameters 73

5.2. Design 73

5.2.1. Loading Cases

5.2.2. Serviceability

5.2.3. Strength

5.2.4. Thermal insulation

5.3. Modelling and analysis 79

5.3.1. Test beam

5.3.2. Final Panel Design

5.4. Cost analysis 83

5.4.1. Sandwich panels

5.4.2. Traditional materials

5.4.3. Existing sandwich panels

5.4.4. Conclusion

Chapter 6. Conclusions and future work 87

6.1. Introduction 87

6.2. Design requirements 87

6.3. Testing results 87

6.4. Final design 88

6.5. Summary 89

6.6. Recommendations and future work 89

References 91

Appendices 95

Appendix A – Project Specification 95

Appendix B – Risk Management Plan 97

Appendix C - Time line 104

Appendix D – Creo Simulation 105

List of Figures

Figure 1 - Typical Roof Truss 3

Figure 2 - Modular Roof Concept 3

Figure 3 - Composite sandwich panel 4

Figure 4 - Tongue and groove connection 4

Figure 5 - Concept Design 5

Figure 6 - Fibreglass sailboat and car 8

Figure 7 - Pultrusion Process adopted by (*Pultrusion Process* 2015) 9

Figure 8 - Pultruded Decks 10

Figure 9 - (a) solid core, (b) honeycomb core, (c) corrugated core 12

Figure 10 - Reinforcement of Core 14

Figure 11 - BAC FRP Pedestrian Bridge 15

Figure 12 - Complete Modular Homes Granny Flat 16

Figure 13 - Failure modes (Almeida 2009) 17

Figure 14 - Idealised stress-strain curve (Foster 1998) 20

Figure 15 - Micro-cracking (Gurit 2015) 21

Figure 16 - Dimensions of sandwich beam 22

Figure 17 - Values of $\boldsymbol{\beta 1}, \boldsymbol{\beta 2}, \boldsymbol{\beta 3}, \boldsymbol{\beta 4}, \boldsymbol{\beta 5}$ 23

Figure 18 - Values for $\boldsymbol{\beta 6\ and\ \beta 7}$ 26

Figure 19 - Wide beams 27

Figure 20 - 3-Point Mid-Span Loading 32

Figure 21 - 4-Point Quarter-Span and 4-Point Third-Span Loading 33

Figure 22 - Ultimate and working strengths 44

Figure 23 - Foam core, chopped strand mat and woven roving glass 46

Figure 24 - Completed test beams 46

Figure 25 - Loading case 1 47

Figure 26 - Test 3 setup 48

Figure 27 - Specimen 4 during testing process 49
Figure 28 - Test 6 setup 49
Figure 29 - Loading Configuration 51
Figure 30 - Building dimensions 53
Figure 31 - Test 1 (Mid-Span Loading) 450mm span 60
Figure 32 - Core crushing failure mode 61
Figure 33 - Test 2 (Mid-Span Loading) 300mm span 61
Figure 34 - Core crushing 62
Figure 35 - Test 3 (4-point Loading) 1300mm span 62
Figure 36 - Shearing failure 63
Figure 37 - Test 4 (4-Point Loading) 600mm span 63
Figure 38 - Test 5 (4-Point Loading) 450mm span 64
Figure 39 - Support shear failure and delamination 65
Figure 40 - Test 6 (Quarter Point Loading) 450mm span 65
Figure 41 - Linear-elastic zone 67
Figure 42 - Core crushing load 71
Figure 43 - Final panel dimensions 74
Figure 44 - FEA test beam configuration 80
Figure 45 - FEA test beam deflection 80
Figure 46 - FEA panel loading configuration 81
Figure 47 - FEA panel deflection 81
Figure 48 - FEA panel stress top 82
Figure 49 - FEA panel stress bottom 82
Figure 50 - The risk management process 98
Figure 51 - Risk Matrix 100
Figure 52 - Foam core inputs 105
Figure 53 - FRP skin input 106

Figure 54 - FEA test beam loading 107

Figure 55 - FEA test beam restraints 108

Figure 56 - FEA test beam stress top 109

Figure 57 - FEA test beam stress bottom 110

Figure 58 - FEA test beam 500N deflection 111

Figure 59 - FEA panel mesh geometry 112

List of Tables

Table 1 - Nomenclature and Acronyms xvi

Table 2 - Values of $\boldsymbol{Kg}$ and $\boldsymbol{Ks}$ for different supporting conditions 24

Table 3 - Effective width 27

Table 4 - E glass properties 36

Table 5 - Comparison of E-glass composites with different yarn processing types 37

Table 6 - Typical liquid properties 38

Table 7 - Typical cured properties 38

Table 8 – BFE35 Typical physical properties 39

Table 9 - Testing results of 16 & 62kg/m³ PU foam 40

Table 10 - Laminate Layup 41

Table 11 - Serviceability limits 56

Table 12 - Minimum total R-Values 57

Table 13 - Results summary 66

Table 14 - 50mm core stiffness properties 67

Table 15 - 75mm core stiffness properties 68

Table 16 - Revised 75mm core stiffness properties 69

Table 17 - Sandwich beam property summary 70

Table 18 - Final panel properties 73

Table 19 - Custom ORB limit state wind pressure capacities (kPa) 0.42BMT 74

Table 20 - Design capacities 78

Table 21 - Material rates 84

Table 22 - Panel costing... 84

Table 23 - Insulation rates (Schneider 2015)... 85

Table 24 - Roofing rates (*Roofing Fundamental* 2015).. 85

Table 25 - Cost comparison 86

Table 26 - Important results 89

Table 27 – Identified hazards 99

Table 28 - Other hazards 100

Table 29 - RMP 101

Table 30 - Project timeline 104

Nomenclature and Acronyms

The following abbreviations have been used throughout the text and bibliography:-

Table 1 - Nomenclature and Acronyms

AS/NZS	Australian Standard / New Zealand Standard
ASTM	American Society for Testing and Materials
BAC	Buchanan's Advanced Composites
BCA	Building Code of Australia
Biaxial	Reinforcement fabric laid down parallel in the 0° and 90° axes
CEEFC	Centre of Excellence in Engineered Fibre Composites
Composite	made up of disparate or separate parts or elements (refer 2.2.1)
CSM	Chopped Stand Mat
FEA	Finite Element Analysis
FRP	Fibre-Reinforce Polymer
NCC	National Construction Code
PET	polyurethane terephthalate
PU	Polyurethane – a thermoplastic polymer composed of a chain of organic units joined together by urethane links
Sandwich Panel	a structural panel consisting of a core of one material enclosed between two sheets of a different material
SLS	Serviceability Limit States
ULS	Ultimate Limit States
WR	Woven Roving

Chapter 1. Introduction

> "Composite materials, based on the principal that the sum is greater than the parts, are beginning to offer engineers new choices in materials selection for product design. With composites already in use for products ranging from golf-club shafts to turbine blades, many feel that the composite industry is poised for spectacular growth in the coming decades. To the majority of engineers, however, composite materials are viewed as uncharted waters: a vast expanse of technology sure to yield improved performance-but where does one begin? . . ."
> (Gall 1987, p. 5)

This chapter, along with outlining the objectives and justification of the project, provides a basic overview of the conceptual design of fibre composite sandwich roofing panels and more importantly, an insight into what future developments in fibre composite technology could lead to.

1.1. Topic

'Numerical modelling and testing of fibre composite sandwich panels for residential and commercial roofing applications'

1.2. Background

The market for modular housing and infrastructure is growing remarkably quickly. Fibre cement panels with corrugated steel shells have been on the forefront of the quick build industry. Products that incorporate these materials have the advantages of a high strength to weight ratio, great durability and fire resistance however they rate poorly in thermal resistance and sound transmission. Fibreglass sandwich panels share similar properties to that of fibre cement panels. The proposed fibre composite sandwich panels for this project were constructed from two main components, a fibreglass skin (E glass and resin) and a rigid polyurethane foam core.

1.3. Aim and objectives

The primary objective of this research project was to investigate the viability of using fibre composite sandwich panels for roofing applications. To do this, a thorough understanding of how the core thickness of a panel will affect the strength and thermal insulation of the structure must be obtained. The research objectives of this project have been listed below:

- Research the background information relating to fibre composite sandwich panels used in the construction industry.
- Determine the typical loading cases that a roofing panel would be exposed to by the use of Australian Standards.
- Determine the thermal insulation property required from a sandwich panel in a roofing application.
- Design and test fibre composite sandwich beams (fibreglass skins with low density PU cores of varying thickness).
- Analyse the strength, serviceability and thermal insulation properties of the beams obtained from the testing to generate a final design.
- Conduct a FEA on the proposed final panel design.
- Conduct a cost analysis of producing the panels in comparison to traditional roofing techniques.

The findings of this research project will aid BAC Technologies in developing a fibre composite modular roof design.

1.4. Justification of project

Increasing costs of labour and the demand for energy efficient, long lasting buildings are the driving factors for conducting this research. With global warming becoming a major issue amongst today's society, there has been an increasing demand for infrastructure with superior energy efficiency. The thermal insulation provided in the roofing of such structures is vital to reducing the energy consumption. Along with the tremendous insulation properties of fibre composite sandwich panels they also offer an outstanding lifespan.

1.5. Design Concept

The thermal efficiency, weight reductions, cost savings and ease of installation form the key elements of the conceptual design driving this research project. The average residential house roof structure in Australia is comprised of a timber roof truss, thermal insulation, roof sheeting, ridge capping, overhangs and gutters. The thermal insulation is usually provided in the form of expanded fibreglass, cork or foam. Figure 1 below details the battens, purlins, wind braces and ties that make up a typical roof truss.

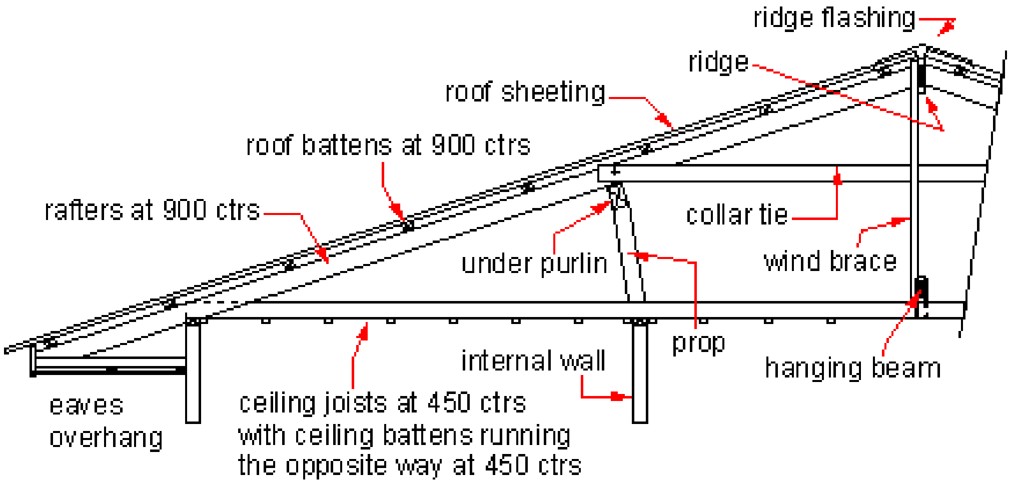


Figure 1 - Typical Roof Truss

(Bradley 2007)

The fibreglass conceptual design incorporates all of these elements into a single modular design meaning that the roof can be installed over a much shorter period of time.

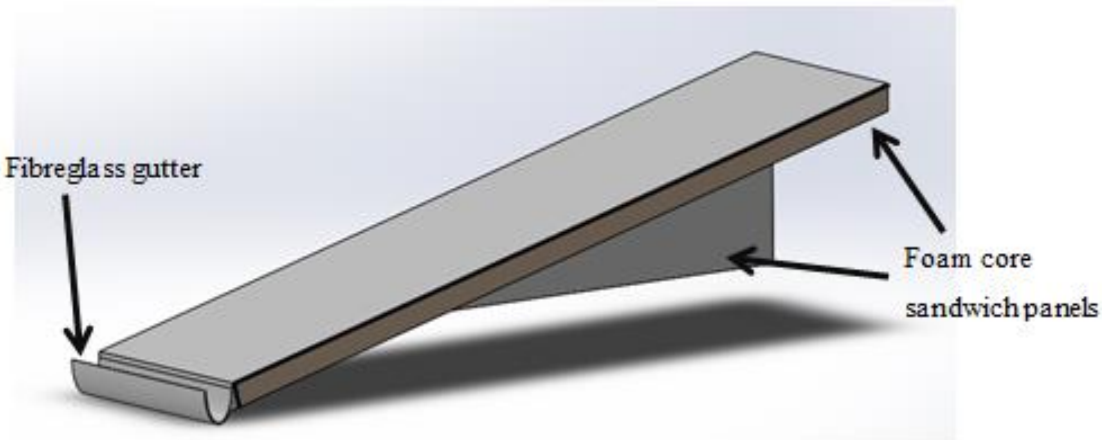


Figure 2 - Modular Roof Concept

Framing is no longer required as the lightweight roof is supported by structural sandwich panels at each module connection. The supporting ribs rest on both the internal and external walls.

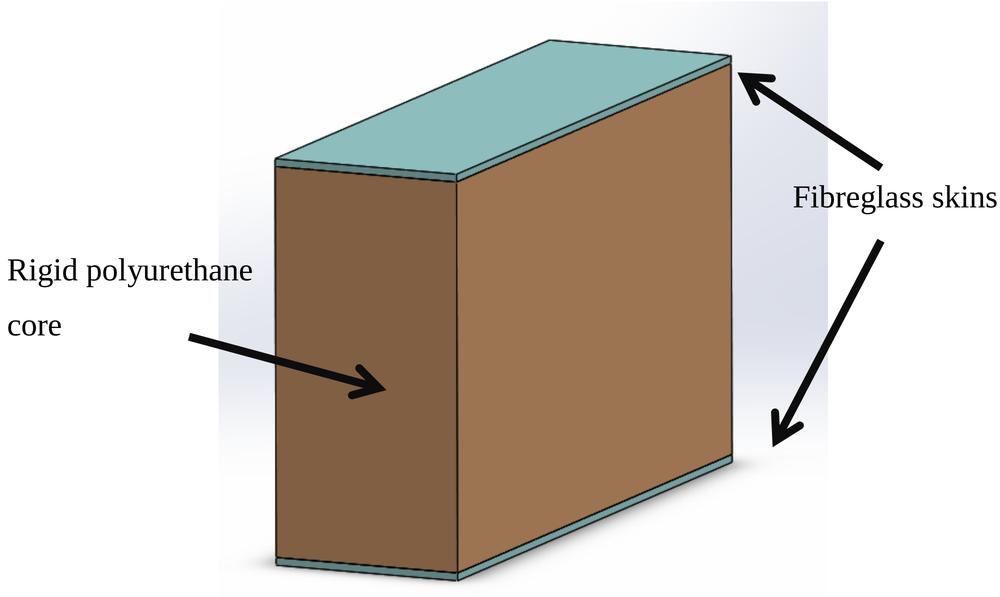


Figure 3 - Composite sandwich panel

A tongue and groove connection provides a water tight connection of each module meaning the panels can be slid into place before fixing.

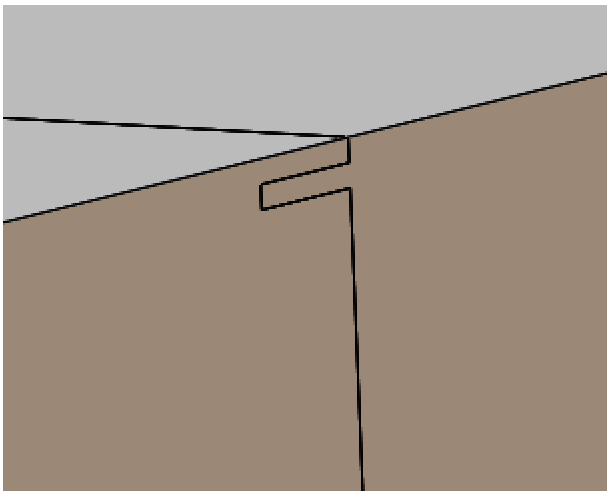


Figure 4 - Tongue and groove connection

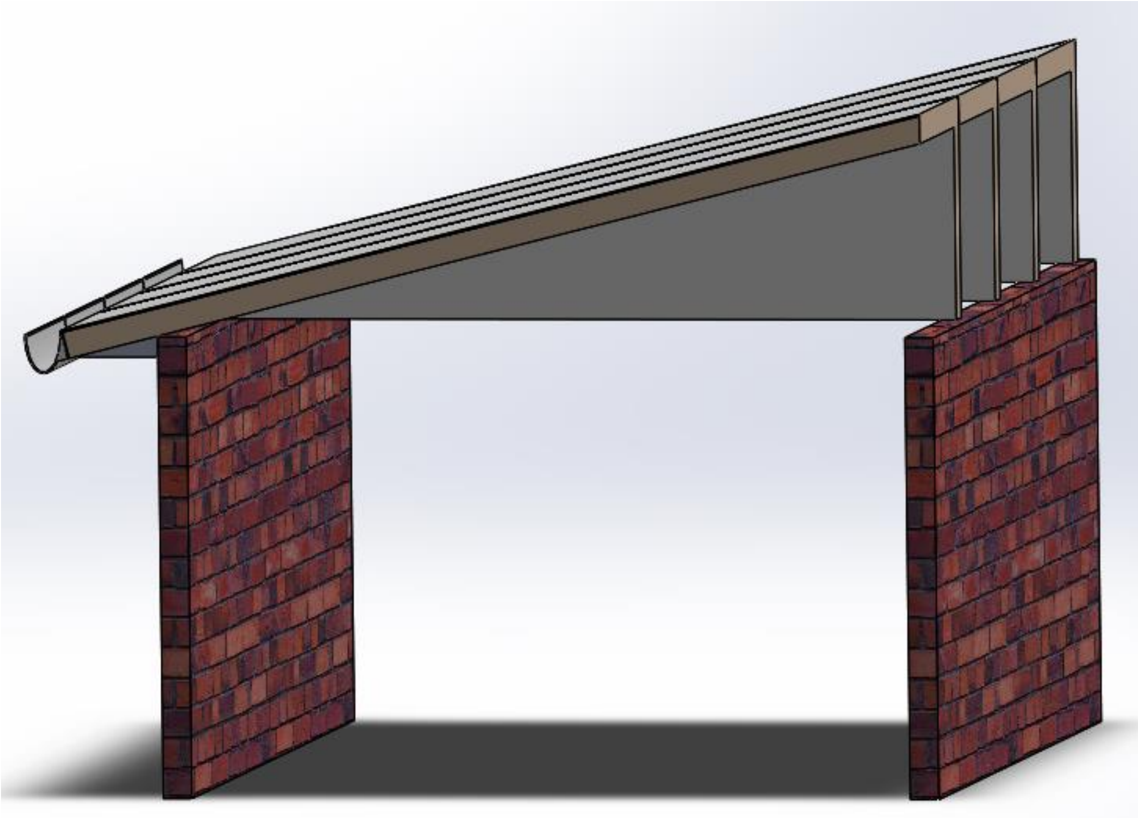


Figure 5 - Concept Design

For the purposes of this research project, the concept design was simplified to focus on the sandwich panels solely spanning on timber or steel roofing battens as shown in Figure 1 - Typical Roof Truss, rather than looking at the design as a modular structure. The details of the design are discussed further in Chapter 4 and 5. Focusing on developing the panels as a component of a roofing system, rather than as a whole structure means that the product is more suitable for a larger market. Should the fibreglass panels be found to be a viable option, further research and development should be carried out regarding the modular design.

Chapter 2. Literature Review

2.1. Introduction

The topic under consideration in this literature review is fibre composite sandwich panels in roofing applications and in particular the mechanical properties achieved by use of different materials. This review provides a brief overview of fibre composites in construction by noting some significant projects that have shaped the industry as well as outlining the history and the recent developments of composites before narrowing down to a critical review of studies relating to sandwich panels. The aim of the review was to critique previously conducted studies so as to determine the gaps in the research. As there is a significant amount of research available already, this literature review was aimed at linking the existing information to construction applications rather than focussing solely on the research. The information discussed in this review is from studies conducted by others, non-published works and guidance provided by industry professionals, university supervisors and peers.

2.2. Fibre composites

2.2.1. History

A composite is a combination of two or more different materials which together make a unique and superior material (Johnson 2015). Egyptians were one of the first civilisations to discover the benefits of composites by using a mixture of straw and mud to construct buildings back in the 1500s B.C. The mud provided the bulk material and the straw was used as reinforcement. It is said that composites in the form of plywood were constructed by humans even earlier. Progressing through time, materials such as wood, bone, cattle tendons, horns, silk, 'animal glue' and natural pine resin were used to construct composites such as the Mongolian bow which dominated in warfare until the discovery of gun powder (*History of Composites* 2015). Up until about the 1800s the only binder and glues available were made from natural resins derived from plants and animals. Synthetic resins such as celluloid, melamine and Bakelite were developed marking a revolution in chemistry that saw the development of plastics such as vinyl, phenolic, polystyrene and polyester.

Glass fibre as a reinforcement material was first introduced in the 1930s. This may be considered the most significant advancement in composite history. It forms the backbone of the composite industry in modern times. Advancements in FRP technology led to applications in the marine, automotive, and later on, the aviation industry.

Figure 6 - Fibreglass sailboat and car

2.2.2. Development and applications

The American Society of Civil Engineers published a paper in the journal of composites for construction in 2002 (Bakis, Bank & Brown 2002). The paper discussed the developments of composites in construction in topic areas such as structural shapes, highway bridge decks, internal FRP reinforcements and externally bonded reinforcements. Also discussed in the paper is the use of Standards and Codes. The article, outdated as it may be, gives an interesting insight into the development of fibre composites over the last decade especially when compared with development reviews published more recently. A more recent paper by Allan Manalo (2013) entitled “Fibre reinforced polymer composites sandwich structure: Recent developments and applications in civil infrastructure” is reviewed in full in this literature review.

A structural shape, as discussed by E. Bakis, refers to the structural profiles produced for use in the construction industry in applications such as buildings and bridge superstructures. Traditionally made from steel, these profiles are used as beams, girders and columns. The composite alternatives, developed since the late 1950s, offer a lightweight solution to the traditional steel design. The structural profiles include shapes such as square hollow section (SHS), round hollow section (RHS), I Beams, L Beams and U beams. Due to the constant cross section of the profiles, the manufacturing method of choice is the pultrusion process. This continuous manufacturing process consists of “pulling” resin impregnated reinforcing fibres and fibre fabrics through a heated curing die.

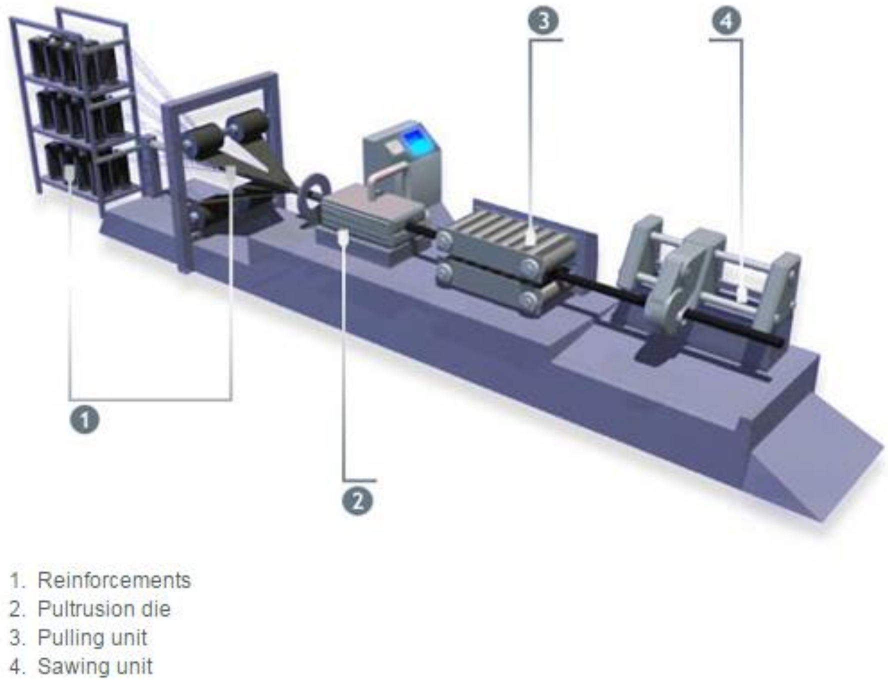


Figure 7 - Pultrusion Process adopted by (*Pultrusion Process* 2015)

According to Bakis, one of the major limitations with the pultrusion process is the tooling costs of setting up the pultrusion dies. This limits the opportunity to optimise profile dimensions to suit load cases. As pultruded profile sections have become more popular however, the range in standard sizes has also expanded. Refer Exel Composites Standard Industrial Profile List for current available structural profiles (*Exel Australia Standard Industrial Profile List* 2015).

The development of fibre composites within the field of highway structures is a topic written about by Professor John J. Lesko in the state of the art review paper. The section touches on various composite highway structures such as concrete filled FRP shells for drivable piles, wood FRP composite girders and rehabilitation of new and used bridge decks. As of 2003, bridge decks had received the greatest amount of attention which John suspects was due to the inherent advantages in strength and stiffness per unit weight as compared to traditional steel reinforced concrete decks (Bakis, Bank & Brown 2002). The two most common composite deck types are the sandwich and adhesively bonded pultruded shapes. The latter is simply a process of bonding continuous lengths of structural profiles to each other resulting in a structure that resists loading as a single member. The profiles are usually bonded in factories off site to maximise quality control. Four typical pultruded member deck designs are shown below in Figure 8.

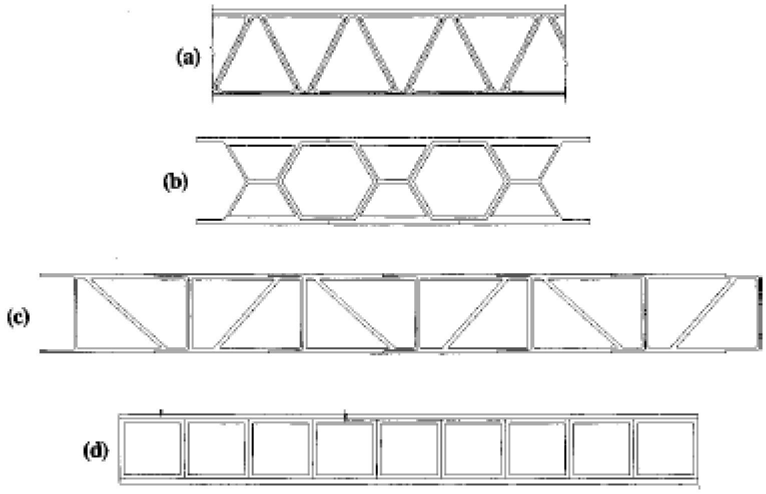


Figure 8 - Pultruded Decks

a**) EZSpan (Atlantic Research); b) Superdeck (Creative Pultrusions); c) DuraSpan (Martin Marietta Materials); d) square tube and plate deck (Strongwell) (Bakis, Bank & Brown 2002)**

Sandwich construction, as used primarily in marine and automotive industries, is the other common deck type. The sandwich deck type is used when the weight of the structure must be kept to a minimum. The sandwich manufacturing process is discussed further in clause 2.3. The two fabrication methods are compared technically in the report. The results suggest that a greater stiffness is achieved by sandwich construction than that of adhesively bonded pultrusions. The comparison also includes costs per square meter which are somewhat redundant being over ten years old. With materials relatively inexpensive in comparison to labour these days, it is suspected that the unit rate of the two types of fabrication would be somewhat similar. The cost comparison of composite sandwich panels with traditional roofing materials is explored further in this dissertation.

Internal FRP reinforcements have been in development since the 1960s. Professor Vicki L. Brown from the American Society of Civil Engineers noted that FRP reinforcement in concrete is mainly used in environments that require improved corrosion resistance (Bakis, Bank & Brown 2002). The anitcorrosive properties of FRP led to a great increase in design life. The significant difference between FRP reinforced concrete and traditional steel reinforced concrete is the ductility of the reinforcment which adversaly effects how the concrete must be designed. Reinforced concrete is usually designed so that the reinforcement fails before the concrete. This yeilds a safer design as it gives time for people to evacuate the site. FRP is brittle and therefore FRP reinforced concrete must be designed differently to steel reinforced concrete. The design of FRP reinforced concrete is generally governed by the servicability limits.

As design requirements become more stringent we see more and more drive to improve the strength of existing structures to meet current standards. This drive has seen a significant focus on the development of externally bonded fibre composite reinforcements. Professor Thanasis Triantafillou of the University of Patras in Greece, notes strength, weight, chemical resistance and ease of installation/application as the key advantages to the composite solutions (Bakis, Bank & Brown 2002). Such applications include FRP wraps of concrete columns to improve strength and epoxy bonding materials to portions of beams subject to tension to reduce stress in the members and overall deflection. Epoxy bonding compoposites to masonary structures has become common where historical structures are in need of upgrading but cosmetic appeal is still a governing factor.

‘Fiber-Reinforced Polymer Composites for construction - State-of-the-Art Review’ published by the American Society of Civil Engineers is an informative paper that accurately portrays the development that was occuring in the FRP industry in 2002. Although the paper was published in 2002, the information contained in the document is considered valuable for this research project. The applications of composite technology discussed have been mainly to do with the construction industries. Composites however have been used in recreational, automotive, aerospace, marine, medical and electronic applications. These applications are discussed in further detail with respect to sandwich panels in section 2.3.4 ‘Applications’.

2.3. Composite sandwich panels

2.3.1. Introduction

Sandwich construction as defined by Frederick Plantema (1966) is a "three-layer type of construction, consisting of two thin sheets of high-strength material between which a thick layer of low average strength and density is sandwiched". The two thin sheets of high strength material are generally referred to as skins or faces. The material used for skins varies depending on the application of the composite panel. Aluminium, reinforced plastic, steel and titanium are just some of the materials used for skins. This project will be focusing on fibreglass skins. The thick layer between the two skins is called the core which can vary again in material and geometry. The core of the sandwich panel serves two critical purposes: firstly, the core must be stiff enough in the direction perpendicular to the skins to ensure that they remain the same distance apart; and secondly, the core must also resist shearing of the skins. The core must therefore possess a certain shearing rigidity in planes perpendicular to the skins. If sliding occurs the skins will act simply as two independent members and the sandwich effect will be lost. I beams in bending work on the same concept as sandwich panels. The resistance to bending is provided by the flanges. The greater the distance from the flanges to the centroid, the greater the resistance to bending provided the web has sufficient shear capacity (Plantema 1966). Some core structures include the honeycomb core, corrugated core and solid core which are shown below in Figure 9 (Howard 1969).

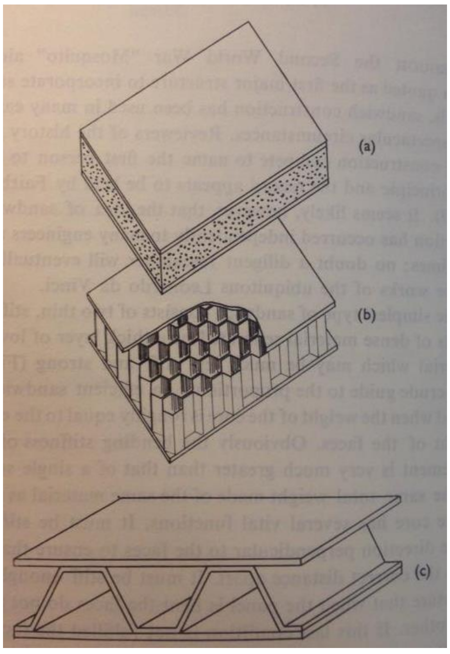


Figure 9 - (a) solid core, (b) honeycomb core, (c) corrugated core

Solid Cores made of materials such as balsa wood, perforated chipboard, expanded plastic, foam and clay products are the most common type of core used in the building industry. They offer a lightweight solution however the final product is much cheaper than honeycomb or corrugated core panels. Solid cores are ideal in situations where the member is carrying a relatively small load over a large span. Solid cores also have the advantage of thermal insulation which is very important when used in housing applications. Foam cores when compared with honeycomb and corrugated cores may be considered solid when in fact the nature of low density foam is such that there are air voids throughout. Foam cores were of focus for this project as it is these voids that contribute to the superior thermal insulation. Honeycomb core sandwich panels are predominantly used in the aerospace and aviation industries as they are the most efficient of the sandwich designs with respect to weight and mechanical performance. The production of honeycomb sandwich panels is labour intensive and relatively expensive. This limits its use in other industries where weight is not as crucial such as the civil infrastructure industry. Corrugated Core sandwich panels are similar to honeycomb core in the fact that they are both labour intensive constructions. The corrugated core is again a lighter solution than the solid core type. The geometric shape of the corrugations varies significantly in design however the most common shape is that shown in Figure 9.

2.3.2. Fabrication

There are two general types of fiberglass fabrication; open moulded which includes both hand layup and spray layup (chopping) and closed moulded which includes fabrication methods such as vacuum infusion, pultrusion, compression moulding and continuous lamination. The traditional hand layup fabrication technique has been in most cases superseded by the closed moulded methods however for the large flat laminates that make up the skins of the sandwich panel, hand layup is usually the method of choice (*Composites Australia* 2015).

2.3.3. Development

Allan Manalo from the Centre of Excellence in Engineered Fibre Composites (CEEFC) at the University of Southern Queensland (USQ) produced a report discussing the recent developments of fibre reinforced polymer composite sandwich structures and their applications to civil infrastructure. The report reviews how such composite sandwich structures are currently used in the civil construction industry and details a number of barriers that are limiting the growth and development of the material (Manalo 2013). Manalo says that the poor understanding of the overall behaviour of composite sandwich structures combined with the lack of appropriate design codes and standards is the reason there is such a disadvantage evident when composites are compared with traditional construction materials. Although research and development into the use of fibre composites in civil infrastructure has continued, the lack of application of these products suggests that the potential for this type of construction has not yet been fully explored.

Manalo notes that research into improving the performance of core materials in composite sandwich structures has been of significant focus in the past few years. Efforts to improve the strength of composite sandwich cores have been attempted by cellular manipulation and reinforcement of the core material. Refer Figure 10 (Manalo 2013). Reinforcement of the core material helps to prevent delamination failure while cellular manipulation has been proven to improve flexural stiffness and strength.

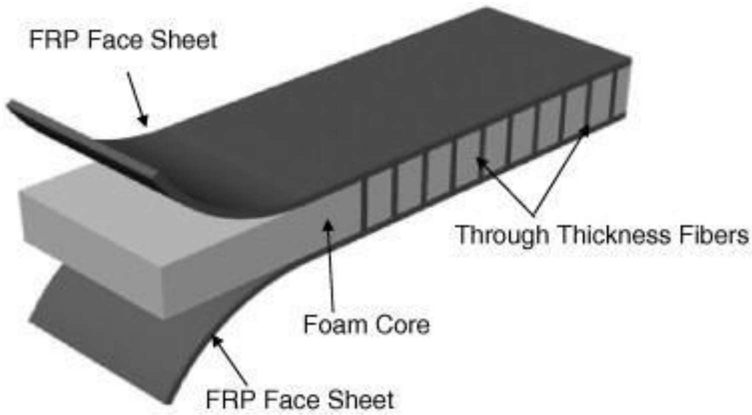


Figure 10 - Reinforcement of Core

2.3.4. Applications

With the large amount of research and development going into fibre composite sandwich panels, there has been a significant increase in new and innovative ways of practically applying the technology to civil engineering. Sandwich panel technology has been utilised in applications such as housing, bridge decks, pedestrian decks, tanks and railway sleepers.

Fibre composite sandwich technology has been utilised by companies around the world for bridge deck and pedestrian walkway constructions. In the local market are companies such as ‘Wagner’s’ and ‘BAC Technologies’. Fibre composite bridge decks are growing in demand due to the significant long term cost benefits that come with the minimal maintenance requirements and the prolonged service life of these materials. Figure 11 shows a fibre composite bridge manufactured by BAC Technologies which has a service life of approximately 100 years (*Modular FRP Pedestrian Bridge* 2015).

Figure 11 - BAC FRP Pedestrian Bridge

With composite sandwich technology advancing so well in the marine, aeronautical and transport industries it is not surprising that the technology is also being used in housing applications. Similarly to other industries the key advantage of using composite sandwich panels in housing applications is materials weight. As the panels are much lighter than traditional construction materials they can be easily transported, handled and installed reducing construction costs (Manalo 2013). Composite panels lend themselves to repetitive construction which is why they are so widely used in modular building designs such as in mining camps, unit blocks and flats.

Maunsell Structural Plastics, a company based in London developed a system comprising of pultruded FRP composite with a polyethylene foam core for use in walls and floors of building structures. The Advanced Composite Construction System (ACCS) as they call it allows for rapid installation on site (L.C. Hollaway 2001). This system is very similar to the design that will be investigated in this report. Shifting closer to the subject of roofing applications, a company by the name of Complete Modular Homes is currently producing a propriety roofing system called fast fix which is also known as Structurally Insulated Panels (SIP). Similar to the ACCS, the panels have a polyurethane foam core used for insulation. Sandwiching the core on the outer side is a galvanised steel sheet profile and on the underside is a fire retardant PVC sheet. The galvanised steel finish leaves the roof looking similar to a conventional steel sheeted roof however with this design there is no need for roof trusses (*Steel Profile*

Insulated Roofing Panel 2015). A company by the name of Bondor also produce a similar roofing system with a polyurethane core (*Bondor Insulated Roofing Panels* 2015).

Figure 12 - Complete Modular Homes Granny Flat

2.3.5. Benefits

As discussed in previous sections, fibre composite sandwich panels have several significant advantages over other more traditional construction materials such as timber, reinforced concrete and steel. The most well-known benefit of fibre composite sandwich panels would be the superior strength to weight ratio they offer. The panels also have the advantage of being flexible in design, fire resistant, corrosion resistant and have a low thermal conductivity (*DIAB Group* 2015). The strength and thermal conductivity will be discussed in detail in sections 2.4 'Flexural strength and deflection of sandwich panels' and 2.5 'Thermal insulation of sandwich panels' respectively. Fibreglass can be shaped and modified up to the last stage of manufacturing. This allows for countless adjustments and or changes to designs. Fibreglass is also a versatile material in that it can be easily repaired or 'built on to' by the same process used in manufacturing resulting in a seamless finish. It is these traits that make fibre composite sandwich panels so flexible in design. The fire resistance of the composite panels is attributed to the fibreglass skins that somewhat shield the light weight core. It is therefore important to look at the fire resistance of the two materials separately. The fire resistance of sandwich panels is covered in more detail in section 2.6 'Fire resistance'. The superior corrosion resistance of fibreglass is a trait commonly known. Fibreglass boat hulls have stood the test of time being exposed to the harshest of environments for lifespans in excess of 100 years. With this in mind it was predictable that fibreglass solutions would become more common in the field of civil infrastructure.

2.4. Flexural strength and deflection of sandwich panels

2.4.1. Strength of composites

Composite materials constructed with fibre reinforcement embedded in a matrix are orthotropic in that the mechanical properties in the x, y and z directions vary. Therefore to characterise the strength of the material, three strength parameters must be determined. The compressive and tensile strength, (parallel and perpendicular to the fibres) and the shear strength (measured parallel to the fibres) must be determined. The longitudinal tensile strength is governed by the tensile strength of the fibres whereas the compressive strength is determined largely by the stability of the fibres. If the reinforcement is unidirectional, the transverse and shear strengths are limited by the strength properties of the matrix (*Concise encyclopedia of composite materials* 1989). In practical situations such as the roofing panels, the reinforcement is usually biaxial so as to provide bending resistance both laterally and longitudinally. Basic models can be used to estimate the strength properties of composites with reinforcement provided in multiple directions however a significant error is present due to the presence of hydrothermal strains, development of non-catastrophic damage and material nonlinearity. Generally, manufacturers will conduct testing resulting in accurate mechanical properties for design.

The load bearing capacity of a sandwich panel is determined based on several different failures modes. For a sandwich structure subject to loads inducing flexural stress, the failure modes include tensile or compressive failure of the skins (a), buckling failure of the skins (delamination) (b), core shear failure (c) and crushing failure of the skins and the core (d). The modes of failure are illustrated below in Figure 13 - Failure .

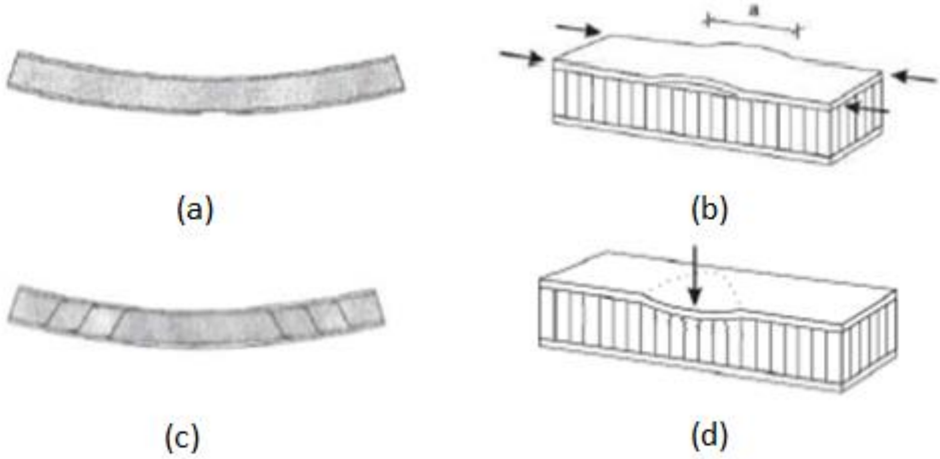


Figure 13 - Failure modes (Almeida 2009)

2.4.2. Volume Fraction

The volume fraction of the glass and resin are important properties used to calculate the strength and stiffness of a laminate. Generally provided by the supplier are the weight per square metre and density of the materials. Equation (1) describes the conversion from weight fraction to volume fraction (*Design Data* 1994).

$$V_1 = \frac{\frac{W_1}{\Delta_1}}{\frac{W_1}{\Delta_1} + \frac{W_2}{\Delta_2} + \frac{W_3}{\Delta_3}} \quad (1)$$

Where:

V = volume fraction of the constituent

W = weight fraction of the constituent

Δ = density of the constituent

2.4.3. Rule of mixtures

As the composite skin of a sandwich panel is made up of fibres embedded within a matrix, the mechanical properties of the composite must be determined from the properties of both the fibre and the matrix. The rule of mixtures is used to determine mechanical properties such us the modulus of elasticity, ultimate tensile and compressive stress and density. The equations for modulus of elasticity and ultimate stress and are presented below.

Assuming that the composite will only be subject to elastic deformation, the modulus can be calculated using the following equation.

Modulus of Elasticity

$$E_c = E_f V_f + E_m V_m \quad (2)$$

Where:

E_m = modulus of elasticity of the composite

E_f = modulus of elasticity of the fibre

V_f = volume fraction of the fibre

E_m = modulus of elasticity of the matrix

V_f = volume fraction of the matrix

(John W. Weeton 1987)

The tensile and compressive strength equation is of the same form.

$$\sigma_c^* = \sigma_f^* V_f + \sigma_m^* V_m \tag{3}$$

Where:

σ_c^* = stress carried by the composite at a particular strain

σ_f^* = stress carried by the fibre at a particular strain

V_f = volume fraction of the fibre

σ_m^* = stress carried by the matrix at a particular strain

σ_m = ultimate tensile strength of the matrix

V_f = volume fraction of the matrix

(John W. Weeton 1987)

Equation (3) is true provided that the fibre fraction is great enough so as to begin strengthening the matrix. The critical fibre content may be calculated with equation (4).

$$V_{crit} = \frac{\sigma_m - \sigma_m^*}{\sigma_f - \sigma_m^*} \tag{4}$$

For composites made up of E glass and either polyester, vinyl ester or epoxy resin, the critical fibre content required is generally very low due to the glass having a significantly higher modulus of elasticity then the resin. Although in most cases the critical fibre content will be quite low, it is still important and must be checked for design.

When a composite is subjected to a tensile load, the strain ε in the fibres will be equal to the strain in the matrix provided that the fibres share a perfect bond with the matrix. Thus the axial stresses in the fibres and matrix can be approximated simply by equation (5) and (6).

$$\sigma_f = E_f \epsilon \tag{5}$$

$$\sigma_m = E_m \epsilon \tag{6}$$

(Foster 1998)

As the two materials will undergo identical strain when subject to an axial load, it is assured that one of the materials will reach its ultimate strength prior to the other. In this case, the resin matrix will have a much lower ultimate strength than the glass fibres and therefore will fail first. Assuming an idealised stress-strain curve shown in Figure 14, the ultimate stress of the composite may be calculated as the maximum of the working strength (stress when matrix subject to its ultimate strength) and the ultimate strength of the fibres as given in the following equations.

$$\sigma_{Working} = (V_f E_f + V_m E_m)\epsilon_m \tag{7}$$

$$\sigma_{Ultimate} = V_f \sigma_f \tag{8}$$

(Foster 1998)

Equation (8) is valid provided that the matrix break elongation is not exceeded. Note that the matrix yield stress is not considered to strengthen the composite in equation (8).

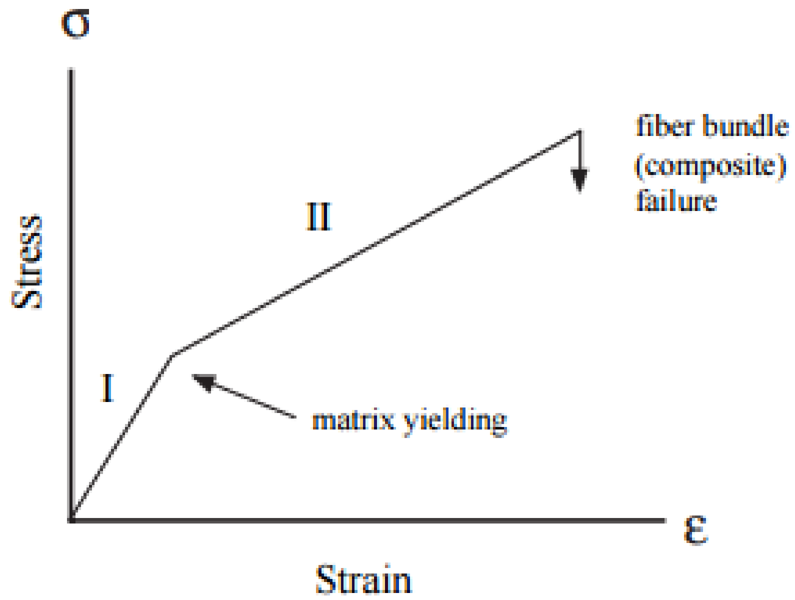


Figure 14 - Idealised stress-strain curve (Foster 1998)

2.4.4. Micro-Cracking

For design purposes it is important to understand the characteristic of composite laminates that is micro-cracking. The ultimate strength of a composite is the point at which the material exhibits catastrophic breakdown. Prior to this stage however, the composite is likely to reach a stress level at which the resin matrix will crack away from fibres. The laminate is beginning to breakdown at this point however it is not considered to have failed completely (Gurit 2015). Figure 15 indicates the micro-cracking phenomenon on a stress-strain graph.

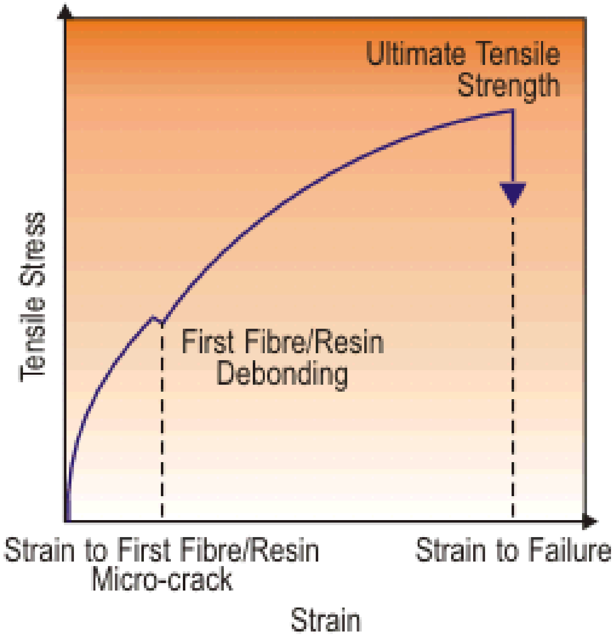


Figure 15 - Micro-cracking (Gurit 2015)

Although the laminate can generally withstand much greater stresses that observed during initial micro-cracking, the laminate must be designed so as not to exceed the micro-cracking strain as long term effects of moisture attack can result in reduced stiffness and strength. The strain at which micro-cracking occurs depends largely on the fibre layup schedule and the type of resin used. Generally epoxy resin has a greater micro-cracking strain then vinyl ester resin which has a greater micro-cracking strain then polyester. Clause 4.3.2 of the Eurocomp design code specifies a maximum strain of 0.002 due to tensile force for laminates that require resistance to chemical attack during service (*Structural Design of Polymer Composites Eurocop Design Code* 1996).

2.4.5. Flexural rigidity

Fundamentally, a sandwich structure should be designed to ensure that it has sufficient shear strength and flexural rigidity to prevent failures when subject to applied loads (Gryzagoridis, Oliver & Findeis 2015). The flexural rigidity of the composite beam is equal to the sum of the flexural rigidities of the faces and the core, measured about the centroidal axis of the entire cross section.

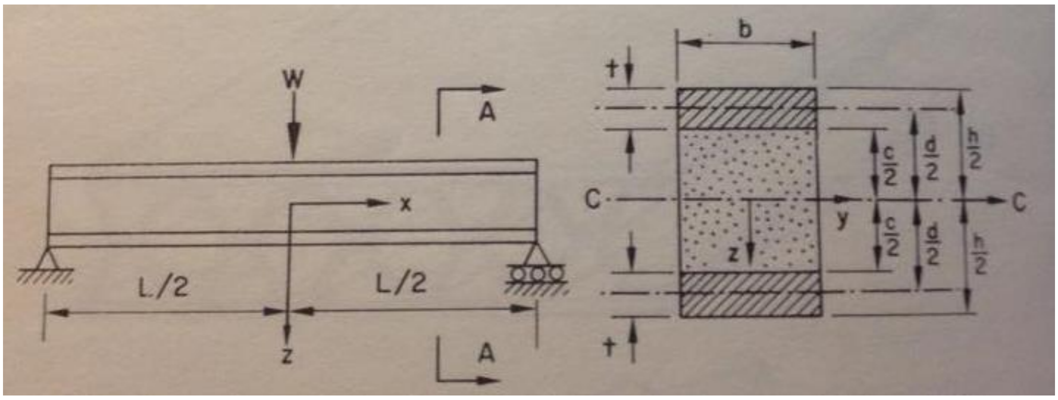


Figure 16 - Dimensions of sandwich beam

The flexural rigidity is the product of the Modulus of Elasticity (E) and the second moment of area (I) and may be calculated with equation (9).

$$EI = E_f \cdot \frac{bt^3}{6} + E_f \cdot \frac{btd^2}{2} + E_c \cdot \frac{bc^3}{12} \quad (9)$$

Where:

b, t and d are shown in Figure 16

E_f and E_c are the modulus of elasticity of the faces and the core respectively

(Howard 1969)

If the first and third terms on the right side of the equation are less than 1% of the second term, they may be neglected from the calculations.

2.4.6. Bending stress

The bending stresses in the face and core can be calculated using ordinary bending theory as per equation (10) and (11) respectively.

$$\sigma_f = \frac{Mz}{D} E_f \tag{10}$$

$$\sigma_c = \frac{Mz}{D} E_c \tag{11}$$

Where:

M = resulting bending moment due to loading

z = distance from the centroidal axis

D = EI

(Howard 1969)

As the panels are proposed to span in one direction, they will be analysed as a sandwich beam rather than a plate. If however a design change occurs leaving the panel supported on all four sides, therefore bending occurs in both the x and y planes, the stresses in the panels may then be expressed by the following.

$$\sigma_x = \frac{qb^2}{dt} (\beta_3 + v\beta_4) \tag{12}$$

$$\sigma_y = \frac{qb^2}{dt} (\beta_4 + v\beta_3) \tag{13}$$

Where:

v = poisons ratio

$\beta_3, \beta_{4,}$ are given in Figure 17 - Values of $\boldsymbol{\beta_1}, \boldsymbol{\beta_2}, \boldsymbol{\beta_3}, \boldsymbol{\beta_4}, \boldsymbol{\beta_5}$ for different a/b ratios

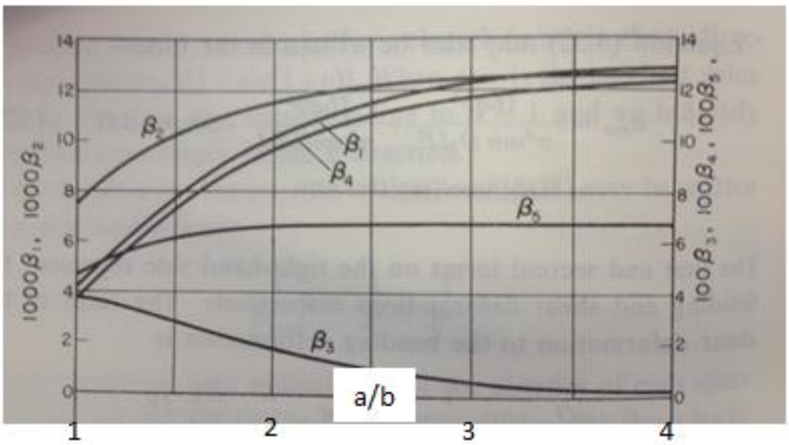


Figure 17 - Values of $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$

(Howard 1969)

2.4.7. Deflection

The mid span deflection of a sandwich beam with a uniformly distributed load is equal to the central bending deflection (Δ_1) plus the central shear deflection (Δ_2) as given in equation (14).

$$\Delta = \Delta_1 + \Delta_2 = \frac{K_g q L^4}{D} + \frac{K_s q L^2}{AG} \tag{14}$$

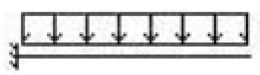
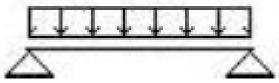
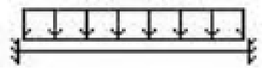
Where:

G = modulus of rigidity of the core material

A $= \frac{bd^2}{c}$

K_g and K_s are given in table for different support conditions.

Table 2 - Values of K_g and K_s for different supporting conditions

Support Condition	K_g	K_s
	1/8	1/2
	5/384	1/8
	1/384	1/8

(Almeida 2009)

Similarly to the bending stress equations, if the sandwich panel is subject to bending in both the x and y plane, deflection may be calculated as per equation (15).

$$W_{max} = \frac{qb^4}{D_2}(\beta_1 + \varrho\beta_2) \tag{15}$$

Where:

D_2 = flexural rigidity = $E_f t d^2/2\left(1 - V_f^2\right)$

ϱ $= \frac{\pi^2}{b^2}\frac{E}{G}\frac{ct}{2g}$ and $g = 1 - v^2$

. $\beta_1, \beta_{2,}$ are given in Figure 17 - Values of $\boldsymbol{\beta_1}, \boldsymbol{\beta_2}, \boldsymbol{\beta_3}, \boldsymbol{\beta_4}, \boldsymbol{\beta_5}$ for different a/b ratios (Howard 1969)

The mid span deflection of a simply supported sandwich beam subject to a point load is given below in equation (16) where the point load is denoted as P.

$$\Delta = \Delta_1 + \Delta_2 = \frac{PL^3}{48D} + \frac{PL}{4AG} \tag{16}$$

(Howard 1969)

2.4.8. Delamination

Sandwich panel facing delamination from the core is perhaps the most difficult failure mode to predict. Delamination is highly dependent on the skin to core bond and occurs just below the face of the core. The forces that cause the delamination result from varying stiffness of the core and the facing. Delamination of the skins from the core can result in localised skin wrinkling and core shear failure.

2.4.9. Wrinkling

The local buckling phenomenon known as skin wrinkling occurs when the skins separate from the core and buckle on their own. The wrinkling can occur due to a weakness in the bond holding the core and the skins together or by buckling instability of the skins themselves. Buckling instability of the cores occurs when the skins are too thin or too soft. For practical design purposes, Plantema (1966) recommends the wrinkling stress be calculated from equation (17).

$$\sigma_{wr} = 0.5\left(G_c E_{cz} E_f\right)^{\frac{1}{3}} \tag{17}$$

Where:

E_{cz} = modulus of elasticity of the core parallel to the z-axis

2.4.10. Core shear failure

When subject to a transverse shear force, the sandwich beam carries the shear force mainly by the core. Plastic collapse of the core can occur causing a catastrophic failure. It is important therefore to ensure that the core has sufficient shear strength. The shear stress in a sandwich beam can be calculated using the following expression.

$$\tau = \frac{Q}{Db}\sum(SE) \tag{18}$$

Where:

Q = shear force at the section under consideration

D = flexural rigidity of the entire section

$\sum(SE)$ = sum of the products of S and E of all parts of the section for which z>z_1

z_1 = depth of interest

Equation (19) may be simplified where it is deemed that the core is too weak to provide a significant contribution to the flexural rigidity of the sandwich structure. The shear stress is therefore assumed constant over the depth of the core and can be calculated by the following:

$$\tau = \frac{Q}{bd} \tag{19}$$

Similarly to the bending stress and deflection, if the sandwich panel is subject to bending in the x and y plane, the core shear stress shall be calculated using equation (20).

$$\tau_{zx} = \frac{qb}{d}\beta_6 \tag{20}$$

β_6 is given in Figure 18 - Values for $\boldsymbol{\beta_6}$ ***and*** $\boldsymbol{\beta_7}$

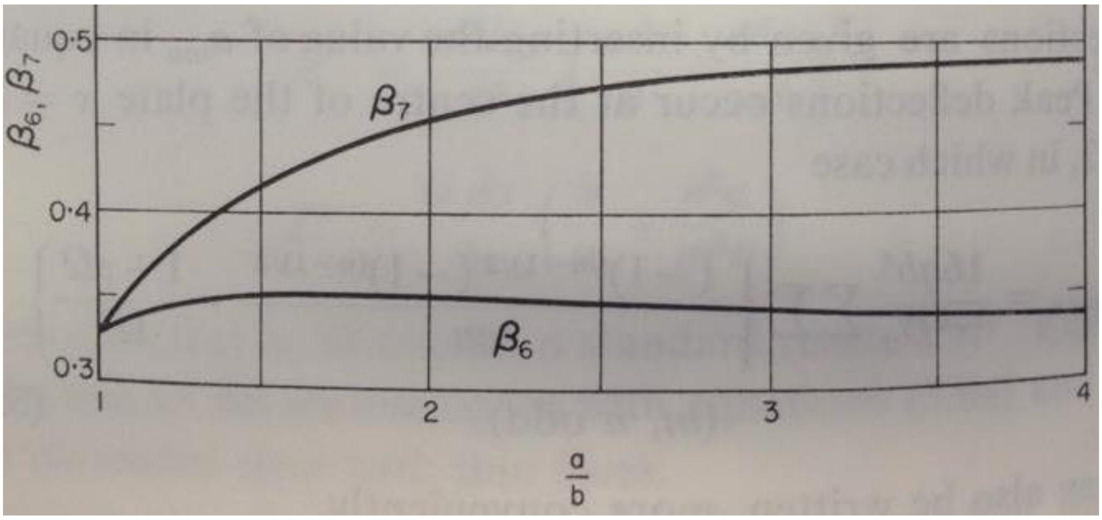


Figure 18 - Values for β_6 *and* β_7

(Howard 1969)

2.4.11. Crushing

Crushing failure of the core can occur when subject to a point load. It is important that the composite sandwich roofing panels be designed to allow for point loads experienced during construction. The crushing load of a sandwich panel is attributed to the compressive strength of the foam core.

2.4.12. Wide beams and effective width

As previously stated in section 2.4.6 'Bending Stress', the panels will be bending about one axis only, meaning they will only be supported on two sides. Due to the prevention of lateral deformation that would otherwise occur is narrow beams, wide beams are in fact more rigid than described in equations give in section 2.4.6 and 2.4.7. Young and Budynas (2002) state that the stiffening effect can be taken into account by using the following formula instead of the modulus of elasticity for deflection and curvature calculations.

$$E_{sub} = E/(1 - v^2) \tag{21}$$

Where v is poisons ratio.

The curvature that exists in narrow beams is still present however at the extreme edges of a wide beam. For stress calculations the concept of effective width should be taken into consideration. The effective width is described as the width of a strip that when acting as a beam with an equal maximum stress as the panel, develops an equal resisting moment. The effective width (b_{eff}) is dependent on the nature of the supports and loading and the breadth to span ratio (b/a) as shown in Figure 19.

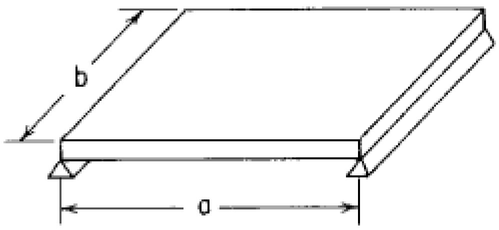


Figure 19 - Wide beams

Young and Budynas (2002) have provided the effective width for a number of different conditions of which are given below in Table 3 - Effective width. The effective width is denoted as e and central circular loading radius is denoted as c.

Table 3 - Effective width

Loading	Values of e/a for				
	$b/a = 1$	$b/a = 1.2$	$b/a = 1.6$	$b/a = 2$	$b/a = \infty$
Uniform	0.960	1.145	1.519	1.900	
Central, $c = 0$	0.568	0.599	0.633	0.648	0.656
Central, $c = 0.125h$	0.581	0.614	0.649	0.665	0.673
Central, $c = 0.250h$	0.599	0.634	0.672	0.689	0.697
Central, $c = 0.500h$	0.652	0.694	0.740	0.761	0.770

2.5. Thermal insulation of sandwich panels

Thermal energy transfer occurs where a temperature difference exists within an object, between bodies or between a body and its surroundings. This inevitable form of transfer is called heat transfer in which the heat will always flow from a higher temperature region to a lower temperature region (Moaveni 2011). The three types of heat transfer are conduction, convection and radiation. The reduction of heat transfer between objects in thermal contact is known as thermal insulation.

As the composite sandwich panels focused on in this report are made up of laminate and foam, there is more than one type of heat transfer taking place. Within the foam, heat transfer occurs via conduction through the solid material and the gas in the cell interior as well as by radiation (Glicksman 1994). Heat is also transferred by conduction and radiation in the laminate however it is the foam that will provide the panel with the thermal resistance as in almost all insulation materials, it is the air or gas that gives it its insulating capacity. This is due to the fact that solids have a higher thermal conductivity then liquids which have a higher thermal conductivity than gasses (*DIAB guide to core and sandwich* 2012).

2.5.1. Thermal conductivity (λ)

The thermal conductivity of a material is primarily evaluated in terms of Fourier's law for heat conduction. The law states 'that the rate of heat transfer through a material is proportional to the temperature difference, normal area A, through which heat transfer occurs, and the type of material involved' (Moaveni 2011, p315). The heat transfer rate is inversely proportional to the material thickness of which the temperature difference exits. The general form of Fourier's Law is given below.

$$q = \lambda A \frac{dt}{L} \tag{22}$$

Where:

q = heat transfer rate (W)

λ = thermal conductivity also referred to as k ($\frac{W}{m \times {}^{\circ}C}$)

A = cross sectional area normal to heat flow (m^2)

dt = temperature difference across the material thickness L (${}^{\circ}C$)

L = material thickness (m)

The thermal conductivity is a property that describes a material's ability to conduct heat. From equation (22) we learn that a material with a high thermal conductivity will in turn have a high heat transfer rate. Materials with low thermal conductivities are therefore usually selected for use as thermal insulation. The thermal conductivity is not however constant, rather a property that changes with temperature, density, time and moisture content. For the purposes of this project, the thermal conductivities of the foam cores and E glass laminates are supplied by the manufacturers. As a general estimate, fibreglass has a thermal conductivity of 0.04 $\frac{W}{mK}$ at a temperature of approximately 25°C and polyurethane cores approximately 0.03$\frac{W}{mK}$ at temperatures above 20°C.

2.5.2. Thermal resistance (R')

The thermal resistance, referred to as an R-value or R-factor in the building and construction industry, is a property that provides resistance to heat flow. The thermal resistance of a material is given in equation (23).

$$R' = \frac{L}{kA} \tag{23}$$

It is important to note that heat transfer is directly proportional to the temperature difference and is inversely proportional to the thermal resistance (Moaveni 2011). When equation (23) is expressed per unit area of material it is referred to as the R-value.

$$R = \frac{L}{k} \tag{24}$$

R has the metric units of $\frac{m^2 \times °C}{W}$ however it is most commonly expressed in imperial units of $\frac{ft^2 \times °F \times h}{BTU}$. AS/NZS 4859.1:2002, Materials for the thermal insulation of buildings, clause 2.3.3 specifies the standard methods for determination of thermal properties including R values for insulation (*AS4859.1 2002 Materials for the thermal insulation of buildings* 2002).

2.5.3. Thermal diffusivity (D)

Thermal diffusivity denoted as D or α measures the ability of a material to conduct thermal energy with respect to its ability to store it. The equation for thermal diffusivity is given below:

$$D = \frac{k}{\rho C_p} \quad (25)$$

Where:

ρ = density ($\frac{kg}{m^3}$)

C_p = specific heat capacity ($\frac{J}{kg \times K}$)

(Carslaw & Jaeger 1986)

2.6. Fire resistance

2.6.1. PU core

When subject to a sufficient heat source, polyurethane foam can ignite and burn. Generally for insulation applications the foam will contain fire retardants however it is important that the foam be manufactured, transported and used in accordance with the relevant building codes and standards (*American Chemistry Council - Polyurethane* 2015). The Building Code of Australia (BCA) Section C Fire Resistance specifies both the fire resistance and reaction to fire requirements for insulated sandwich panels (Rakic 2003). For insulation materials other than sarking-type materials, the member when tested in accordance with AS1530.3 must have a spread of flame index not exceeding 9. Where the spread of flame index is greater than 5, it must also have a smoke developed index not exceeding 8 (*National Construction Code Series Volume 1* 2015). The national regulatory requirements are based on accepted safety levels concerning human life where as insurance company regulations are also concerned with ensuring protection of property. Hence, over the past decade it has been the insurance requirements governing the fire resistance properties rather than the national regulatory requirements.

2.6.2. Fibreglass skins

As discussed previously, the fibreglass skins act similarly to the concrete cover provided for reinforcement steel in that it limits the exposure of the foam core to the heat source. In fact the BCA states that in the case of a composite member assembly, the core is not required to meet the flame index or smoked developed index provided that the structure as a whole satisfies the requirement. The core must also be protected on all sides and edges from exposure to the air for a period of not less than ten minutes (*National Construction Code Series Volume 1* 2015).

2.7. Testing

Testing of fibre composites for structural design is of great importance as in many cases, the actual strength and deflection of a member will vary significantly from the theoretical values. The calculated properties of composite materials can vary due to several reasons. Two of the most common causes for these variances are quality control during manufacture and the uncertainty involved with the bonding strength between two different materials. Quite often even after extensive research and repetitive application of a product, testing is still required before the product can be considered a safe design for each individual case.

2.7.1. Stiffness

For roofing applications it is important to determine the sandwich panels flexural and shear stiffness so as to ensure the design requirements are met. ASTM D7250/D7250M details the standard practice for determining sandwich beam flexural and shear stiffness. The practice uses test results obtained from the standard test method for facing properties of sandwich constructions by long beam flexure (ASTM D7249/D72490M) and the standard test method of core shear properties of sandwich constructions by beam flexure (ASTM C393/C393M).

ASTM D7250/D7250M gives solutions for the flexural and shear stiffness for common combinations of loading conditions. The sandwich beam testing will consist of several different loading conditions of which include 3-Point Mid-Span Loading and various 4-Point Loading configurations including Third-Span and Quarter-Span. The equations for the flexural stiffness (D), transverse shear rigidity (U) and core shear modulus (G) are given for the two loading combinations used in the testing. For each set of loading combinations, D, U and G must be calculated for at least ten (10) force levels evenly spaced over the linear elastic force range. The final values for each parameter may then be calculated as the average of the set.

Two 3-Point Mid-Span Loading Configurations

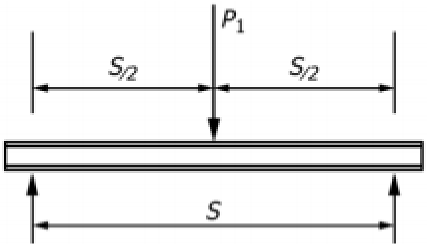


Figure 20 - 3-Point Mid-Span Loading

$$D = \frac{P_1 S_1^3 (1 - S_2^2 / S_1^2)}{48\Delta_1 (1 - P_1 S_1 \Delta_2 / P_2 S_2 \Delta_1)} \tag{26}$$

$$U = \frac{P_1 S_1 (S_1^2 / S_2^2 - 1)}{48\Delta_1 [(P_1 S_1^3 \Delta_2 / P_2 S_2^3 \Delta_1) - 1]} \tag{27}$$

Where:

P_1 = total applied force (configuration #1) (N)

P_2 = total applied force (configuration #2) (N)

S_1 = support span length (configuration #1) (mm)

S_2 = support span length (configuration #2) (mm)

Δ_1 = beam mid-span deflection (configuration #1) (mm)

Δ_2 = beam mid-span deflection (configuration #2) (mm)

G = core shear modulus (MPa)

D = flexural stiffness (Nmm^2)

U = transverse shear rigidity (N)

One 4-Point Quarter-Span Loading Configuration and One 4-Point Third-Span Loading Configuration

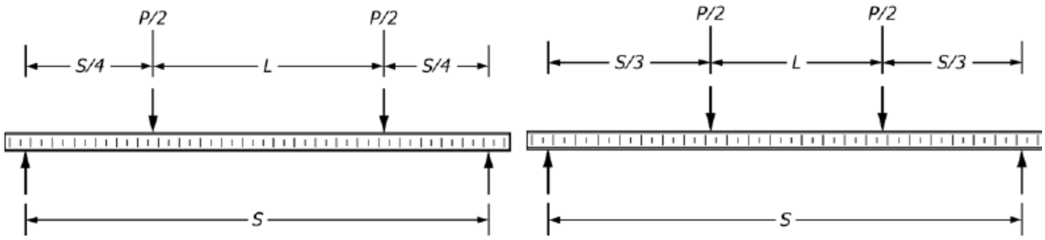


Figure 21 - 4-Point Quarter-Span and 4-Point Third-Span Loading

$$D = \frac{99P_1S_1^3(1 - 92S_2^2/99S_1^2)}{6912\Delta_1(1 - 3P_1S_1\Delta_2/4P_2S_2\Delta_1)} \tag{28}$$

$$U = \frac{P_1S_1(99S_1^2/92S_2^2 - 1)}{2\Delta_1[297(P_1S_1^3\Delta_2/368P_2S_2^3\Delta_1) - 1]} \tag{29}$$

For both loading combinations the core shear modulus is calculated with the same equation.

$$G = \frac{U(d - 2t)}{(d - t)^2 b} \tag{30}$$

Where:

d = sandwich thickness (mm)

t = facing thickness (mm)

b = sandwich width (mm)

2.7.2. Strength

ASTM D7249/D7249M and C393/C393M are the standard test methods for determining facing properties and core shear properties of sandwich panels. Both tests consist of subjecting a sandwich beam a bending moment normal to the plane of the sandwich with either a 3 or 4 point bending test. The deflection (mm), load (N) and time (s) are recorded throughout the duration of the test. ASTM D7249/D7249M is a long beam flexure test in which the unsupported span must be sufficient to ensure the failure occurs in the facing. Similarly for ASTM C393/C393M, the short beam test, the unsupported span must be short enough so as to induce shear failure of the core. The test methods include specimen design requirements to ensure the correct failure modes occur. Properties determined from these tests include the facing ultimate stress, effective facing chord modulus and core shear ultimate stress.

Chapter 3. Methodology and Manufacture

3.1. Introduction

This chapter details the analysis methods and design processes followed throughout the duration of the project. The method for analysing the composite sandwich panels for roofing applications may be broken down into several phases:

- determination of design loads, serviceability and insulation requirements;
- design;
- manufacture;
- testing; *and*
- modelling.

The timeline for the various phases of the project has been attached as appendix C.

3.2. Design requirements

<u>Design loads and serviceability</u>

The design loads and serviceability limits were calculated using the relevant standards for roofing design which include AS1170.0, AS1170.1 and AS1170.2. The loads determined included dead load, superimposed point and distributed live loads as well as wind loads.

<u>Insulation</u>

The insulation requirements were determined according to Section J ‘Energy Efficiency’ of the National Construction Code (NCC) otherwise known as the Building Code of Australia (BCA). Based on findings from the literature review, the local council requirements for thermal insulation will also need to be determined and designed for.

3.3. Initial design

As stated in the literature review, there have been many studies conducted on the flexural strength of sandwich panels of which the results are widely published. Using the published equations, the theoretical capacities of the sandwich panels subject to transverse loads were calculated numerically. This was carried out with the use of the program Microsoft Excel. Similarly the thermal insulation or resistance (R) was calculated in the same way.

3.4. Properties of materials

3.4.1. Introduction

This section details the properties of the foam core and glass reinforcements for the proposed design. The foam cores utilised were from the manufacturer Australian Urethane Systems, the glass from Colan Australia and the resin from NCS Resins.

3.4.2. Glass

The fibreglass skins were woven roving (E glass) in a polyester resin of which number of layers (thickness) and weight were determined during the design. The biaxial glass provides strength in both directions of bending. The general properties of Colan Australia's E Glass are given below in a comparison chart with various other reinforcements (*Colan Australia* 2013).

Table 4 - E glass properties

Property		Glass Fibre		p-Aramid (Kevlar) Fibre	Carbon Fibre		HM Polyethylene Fibre	Basalt Fibre	Polyester Fibre
		E	S		HS	HM			
Density	g/cm³	2.54	2.46	1.45	1.76	1.80	0.97	2.66	1.38
Tensile Modulus	GPa	72	87	124	235	338	87	93	14
Tensile Strength	MPa	3400	4600	3600	3500	2480	2650	4500	1200
Specific Modulus	GPa/g/cm³	28	35	85	133	188	90	-	10
Specific Strength	MPa/g/cm³	1340	1870	2480	1990	1380	2730	-	870
Elongation at Break	%	4.8	5.4	2.0	1.2	0.5	3.5	3.1	13.5
Coefficient of thermal Expansion (+expand:-contract)	10^{-6}m/mK	+5.0	+2.4	-3.5	-0.36	-0.54	-12.0	8.0	+60.0

E-glass composites with different yarn processing are presented in Table 5.

Table 5 - Comparison of E-glass composites with different yarn processing types

Property		Random Fibre Chopped Strand Mat	0° / 90° Woven Roving	0° / 90° Knitted Bidirectional Roving
Tensile Strength	MPa	105	250	320
Tensile Modulus	GPa	8.1	13.3	16.2
Flexural Strength	MPa	188	400	511
Flexural Modulus	GPa	6.8	12.1	15.2
Inter-laminar Shear Strength	MPa	21.5	25.0	26.5
Glass Content	%	31	50	50

The theoretical laminate properties are calculated in section 3.4.5.

3.4.3. Resin

Ultimately, a fire retardant vinyl ester resin will be used for roofing applications. Unfortunately fire retardant resins were not available to manufacture the sample panels. Although the differences in resin type will make a substantial difference to the fire resistance properties of the design, it will not affect the strength of the composite dramatically. Future fabrication of the panels will be on a much larger scale using a vacuum infusion technique which may also produce slightly different properties to that observed here. The resin used for the sample panels was NCS 991 PA U-40 supplied from NCS resins which is a versatile, pre-accelerated, unwaxed, isophthalic, unsaturated polyester resin. The typical liquid and cured properties are provided in Table 6 and Table 7 respectively ('NCS 991 PAU-40' 2015).

Table 6 - Typical liquid properties

PROPERTY	SPECIFICATION	NCS TEST METHOD
Relative density 25°/25°C	1,10 - 1,12	14
Viscosity @ 25°C, mPa.s	450 - 550	5.2
Acid value, mg KOH/g	14 - 22	13
Volatile content, %	43 - 46	7A
Geltime @ 25°C, 1 phr* BUTANOX M50, minutes	37 - 43	8
Stability in the dark @ 25°C, months	6 minimum	4.1
*phr = parts per hundred resin, by mass		

Table 7 - Typical cured properties

Specific gravity at 25°C	1,11
Elongation at break * %	5
Tensile strength, MPa	82
Tensile modulus, MPa	3 500
Volumetric shrinkage, %	8,1
* Filtered resin, void-free casting	

3.4.4. Foam Cores

The proposed core material is BFE35 from Australian Urethane Systems which is a general purpose flame retardant, rigid cellular polyurethane foam of nominal density 35kg/m³. The foam provides great thermal and acoustic insulation however it is weak in shear and compression. The foam is recommended for use in insulation applications in tank, pressure vessels, concrete slab under floor insulation, insulation panels, cold room manufacture and marine buoyancy applications. Due to the weak mechanical properties, the foam is not generally recommended for structural applications however due to the limited availability of higher density foams at BAC, the BFE35 foam was selected. The typical physical properties are provided below in Table 8.

Table 8 – BFE35 Typical physical properties

Property	AS Test Method	Results for AUSTHANE BFE35			AS 1366.1992 Australian Standard Test Requirements
Density	Not specified	35 kg/m^3 nominal Typical Result: 34 -38 kg/m^3			No specification
Compressive Stress at 10 % deformation	AS 2498.3	Parallel to Rise: > 200 kPa Perpendicular to Rise: > 140 kPa			**Results to Pass AS Standard** Parallel to Rise: > 175 kPa Perpendicular To Rise: > 100 kPa
Closed Cell Content	AS 2498.7	> 91 %			**Minimum of 85%**
Thermal Resistance at a mean temperature of 17.52°C	AS 2464.5	R = 2.12 m^2.K/W @ 50 mm [Equivalent to a k factor of 0.0236 W/m.K]			**Minimum Required Value:** **R = 1.8m^2.K/W [at 50 mm]** [Equivalent to a k factor = 0.027 W/m.K]
Dimensional Stability at 90°C and at - 20°C 72 hours Exposure Time	Based on AS 2498.6	**Dimension**	**90°C**	**– 20°C**	Test Sample Nominal Size: 100 mm x 100 mm x 25 mm **Note:** Measurement Limit for Dimensional Change is < 0.5%
		Length	< 0.5%	< 0.5%	
		Width	< 0.5%	< 0.5%	
		Thickness	< 0.5%	< 0.5%	
Water Absorption / Marine Buoyancy application	AUS/07	< 2 % 'Buoyancy' Loss Surface Absorption Rate < 400 gms per square metre of exposed surface Exposure Time: 30 days immersion Water Temperature: 27 ± 2°C			No specification

(*AUSTHANE BFE 35 Rigid FR Polyurethane Foam* 2011)

As the shear strength of the foam has been predicted to be so low, Australian Urethane Systems have not conducted shear testing on this particular density however testing results on higher density foam is available. The physical, mechanical and chemical parameters of 62 and 16kg/m^3 foam are given on the next page in Table 9.

Table 9 - Testing results of 16 & 62kg/m³ PU foam

Property	Test standard or specimens dimensions	Unit	Property at different foam density	
Apparent density	ISO 845	kg/m³	62	16
Compressive strength parallel to foam rise	ISO 844	MPa	0.64	0.033
Compressive stress perpendicular to foam rise			0.41	0.018
Compressive modulus parallel to foam rise			19.5	0.92
Compressive modulus perpendicular to foam rise			10.1	0.34
Tensile strength parallel to foam rise	ISO 1926		0.79	
Tensile strength perpendicular to foam rise			0.44	
Tensile modulus parallel to foam rise			26.7	
Tensile modulus perpendicular to foam rise			12.3	
Poisson`s ratio ν_{12}	75x50x50		0.72	
Poisson`s ratio ν_{22}			0.32	
Poisson`s ratio ν_{21}			0.30	
Shear strength in plane parallel to foam rise	ASTM C-273	MPa	0.34	
Shear strength in plane perpendicular to foam rise			0.36	
Shear modulus in plane parallel to foam rise			6.4	
Shear modulus in plane perpendicular to foam rise			6.2	
Reduction of buoyancy after 7 day immersion in water	150x150x150	pct.	0.62	8.05
Reduction of buoyancy after 30 day immersion in water			1.05	17.8
Maximum compressive stress no causing plastic deformation above 5% after 10,000 cycles, perpendicular to foam rise	ISO 844	MPa	1.24	
Average burning rate after exposure at 48 h for °C	ISO 9722	mm/min	45.80	
Average burning rate after exposure at 168 h for 70°C			54.90	

For design purposes, the ultimate shear strength of the 35kg/m³ foam was taken as half of the ultimate shear strength of the 62kg/m³ foam. This assumption was then checked with results from the core shear tests. Refer section 3.6 for both short beam and long beam flexure procedure. The properties for Australian Urethane Systems full range of foam cores are available on their website at http://www.ausurethane.com (Wit Witkiewicz 2006).

3.4.5. Theoretical properties

The theoretical mechanical properties of the laminate used for design were calculated using the rule of mixtures as noted in section 2.4.3.

3.4.5.1. Volume fraction

The volume fraction of both glass and resin are calculated below. The following layup schedule was proposed after direct consultation with the floor manager and other experienced fabricators. Chopped strand mat and woven roving are denoted as CSM and WR respectively with the prefix number representing the materials mass per square meter.

Table 10 - Laminate Layup

Layer 1	225 CSM
Layer 2	900 WR
Layer 3	225 CSM
Layer 4	900 WR
Layer 5	225 CSM

The woven roving provides rigidity in both the 0º and 90º axes whilst being substantially cheaper than using a biaxial stitched fabric. The chopped strand mat doesn't add to the strength of the laminate dramatically; however it acts as resin filler. Chopped strand mat requires a glass to resin weight ratio of approximately 1:2 when wetting whereas woven roving requires less resin at a ratio of 1:1. The chopped stand mat is much cheaper than the woven roving making for cheap, bulky filler that brings more resin to the laminate.

The total weight of each of the materials was found by simple multiplication.

CSM = 225x3 = 675 g/m^2

WR = 900x2 = 1800g/m^2

Therefore the resin by weight was calculated as:

Resin = $\frac{675}{31\%} \times 69\% + \frac{1800}{50\%} \times 50\%$ = 3302g/m^2

The rule of mixtures requires a volume fraction which was calculated using equation (1).

$$V_1 = \frac{\frac{W_1}{\Delta_1}}{\frac{W_1}{\Delta_1} + \frac{W_2}{\Delta_2} + \frac{W_3}{\Delta_3}}$$

$$V_{WR} = \frac{\frac{1800}{2.54}}{\frac{1800}{2.54} + \frac{675}{2.54} + \frac{3302}{1.11}} \approx 17.9\%$$

$$V_{CSM} = \frac{\frac{675}{2.54}}{\frac{1800}{2.54} + \frac{675}{2.54} + \frac{3302}{1.11}} \approx 6.80\%$$

$$V_{Resin} = \frac{\frac{3302}{1.11}}{\frac{1800}{2.54} + \frac{675}{2.54} + \frac{3302}{1.11}} \approx 75.3\%$$

3.4.5.2. Thickness of laminate

The ACI Composite Handbook (*Design Data* 1994) contains a table of thickness constants for various composite materials. The thickness constants were calculated using the formula given below:

$$\frac{1}{density} = thickness\ constant \tag{31}$$

The thickness constant for E glass with a density of 2.56 g/cm³ and polyester resin with a density of 1.1 g/cm³ are 0.391 and 0.909 respectively, where the thickness is calculated in mm attributable to 1kg/m² of the material. The predicted thickness of the laminate was therefore calculated as:

Predicted thickness = 0.391 x (0.675 kg/m² + 1.8 kg/m²) + 0.909 x 3.302 kg/m²

= 3.97mm

3.4.5.3. Composite density

Ignoring the void content of the laminate, which couldn't be determined without conducting a burn off test, the composite density was estimated by simply applying the law of mixtures once again.

$$\rho_{comp} = \rho_f V_f + \rho_m V_m$$

$$\rho_{comp} = 2.54 \times 24.7\% + 1.1 \times 75.3\%$$

$$\rho_{comp} = 1.46 g/cm^3 = 1460 kg/m^3$$

3.4.5.4. Modulus of elasticity

The flexural modulus of elasticity of the composite skin was calculated using equation (9).

$$E_c = E_f V_f + E_m V_m$$

It is estimated that half of the volume of both the CSM and WR fibres are acting in the X direction and conversely half of the volume is acting in the Y direction. Therefore it was assumed that only 50% of the fibre volume would contribute to the modulus of elasticity.

$$E_c = 72000 MPa \times 24.7\%/2 + 3500 MPa \times 75.3\%$$

$$E_c \approx 11528\ MPa$$

$$E_c \approx 11.5\ GPa$$

This value is consistent with the data given in Table 5 as it falls in between 6.8GPA for a typical CSM laminate and 12.1 GPa for a typical WR laminate. According to the ACI handbook, CSM modulus may be estimated as 3/8E_L + 5/8E_T where E_L and E_T are the longitudinal and transverse modulus of the assumed uni- directional layer respectively (*Design Data* 1994). Therefore the modulus calculated was considered to be conservative.

3.4.5.5. Tensile strength

The working strength and ultimate tensile strength of the composite skin were determined using the equations provided in section 2.4.3 where again it was assumed that only 50% of the fibres contributed to the strength. The stain at which each of the materials would reach their ultimate stress was firstly determined.

Fibre failure strain = $\frac{\sigma_f}{E} = \frac{3400 MPa}{72000 MPa}$ = 0.0472

Matrix failure strain = $\frac{\sigma_m}{E} = \frac{82 MPa}{3500 MPa}$ = 0.0234

Therefore it was concluded that the resin matrix will reach its failure strength prior to the glass failing. The tensile working strength was calculated using equation (7).

$$\sigma_{Working} = (V_f E_f + V_m E_m)\epsilon_m$$

$$\sigma_{Working} = (24.7\%/2 \times 72000MPa + 75.3\% \times 3500MPa)0.0234$$

$$\sigma_{Working} \approx 270\text{MPa}$$

The ultimate tensile strength was then taken as the greater of $\sigma_{Working}$ and $\sigma_{Ultimate}$ calculated from equation (8).

$$\sigma_{Ultimate} = V_f \sigma_f$$

$$\sigma_{Ultimate} = 24.7\%/2 \times 3400MPa$$

$$\sigma_{Ultimate} \approx 420\ MPa$$

As the ultimate fibre strain calculated is less than the matrix break elongation strain of 0.05, the ultimate tensile strength of the composite was taken as 420MPa. The ultimate tensile strength, working strength and eurocomp serviceability limits are shown below in Figure 22:

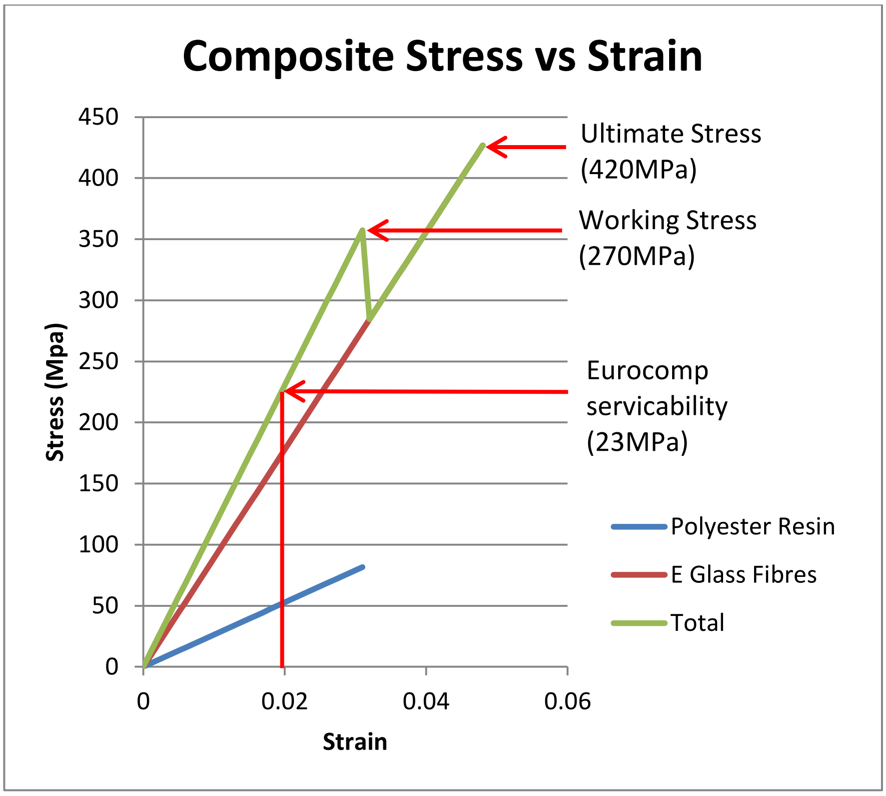


Figure 22 - Ultimate and working strengths

3.5. Manufacture

The composite sandwich panels used for testing were manufactured at BAC's workshop over a period of one week in strict accordance with project risk management plan and BAC's safety policy. The following procedure outlines the method of manufacture as well as the materials and tools required:

3.5.1. Materials

The materials used for manufacture were:

- Australian Urethane Systems BFE35 Rigid block foam;
- AkzoNobel Butanox M-50 Catalyst;
- NCS 991PAU-40 Resin;
- Colan Australia 830g/m2 Woven roving; *and*
- Colan Australia 225g/m2 Chopped strand mat.

3.5.2. Procedure

1) The BFE35 Rigid block foam was cut to the following panel sizes using a band-saw:
   - 2x 75x250x1450mm;
   - 1x 75x250x1200mm; *and*
   - 3x 50x250x1200mm.
2) Saw dusts and other foreign materials were removed from the foam with compressed air.
3) The woven roving and chopped strand mat glass were cut into the required lengths.
4) A catalyst to resin ratio of 2% was achieved by adding approximately 60mL of M-50 Catalyst to 3000mL of 991PAU-40 Resin in several milk containers.
5) The foam cores were prepared for the first layer of glass by applying a thin film of resin with a paintbrush. The resin soaked into the core providing for a strong skin to core bond.
6) The glass was placed according to Table 10 - Laminate Layup with the use of a paintbrush and roller when applying the resin mix.
7) The panels were placed to the side for three hours allowing for the laminate to set before flipping over.
8) Step 5,6 and 7 were repeated for skins on the opposite sides of the panels.

9) The panels were cut to the following required testing sizes using a diamond tip blade on the band-saw:
    - 3x 75x100x1400mm;
    - 6x 75x100x550mm;
    - 3x 50x100x1100mm; *and*
    - 6x 50x100x550mm.
10) The test beams were once again cleaned using compressed air before transportation to the CEEFC at USQ.

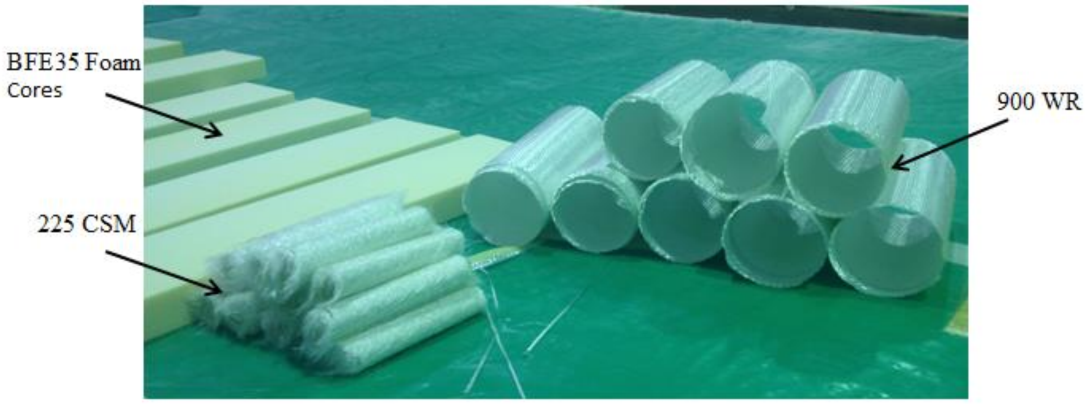


Figure 23 - Foam core, chopped strand mat and woven roving glass

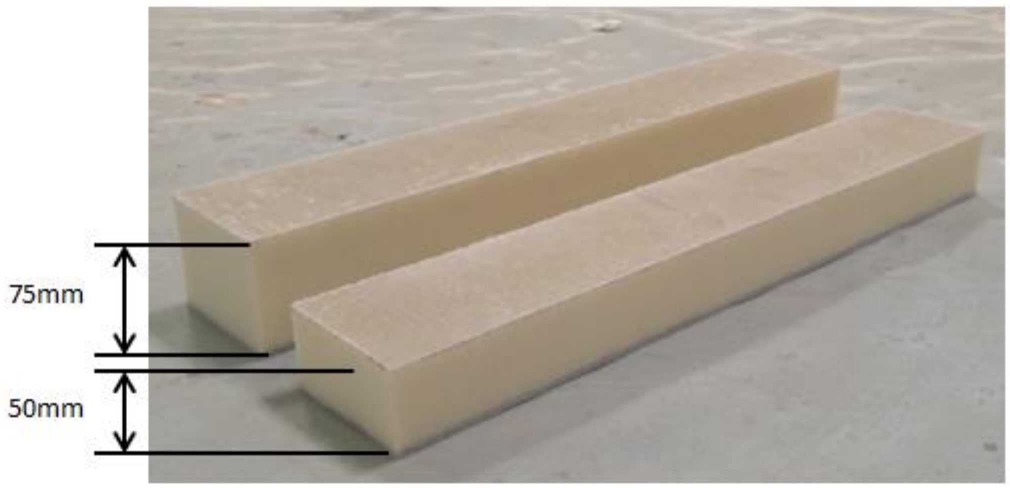


Figure 24 - Completed test beams

3.6. Testing procedures

The following section outlines the testing procedures followed throughout the testing period at the Centre of Excellence in Engineered Fibre Composites. Initially two tests were planned; long beam flexure to determine the facing properties and short beam flexure to determine the core shear properties of the sandwich construction. Unexpected failure modes in the first two samples resulted in a change in the testing plan as discussed in Chapter 4.

All of the testing was conducted at the CEEFC testing facility in block P9 with the 100kN capacity load cell. The loading and support conditions were then adjusted for each of the different tests. The first test conducted was a 3-Point Mid-Span Loading Deflection Test with a span of 450mm and a nominal foam core depth of 50mm. The beam was supported by two 50mm steel plates of which were fastened to a steel I beam to ensure no movement throughout the duration of the test. The loading consisted of the 100kN capacity load cell and a 40mm wide load distribution plate running along the width of the beam. Both the 50mm steel support plates and the 40mm load distribution plate were utilised to prevent localised crushing of the foam core. The testing setup is shown below in Figure 25.

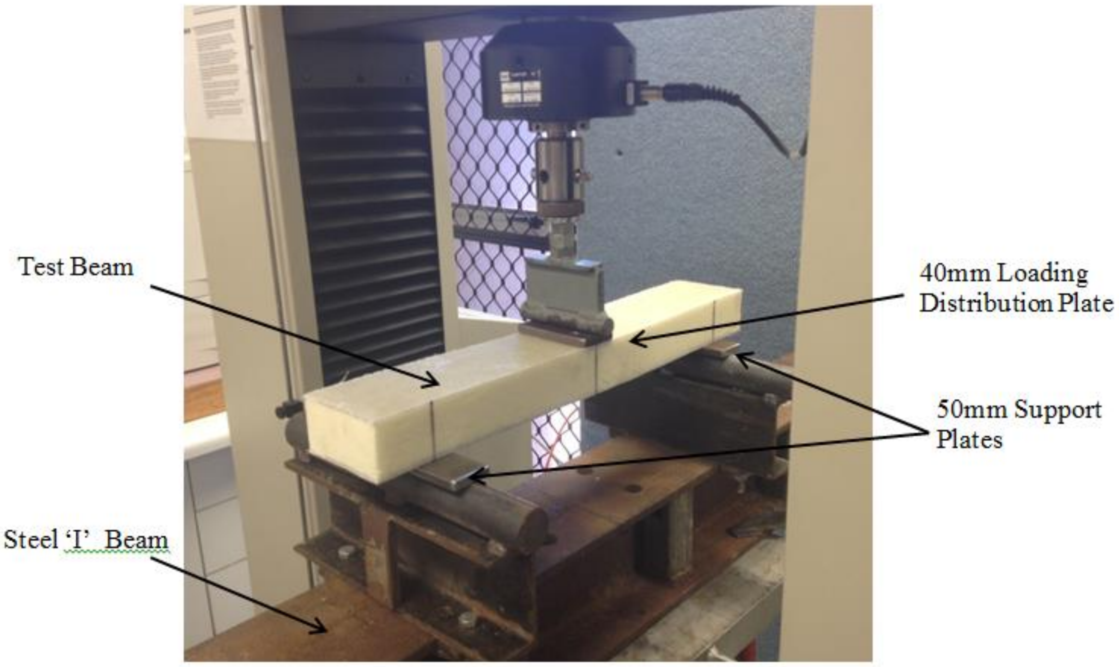


Figure 25 - Loading case 1

Prior to loading the beam, the core thickness, skin thickness and beam width were measured with a set of digital Vernier Callipers. ASTM C393/C393M recommends setting the testing speed to produce failure within 3 to 6 minutes. As the ultimate strength of the beam was unknown, the crosshead displacement was set at 5mm/minute which is slightly slower than the suggested standard speed of 6mm/minute. After completing the first test and determining the failure load, the testing speed was increased to achieve failure within the specified time frame. After setting the testing speed, the test was initiated with the time in seconds, crosshead movement in mm and applied load in Newtons recorded directly to the computer for analysis post testing.

The desired failure mode for the first test was not observed and therefore the support conditions were adjusted for test two. This result is discussed in further detail in Chapter 4. The supporting width was reduced to 300mm before testing specimen two and three of which both had a nominal foam core depth of 50mm. The testing speed was increased to 10mm/minute for both specimens. Test number three was a 4-Point bending test with dimensions as given below in Figure 26.

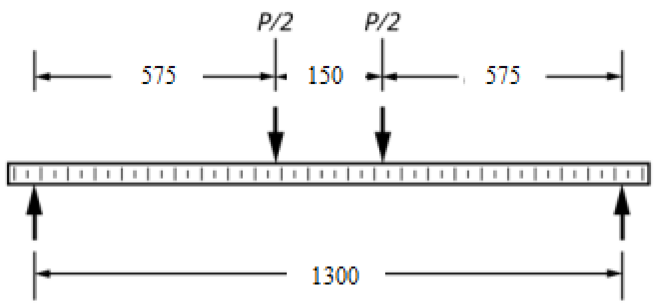


Figure 26 - Test 3 setup

Load distribution plates were provided for both loading points however this test did not include support plates as in the first two testing configurations. The testing speed was again increased to 20mm/minute and specimen 4 and 5 (75mm nominal core depth) were tested. Figure 27 shows specimen 4 during the testing process.

Figure 27 - Specimen 4 during testing process

The support span was reduced to 600mm for test 4 with all other parameters kept the same. Specimen 6 was disregarded due to incorrect support spacing however specimen 7 (50mm nominal core) was tested.

The configuration for test 5 was similar to that of test 3 and 4 however the span was reduced to 450mm. Both nominal core depths of 50mm and 75mm were tested with this configuration.

The last test involved increasing the load span length to achieve a 4-Point Quarter-Span load configuration as shown in Figure 28. Test specimen 10, 11 and 12 were tested with this configuration.

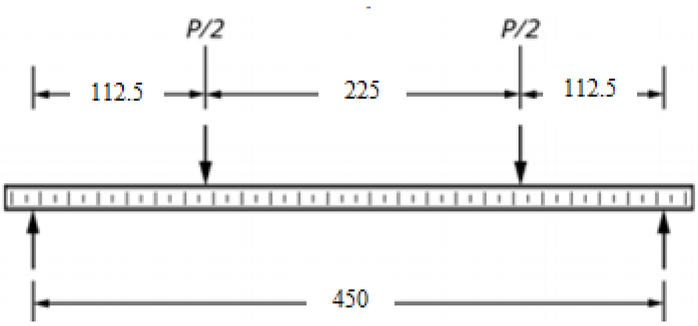


Figure 28 - Test 6 setup

The results of test 1 through to 6 are given in Chapter 4.

3.7. Modelling and final design

The mechanical property results from the composite sandwich beam tests, along with the knowledge of failure modes gained throughout the testing period were used to redesign the sandwich panels to fully satisfy the design requirements discussed in section 3.2. The final design was modelled in Creo Parametric with an FEA conducted using the Creo Simulation package. An FEA was also conducted on a beam to compare with the physical test results from the three point bend test validating the model.

3.8. Resource requirements

In addition to the resources such as the materials listed for manufacture and the equipment required for testing in section 3.5 and 3.6 respectively, several other resources were required to complete the project. Software packages such as Solidworks, Creo Parametric and the Microsoft Office suite were used throughout the project both on the university computers as well as on the work computers at BAC. Planning the tests at USQ was the only resource management challenge as the testing period had to be booked at a time when both the testing staff and project supervisor were available. As testing was completed within one afternoon this challenge was easily overcome.

Chapter 4. Results and Analysis

4.1. Introduction

This chapter contains an in depth analysis and discussion on the results of the initial design and testing components of the project.

4.2. Design loads

The design loads for the composite sandwich roofing panel were determined in accordance with AS1170.0, AS1170.1 and AS1170.2. The loading cases applicable to the design are as follows:

$$\text{ULS Inward Load } w = 1.2G + 1.5Q \tag{32}$$

$$\text{ULS Outward Load } w = 0.9G + W_u \tag{33}$$

$$\text{SLS Outward Load } w = W_s \tag{34}$$

$$\text{SLS Inward Load } w = \varphi_s Q \tag{35}$$

Where: G = Dead Load

Q = Live load

W_u = Ultimate Wind load

W_s = Service Wind load

<AS1170.0 clause 4.2>

For the case of roofing panel design, inward loads are those that are increased by the effects of gravity whereas outward loads are reduced as shown in the figure below.

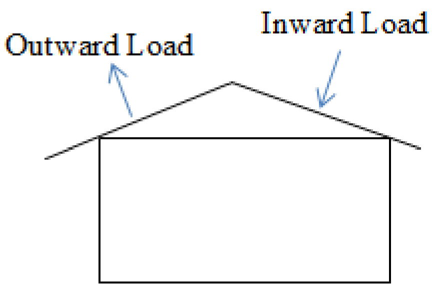


Figure 29 - Loading Configuration

4.2.1. Dead load

The dead load for the purposes of this project was taken to include the self-weight of the panel only. The provision for solar panels and other partitions were not taken into account for this design but rather will be checked for as part of the future works. The dead load of the composite sandwich panel is therefore equal to the specific weight of each material multiplied by its respective volume. The self-weight calculations of the 50mm thick core panel are provided below:

$$Selfweight_{50mm} = \rho g t_{core} + 2 \times \rho g t_{skin}$$

$$Selfweight_{50mm} = 35 \times 9.81 \times 0.05 + 2 \times 1460 \times 9.81 \times 0.003$$

$$Selfweight_{50mm} = 103Pa$$

$$Selfweight_{75mm} = 112Pa$$

The manufactured test beams were measured and weighed to determine their actual densities. The 50mm core and 75mm core test beams were measured to have a self-weight of 127Pa and 133Pa respectively. As the core density was known it was determined that the laminate density was actually higher than what was calculated. The actual density of the laminate skins was calculated to be 1800kg/m³. The difference observed between the theoretical and actual density could be due to some resin filtering through the foam core.

4.2.2. Live load

The uniformly distributed live load was taken as = (1.8/A + 0.12)kPa but not less than 0.25kPa and the point load as = 1.4kN. Note that for residential houses the loads can be reduced to 0.25kPa and 1.4kN respectively.

<AS1170.1 Table 3.2>

4.2.3. Wind load

As the coefficients used to determine the wind loads vary substantially depending on the site and structure, the wind load was calculated for the worst case scenario. To simplify the process of determining the design loads and thermal insulation requirements, the properties were determined for a two story building in the Toowoomba region as per Figure 30.

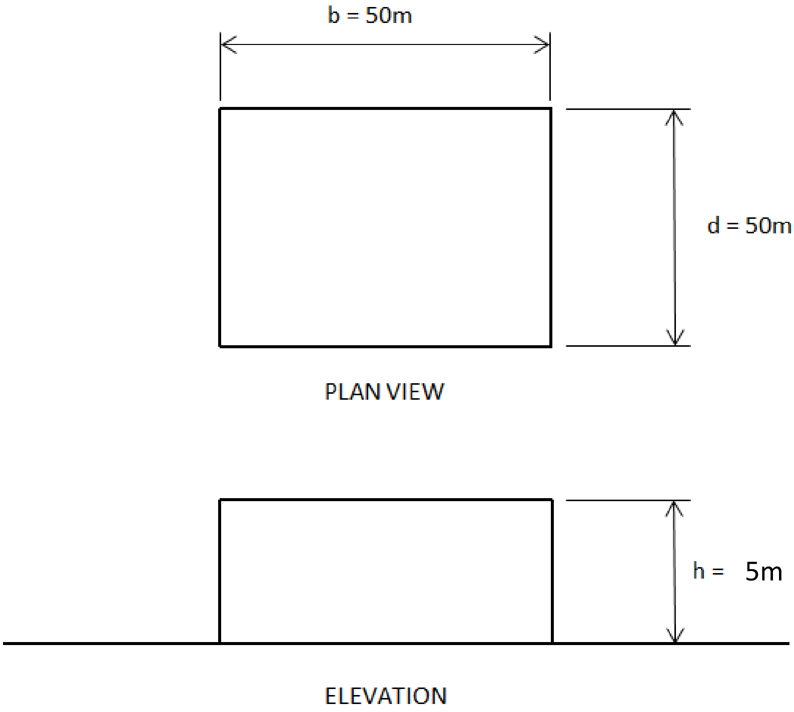


Figure 30 - Building dimensions

<u>Site wind speed</u>

The site wind speed was calculated using equation (36).

$$V_{sit},\beta = V_R M_d (M_z, cat M_s M_t) \tag{36}$$

<AS1170.2 clause 2.2>

The structure was considered to have a high consequence of failure and therefore an importance level of 3 was adopted.

<AS1170.0 Table 3.1>

For a design life of 50 years the annual probability of exceedance for ultimate limit states is 1/1000 and the annual probability of exceedance for serviceability limit states is 1/25.

<AS1170.0 Table 3.3>

Toowoomba is categorised as Region A4.

<AS1170.2 Figure 3.1>

V_R , the regional wind speed for region A4, is 46m/s for ultimate limit states and 37m/s for serviceability.

<AS1170.2 Table 3.1>

The worst case wind directional multiplier (M_d) is 0.95 for the Westerly direction however M_d was taken as 1.0 to allow for any direction.

<AS1170.2 Table 3.2>

Terrain category was taken as TC1 for worst case.

<AS1170.2 clause 4.2.1>

Roof height = 5m therefore the Terrain/height multiplier (M_z, cat) was taken as 1.12.

<AS1170.2 Table 4.1>

Assumed no shielding M_s = 1.0

<AS1170.2 Table 4.3>

Allowed for structure to be located for worst case on a hill M_t = 1.5

<AS1170.2 Table 4.3>

For ultimate limit states:

$$V_{sit} = (46)(1.0)(1.12)(1.1)(1.5)$$

$$V_{sit} = 85\ m/s$$

For serviceability:

$$V_{sit} = (37)(1.0)(1.12)(1.1)(1.5)$$

$$V_{sit} = 68\ m/s$$

<AS1170.2 clause 2.2>

The design wind speed was taken as the site wind speed based on the assumption that the building faces are perpendicular to the cardinal directions.

<AS1170.2 clause 2.3>

Design wind pressure

The design wind pressure was calculated using equation (37).

$$P = (0.5\rho_{air})[V_{des}\theta]^2 C_{fig} C_{dyn} \qquad (37)$$

<AS1170.2 clause 2.4.1>

ρ_{air}= 1.2kg/m^3

Assuming none of the structural elements will have a natural frequency less than 1.0Hz therefore C_{dyn} = 1.0.

For ultimate limit states:

$$P = 4335C_{fig}$$

For serviceability:

$$P = 2774.4C_{fig}$$

There for $P_{sericeability} = 0.64P_{ultimate}$

The aerodynamic shape factors (C_{fig}) for external and internal pressure were calculated using equation (38) and (39) respectively.

$$C_{fig} = C_{pe} K_a K_c K_l K_p \tag{38}$$

$$C_{fig} = C_{pi} K_c \tag{39}$$

<AS1170.2 clause 5.2>

For internal pressure the worst case will occur when C_{fig} is maximum positive value. For worst case (windward wall permeable, all others impermeable) C_{pi} = 0.6.

<AS1170.2 Table 5.1(A)>

For external pressure the worst case will occur when C_{fig} is maximum negative value. Allowing for an h/d ratio greater than 1 and a roof pitch less than 10°, C_{pe} = -1.2.

<AS1170.2 Table 5.3(B)>

The area reduction factor was taken as K_a = 1.0 for worst case.

<AS1170.2 Table 5.4>

Both combination factors were taken as K_{ce} and K_{ci} = 0.9 assuming two effective surfaces.

<AS1170.2 Table 5.5>

Local pressure factor (K_l) was taken as 3.0 for upwind corners of roofs with pitch <10°.

<AS1170.2 Table 5.6>

The permeable cladding reduction factor was taken as ($K_{p)}$ = 1.0 as composite sandwich panels are non-permeable.

<AS1170.2 Table 5.8>

For external:

$$C_{fig} = C_{pe} K_a K_c K_l K_p$$

$$C_{fig} = (-1.2)(1.0)(0.9)(3.0)(1.0)$$

$$C_{fig} = -3.24$$

$$P_e = 4335 C_{fig}$$

$$P_e = 4335(-3.24)$$

$$P_e = -14.1 kPa$$

For internal:

$$C_{fig} = C_{pi} K_c$$

$$C_{fig} = (0.6)(0.9)$$

$$C_{fig} = 0.54$$

$$P_i = 4335C_{fig}$$

$$P_i = 4335(0.54)$$

$$P_i = 2.3kPa$$

The net pressure for ultimate limit states is given in equation (40).

$$P_{ult} = P_e - P_i \qquad (40)$$

$$P_{ult} = -14.1 - 2.3$$

$$P_{ultimate} = -16.4kPa$$

Therefore for serviceability limit states:

$$P_{sericeability} = 0.64(-16.4)$$

$$P_{sericeability} = -10.5kPa$$

Note that these wind loads were calculated for the worst case possibility to maximise the versatility of the sandwich panel design.

4.3. Serviceability limits

AS1170.0 suggests several serviceability limits that are relevant to the design of sandwich panels for roofing. As the proposed structure is not steel cladding, nor is it concrete or ceramic, it doesn't fit well in the categories outlined in Table C1 of AS1170.0. The proposed design could be categorised as both cladding and a roof supporting structure therefore the following serviceability limits were adopted.

Table 11 - Serviceability limits

Element	Phenomenon controlled	Serviceability parameter	Applied action	Element response
Roof Cladding	Indentation	Residual deformation	Q = 1 kN	Span/600 but <0.5mm
Roof supporting elements	Sag	Mid-Span deflection	G, $\varphi_s Q$ or W_s	Span/300

<AS1170.0 Table C1>

In addition to the above deflection limits, Clause 4.3.2 of the Eurocomp design code specifies a maximum strain of 0.002 due to tensile force for laminates that require resistance to chemical attack during service. This maximum strain was also adopted for design.

4.4. Thermal insulation requirements

Section J 'Energy Efficiency' of the BCA specifies the minimum total R values for composite roofs and ceilings which is the sum of all element including any building material, insulating material, airspace and associated surface resistances. Toowoomba is considered to be in climate zone 5 according to figure A1.1 and table A1.1 of NCC 2015 BCA Volume One. The minimum total R values for varying levels of solar absorptance are given below in Table 12 which is adapted from the National Construction Code (NCA) Volume 2 Table 3.12.1.1a.

Table 12 - Minimum total R-Values

Climate zone	**1, 2, 3, 4 and 5**	**6**	**7**	**8**
Direction of heat flow	**Downwards**		**Upwards**	
Minimum *Total R-Value* for a roof or ceiling with a roof upper surface solar absorptance value of not more than 0.4	3.2	3.2	3.7	4.8
Minimum *Total R-Value* for a roof or ceiling with a roof upper surface solar absorptance value of more than 0.4 but not more than 0.6	3.7	3.2	3.7	4.8
Minimum *Total R-Value* for a roof or ceiling with a roof upper surface solar absorptance value of more than 0.6	4.2	3.2	3.7	4.8

The solar absorptance affects the flow of heat from solar radiation and varies depending on the colour of the surface. The lower the value or absorptance, the greater the reduction in heat flow. Typically the composite sandwich panels will have an off white colour which has an absorptance value of 0.35. Therefore the minimum total R value for downwards heat flow is 3.2.

4.5. Initial design

Initially the shear deflections of the beams were disregarded and the design was considered to satisfy the deflection requirements for a span of 900mm. After revisiting the calculations it became apparent that the shear deflections made a significant difference to the total deflections rendering the design as not safe. The following design calculations are for the 50mm nominal core depth beam spanning 450mm which have been included for comparison with the testing results only.

4.5.1. Flexural rigidity

Using equation (9), the flexural rigidity of the two different size beams was calculated. The calculations for the 50mm nominal depth core are given below.

$$EI = E_f \cdot \frac{bt^3}{6} + E_f \cdot \frac{btd^2}{2} + E_c \cdot \frac{bc^3}{12}$$

$$EI = 11500 \cdot \frac{100 \times 3^3}{6} + 11500 \cdot \frac{100 \times 3 \times 53^2}{2} + 12.3 \cdot \frac{100 \times 50^3}{12}$$

$$EI = 4.80 \times 10^9 \ Nmm^2$$

Where E_c is taken from the 62kg/m³ foam properties.

The flexural rigidity of the 75mm core beams was calculated as$1.04 \times 10^{10} \ Nmm^2$.

The total deflection of the beam when subject to the 1kN service point load was calculated using equation (16).

$$\Delta = \Delta_1 + \Delta_2 = \frac{PL^3}{48D} + \frac{PL}{4AG}$$

$$\Delta = \frac{1000 \times 450^3}{48 \times 4.80 \times 10^9} + \frac{P1000 \times 450}{4 \times 5550 \times 2.6}$$

$$\Delta = 8.19mm$$

4.5.2. Compressive strength

Based on the loading being spread over a 40x100mm plate, the ultimate loading that could be applied to the beam before localised crushing of the core occurs was calculated as:

$$F = \sigma A$$

$$F = 0.41MPa \times 40mm \times 100mm$$

$$F = 1640N$$

4.5.3. Shear strength

The ultimate shear strength assuming that the core does not contribute significantly to the flexural rigidity of the beam is calculated by rearranging equation (19).

$$Q = \tau bd$$

$$Q = 0.34MPa \times 100mm \times 50mm$$

$$Q = 1700N$$

4.5.4. Bending moment

The ultimate bending moment of the beam is effected by the flexural rigidity and the flexural strength of both the laminate skin and the foam core. Equations (10) and (11) were rearranged to solve for the ultimate bending moment of the core and laminate separately.

$$M = \frac{D\frac{\sigma_f}{E_f}}{z}$$

$$M = \frac{4.80 \times 10^9 Nmm^2 \times \frac{420MPa}{11500MPa}}{26.5}$$

$$M = 6.27kN.m$$

$$M = \frac{D\frac{\sigma_c}{E_c}}{z}$$

$$M = \frac{4.80 \times 10^9 Nmm^2 \times \frac{0.44MPa}{12.1MPa}}{25}$$

$$M = 6.99kN.m$$

Therefore the estimated ultimate bending is 6.27kN.m

4.5.5. Thermal insulation

The ‘R’ value or thermal resistance value of the beams were calculated using equation (24). The thermal resistance of the sandwich structure is equal to the sum of the thermal resistance of each component. The k factor for BFE 35 foam has been given as 0.0236W/m.K by the supplier. The k factor of the fibreglass skins was taken as 0.004 W/m.K.

$$R = \frac{L}{k}$$

$$R_{50\ core} = \frac{0.05}{0.0236} = 2.12\ m^2k/W$$

$$R_{75\ core} = \frac{0.075}{0.0236} = 3.18\ m^2k/W$$

$$R_{3\ skin} = \frac{0.003}{0.004} = 0.75\ m^2k/W$$

$$R_{50mm} = 2.12 + 2 \times 0.75 = 3.62 > 3.2m^2k/W\ (OK)$$

$$R_{75mm} = 3.18 + 2 \times 0.75 = 4.68 > 3.2m^2k/W\ (OK)$$

The insulation of both of the beam sizes is more than required as per the BCA. Increasing the thickness of the core increases the insulating properties of the sandwich structure. The optimum thickness for insulation is therefore determined by compromising between material costs, weight and insulation.

4.6. Testing

This section contains the results from the six tests conducted throughout the duration of the project as well as an in depth analysis of the failure modes observed. The testing analysis also includes the calculations determining the facing properties, core shear properties, the flexural stiffness and shear stiffness of the sandwich beams.

4.6.1. Test 1

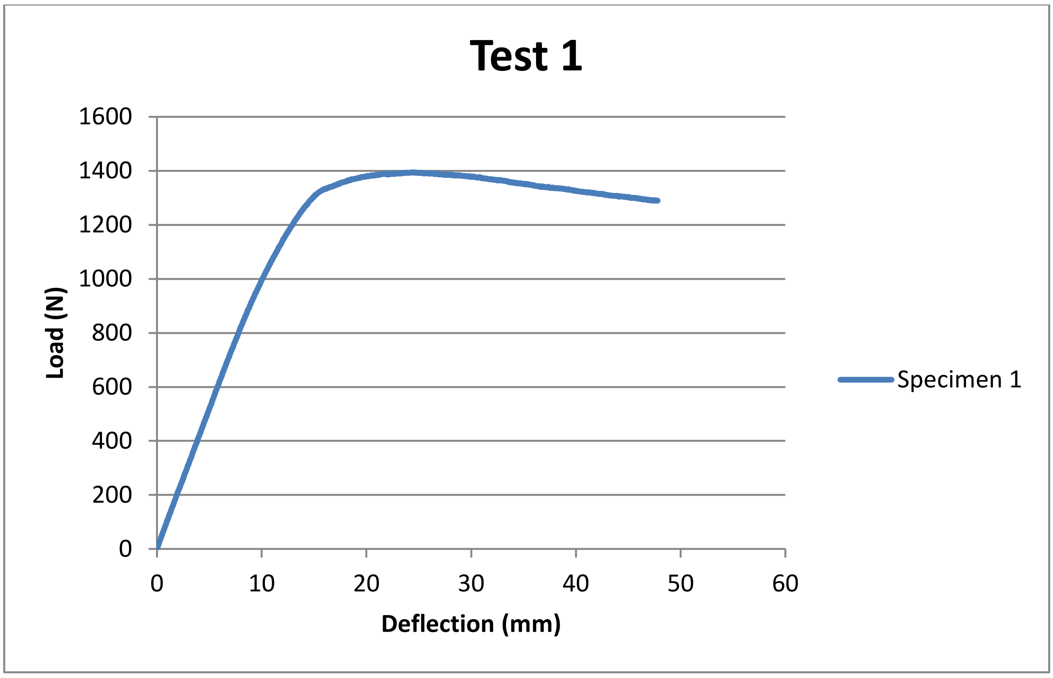


Figure 31 - Test 1 (Mid-Span Loading) 450mm span

Figure 31 displays the deflection and load recorded during the first test. The 50mm nominal depth core specimen failed due to crushing of the core which resulted from the excessive deflection as can be observed in Figure 32. The core did not shear as expected which may have been due to the superior strength of the facing skins. With the deflection observed being significantly higher than that predicted, and the unexpected failure mode occurring, the span was reduced for test 2.

Figure 32 - Core crushing failure mode

The maximum loading as well as the support length and width of each test are summarised in Table 13.

4.6.2. Test 2

After reducing the span to 30mm and increasing the test speed to 10mm per minute no significant change in results was observed. Both specimens two and three failed due to crushing of the core resulting from excessive deflection as did specimen 1. As the core crushed the beams appeared to deform plastically whilst the loading plateaued. Yielding when subject to high loads rather than failing catastrophically is a common trait to many composites due to their relative low stiffness. The recorded data for test 2 is given below in Figure 33.

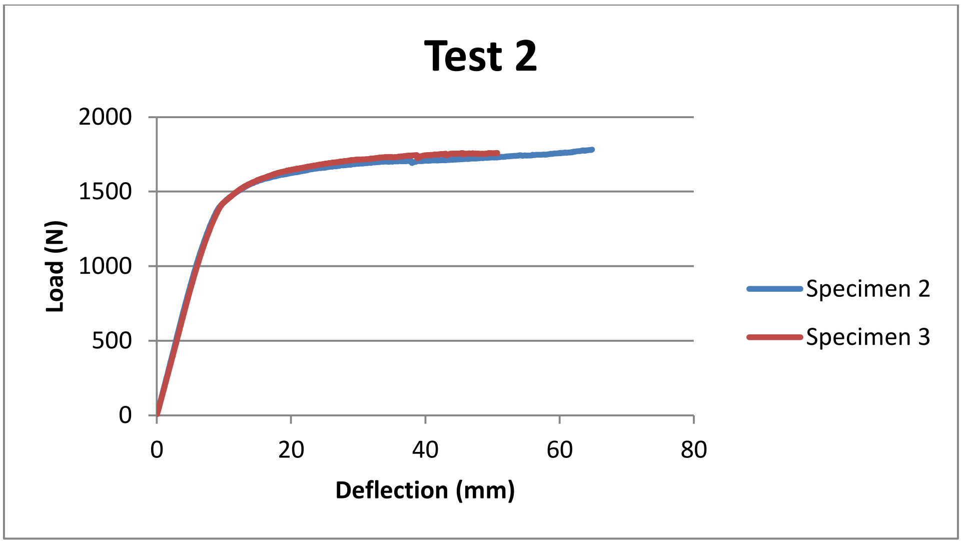


Figure 33 - Test 2 (Mid-Span Loading) 300mm span

After removing the load, the sandwich beam retracted to its original form however a significant amount of core crushing (permanent deformation) was evident as shown below in Figure 34.

Figure 34 - Core crushing

4.6.3. Test 3

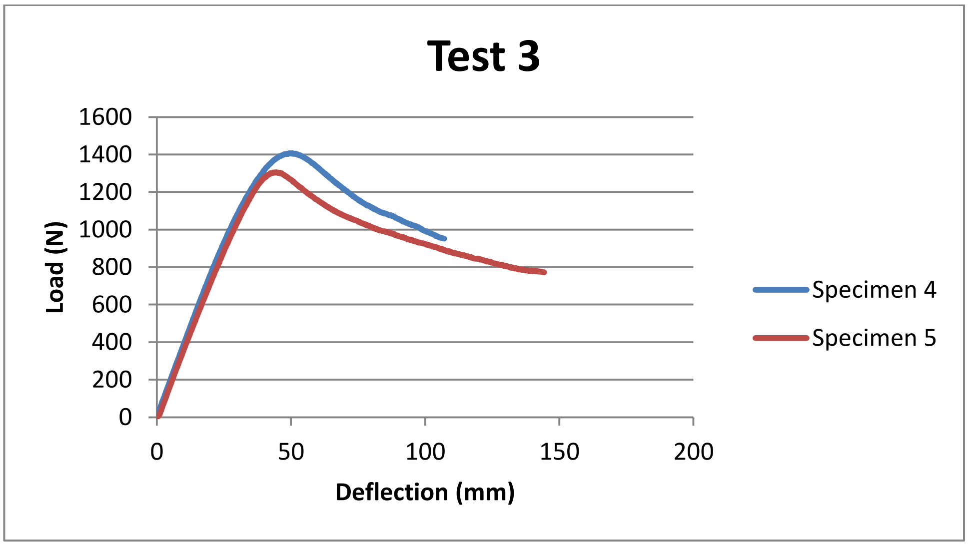


Figure 35 - Test 3 (4-point Loading) 1300mm span

Figure 35 displays the deflection and loads recorded during test 3 which was a 4-Point configuration flexural test with a span of 1300mm and a test speed of 20mm per minute. Specimen 4 failed when the upper facing skin delaminated from the core resulting in the core shearing. Specimen 5 saw only crushing of the core however it did not exhibit the same load bearing capacity as per specimen 4.

4.6.4. Test 4

As discussed is the methodology, specimen 6 was disregarded from further analysis due to incorrect support spacing. The failure mode observed in specimen 6 is however worth noting as the foam core sheared cleanly prior to the skin delaminating unlike any of the other samples.

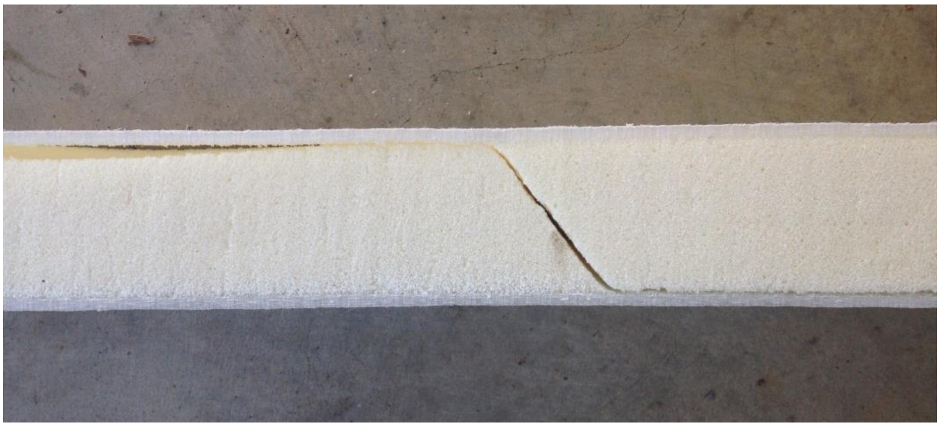


Figure 36 - Shearing failure

As shown in Figure 36, either side of the shearing plane the skin has delaminated from the core. Specimen 7 experienced core crushing however it did not fail critically as specimen 6 did. The load vs deflection curve is presented below in Figure 37.

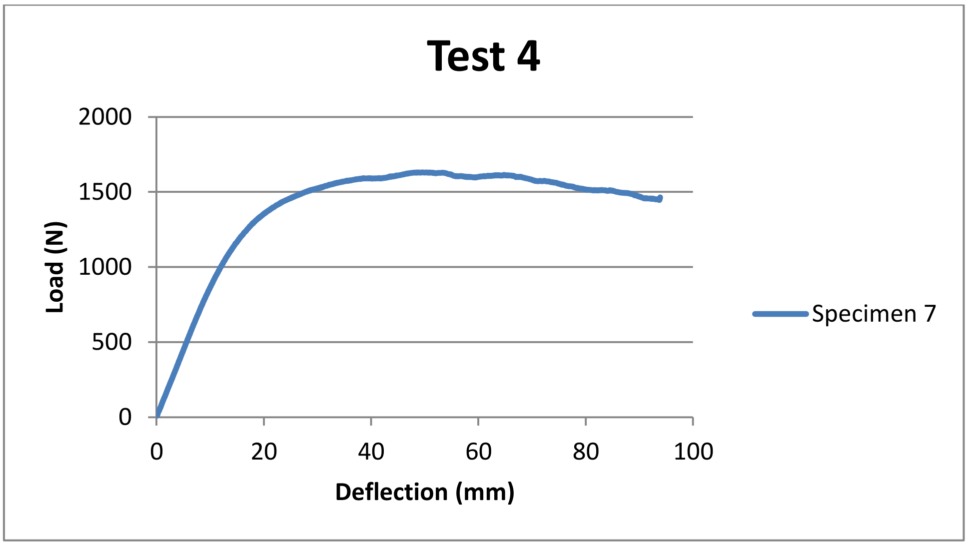


Figure 37 - Test 4 (4-Point Loading) 600mm span

4.6.5. Test 5

Test 5 was similar to test 4 being of 4-Point configuration however the span was reduced to 450mm. The load and deflection recorded during the test in presented below in Figure 38 where specimen 8 was of 50mm nominal core depth and specimen 9 of 75mm nominal core depth.

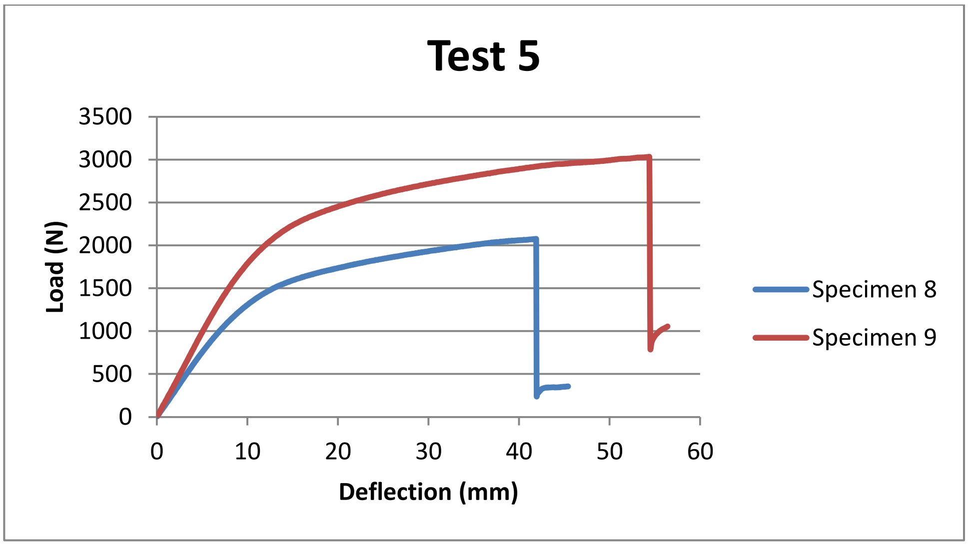


Figure 38 - Test 5 (4-Point Loading) 450mm span

Both of the samples suffered core crushing and secondary facing delamination.

4.6.6. Test 6

The final test conducted was with a Quarter Point Loading configuration as per Figure 21. Specimens 10 and 12 failed due to delamination whereas specimen 11 sheared at one of the supports resulting in facing delamination. The sandwich beams post testing are shown in Figure 39 with the load and deflection curve presented in Figure 40.

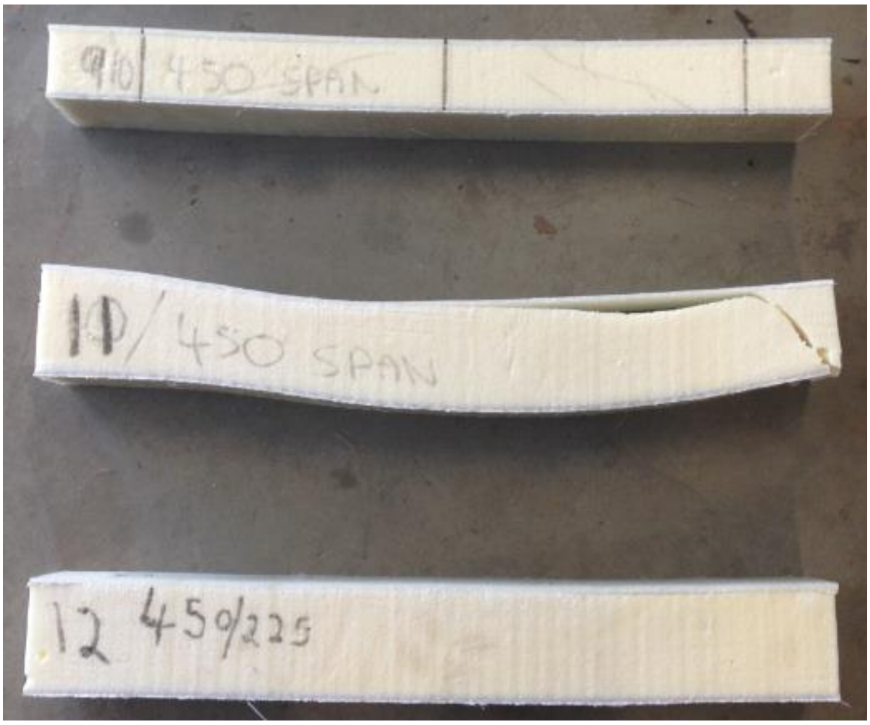


Figure 39 - Support shear failure and delamination

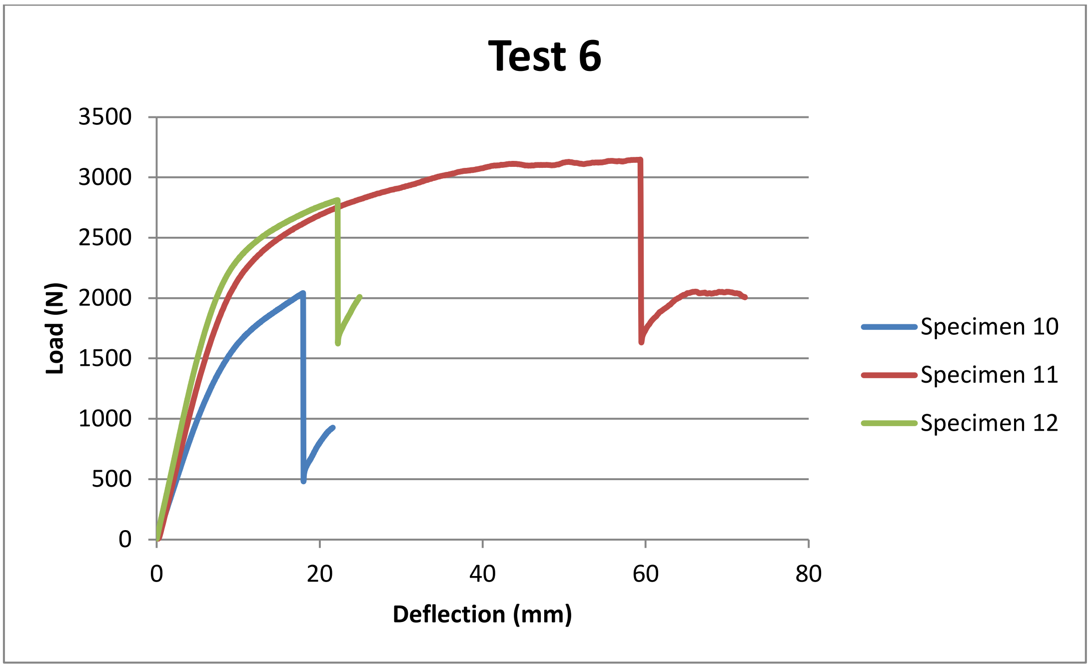


Figure 40 - Test 6 (Quarter Point Loading) 450mm span

4.6.7. Testing summary

The results from the six tests are summarised in the Table 13 below.

Table 13 - Results summary

Test	Specimen #	Nominal core depth (mm)	Width (mm)	Support Span (mm)	Configuration	Failure Mode	Peak Load (N)	Deflection at Peak (mm)
1	1	50	98.8	450	3-Point Mid-Span	Core crushing	1394	24.32
2	2	50	99.5	300	3-Point Mid-Span	Core crushing	1782	64.84
	3	50	98.6	300	3-Point Mid-Span	Core crushing	1759	45.38
3	4	75	98.7	1300	4-Point (150mm)	Delamination	1407	50.5
	5	75	97.7	1300	4-Point (150mm)	Core crushing	1306	44.38
4	~~6~~	~~50~~	~~98~~	~~900~~	~~4-Point (150mm)~~	~~Shear~~	~~1388~~	~~46.18~~
	7	50	98.3	600	4-Point (150mm)	Core crushing	1630	48.45
5	8	50	98.4	450	4-Point (150mm)	Delamination	2075	41.89
	9	75	98.7	450	4-Point (150mm)	Delamination	3031	54.39
6	10	50	97.8	450	4-Point Quarter Span	Delamination	2042	17.97
	11	75	99.2	450	4-Point Quarter Span	Delamination/shear	3147	59.36
	12	75	99.1	450	4-Point Quarter Span	Delamination	2812	22.21

As anticipated, the specimens subjected to a larger span produced lower peak loads than the specimens subjected to smaller spans. In general the longer spans resulted in crushing of the polyurethane core due to the excessive deflections whereas the shorter spans saw the facing skins delaminating from the core.

4.6.8. Stiffness

The determination of the flexural and transverse shear stiffness properties of the testing panels was completed in accordance with ASTMD7250/D7250M. The 50mm nominal core depth panel properties were determined by using the results of two 3-Point Mid-Span Loading configurations (Specimen 1 and 2) and the 75 mm nominal core depth panel properties were determined using the results from one 4-Point Quarter-Span Loading configuration and one 4-Point Third-Span Loading configuration (Specimen 9 and 11).

50mm nominal core

Equations (26), (27) and (30) were used to calculate the flexural stiffness, transverse shear rigidity and core shear modulus for ten different loadings of which are provided below in Table 14. The ten loadings were selected evenly from the linear elastic range as shown in Figure 41.

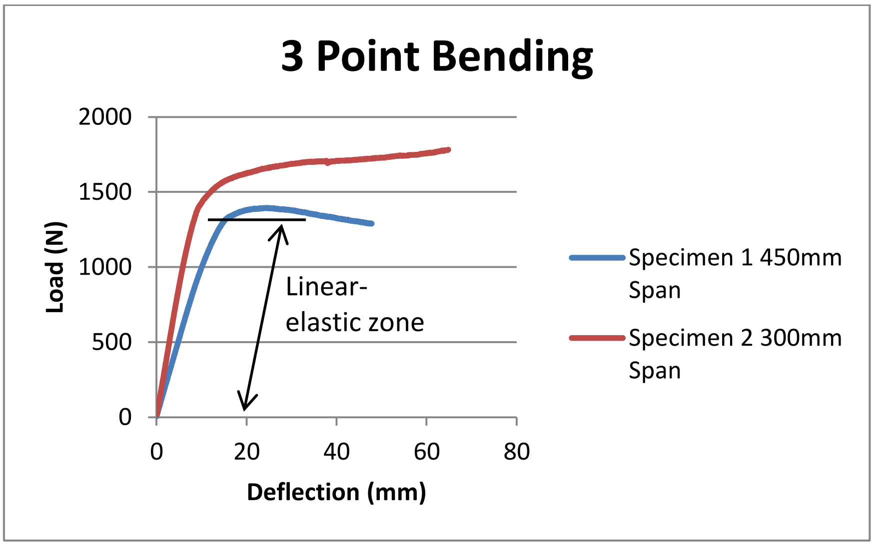


Figure 41 - Linear-elastic zone

Table 14 - 50mm core stiffness properties

Δ1 (mm)	P1 (N)	Δ2 (mm)	P2 (N)	D (Nmm²)	U (N)	G (MPa)
0.16	18	0.1	18	1.90E+09	14261	2.58
1.01	109	0.64	109	2.30E+09	13329	2.41
2.45	258	1.49	258	1.27E+09	14069	2.54
3.57	372	2.13	372	1.05E+09	14456	2.61
4.85	504	2.88	503	1.02E+09	14496	2.62
6.13	636	3.62	637	9.47E+08	14738	2.66
7.25	748	4.26	749	9.08E+08	14798	2.67
8.75	889	5.12	889	8.76E+08	14656	2.65
10.13	1005	5.86	1004	7.96E+08	14619	2.64
11.52	1108	6.61	1108	7.28E+08	14442	2.61
Average				**1.18E+09**	**14386**	**2.60**

75mm nominal core

Equations (28), (29) and (30) were used to calculate the stiffness properties of the 75mm nominal depth core sandwich beams. The results are tabled below.

Table 15 - 75mm core stiffness properties

Δ1 (mm)	P1 (N)	Δ2 (mm)	P2 (N)	D (Nmm²)	U (N)	G (MPa)
0.42	42	0.21	40	1.52E+07	-2971	-0.37
0.74	125	0.63	124	4.37E+07	-9408	-1.18
0.95	184	0.95	185	7.04E+07	-16806	-2.11
1.49	328	1.7	329	1.38E+08	-45966	-5.77
1.81	418	2.13	413	2.00E+08	-102025	-12.81
2.13	506	2.55	499	2.45E+08	-200922	-25.22
2.45	596	3.09	606	3.22E+08	3808343	478.01
2.87	716	3.62	713	4.60E+08	191918	24.09
3.19	805	4.15	819	5.68E+08	135021	16.95
3.62	921	4.69	926	7.00E+08	108966	13.68
Average				**2.76E+08**	**386615**	**48.53**

Conclusions

The results for the 75mm core shown in Table 15 are not consistent nor are they comparable with the results obtained from the 50mm core tests. There are several possible theories as to why the error in the result occurred. Firstly, the unsupported span of specimen 9 and 11 was only 450mm giving a span to core depth ratio of 6. Literature suggests that deformation at this span will predominately be of shear nature. This span does not satisfy the requirements of ASTM D7249/D7249M for long beam flexure. The equation provided in ASTM D7250/D7250M appears to be empirical (derived from test data) of which may have required spans in accordance with D7249/D7249M. Secondly, the deflection recorded during the 4 point bend tests was at the loading points on the beam, rather than at the centre of the beam where the maximum deflection occurred. As equation (28) and (29) refer specifically to the mid-span deflection the results may be considered nonconforming with the standard procedure.

The flexural stiffness of the 75mm core depth beams were calculated using the results from the 50mm core depth beams. The modulus of elasticity of the fibreglass skins were estimated by back calculating form the flexural rigidity assuming that the core did not contribute significantly to the stiffness of the sandwich beam.

For the 50mm nominal core:

$$EI = E_f \cdot \frac{bt^3}{6} + E_f \cdot \frac{btd^2}{2} + E_c \cdot \frac{bc^3}{12}$$

$$EI = E_f \left(\frac{bt^3}{6} + \frac{btd^2}{2} \right)$$

$$E_f = \frac{EI}{\left(\frac{bt^3}{6} + \frac{btd^2}{2} \right)}$$

$$E_f = \frac{1.18 \times 10^9}{\left(\frac{100 \times 3^3}{6} + \frac{100 \times 3 \times 53^2}{2} \right)}$$

$$E_f = 2797.5\ MPa$$

The flexural stiffness of the 75mm core depth beams was then calculated as:

$$EI = E_f \left(\frac{bt^3}{6} + \frac{btd^2}{2} \right)$$

$$EI = 2797.5 \left(\frac{100 \times 3^3}{6} + \frac{100 \times 3 \times 78^2}{2} \right)$$

$$EI = 2.55 \times 10^9$$

By rearranging the standard 4 point deflection equation provided in ASTMD7250/D7250M the transverse shear rigidity was calculated. The rearranged equation is provided below with the results table for 10 evenly spaced data points following.

$$U = \frac{P(S_1 - L_1)}{4[\Delta - \frac{P(2S_1^3 - 3S_1L_1^2 + L_1^3)}{96D}]}$$

Table 16 - Revised 75mm core stiffness properties

Δ (mm)	P (N)	D (Nmm²)	U (N)	G (MPa)
0.42	42	2.55E+09	8008	1.01
0.74	125	2.55E+09	14189	1.78
0.95	184	2.55E+09	16560	2.08
1.49	328	2.55E+09	19189	2.41
1.81	418	2.55E+09	20292	2.55
2.13	506	2.55E+09	20977	2.63
2.45	596	2.55E+09	21573	2.71
2.87	716	2.55E+09	22228	2.79
3.19	805	2.55E+09	22532	2.83
3.62	921	2.55E+09	22753	2.86
Average		**2.55E+09**	**18830**	**2.36**

The results shown in Table 16 are more similar to the 50mm core results than the original properties calculated. The flexural stiffness and shear rigidity of the two panels are summarised below.

Table 17 - Sandwich beam property summary

Nominal Core Depth (mm)	D (Nmm^2)	G (MPa)
50.00	1.18E+09	2.60
75.00	2.55E+09	2.36

As anticipated, the 75mm beams appear to have a higher flexural stiffness than the 50mm core beams. Both of the flexural stiffness values calculated are however significantly lower than that predicted in section 4.5.1. This may be due to the core beginning to crush early during the testing period resulting in a non-linear deflection curve. This theory is supported by the values shown in Table 14 and Table 15 where the flexural stiffness calculated is higher for the smaller loadings. The variation in stiffness from the predicted values is concerning as the design of composites is generally governed by the serviceability or deflection limits. The shear rigidity is less in the 75mm core than it is in the 50mm core samples. This result is supported by the theory that as the core thickness increases, the facing skins have less effect on the shear resistance of the beam (Howard 1969).

To validate the results given above, the standard three point deflection equation was solved simultaneously for the flexural stiffness and shear rigidity of the 50mm core beams using two different load cases. Two data points were selected from the test results of specimen 1 and 2 resulting in a flexural stiffness (D) of $1.8 \times 10^9 Nmm^2$ and shear rigidity (G) of 2.73MPa. The results from the 1300mm span test on the 75mm core were used to validate the flexural stiffness results provided above. The span to core thickness ratio for this test was greater than 17 meaning that the deflection recorded, especially at low loads, would predominantly have been of flexural nature. The flexural stiffness was therefore calculated with the assumption that the shear deflection was negligible. The results are shown below.

$$\Delta = \frac{P(2S^3 - 3SL^2 + L^2)}{96D}$$

$$D = \frac{P(2S^3 - 3SL^2 + L^2)}{96\Delta}$$

Arbitrary data point from test 4

P = 105N, Δ = 1.17mm, S = 1300mm L = 150

$$D \ = \ 4.03 \times 10^9 Nmm^2$$

Both validation techniques supported the values given in Table 17 and therefore such values were used for further design.

4.6.9. Strength

Based on the failure modes observed, it is apparent that the compressive strength of the core is the limiting factor of the design. That is of course due to the excessive deflections that are resulting from the low shear rigidity of the sandwich beams. The compressive strength of the foam was derived from the test results and checked with the properties provided by the supplier. The compressive strength of the polyurethane foam core was calculated and is provided below:

To determine the stress in the foam when the crushing begins to occur, the force was read from the load-deflection curve as shown below for specimen 2 and 3.

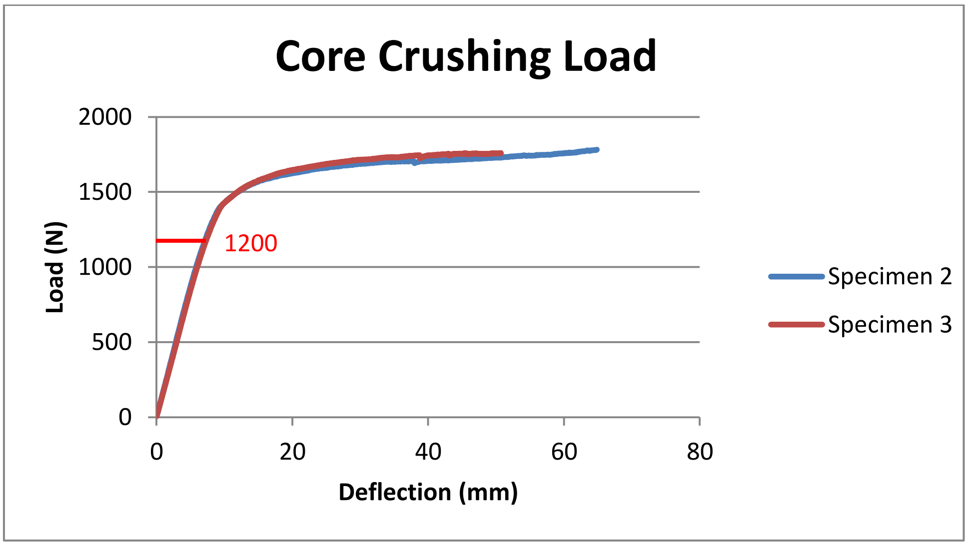


Figure 42 - Core crushing load

$$\sigma_c = \frac{F}{A}$$

$$\sigma_c = \frac{1200}{40 \times 100}$$

$$\sigma_c = 0.3 \text{ MPa}$$

The compressive stress of the core is slightly lower than the provided compressive stress of 0.41 MPa for the 62kg/m³ foam. This was expected for the 35kg/m³ foam. The test results support the predicted core failure load of 1640N calculated for the initial design.

As none of the specimens failed in shear directly, the ultimate shear strength of the beams could not be determined accurately. It could be assumed however that the ultimate shear strength of the beams must be greater than the maximum shearing force that acted on the core during the testing. The peak load applied to the 50mm nominal core beams was 2075N in a 4-Point Configuration and 1782N in a 3-Point Configuration test. Therefore the ultimate shear strength of the core could be calculated as:

$$\tau_{ult} > \frac{Q}{bd}$$

$$\tau_{ult} > \frac{1782}{50 \times 100}$$

$$\tau_{ult} > 0.35MPa$$

The peak load applied to the 75mm nominal core beams was 3147N in a 4-Point Configuration test.

$$\tau_{ult} > \frac{3147/2}{75 \times 100}$$

$$\tau_{ult} > 0.201\, MPa$$

Therefore the ultimate shear strength of the core may be assumed to be greater than 0.35MPa. During the initial design the ultimate shear strength was estimated as 0.34MPa with an ultimate shearing load of 1700N. As the sandwich beams were subject to shearing forces up to 1782N it may be concluded that ultimate shearing strength is greater than that provided by the supplier. The shearing strength calculated from the testing results may have an error due to the fibreglass skins carrying some of the load. For design purposes it would be safe to use an ultimate shearing stress of 0.34MPa.

As neither the polyurethane core nor the fibreglass skins displayed any kind of flexural failure, the ultimate moment for each of the materials cannot be calculated from the test results. The ultimate flexural stress of each of the materials used in future designs should therefore be taken from the theoretical values given in section 4.5 or from test results of similar materials.

Chapter 5. Modelling and final design

5.1. Parameters

Based on the results from the flexural bending tests and properties provided by manufacturers, the following mechanical properties were adopted for the final design of the sandwich panels.

Table 18 - Final panel properties

Core material – BFE35 PU Block Foam		**Skins – BAC FRP**	
Density ρ	35kg/m³	Density ρ	1800kg/m³
Shear Rigidity G	2.4MPa	Modulus of Elasticity E	2797.5MPa
Ultimate Shear Strength	0.34MPa	Tensile Working Strength	270MPa
Ultimate Compressive Strength	0.3MPa	Ultimate Shear Strength	25MPa

5.2. Design

After completing the initial design and testing, it became clear that the deflection criterion was the governing design factor for the sandwich roofing panels. The wind uplift load in particular had a huge effect on determining the appropriate span and required thickness of the panels. The service wind load calculated for the worst case scenario was 10.5kPa. This loading is two times greater than the design live load for most pedestrian structures. The final sandwich panel design was therefore designed for a decreased wind load to that of which was originally determined. The final design was based on meeting the mechanical performance of the Lysaght Custom ORB traditional corrugated steel cladding whilst also satisfying the remaining load combination requirements discussed in Chapter 4. Meeting the ability of the corrugated steel cladding means that the product can be targeted to a similar market. Table 19 provides the limit state wind pressure capacities for the Custom ORB corrugated steel (Lysaght 2015).

Table 19 - Custom ORB limit state wind pressure capacities (kPa) 0.42BMT

Span Type	Fasteners per sheet per support	Limit State	Span (mm)			
			600	900	1200	1500
Single	3	Serviceability	1.91	1.46	1.08	0.77
		Strength	12.00	8.60	5.80	4.65
	5	Serviceability	5.39	3.20	1.75	0.94
		Strength	12.00	12.00	10.15	8.10
End	3	Serviceability	1.66	1.40	1.18	1.00
		Strength	9.15	7.55	5.90	4.50
	5	Serviceability	6.08	4.27	2.79	1.59
		Strength	12.00	12.00	9.90	7.55
Internal	3	Serviceability	1.91	1.67	1.45	1.23
		Strength	11.35	9.25	7.45	6.00
	5	Serviceability	7.00	4.92	3.32	2.21
		Strength	12.00	12.00	12.00	10.80

Based on the capacities provided above, the serviceability and ultimate wind loads were taken as 5kPa and 12kPa respectively so as to meet the capacities of the Lysaght product over a span of 900mm.

The final design was conducted using the published equations as per the initial design however the shear deflection was this time taken in to account along with using the revised material properties. The final design is given below in Figure 43.

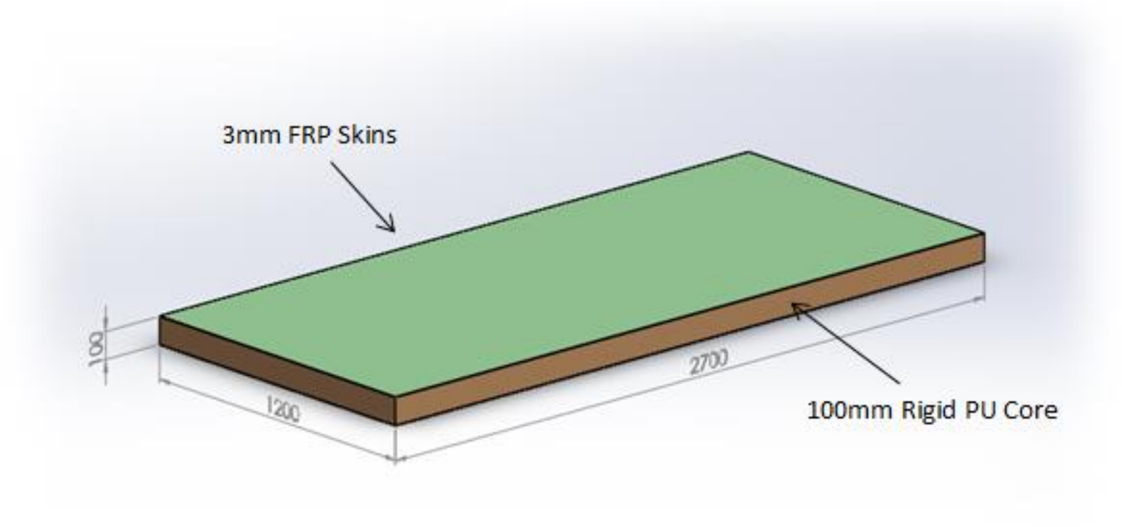


Figure 43 - Final panel dimensions

The design checks for these dimensions are provided below.

5.2.1. Loading Cases

Self-weight G = 9.81m/s² (1800kg/m³ x 0.003m x 2 + 35kg/m³ x 0.1) = 0.14kPa

Live Load Q = $1.8/\text{A} + 0.12$ but not less than 0.25kPa

= $1.8/(0.9 \times 1.2) + 0.12$ = 2kPa

<AS1170.1 Table 3.2>

ULS Inward Distributed Load $w = 1.2G + 1.5Q$

$$w = 1.2(0.14) + 1.5(2) = 3.17kPa \downarrow$$

ULS Outward Distributed Load $w = 0.9G + W_u$

$$w = 0.9(0.14) - 12 = -11.88kPa \uparrow$$

ULS Point Load $P = 1.5Q$

$$P = 1.5(1.4) = 2.1kN \downarrow$$

SLS Inward Distributed Load $w = \varphi_s Q$

$$w = 0.7(2) = 1.4kPa \downarrow$$

SLS Outward Distributed Load $w = W_s$

$$w = -5kPa \uparrow$$

SLS Point Load $P = 1kN$ for residual deformation and sag

5.2.2. Serviceability

Flexural Rigidity

$$EI = E_f \cdot \frac{bt^3}{6} + E_f \cdot \frac{btd^2}{2} + E_c \cdot \frac{bc^3}{12}$$

$$EI = 2797.5 \cdot \frac{1200 \times 3^3}{6} + 2797.5 \cdot \frac{1200 \times 3 \times 103^2}{2} + 12.1 \cdot \frac{1200 \times 100^3}{12}$$

$$EI = 5.46 \times 10^{10} Nmm^2$$

Resistance to lateral deformation

$$g = 1 - v^2$$

$$g = 1 - 0.33^2 = 0.891$$

$$D/g = 6.13 \times 10^{10} Nmm^2$$

Deflection due to point load

$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4AG}$$

$$\Delta = \frac{1 \times 900^3}{48 \times 6.13 \times 10^{10}} + \frac{1 \times 900}{4 \times 100 \times 1200 \times 2.4}$$

$$\Delta = 1.38mm < L/300\ (OK)$$

Deflection due to distributed load

$$q = 5kPa \times 1.2m$$

$$q = 6kN/m$$

$$\Delta = \frac{K_g q L^4}{D} + \frac{K_s q L^2}{AG}$$

$$\Delta = \frac{5 \times 6 \times 900^4}{384 \times 6.13 \times 10^{10}} + \frac{6 \times 900^2}{8 \times 100 \times 1200 \times 2.4}$$

$$\Delta = 2.82mm < L/300\ (OK)$$

5.2.3. Strength

Partial safety factor

The partial safety factor (γ_m) for FRP, at the ultimate limit state, is given by the expression:

$$\gamma_m = \gamma_{m1}\gamma_{m2}\gamma_{m3}$$

Where γ_{m1}, γ_{m1} and γ_{m3} are partial coefficients found in clause 2.3.3.2 of the Euro comp Design Code.

The laminate properties are derived from theory.

$$\gamma_{m1} = 2.25$$

<Eurocomp Table 2.4>

Hand layup manufacture fully post cured at works.

$$\gamma_{m2} = 1.4$$

<Eurocomp Table 2.5>

The operating design temperature will be within the higher bracket at approximately 25-50ºC. The heat distortion temperature of the laminate may be estimated as 80 ºC however this will vary depending on the resin type. As the panels have been designed for wind loads being the worst case loading, the loading duration is considered short term

$$\gamma_{m3} = 1.2$$

<Eurocomp Table 2.5>

Therefore the partial safety factor was calculated as:

$$\gamma_m = 2.25 \times 1.4 \times 1.2$$

$$\gamma_m = 3.78$$

As the Australian Standards use a capacity reduction factor (ϕ), the partial safety factor must be converted.

$$\phi = \frac{1}{\gamma_m}$$

$$\phi = \frac{1}{3.78} = 0.26$$

The capacity reduction factor was taken as 0.26 for both the laminate and foam.

Effective width

$$b/a = 1200/900 = 1.33$$

From Table 3 the ratio of effective width to span (e/a) for point loads and distributed loads was taken as 0.61 and 1.27 respectively. This resulted in an effective width for point loads of 549mm and an effective width for distributed loads of 1143mm.

The flexural rigidity for each effective width is given below where E was taken as E_{sub} for each material.

$$EI_{point} = 2.81 \times 10^{10} Nmm^2$$

$$EI_{distributed} = 5.84 \times 10^{10} Nmm^2$$

Capacities

As the flexural rigidity is different for each loading configuration, the moment and shear capacities for each configuration are also different. The compressive capacity is the same for both cases.

$$\phi M_{skin} = \frac{\phi \sigma_{work} D}{E_f z}$$

$$\phi M_{skin_{point}} = \frac{0.26 \times 270 \times 2.81 \times 10^{10}}{3139 \times 53} = 11.85 kN.m$$

$$\phi M_{skin_{dist}} = \frac{0.26 \times 270 \times 5.84 \times 10^{10}}{3139 \times 53} = 24.6 kN.m$$

$$\phi M_{core} = \frac{\phi \sigma_{ult} D}{E_c z}$$

$$\phi M_{core_{point}} = \frac{0.26 \times 0.44 \times 2.81 \times 10^{10}}{13.7 \times 50} = 4.69 kN.m$$

$$\phi M_{core_{dist}} = \frac{0.26 \times 0.44 \times 5.84 \times 10^{10}}{13.7 \times 50} = 9.75 kN.m$$

$$\phi V = \phi \tau_{ult} bc$$

$$\phi V_{point} = 0.26 \times 0.34 \times 549 \times 100 = 4.85 kN$$

$$\phi V_{dist} = 0.26 \times 0.34 \times 1143 \times 100 = 10.1 kN$$

$$\phi C = \phi C_{ult}$$

$$\phi C = 0.26 \times 0.3 = 0.078 MPa$$

The panel capacities are summarised in the table below:

Table 20 - Design capacities

Loading Configuration	Point	Distributed
ϕM	4.69kN.m	9.75kN.m
ϕV	4.85kN	10.1kN
ϕC	78kPa	78kPa

Point load design actions

$$M^* = \frac{PL}{4}$$

$$M^* = \frac{2.1 \times 900}{4} = 0.47kN.m < \phi M\ (OK)$$

$$V^* = \frac{P}{2}$$

$$V^* = \frac{2.1}{2} = 1.05kN < \phi V\ (OK)$$

$$C^* = P/A$$

Assume a 250mmx250mm point load area

$$C^* = \frac{2.1}{0.25 \times 0.25} = 33.6kPa < \phi C\ (OK)$$

Distributed load design actions

$$q\ = 11.88kPa \times 1.2m$$

$$q\ = 13.6kN/m$$

$$M^* = \frac{wl^2}{8}$$

$$M^* = \frac{13.6 \times 900^2}{8} = 0.66kN.m < \phi M\ (OK)$$

$$V^* = \frac{wl}{2}$$

$$V^* = \frac{13.6 \times 900}{2} = 2.93kN < \phi V\ (OK)$$

Wrinkling stress check

$$\sigma_{wr} = 0.5\left(G_c E_{cz} E_f\right)^{\frac{1}{3}}$$

$$\sigma_{wr} = 0.5(2.4 \times 12.1 \times 2797.5)^{\frac{1}{3}}$$

$$\sigma_{wr} = 21.6MPa$$

The maximum compressive stress in the facing skin was calculated from the maximum moment.

$$\sigma_c = \frac{Mz}{D} E_c$$

$$\sigma_{c\_point} = \frac{0.47 \times 10^6 \times 53}{2.81 \times 10^{10}} \times 3139 = 2.8MPa \ll 21.6MPa\ (OK)$$

$$\sigma_{c\_dist} = \frac{0.66 \times 10^6 \times 53}{5.84 \times 10^{10}} \times 3139 = 1.7MPa \ll 21.6MPa\ (OK)$$

$$FOS = \frac{21.6}{2.8} = 7.7$$

5.2.4. Thermal insulation

The thermal insulation ‘R’ value of the panel was calculated by summing the resistance of both the FRP skins and the PU core. The thermal resistance is calculations are provided below:

$$R = \frac{L}{k}$$

$$R_{core} = \frac{0.1}{0.0236} = 4.24\ m^2k/W$$

$$R_{skin} = \frac{0.003}{0.004} = 0.75\ m^2k/W$$

$$R_{panel} = 4.25 + 2 \times 0.75 = 5.75 > 3.2m^2k/W\ (OK)$$

5.3. Modelling and analysis

The composite panel was modelled in Creo Parametric so as to conduct an FEA to validate the final design. A test beam was also modelled to check with testing results from one of the three point bending tests previously conducted. The material properties that were used for the FEA are given in Table 18 with the input interface available in Appendix D.

5.3.1. Test beam

The test beam was modelled as two separate parts; the FRP skins and the PU core. After modelling each part separately, they were combined in an assembly using coincident restraints which simplified the model by assuming a perfect skin to core bond. The beam was 400mm long by 100mm wide with a 50mm core. Pinned restraints were applied to the bottom skin providing a 300mm free span simulating the conditions of Test 2. A 1kN point load was applied to the centre of the top skin over a 40x100mm area simulating the load distribution plate. The loading and restraint configuration is shown in Figure 44.

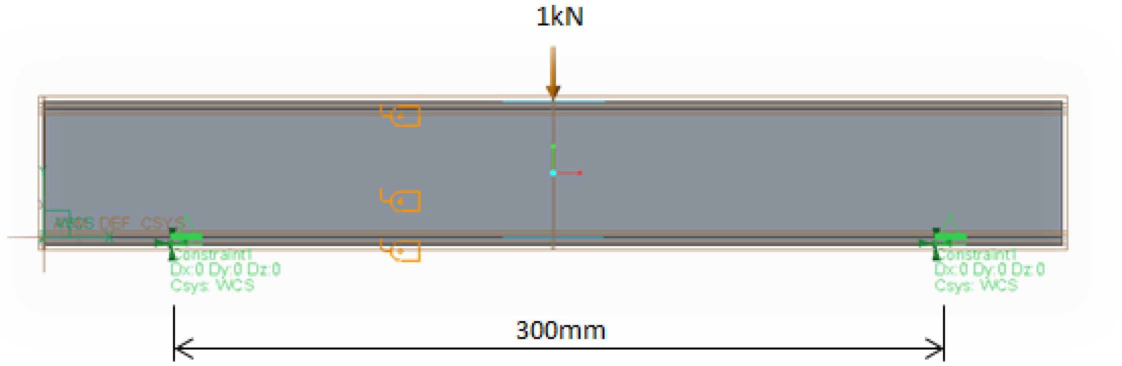


Figure 44 - FEA test beam configuration

The deflection results from the FEA are provided below in Figure 45.

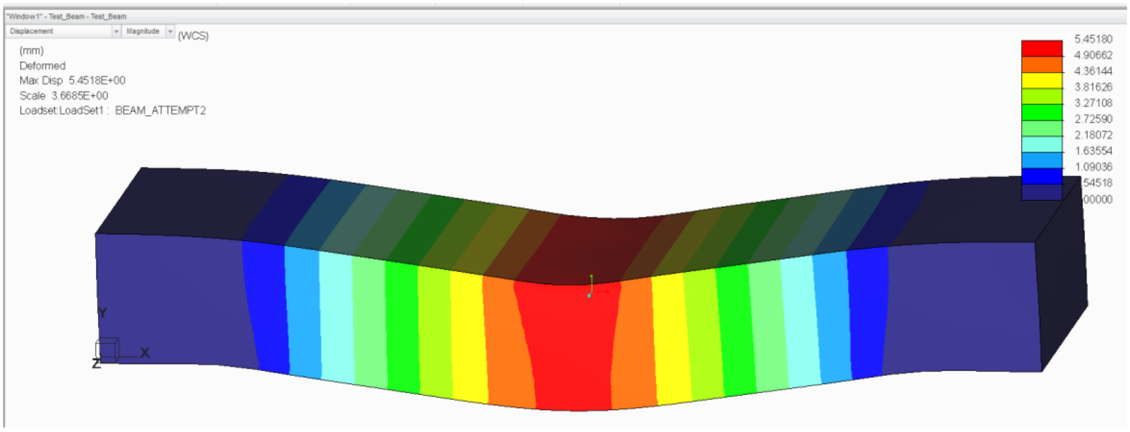


Figure 45 - FEA test beam deflection

The maximum deflection, occurring at the centre of the beam, was 5.45mm. Specimen 2 and 3 were recorded to deflect 5.86mm and 6.02mm respectively when tested in the laboratory under the same loading conditions. The average error equates to approximately 9%. To ensure consistency of the model, an FEA was also conducted for a load of 500N resulting in a deflection of 2.73mm. Specimen 2 and 3 recorded deflections of 2.88mm and 2.98mm respectively equating to an average error of approximately 7%. The variation in the results between the FEA and the physical tests was considered acceptable for design. The final sandwich panel design was then modelled using the same material properties. The resulting stress and deflection diagrams for the test beam are provided in Appendix D.

5.3.2. Final Panel Design

The panel was modelled in Creo Parametric with a FEA conducted in Creo Simulation. Similarly to the test beam, the panel was modelled as three parts in an assembly assuming a perfect bond between the foam core and the FRP skins. The panel dimensions were as per Figure 43 however the length was reduced to 1m to reduce the running time simulating only one 900mm span. In a practical situation, the end conditions provided by adjoining spans will reduce the mid-span deflection. The simply supported span was considered worst case scenario for deflection. A pressure of 5kPa was applied to the face of the skin and pinned supports at 900mm centres as shown in Figure 46.

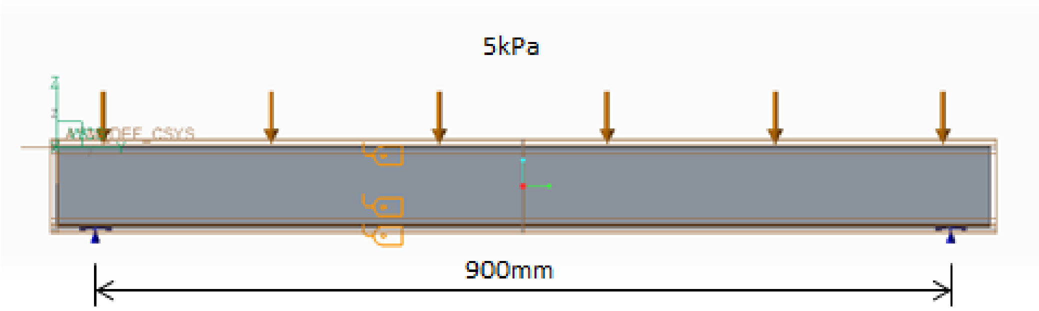


Figure 46 - FEA panel loading configuration

To simplify the model the Auto GEM meshing function was used. As a result, the mesh size of the skins became much smaller than the mesh size of the foam. The mesh geometry is provided in Appendix D. The deflection results from the FEA are shown in Figure 47 where the maximum deflection observed was 3.1mm.

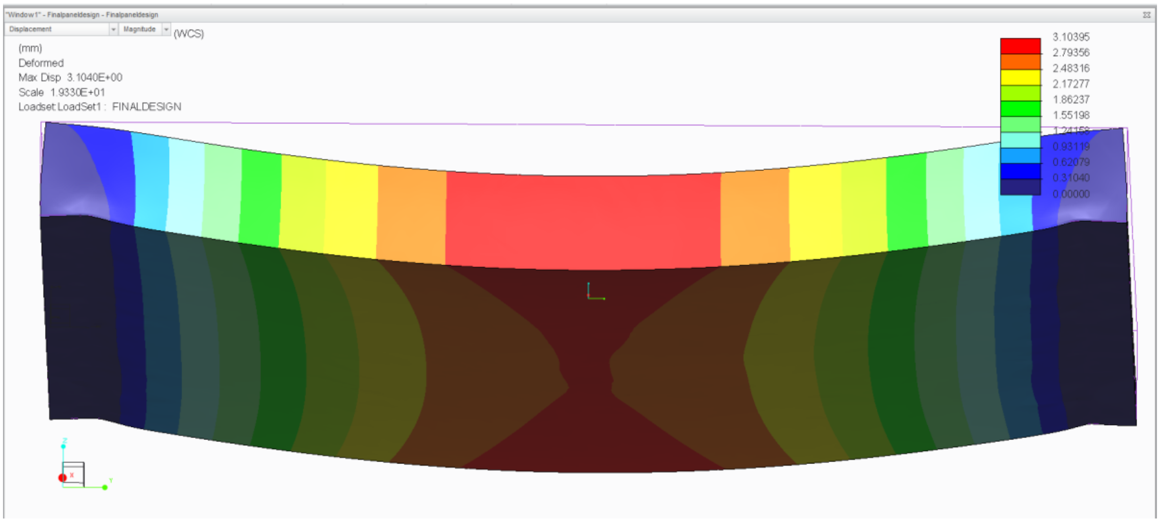


Figure 47 - FEA panel deflection

As shown in Figure 47, larger deflection occurs at the edges of the panel where the resistance to lateral deformation is the smallest. Based on equation (14) the maximum deflection was estimated at 2.82mm. The variation in results equates to approximately 10%. In reality, the panels will be somewhat supported along the spaning edges by adjacent panels. At least one end of each span will also resist rotation as the panels will have multiple spans. The deflection of 3.1mm has therefore been considered okay for serviceability limits (≈Span/300). The loading pressure was then changed to 12kPa to simulate the ultimate limit states load. The resulting stresses from the analysis are shown in Figure 56 and Figure 57.

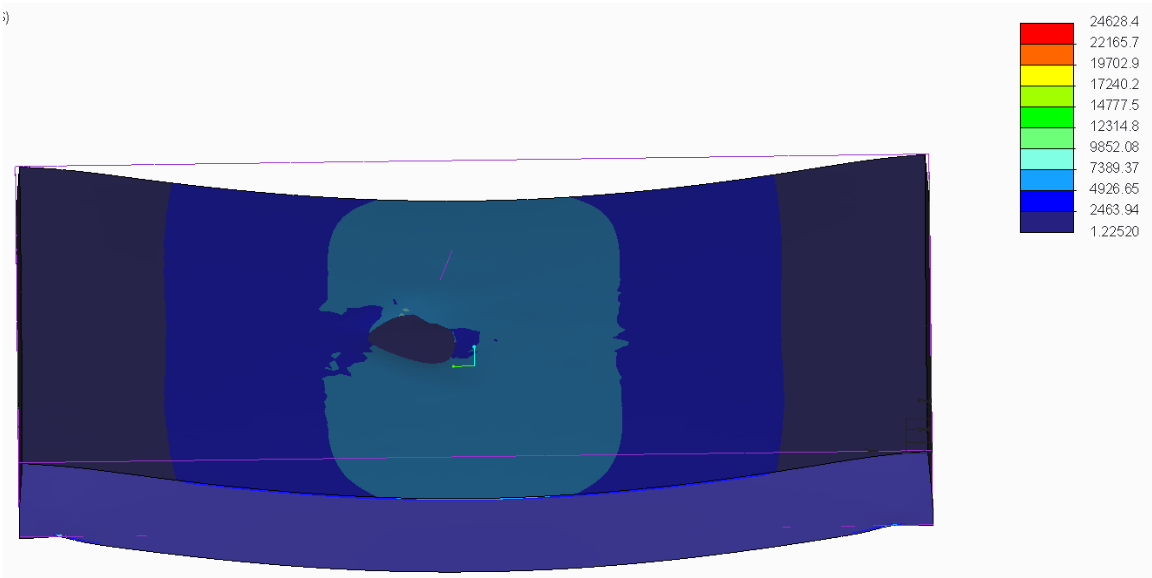


Figure 48 - FEA panel stress top

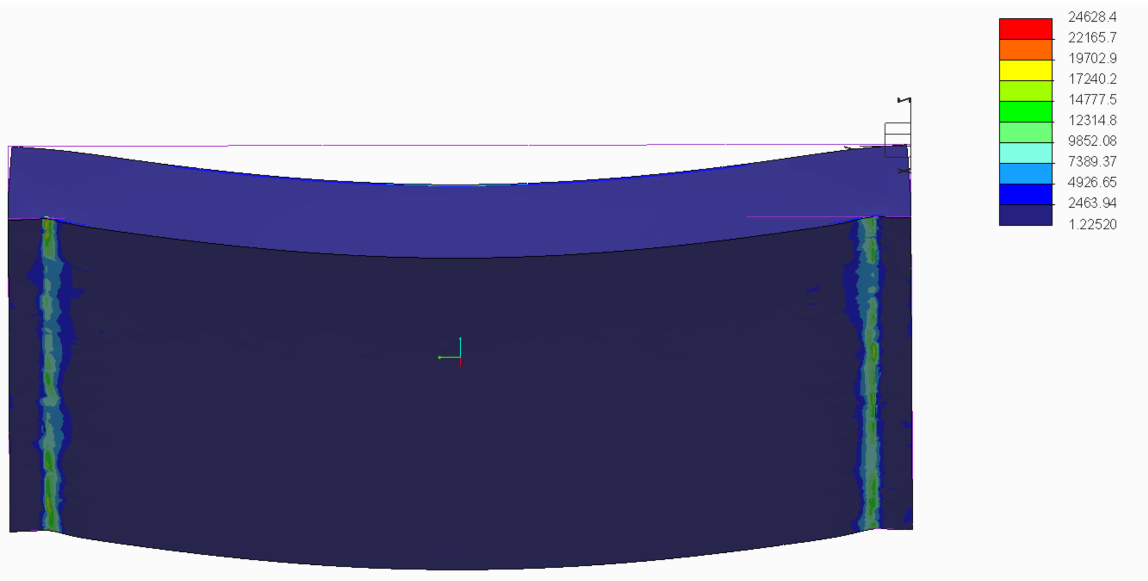


Figure 49 - FEA panel stress bottom

The maximum stress within the skin at centre span is approximately shown as 5MPa on the top surface which is well below the allowable compressive stress and the wrinkling stress of the FRP skins. The load appears to be distributed throughout the facing skins with the foam subjected to a maximum stress of only 1.3kPa. This is much less than the allowable bending stress of the foam and therefore shall be considered safe. The maximum stresses shown at the restraints should be disregarded as the support width or bearing area was simplified as a line for this analysis. In a real situation, the bearing area will be much larger and therefore the stress concentrations will be reduced. An analysis on the bearing stresses should be conducted at a later stage in the design process when the fixings are known. Based on the results from the design calculations and the finite element analysis, the proposed panel design satisfies the ultimate limit states and serviceability limit states requirements.

5.4. Cost analysis

This section looks briefly at the costings involved with manufacturing and installing fibre composite sandwich panels in comparison to traditional building materials such as timber, ceramic tiles and steel and other sandwich designs on the market.

5.4.1. Sandwich panels

The most significant cost involved with using sandwich panels for roofing applications is the manufacturing process itself. The panels made for this assignment were small and therefore the time involved to manufacture the panels was much higher than could be expected when producing larger quantities. For the purpose of this cost analysis, the manufacturing costs were analysed for a large scale production.

As discussed in Chapter 3 the materials required to manufacture the panels include; E glass, Vinyl Ester Resin, Catalyst and Rigid Polyurethane. The approximate rates for each material are provided in Table 21.

Table 21 - Material rates

Material	Unit	Rate
Australian Urethane Systems BFE35 Rigid block foam	m^3	$ 450.00
AkzoNobel Butanox M-50 Catalyst	L	$ 4.00
NCS 991PAU-40 Resin	kg	$ 7.00
Colan Australia 830g/m2 Woven roving	kg	$ 5.60
Colan Australia 225g/m2 Chopped strand mat	kg	$ 5.60

Based on an average resin to glass ratio of 1:1, the material cost for this project was estimated as $6.50/kg of laminate. A cost breakdown for manufacture of a large panel (14m x 3.6m) cut into several panels is shown in Table 22.

Table 22 - Panel costing

Item	Quantity	Unit	Rate	Total
Laminate	544.32	kg	$ 6.50	$ 3,538.08
Foam	5.04	m^3	$ 450.00	$ 2,268.00
Table setup	2	hr	$ 65.00	$ 130.00
Place foam	2	hr	$ 65.00	$ 130.00
Cut glass	1	hr	$ 65.00	$ 65.00
Lay glass and resin	4	hr	$ 65.00	$ 260.00
Flip panel	0.5	hr	$ 65.00	$ 32.50
Lay glass and resin	4	hr	$ 65.00	$ 260.00
Finish edges	10	hr	$ 65.00	$ 650.00
Polish	10	hr	$ 65.00	$ 650.00
Package for freight	2	hr	$ 65.00	$ 130.00
			Grand Total	$ 8,113.58
			Rate/m²	$ 160.98

A basic estimate results in a rate of approximately $160/m² for the sandwich panels. This rate will vary depending on the fire resistance required and the quantity manufactured. This estimate should not be used for anything more than a basic idea of costing.

5.4.2. Traditional materials

For the basis of this cost analysis, the insulation and the outer layer of a traditional roof were considered. As the current sandwich panel design requires roofing battens at 900mm spans, the frame or truss was be included in this analysis. Approximate rates for different types of roofing insulation are provided in Table 23.

Table 23 - Insulation rates (Schneider 2015)

Type	Rate
Reflective sarking	$1.20/m²
Reflective foil with air cell barrier (BCA compliant)	$12/m²
Glass wool batts	$6.70/m²
Polyester batts	$9/m²
Sheep wool	$9/m²

The reflective foil with the air cell barrier is probably the most comparable to the sandwich panel insulation as it complies with the Building Code of Australia. Approximate rates for different roofing materials are provided in Table 24.

Table 24 - Roofing rates (*Roofing Fundamental* 2015)

Type	Rate
Clay tiles	$40/m²
Slate tiles	$60/m²
Concrete tiles	$60/m²
Sheet metal (corrugated iron)	$12/m²
Spanish tiles	$40/m²
Asphalt shingles	$8/m²

There are advantages and disadvantages to each type of roofing material. Although metal roofing is cheap, installation is time consuming and must be done by experienced professionals. Slate tiles require little maintenance and have a long lifespan; however the material costs are relatively high. A sheet metal roof and a slate tile roof with reflective foil insulation will therefore cost $24/m² and $72/m² respectively.

5.4.3. Existing sandwich panels

The existing roofing sandwich panels made from materials such as polystyrene foam, corrugated iron and PVC vary in price from about $50/m² through to $80m² depending on brand, materials, thickness and allowable spans. CSR Bradford (2015), an insulation company, conducted a cost comparison survey in June 2014 on the total costs of installing various types of commercial roofing. Included in the costing were all components, equipment, labour and training time. Three roofing systems were reviewed of which two of them conventional and the third a sandwich panel system. The conventional system had an average rate of $65/m² installed and the sandwich panel $115/m² installed.

5.4.4. Conclusion

In comparing fibre composite sandwich panels with conventional roofing materials, the costing is only a minute section of the overall comparison. Although the costing is a significant selection criterion for consumers, design life, maintenance requirements, performance and aesthetics also contribute to the final decision. The costing, excluding installation labour for the roofing types discussed are compared in Table 25.

Table 25 - Cost comparison

Type	Rate
FRP sandwich panels	$160/m²
Existing sandwich panels	$80/m²
Slate tile with reflective foil insulation	$72/m²
Sheet metal with reflective foil insulation	$24/m²

With the rate of FRP sandwich panels double that of the existing sandwich panels, it may be concluded that the design should be reviewed to reduce materials. With the materials costing over 75% of the total panel price, there is not much room to reduce costs with labour. The design should be reviewed to reduce laminate thickness. This could be achieved by applying ribbing to the extremal face of the panel similar to that of corrugated steel. This will increase the stiffness of the panels requiring less material. External ribbing and other design modifications are discussed further in Chapter 6. As mentioned, the cost estimate provided for the FRP sandwich panels in only very basic and forms only one criterion in the overall roofing selection process. Based on this brief cost analysis along with the provision to improve the sandwich design, the FRP sandwich panels may be considered a viable roofing option.

Chapter 6. Conclusions and future work

6.1. Introduction

The primary objective of this research project was to investigate the thermal insulation and strength properties of varying core thicknesses in fibre composite sandwich panels. Included in the investigation was an in depth literature review on the theory of sandwich panels and the current applications of fibre composite technologies. A set of sample panels were manufactured at Buchanan's Advanced Composites and tested in bending at the Centre for Excellence in Engineered Fibre Composites to compare with theoretical values predicted from equations found in the literature. The testing included 6 different loading configurations varying in span from 300mm through to 1300mm. The results from the tests were used to generate a final panel design. A finite element analysis was conducted in the software package Creo which was used to validate the final design. Finally a basic cost analysis was completed on the final design for comparison with conventional building materials.

6.2. Design requirements

The design requirements adopted for the thermally insulated structural sandwich panels came from several design codes and standards including, but not limited to the Australian Standards 1170 series, Eurocomp Design Code and the Building Code of Australia sections C 'Fire Resistance and J 'Energy Efficiency'. The polyurethane core provided more than adequate insulation properties to satisfy the requirements for energy efficiency however further investigation must be conducted to ensure the FRP skins along with the PU core provide sufficient fire resistance. The sandwich panels were designed to satisfy both ultimate limit states as well as serviceability limit states design requirements. As anticipated the serviceability, in particular the mid-span deflection when subject to wind loads, became the governing design factor.

6.3. Testing results

A series of experimental tests were conducted at the CEEFC on sandwich beams with different core thicknesses. From the tests results, various material properties were calculated such as the core shear rigidity, core ultimate compressive stress, core ultimate shear stress and facing modulus. The core properties calculated from the tests results were similar to that of which were predicted using properties of similar cores. The facing modulus calculated was however much smaller than predicted using the rule of mixtures for fibre composite laminates. This variation may have been caused by improper manufacturing techniques. As the sample panels were not manufactured by professionals, the resin to glass ratio may have been less than ideal causing a reduction in material properties. Localised crushing of the core during the test may also have caused a reduction in the calculated modulus. The core shear rigidity calculated from the test results was lower for the thicker core size. This is caused by the facing skins contributing to the shear stiffness of the beam. As the core thickness increases, the facing skins contribute less to the shear stiffness.

Along with determining material properties, the tests were also used to gain a better understanding of the failure modes applicable to the design. In most cases, the failure mode observed was delamination of the facing skins from the core. The core would then shear at the location of the delamination. The failure modes occurred when the beams were subject to excessive deflections. The failure modes were not considered catastrophic as the beams continued to support loads after delamination.

6.4. Final design

The final design of the sandwich panels was conducted using material properties derived from testing results as well as from theory resulting in a core thickness of 100mm. The final panel design is provided in Figure 43. A finite element analysis was conducted on the final panel design to check with the results from the design calculations. The results from the FEA varied by approximately 10% from the results of the design calculations. A FEA was also conducted on a test beam identical to specimen 2 and 3 used in the laboratory. Results from the analysis were closely compared with the physical testing results observing an error of approximately 10% validating the Creo model.

The final panel design has a thermal resistance R value of 5.75 and has been deemed to satisfy both the serviceability and strength requirements for the application. A cost analysis revealed that the FRP sandwich panels were significantly more expensive than conventional roofing materials. Several design changes have been identified such as external ribbing that may reduce the overall cost of FRP sandwich panels.

6.5. Summary

As predicted, increasing the thickness of the sandwich core improves the thermal resistance immensely. Increasing the core thickness also separates the skins further providing for an increase in flexural stiffness. Disadvantages of increasing the core size include a reduction in shear stiffness of the panel as well as increased chance of skin wrinkling or delamination. Table 26 provides a summary of the important results from the research.

Table 26 - Important results

Final Proposed Panel Design	
Core thickness (c)	100mm
Skin thickness (t)	3mm
Core type	BFE35 PU Rigid Foam
Skin laminate	2xWR830g/m² + 3xCSM225g/m² with VE Resin
Span (a)	900mm
Ultimate wind load (W_u)	12kPa
Service wind load (W_u)	5kPa

6.6. Recommendations and future work

The results of this research suggest a promising future for the development and use of FRP sandwich panels for roofing applications. The advantages of FRP sandwich panels such as their high strength to weight ratio, superior lifespan, fire and thermal resistance gives then a favourable advantage over conventional roofing systems. The costing, as discussed in Chapter 5, will need to be decreased for the panels to become a viable solution in the future. This could be achieved by reviewing the sandwich panel design so as to decrease the material required whilst sustaining the same level of stiffness.

Research into various other core types may help to develop a cheaper panel design with an increased span. The addition of corrugated FRP or FRP ribs to the outer skin will also increase the stiffness of the panel allowing for a reduction in the material required. Stiffening ribs can easily be incorporated into the design equations however as with all fibre composites, physical testing must be conducted to ensure the product is safe for the application.

There are several design components that must be completed for the proposed final design to be ready for the market. Firstly and most importantly, the fire resistance of the panels must be tested and analysed so as to ensure that the product complies with Section C of the Building Code of Australia. The results should also be checked against the insurance industry fire requirements. The connection and fixing details of the panels must also be designed and these could incorporate channelling for electrical conduit. Large scale load testing including impact testing would also aid in making the product more marketable.

With the FRP sandwich panel design completed, further research and development into a modular unit that eliminates the need for roof trusses could be carried out. This could involve investigating the attributes of sandwich panels in longitudinal compression. A complete modular unit may result in a higher material price however the overall cost of construction may be reduced as the modules would allow for fast installation.

References

Almeida, MIAd 2009, 'Structural behaviour of composite sandwich panels

for applications in the construction industry', University of lisbon, Portugal.

American Chemistry Council - Polyurethane, 2015, American Chemistry Council, viewed 30 May, <http://polyurethane.americanchemistry.com/Sustainability/Fire-and-Combustibility>.

AS4859.1 2002 Materials for the thermal insulation of buildings, 2002, Part 1: General criteria and technical provisions, Standards Australia, Sydney.

AUSTHANE BFE 35 Rigid FR Polyurethane Foam, 2011, AUSTRALIAN URETHANE SYSTEMS PTY LTD, Sydney.

Bakis, CE, Bank, LC & Brown, VL 2002, 'Fiber-Reinforced Polymer Composites for construction - State-of-the-Art Review', *Journel of Composites for Construction*, pp. 73-87.

Bondor Insulated Roofing Panels, 2015, Metecno Pty Ltd, viewed 7 May, <http://www.bondor.com.au/products/roofing>.

Bradford 2015, *The Cost of a Roof*, CSR Bradford, North Ryde BC NSW, <https://www.architectureanddesign.com.au/getattachment/f2c9d669-4338-43f1-b5a1-39f12c6e6ff7/attachment.aspx>.

Bradley, B 2007, *Typical Roof Truss*, Wikimedia Commons, Wikimedia Commons, <https://commons.wikimedia.org/wiki/File:Rf-trad-section.gif>.

Carslaw, H & Jaeger, J 1986, *Conduction of heat in solids*, 2nd edn, Clarendon Press, New York.

Colan Australia, 2013, viewed 3 June, <http://www.colan.com.au/compositereinforcement/resources/fibre-information/fibre-comparison-charts>.

Composites Australia, 2015, Composites Australia, viewed 30 May, <http://www.compositesaustralia.com.au/fabrication-processes/>.

Concise encyclopedia of composite materials, 1989, Pergamon Press, New York.

Design Data, 1994, ACI Fibreglass.

DIAB Group, 2015, viewed 5 May 2015, <http://www.diabgroup.com/en-GB/Knowledge/Sandwich-technology>.

DIAB guide to core and sandwich, 2012, Rev 1, Diab Group, Laholm, Sweden, Guide.

Exel Australia Standard Industrial Profile List, 2015, Exel Composites, Boronia VIC Australia, 01/06/16.

Flannery, M 2015, *Generic Risk Management Plan*, University of Southern Queensland, Toowoomba.

Foster, GC 1998, 'Tensile and Flexure Strength of Unidirectional Fiber-Reinforced Composites: Direct Numerical Simulations and Analytic Models', Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Gall, TL 1987, *Engineers' guide to composite materials*, American Society of Metals, Metals Park, Ohio.

Glicksman, L 1994, 'Heat transfer in foams', in NC Hilyard & A Cunningham (eds), *Low density cellular plastics*, Springer Netherlands, ch 5, pp. 104-52.

Gryzagoridis, J, Oliver, G & Findeis, D 2015, 'On the equivalent flexural rigidity of sandwich composite panels', *Insight*, vol. 57, no. 3, pp. 140-3, <<Go to ISI>://WOS:000352317400006>.

Gurit 2015, *Gurit.com*, Gurit UK, viewed 14 September, <http://www.azom.com/suppliers.aspx?SupplierID=221>.

History of Composites, 2015, Mar-Bal Inc, viewed 25 April, <http://www.mar-bal.com/applications/history-of-composites/>.

Howard, AG 1969, *Anaylsis and design of structural sanwich panels*, 1st edn, Oxfordm Pergamon Press, New York.

John W. Weeton, DMP, Karyn L. Thomas 1987, *Engineers' guide to composite materials*, American Society of Metals, Metals Park, Ohio.

Johnson, T 2015, *History of Composites*, About Money, viewed 25 April, <http://composite.about.com/od/aboutcompositesplastics/a/HistoryofComposites.htm>.

L.C. Hollaway, PRH 2001, *Advanced polymer composites and polymers in the civil infrastructur*, Elsevier Science Ltd, London.

Lysaght 2015, *Custom ORB Design and Installation Guide*, BlueScope.

Manalo, A 2013, 'Fibre reinforced polymer composites sandwich structure: Recent developments and applications in civil infrastructure', *proceedings of the* Centre of Excellence in Engineered Fibre Composites, University of Southern Queensland, Toowoomba, Queensland 4350, Australia.

Moaveni, S 2011, *Engineering Fundamentals - An introduction to engineering*, Fourth SI edn, Global Engineering, Stamford CT, USA.

Modular FRP Pedestrian Bridge, 2015, BAC Technologies Pty Ltd, Toowoomba, QLD, <http://www.bac.net.au/civil/modular-frp-pedestrian-bridge/>.

National Construction Code Series Volume 1, 2015, Australian Building Codes Board.

'NCS 991 PAU-40', 2015, *NCS Composites*, <http://www.ncscomposites.com.au/wp-content/uploads/datasheets/20130924112307442385368.pdf>.

Plantema, FJ 1966, *Sandwich Construction: the bending and buckling of sandwich beams, plates, and shells*, vol. 3, Wiley, New York.

Pultrusion Process, 2015, Exel Composites, <http://www.exelcomposites.com.au/ManufacturingQuality/Pultrusionprocess.aspx>.

Rakic, J 2003, 'Fire rated insulated (sandwich) panels', *Fire Australia*, no. May 2003, pp. 33-7, <http://www.pfpa.com.au/docs/sandwich%20panels/10-sandwich%20panel.pdf>.

Roofing Fundamental, 2015, viewed 22 October, <http://www.roofingfundamental.com/Roofing-Materials-Costs-Comparison.html>.

Schneider, R 2015, *Roof Insulation*, viewed 22 October, <http://www.homeimprovementpages.com.au/article/how_much_does_roof_insulation_cost>.

Steel Profile Insulated Roofing Panel, 2015, Complete Modular Homes, viewed 7 May, <http://completemodularhomes.com/fast-fix-system/fast-fix-roofing/>.

Structural Design of Polymer Composites Eurocop Design Code, 1996, E & FN Spon, London, UK.

Wit Witkiewicz, AZ 2006, *Properties of Polyurethan (PU) Light Foams*, Gdańsk University of Technology, Department of Materials Science and Engineering, Gdańsk, Poland,<.

Young, WC & Budynas, RG 2002, *Roark’s Formulas for Stress and Strain*, Seventh edn, McGraw-Hill, New York.

Standards:

ASTM C393/C393M-11 - 'Standard test method for core shear properties of sandwich construction by beam flexure'

ASTM D7249/D7249M-12 - 'Standard test method for facing properties of sandwich construction by long beam flexure'

ASTM D7250/D7250M-06 - 'Standard practice for determining sandwich beam flexural and shear stiffness’

AS/NZS 1170-2002 - 'Structural design actions'

Eurocomp Design Code 1996

NCC Vol 1 Section J - 'Energy efficiency'

NCC Vol 1Section C - 'Fire resistance'

Appendices

Appendix A – Project Specification

ENG4111/4112 Research Project

PROJECT SPECIFICATION

STUDENT: **AIDEN FLANNERY**

TOPIC: NUMERICAL MODELLING AND TESTING OF FIBRE COMPOSITE SANDWICH PANELS FOR RESIDENTIAL AND COMMERCIAL ROOFING APPLICATIONS

SUPERVISOR: Dr. Sourish Banerjee
Norman Watt, BAC Technologies Pty Ltd

ENROLEMENT: ENG 4111 – S1 ONC 2015
ENG 4112 – S2 ONC 2015

PROJECT AIM: The objective of this research project is to optimise the thickness of a fibre composite sandwich core so as to provide sufficient thermal insulation and strength. If time permits testing may be completed to compare with the theoretical results. BAC Technologies will supply the materials required in this case. The findings of this research project will aid BAC Technologies in developing a fibre composite modular roof design.

SPONSORSHIP: BAC Technologies Pty Ltd

PROGRAMME: **Issue A, 13th March 2015**

1. Research the background information relating to fibre composite sandwich panels used in the construction industry
2. Determine the typical loading cases that a roofing panel would be exposed to by the use of Australian Standards
3. Determine the thermal insulation property required from a sandwich panel in a roofing application

4. Design and model fibre composite sandwich panels (fibreglass skins with low density PU cores of varying thickness)
5. Analyse the strength and thermal insulation properties of the panels by the use of FE modelling (ANSYS/Strand7)
6. Evaluate the results and determine an optimal thickness for strength and thermal insulation

As time permits:

7. Test sample size composite panels for strength and thermal conductivity (provided by BAC Technologies) and compare with numerical results
8. Conduct a cost analysis of producing the panels in comparison to traditional roofing techniques

Appendix B – Risk Management Plan

The following generic risk management plan was adapted from the current USQ management system (Flannery 2015).

Generic Risk Management Plan

Workplace (Division/Faculty/Section):		
Health, Engineering and Sciences		
Assessment No (if applicable): 0061033162-01-RevA	Assessment Date: 24/08/2015	Review Date: (5 years maximum) / /

Context: What is being assessed? Describe the item, job, process, work arrangement, event etc:

This RMP considers the project in holistic terms but concentrates on the three higher risk areas in more detail. They are:

- The fibre composite test specimen preparation and manufacture,
- The mechanical testing phase, and
- The continuing responsibility beyond the completion of the project.

Assessment Team

Assessor(s): Aiden Flannery

Others consulted: USQ Safety Manager

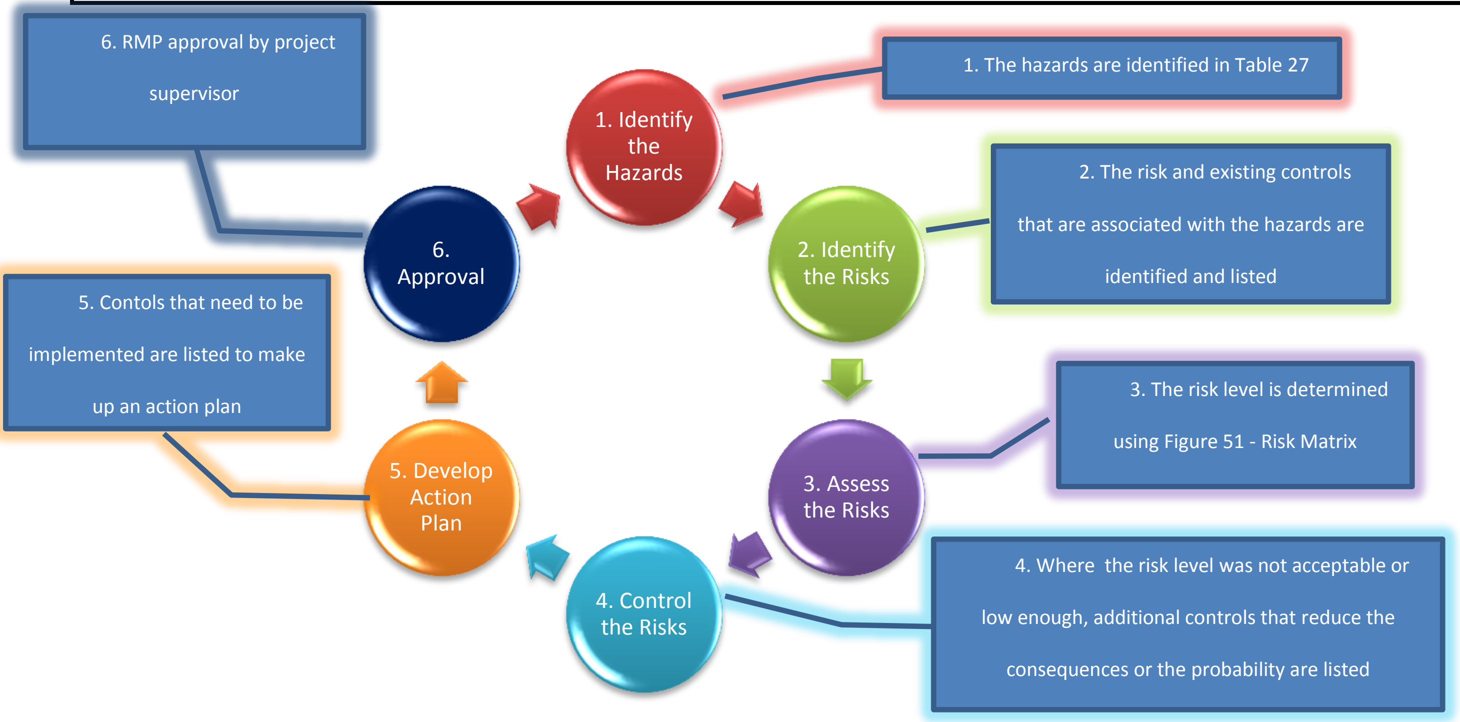


Figure 50 - The risk management process

Table 27 – Identified hazards

Step 1 - Identify the hazards		
General Work Environment		
☐ Sun exposure	☐ Water (creek, river, beach,	☒ Sound / Noise
☐ Animals / Insects	☐ Storms /	☐ Temperature (heat, cold)
☒ Air Quality	☐ Lighting	☐ Uneven Walking Surface
☒ Trip Hazards	☐ Confined Spaces	☐ Restricted access/egress
☐ Pressure (Diving/Altitude)	☐ Smoke	☐
Machinery, Plant and Equipment		
☒ Machinery (fixed plant)	☒ Machinery (portable)	☒ Hand tools
☐ Laser (Class 2 or above)	☐ Elevated work platforms	☐ Traffic Control
☐ Non-powered equipment	☒ Pressure Vessel	☐ Electrical
☐ Vibration	☐ Moving Parts	☒ Acoustic/Noise
☐ Vehicles	☐ Trailers	☐ Hand tools
Manual Tasks / Ergonomics		
☐ Manual tasks (repetitive, heavy)	☐ Working at heights	☐ Restricted space
☐ Vibration	☐ Lifting Carrying	☐ Pushing/pulling
☐ Reaching/Overstretching	☐ Repetitive Movement	☐ Bending
☐ Eye strain	☐ Machinery (portable)	☒ Hand tools
Biological (e.g. hygiene, disease, infection)		
☐ Human tissue/fluids	☐ Virus / Disease	☐ Food handling
☐ Microbiological	☐ Animal tissue/fluids	☐ Allergenic
Chemicals Note: Refer to the label and Safety Data Sheet (SDS) for the classification and management of all chemicals.		
☒ Non-hazardous chemical(s)	☒ 'Hazardous' chemical (Refer to a completed hazardous chemical risk assessment)	
☐ Engineered nanoparticles	☐ Explosives	☐ Gas Cylinders
Critical Incident – resulting in:		
☐ Lockdown	☐ Evacuation	☐ Disruption
☐ Public Image/Adverse Media Issue	☐ Violence	☐ Environmental Issue
Radiation		
☐ Ionising radiation	☐ Ultraviolet (UV) radiation	☐ Radio frequency/microwave
☐ infrared (IR) radiation	☐ Laser (class 2 or above)	☐
Energy Systems – incident / issues involving:		
☐ Electricity (incl. Mains and Solar)	☐ LPG Gas	☐ Gas / Pressurised containers
Facilities / Built Environment		
☐ Buildings and fixtures	☐ Driveway / Paths	☒ Workshops / Work rooms
☐ Playground equipment	☐ Furniture	☐ Swimming pool
People issues		
☒ Students	☐ Staff	☐ Visitors / Others
☐ Physical	☐ Psychological / Stress	☐ Contractors
☐ Fatigue	☐ Workload	☐ Organisational Change
☐ Workplace Violence/Bullying	☒ Inexperienced/new personnel	☐

Table 28 - Other hazards

Step 1 (cont) Other Hazards / Details
Chemicals and substances used:
• Butanox M-50 (curing agent, Methyl ethyl ketone peroxide, solution in dimethyl phthalate)
• AUSTHANE BF35 Rigid PU Foam
• Fibreglass Woven Rovings & Tapes
• 991 UNWAXED RESIN PAU 40 (unsaturated polyester resin)

Eg 1. Enter Consequence

Eg 2. Enter Probability

Eg 3. Find Action

	Consequence				
Probability	**Insignificant** No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injuries $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L

Recommended Action Guide
E=Extreme Risk – Task ***MUST NOT*** proceed
H=High Risk – Special Procedures Required (See USQSafe)
M=Moderate Risk – Risk Management Plan/Work Method Statement Required
L=Low Risk – Use Routine Procedures

Figure 51 - Risk Matrix

Table 29 - RMP

Step 1 (cont)	Step 2	Step 2a	Step 3			Step 4				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Existing Controls:** What are the existing controls that are already in place?	**Risk Assessment:** Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls:** (has the consequence or probability changed?)			**Controls Implemented? Yes/No**
			Consequence	Probability	Risk Level		Consequence	Probability	Risk Level	
Hazardous Chemicals	Misuse of hazardous chemicals leading to serious personnel injury	Close adherence to BAC SOPS, chemical MSDS and workshop principles. Only inducted and trained personnel to work on the project.	Major	Unlikely	Moderate	All processes to be checked and approved by BAC workshop supervisor before and during task.	Major	Rare	Low	Yes
Dust	Inhalation of dusts leading to serious personnel injury	Use of PPE in accordance with MSDS and BAC SOPs. Use of dust minimisation practices.	Major	Unlikely	Moderate	All processes to be checked and approved by BAC workshop supervisor before and during task.	Major	Rare	Low	Yes
Resins and solvents	Fire or explosion from resins and solvents used and the vapours generated	Close adherence to BAC SOPS, chemical MSDS and workshop principles. Only inducted and trained personnel to work on the project.	Major	Unlikely	Moderate	All processes to be checked and approved by BAC workshop supervisor before and during task.	Major	Rare	Low	Yes
Dust	Fire or explosion risk from dust generated during grinding and sanding	Close adherence to BAC SOPS, chemical MSDS and workshop principles. Only inducted and trained personnel to work on the project.	Major	Unlikely	Moderate	All processes to be checked and approved by BAC workshop supervisor before and during task.	Major	Rare	Low	Yes
Waste materials	Risk of fire from spontaneous combustion of waste materials	Strict use of flammable waste bins and adherence to BAC SOPS and workshop principles.	Moderate	Unlikely	Moderate	All processes to be checked and approved by BAC workshop supervisor before and during task.	Moderate	Rare	Low	Yes
Hazardous Chemicals	Explosion risk from incorrectly mixing chemicals	Adhere to manufactures instructions and BAC SOPs.	Catastrophic	Unlikely	Moderate	All processes to be checked and approved by BAC workshop supervisor before and during task.	Catastrophic	Rare	Low	Yes
Manual handing injuries	Improper use of tools and machines leading to personal injuries such as cuts, fractures, abrasions and other more serious injuries.	Only qualified and trained personnel to use tools and machines.	Moderate	Possible	High	Workshop supervisor to oversee tasks using tools and machines.	Moderate	Unlikely	Moderate	Yes
First Aid	Lack of appropriate first aid and emergency procedures leading to delayed treatment	BAC and USQ first aid kits available and emergency procedures in place and current.	Major	Unlikely	Moderate	Only personnel inducted in local emergency procedures to work on project.	Major	Rare	Low	Yes
Misuse of testing	Exposure to moving parts and large amounts of stored energy	USQ SOPs, guards and safety devices in place, safe working zones and minimum	Major	Unlikely	Moderate	Testing to be conducted under the strict supervision of USQ test facility personnel	Major	Rare	Low	Yes

Step 1 (cont)	Step 2	Step 2a	Step 3			Step 4				
Hazards: From step 1 or more if identified	**The Risk:** What can happen if exposed to the hazard with existing controls in place?	**Existing Controls:** What are the existing controls that are already in place?	**Risk Assessment:** Consequence x Probability = Risk Level			**Additional controls:** Enter additional controls if required to reduce the risk level	**Risk assessment with additional controls:** (has the consequence or probability changed?)			**Controls Implemented? Yes/No**
			Consequence	**Probability**	**Risk Level**		**Consequence**	**Probability**	**Risk Level**	
equipment	leading to high velocity projectiles, pinching and crushing	training requirements. Use Safe Work Method Statement.								
Wrongful disposal of materials	Pollution of waterways, skin irritation, harmful by inhalation	Disposal in accordance with BAC SOPs and environmental policy	Moderate	Rare	Low	NA				

Step 5 – Action Plan (for controls not already in place)			
Control Option	Resources	Person(s) responsible	Proposed implementation date
All processes to be checked and approved by BAC workshop supervisor before and during task.	NA	AF	During task
Workshop supervisor to oversee tasks using tools and machines (at BAC).	NA	AF	During task
Only personnel inducted in local emergency procedures to work on project (BAC and USQ).	NA	AF	During task
Testing to be conducted under the strict supervision of USQ test facility personnel (at USQ).	NA	AF	During task

Step 6 – Approval

Drafter's Comments:

The risks associated with the manufacture of fibre composite materials are well documented at BAC and controls are implemented through the safety management system including SOPs, training and induction doctrine. USQ also has a comprehensive safety management system detailing specific requirements that must be followed. This risk management plan recognises these extant systems when assessing the inherent risks and seeks to add additional controls mainly in the form of expert and experienced supervision.

Drafter Details:

Name: Aiden Flannery   Signature: [signature]   Date: 24/08/15

Assessment Approval: (Extreme or High = VC, Moderate = Cat 4 delegate or above, Low = Manager/Supervisor)

I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.

Name: Sourish Banerjee   Signature: Date:

Position Title:

Appendix C - Time line

Table 30 - Project timeline

Semester 1			Semester 2		
Week	**Date**	**Task**	**Week**	**Date**	**Task**
1		Project Generation	1		Model design in Strand7 and Solidworks
2	11/3/15	Project Allocation	2		Results
3	18/3/15	Project Specification	3		Results and discussion
4		Background Info	4		Optimal design
5		Background Info	5		provision for delays + additional literature review
6		General Composites	6		Testing procedure + Fabricate test panels
7		Sandwich Panels In Construction	7		Testing procedure + Risk Assessment
8		Flexural Strength + Thermal Insulation	8		Testing procedure + Risk Assessment
9		Flexural Strength + Thermal Insulation	9	16/9/15	Partial Draft Dissertation
10		Fire Resistance	10		Testing
11		Presentation 1	11		Presentation 2
12		Design Requirements	12		Results and discussion
13		Design Requirements	13		Cost benefit analysis + write up
14	3/6/15	Preliminary Report	14		Finalise dissertation
15		Model design in Strand7 and Solidworks	15	29/10/15	Dissertation Submission
16	17/6/15	Supervisors Progress Assessment	16		
17		Model design in Strand7 and Solidworks	17		

Legend
Literature Review
Analysis
Results and Discussions
Testing
Submissions

Appendix D – Creo Simulation

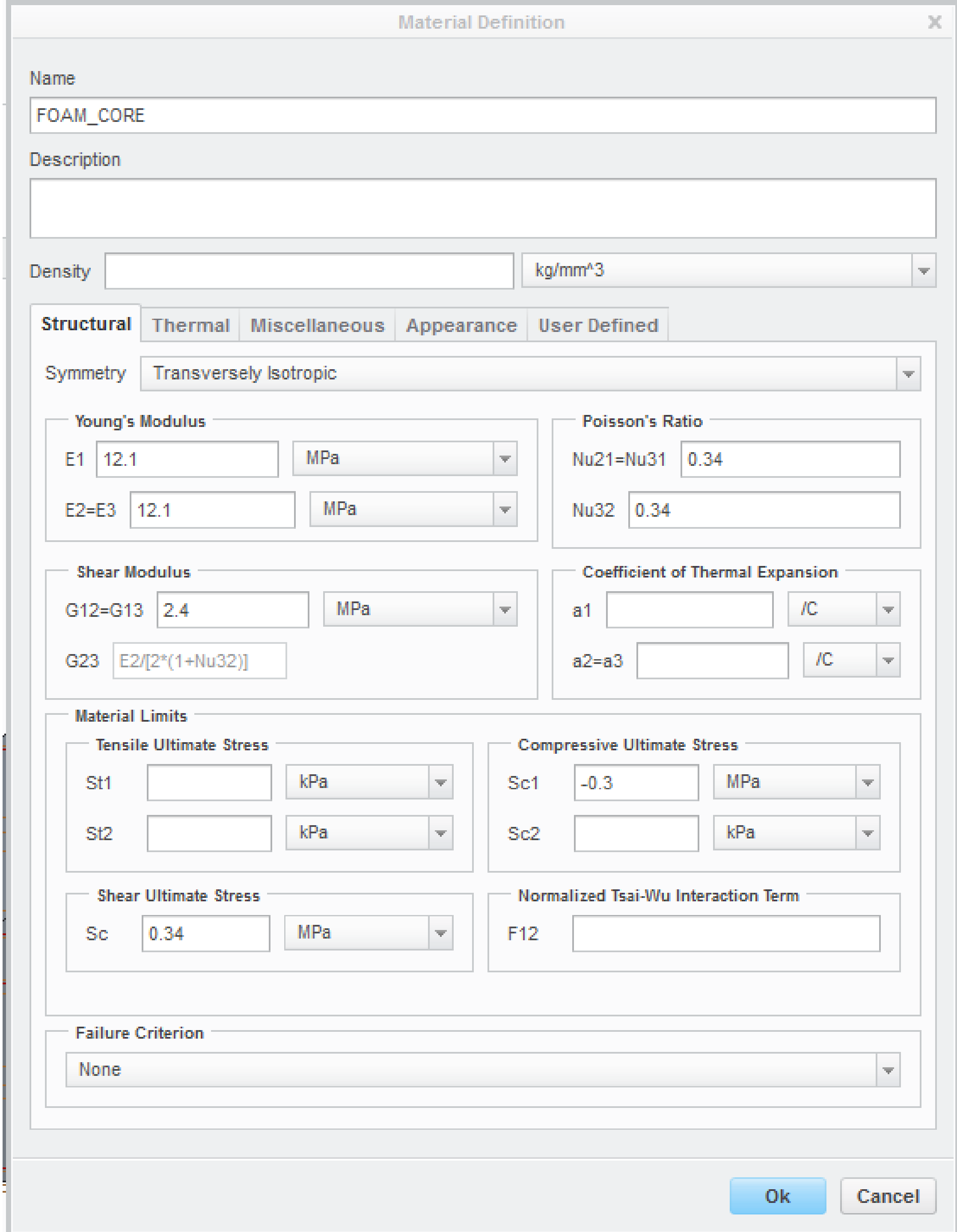


Figure 52 - Foam core inputs

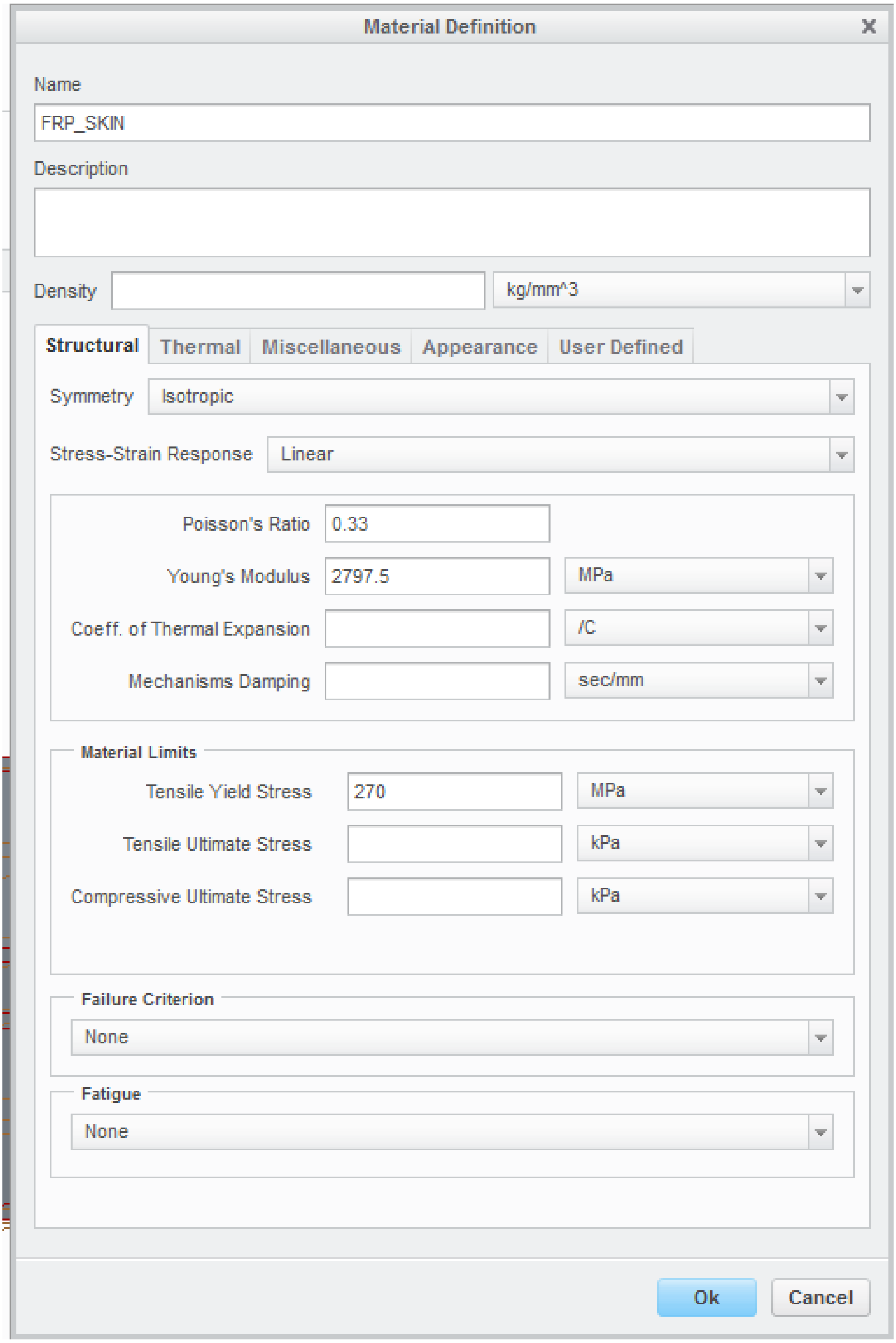


Figure 53 - FRP skin input

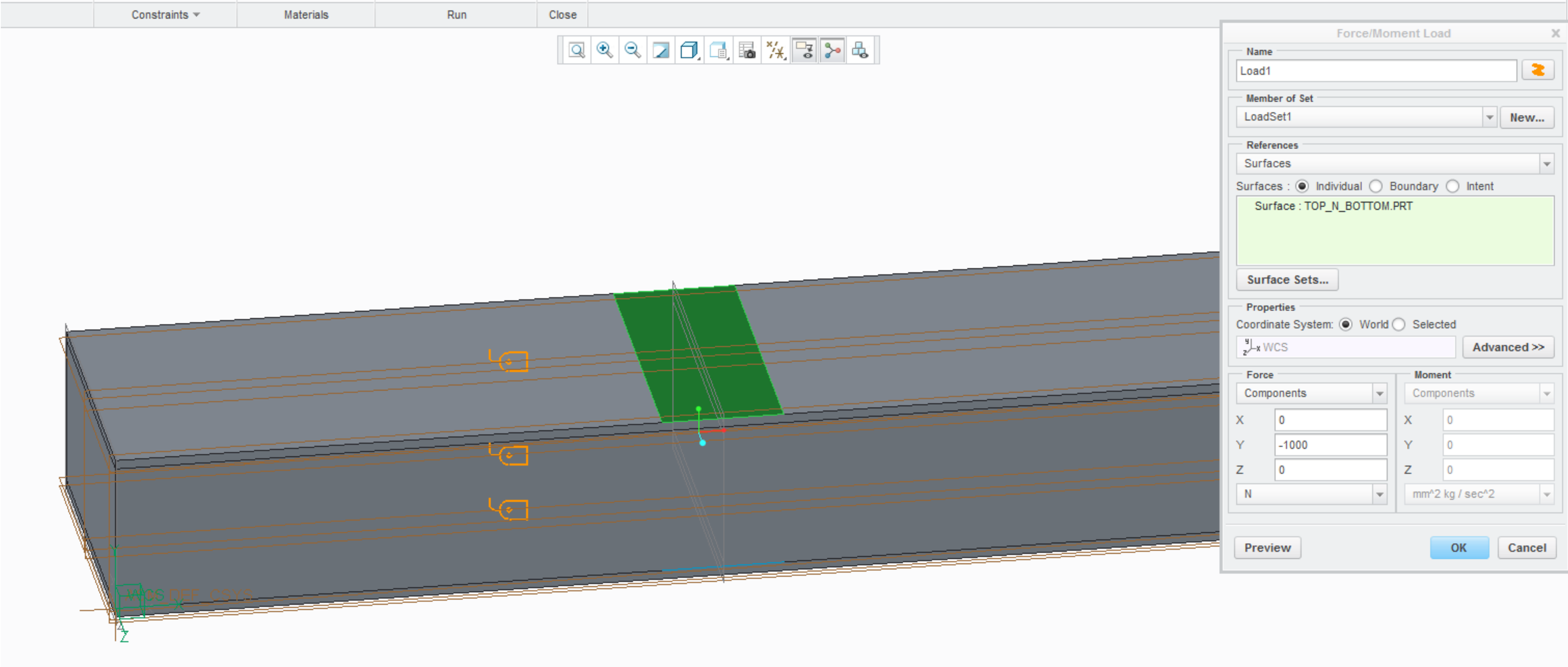


Figure 54 - FEA test beam loading

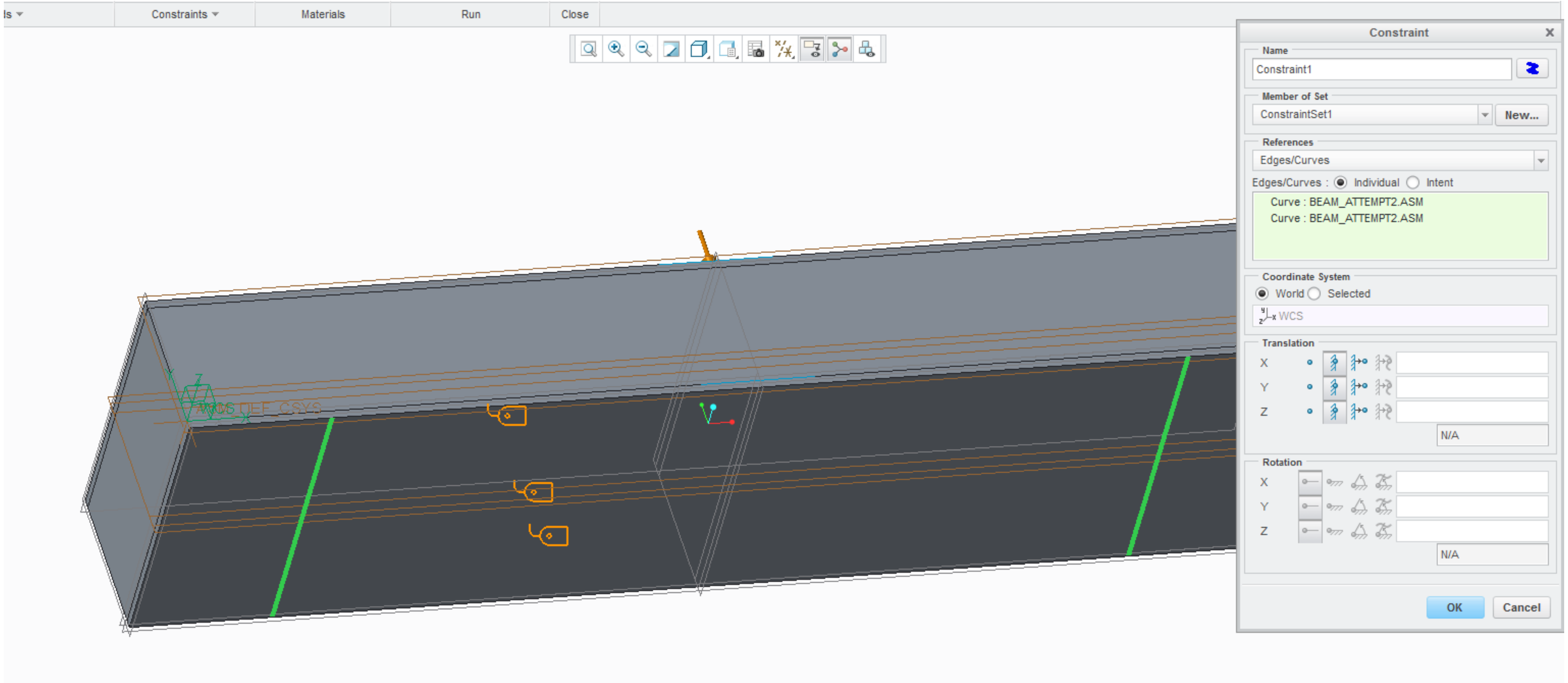


Figure 55 - FEA test beam restraints

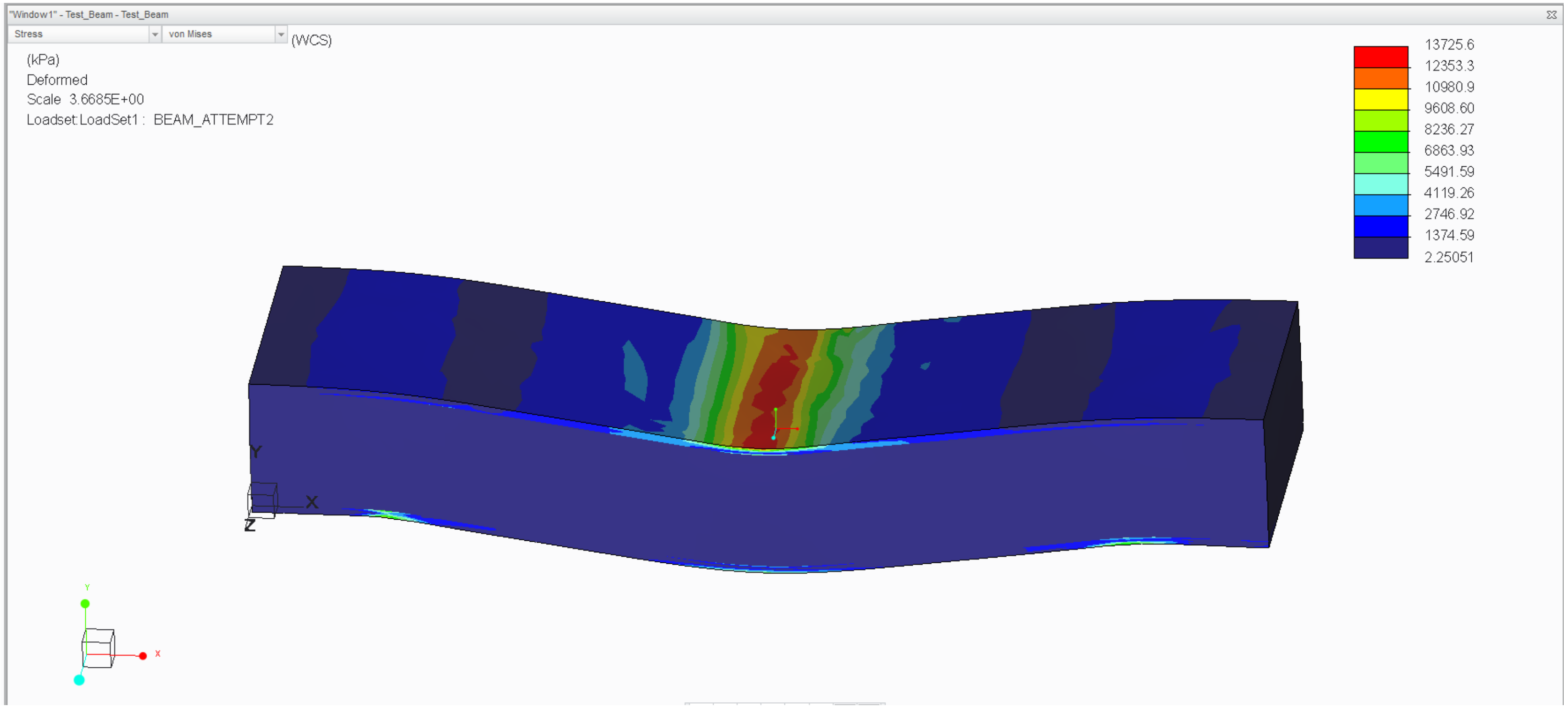


Figure 56 - FEA test beam stress top

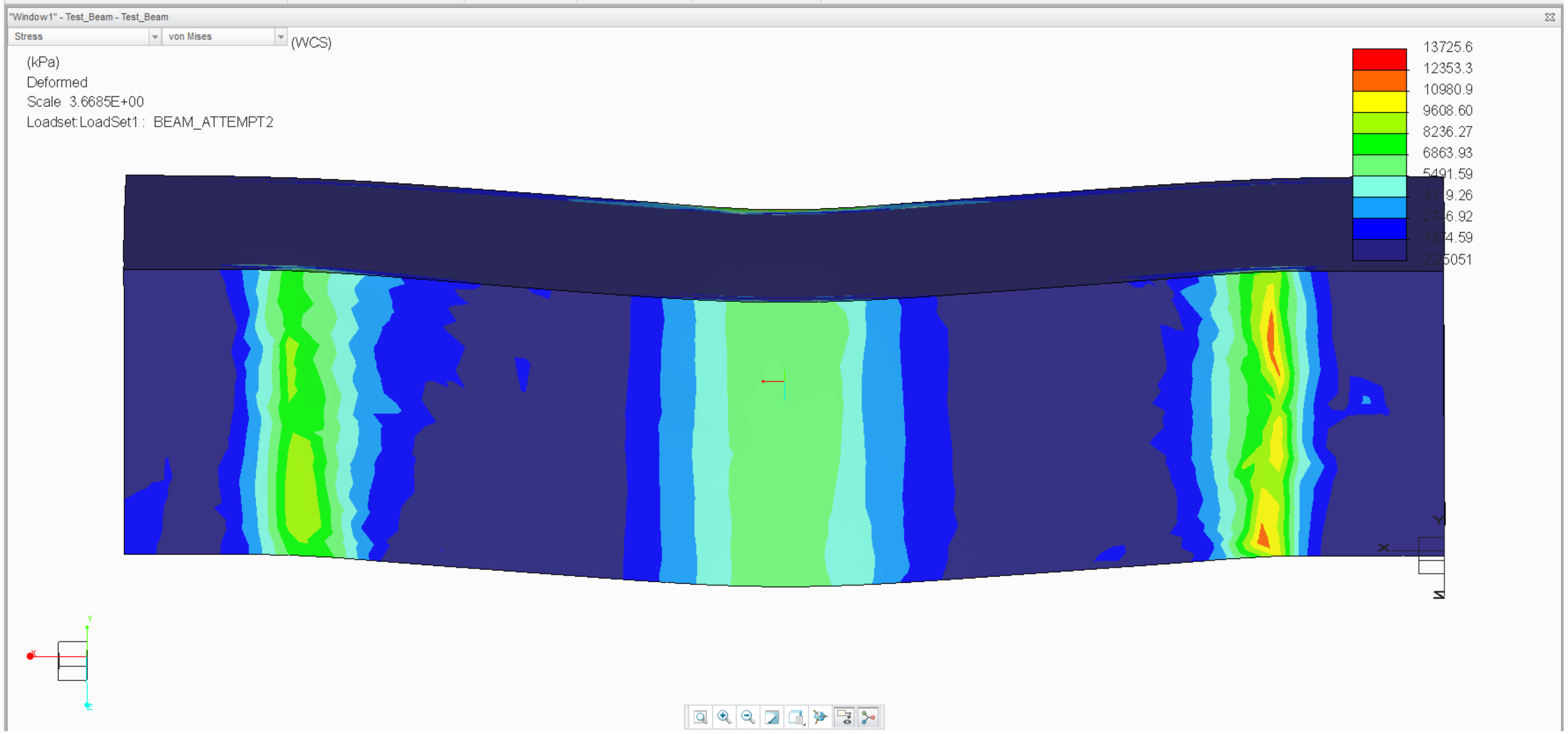


Figure 57 - FEA test beam stress bottom

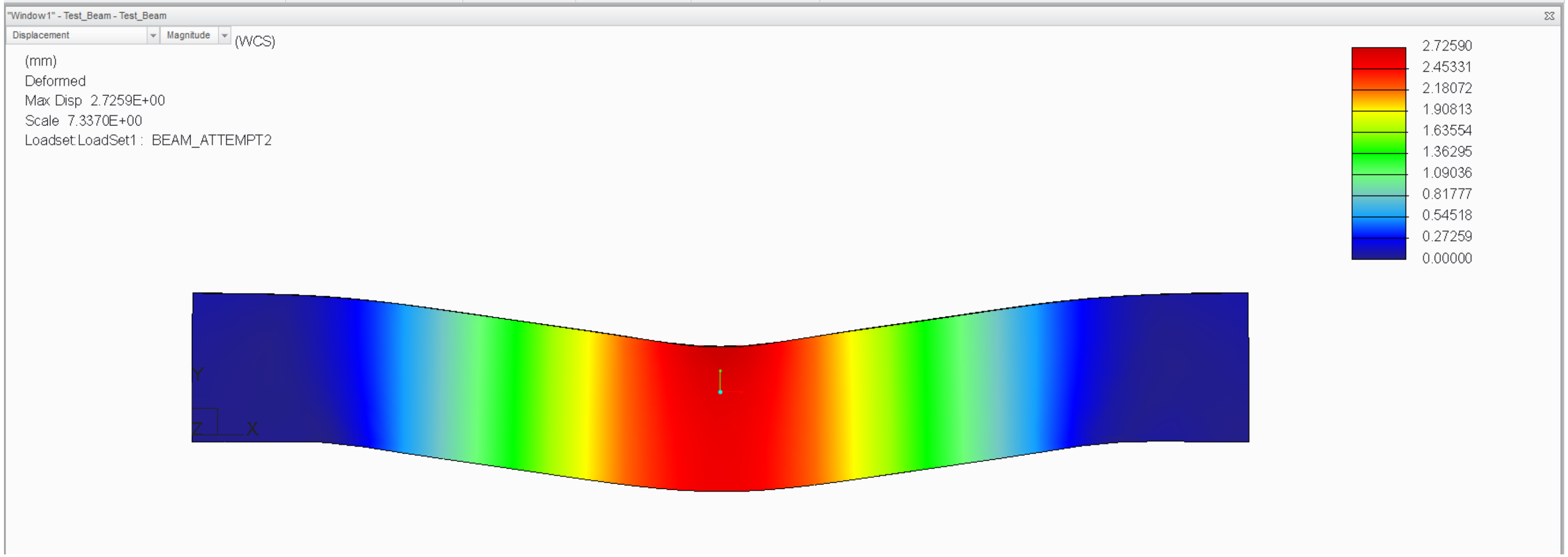


Figure 58 - FEA test beam 500N deflection

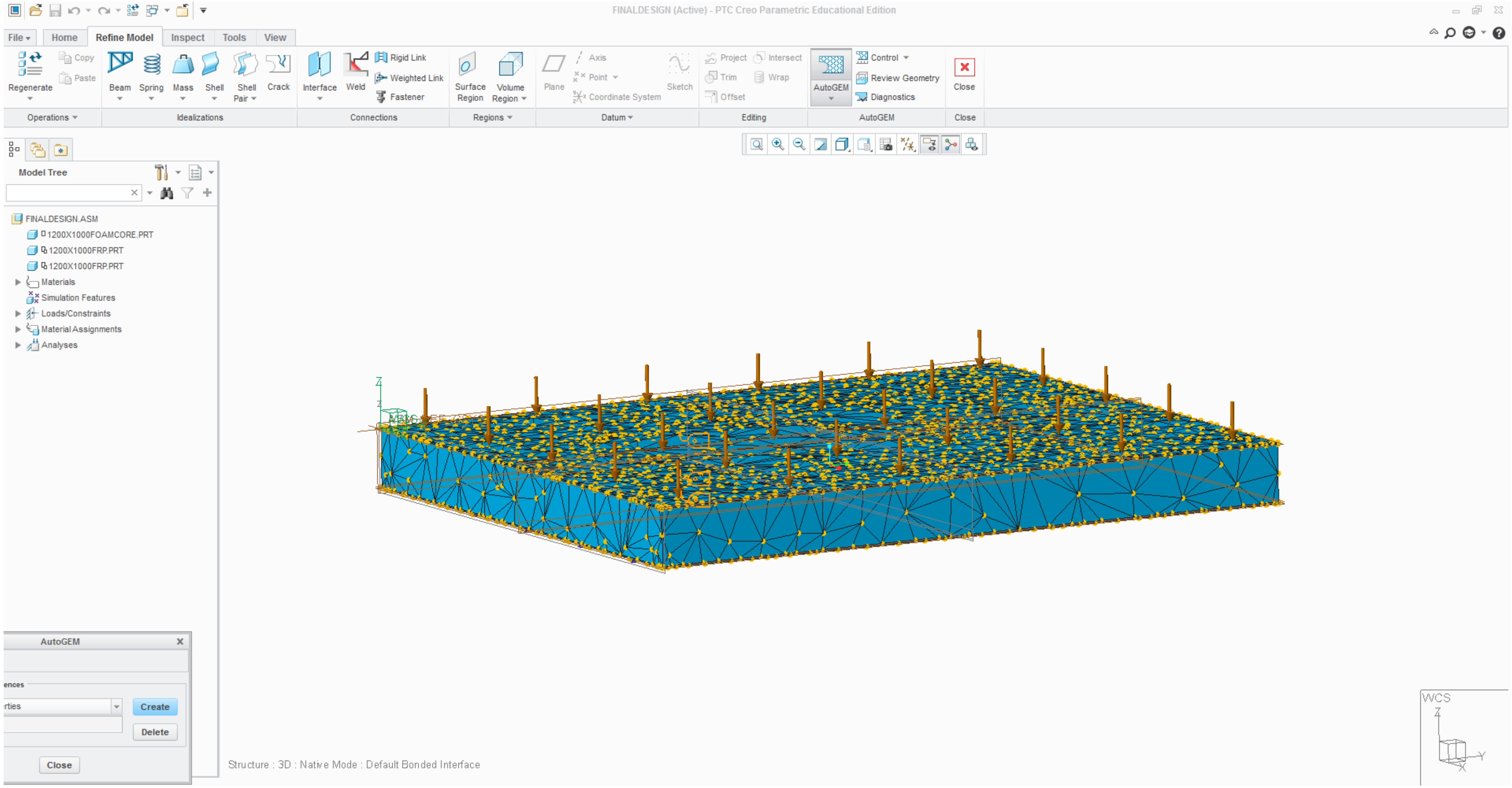


Figure 59 - FEA panel mesh geometry