University of Southern Queensland
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Sandwich Panels for Slab Applications

A dissertation submitted by

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ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

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Abstract

This dissertation is a study on sandwich panels for slab applications looking at expanded polystyrene core sandwich panels with various materials for the face. The aim is to determine the optimum thickness for strength and serviceability of a number of sandwich panels. Finite element analysis using Strand7 and the construction and testing of physical samples were carried out to verify the accuracy of a numerical study.

Four panels were constructed using plywood, oriented strand board, aluminium and steel as the face material and were tested in a SANS material testing machine which measured applied loading and mid-span deflection. These same panels were modelled using finite element analysis in the Strand7 software package under the same conditions as the laboratory tests. The results were compared and found to be in good agreement between them which confirmed the validity of the computer model. Further study was undertaken using Strand7 to model the same panels with the application of domestic floor loading as per AS1170.

Three formulas to calculate the optimum core thickness with respect to the panel failure mode were tested however were found to be unsuitable for the loading arrangement of a uniformly distributed load and a concentrated load. An iterative approach to determining the optimum core thickness was then used. Modelling various thicknesses of the same span panel allowed the optimum core thickness to be determined for that span that would allow the panel to only deflect a maximum of Span/400 or 10 mm. This process was repeated until a span/thickness curve was created that allows the optimum thickness core to be read from the chart for panel spans up to 6 metres.

This research project shows that sandwich panel can be used for slab applications under domestic floor loading. The validity of the Strand7 model has been shown be comparing physical test results to the computer model. By developing span/thickness charts to optimise the core thickness of the panels allows a panel system to be manufactured that will minimise weight and cost while still satisfying strength and serviceability requirements.

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Nomenclature

b	Panel breadth (mm)
E	Modulus of Elasticity (MPa)
E_c	Modulus of elasticity of the core material (MPa)
E_f	Modulus of elasticity of the face material (MPa)
G	Shear modulus (MPa)
G_c	Shear modulus of the core material (MPa)
kg	Kilogram
kPa	Kilopascal
L	Panel length (mm)
q	Imposed load (kPa)
P	Failure load (kN)
t_c	Core thickness (mm)
t_f	Face thickness (mm)
Δ	Limiting deflection – Span/400 (mm)
ν	Poisson’s ratio
ρ	Material density (kg/m^3)
σ_f	Compressive strength of the face material (MPa)
τ_c	Core shear stress (MPa)
ψ_L	Long-term reduction factor

Glossary

2P	2-Part Epoxy Resin
AD	Aquadhere Durabond
ASTM	American Society of Testing and Materials
BFC	Bamboo Fibre Composite
CA	Parfix Maxi Nails Construction Adhesive
EPS	Expanded Polystyrene
FEA	Finite Element Analysis
FPRC	Fibre Reinforced Polymer Composite
GFRP	Glass Fibre Reinforced Plastic
NFRC	Natural Fibre Reinforced Composite
OSB	Oriented Strand Board
PPE	Personal Protective Equipment
SB	SikaBond Techgrip
SIP	Structural Insulated Panel
UPE	Unsaturated Polyester Resin
USQ	University of Southern Queensland

1 Introduction

1.1 Background Information

Sandwich panels are comprised of two thin, stiff face sheets separated by a core of low density material which is typically less stiff and strong as the face sheets (Figure 1.1). This low density core is to provide adequate stiffness in a direction normal to the faces of the panel. The face sheets are generally bonded to the core with adhesives to obtain a load transfer between the components and the result is a panel which has greater bending stiffness than a solid panel of the face material of same weight.

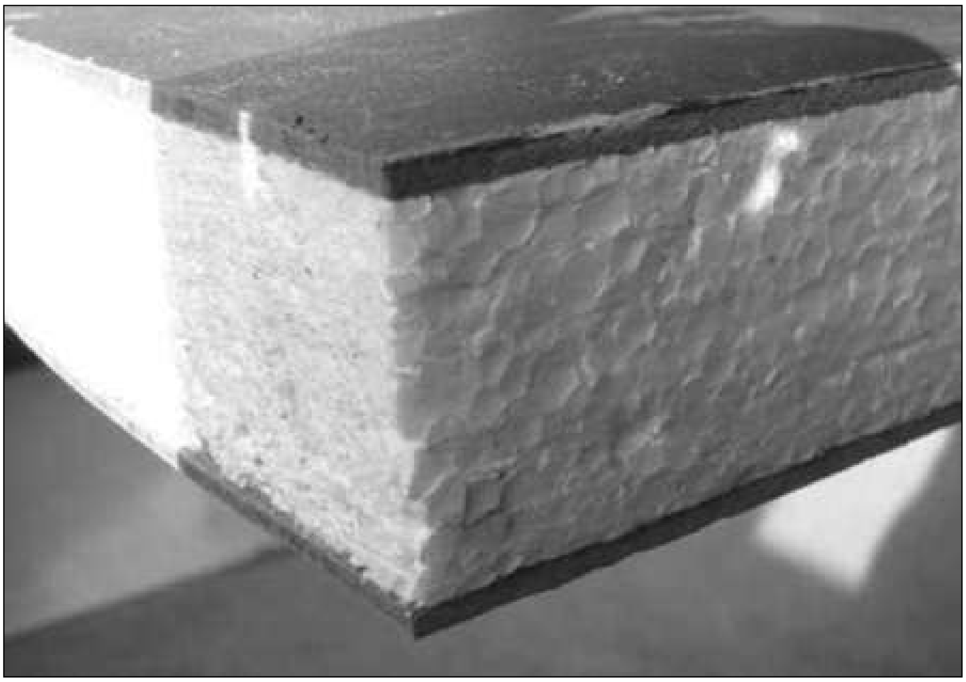


Figure 1.1: A sandwich panel with EPS core and hardboard face (Mills 2007)

Various lightweight materials can be used for the face including but not limited to:

- glass reinforced plastics
- plywood
- glass reinforced cement
- plasterboard
- sheet metal
- hardboard
- resin-impregnated paper.

Likewise, there are many options for the core of the sandwich and these can include:

- metallic honeycomb
- non-metallic honeycomb e.g. paper
- corrugated “truss” structures
- chipboard
- balsa
- expanded polystyrene (EPS)
- foamed glass
- foamed metal
- lightweight concrete e.g. Hebel
- clay.

As development of sandwich panels continues, researchers are always trying to utilise new materials for faces and cores. Research of late has identified the potential use of fibre composites as face materials and aluminium foam as a core material.

These panels are extremely versatile. Originally mass produced in the 1940’s for the aerospace industry, since then the benefits of sandwich panels has been widely recognised. They are now used in ship building, automotive and construction among other industries and it is their use in construction on which this report will focus.

Sandwich panels have many applications in the construction industry; including insulative wall cladding, as evidenced in the construction of refrigerated cold stores, structural wall panels, structural and insulative roof panels and as floor/slab panels. It is for refrigerated cold storage that sandwich panels have seen the most use in Australia, but they are becoming increasingly popular as low cost roof structures for outdoor areas e.g. the Solarspan brand of roof panels.

As a construction material, sandwich panels offer a high load bearing capacity for low weight. They are also able to be mass produced to pre-cut lengths which can create cost savings in manufacture. The weight of the panels as well as the uniform, pre-cut panels allows for rapid erection of structures which creates cost savings in labour and also in expensive lifting equipment. Typically, the panels are manufactured with surface finishes already applied so this saves time and money onsite by not requiring the employment of trades to apply the finishes to the structure.

The panels provide a durable thermal and acoustic insulation and create water and vapour barriers as well as being air-tight. Due to their mass produced nature the panels can be easily replaced if damaged and have a long operative life at low maintenance.

1.2 Project Aim and Objectives

Typically sandwich panels in Australia have been used for small span roof panels or cold storage rooms and little else. As a construction material sandwich panels remain underutilised and the many uses of these panels have the potential to be vastly exploited, particularly if the materials used are cheap and widely available

This project examines sandwich panels being applied for use as slabs. The aim is to determine the optimum thickness for strength and serviceability of a number of sandwich panels. Finite element analysis using Strand7 and the construction and testing of physical samples will be carried out to verify the accuracy of a numerical study.

The specific objectives to which the project's success will be measured are as follows:

- Research various types of sandwich panels to establish a number of different parameters involved in making different types of sandwich panel.
- Select four skin materials from available resources, construct these panels and test them for structural behaviour.
- Perform a Finite Element Analysis (FEA) on these panels in Strand7.
- Compare experimental results to the FEA in order to validate the Strand7 model.
- Carry out a FEA to determine the optimum core thickness for each skin material for a range of spans.
- Make recommendations on the use of these panels in actual slab applications based on weight, cost and structural performance.
- Suggest using these panels in developing countries and make recommendations for further research.

1.3 Dissertation Overview

This research project consists of eight chapters. Chapter 1 is the introductory chapter providing background information on what sandwich panels are and their uses, and describes the projects aims and objectives. Chapter 2 provides an in depth literature review on sandwich panels. A more in depth description on sandwich panels is provided and the sandwich effect, the function of sandwich panels is discussed, along with the methods of failure and previous studies. Finally, this chapter discusses natural fibre composites, their use as construction materials and studies that have been undertaken using these materials.

Chapter 3 focuses on the methodology of the project, describing how sandwich panels as slabs will be analysed. The face and core materials and their properties are presented as are the adhesives used to construct the sample panels. In Chapter 4 the procedure involved in constructing and testing the adhesives and test panels and the results of the laboratory test are presented as load/deflection curves. Chapter 5 uses finite element analysis to verify the results of the laboratory test. Computer models are generated using the Strand7 software package with the idea that the computer model will mimic the results of the laboratory tests. If this is achieved then Strand7 can be used to model sandwich panels under floor loading.

Chapter 6 sees Strand7 used to model the behaviour of sandwich panel slabs. Domestic floor loading is applied to sandwich panels of different spans and thicknesses in order to create thickness tables from which the core thickness for a given span can be determined. Chapter 7 investigates the practicality of sandwich panels as slabs first by comparing the cost of a sandwich panel floor to that of a conventionally framed timber floor. The potential construction uses for the panels are discussed as are any potential problems that could arise from the manufacture and use of panels as a floor structure. Finally, Chapter 8 rounds out this research project. Achievement of the original objectives is examined followed by some conclusions and recommendations for further research.

2 Literature Review

2.1 Introduction

Sandwich panels can be likened to a traditional sandwich; the bread represents the high performing material on the outside and the filling is replaced by the low density material. In more technical terms a sandwich panel comprises two thin stiff and strong sheets of dense material separated by a layer of low density material which may be much less stiff and strong (Allen 1969). The faces are adhesively bonded to the core to obtain a load transfer between components. The advantages of two co-operating faces separated by a distance are believed to have been discussed as early as 1820 by Frenchmen, Duleau and then Fairbaim (Zenkert 1995).

Zenkert (1995) describes panels with asbestos faces and fibreboard cores being used during World War One and prior to World War Two where some use was made of sandwiches in small planes. During the Second World War the De Havilland Mosquito aircraft became the first major structural application of sandwich panels using a veneer face and balsa core. The first theoretical works in sandwich panels were published in the late 40’s which led to significant research into the development of core materials.

Sandwich construction played a major role in the landing of a spaceship on the moon as only with sandwich construction could the shell of the aircraft be light in weight and strong enough to sustain the stresses of acceleration and landing. The Apollo space capsule had two interconnected sandwich shells, the outer shell comprising two thin steel facings and a honeycomb core. Prior to 1960 sandwich technology had been confined almost entirely to the aerospace industry although alternative uses were being developed, particularly as a construction material (Davies 2001).

The use of sandwich panels as a civil construction material has often been overlooked in favour of more traditional materials such as concrete and steel. This is due to cost and availability issues. The current economic climate and the impact rising prices has on traditional materials, teamed with a shortage of natural resources has forced attention onto sandwich panels as a construction material, in particular as wall cladding, structural wall, roof and floor panels and in refrigerated cold storage (Wrzecioniarz 1983). Sandwich panels provide high load bearing capacity at low weight, excellent and durable thermal insulation, create water and vapour barriers, have the capacity for rapid erection, are easy to repair or replace if damaged and provide long life at low maintenance (Davies 2001).

2.2 The Sandwich Effect

The individual components of the sandwich panel work together to create a finished product that is stronger and performs better than its individual components. Zenkert (1995) and Hohan et.al. (2010) liken this sandwich effect to that of an I-beam. In sandwich construction the faces act as the flanges and the core acts as the web of the I-beam (Figure 2.1). A notable difference between sandwich construction and I-beams lies in the core of a sandwich as it is comprised of a different material from the faces and is spread out as a continuous support for the faces rather than concentrated in the narrow web.

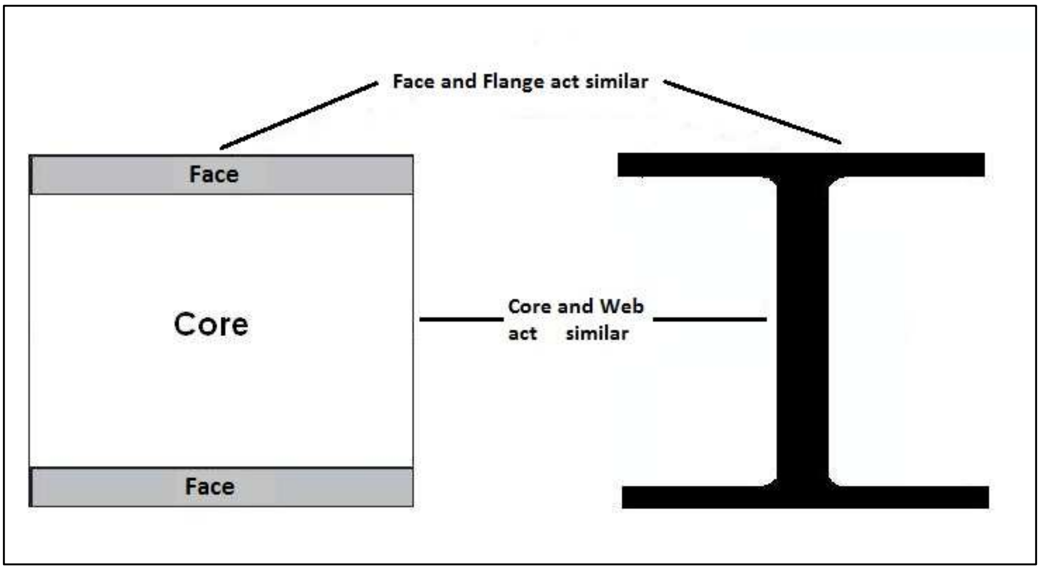


Figure 2.1: Sandwich Panels and I-Beams

Konsta-Gdoutos (2005) states that the faces carry most of the bending and in-plane stress and the core helps stabilise the facings and carry the shear stresses. By separating the faces with a low density core, the moment of inertia is increased resulting in an improved bending stiffness.

Allen (1969), in his widely recognised and cited book on sandwich panels, describes conditions to ensure the panel functions as required. The core must be stiff enough to ensure the faces remain the correct distance apart, they must be stiff enough in shear that the faces do not slide over each other in bending and the core must be stiff enough to keep the faces nearly flat otherwise they may wrinkle under in-plane compression. When constructing the panel the adhesive used should not be flexible enough to allow substantial relative movement of the face and core.

2.3 Methods of Failure

Sandwich panels can fail in a number of ways and an understanding of, and the ability to be able to predict which method of failure will occur is essential in sandwich panel analysis. Mills (2007), Davies (2001) and Konsta-Gdoutos (2005) describe the failure methods as core shear failure, core cracking, debonding, slippage, wrinkling, tensile yield and indentation.

Core shear failure can occur when core shear yield spreads along the beam from the central loading point to the outer loading skins, causing the skins to shear relative to each other, creating the likelihood of collapse. Figure 2.2 shows a panel that has failed via core shear

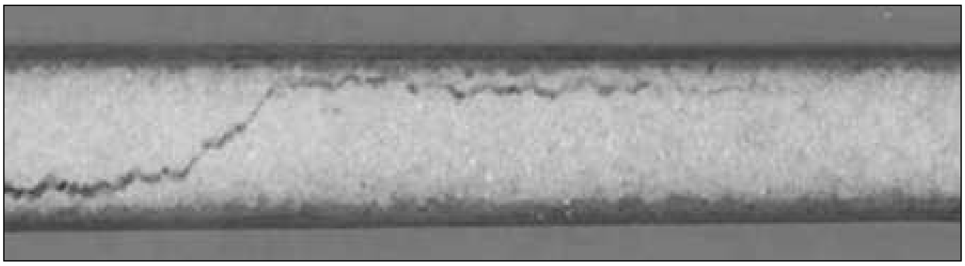


Figure 2.2: Core Shear Failure (Kim et al. 2001)

The failure load under core shear is found using:

$$P = 2t_c \tau_c b \tag{1}$$

where P is the failure load in kN, t_c is the core thickness, τ_c is the core shear stress and b is the breadth of the panel.

Failure via core cracking occurs when cracks propagate through the core parallel to the skin. This can cause delamination of the skins form the core whereas debonding is a failure of the adhesive at the core/skin interface. Slippage occurs when one face slips relative to the other. Wrinkling occurs when the upper face of the panel wrinkles or buckles due to compression, as shown in Figure 2.3. Failure load under face wrinkling is calculated using:

$$P = \frac{2t_f t_c}{L} \sqrt[3]{E_f E_c G_c}\, b \tag{2}$$

where t_f is the thickness of the face, L is the length of the panel E_f and E_c is the modulus of elasticity for the face and core respectively and G_c is the shear modulus of the core.

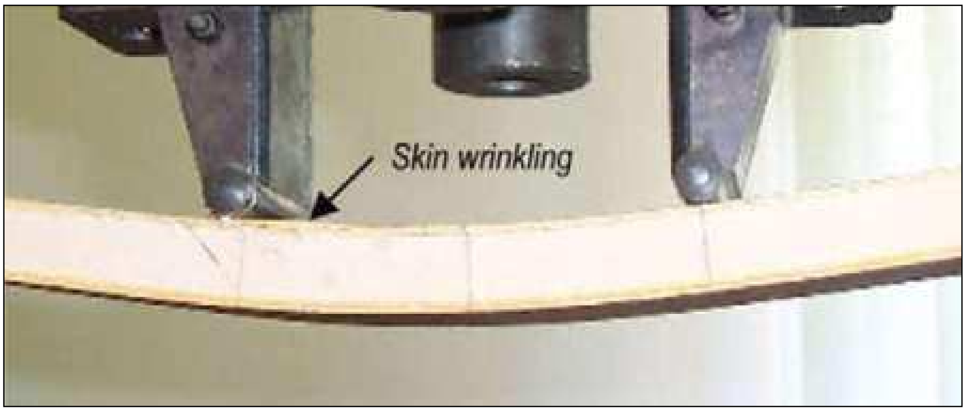


Figure 2.3: Face Wrinkling Under Four Point Bending (Manalo et al. 2010)

Tensile yield or fracture occurs when the lower face is too thin or inadequate that the material fails in tension. This failure method can be a problem when using thin sheet metals for the face of the panels. Indentation failure, as the name suggests, is an indentation of the face and core under localised loading and can occur when the panel is sufficiently stiff enough to resist bending and the localised load pushes into the panel, as shown in Figure 2.4. The failure load under indentation is calculated using:

$$P = \sqrt{\frac{16E_f E_c t_f^3 t_c}{3L^2}} \tag{3}$$

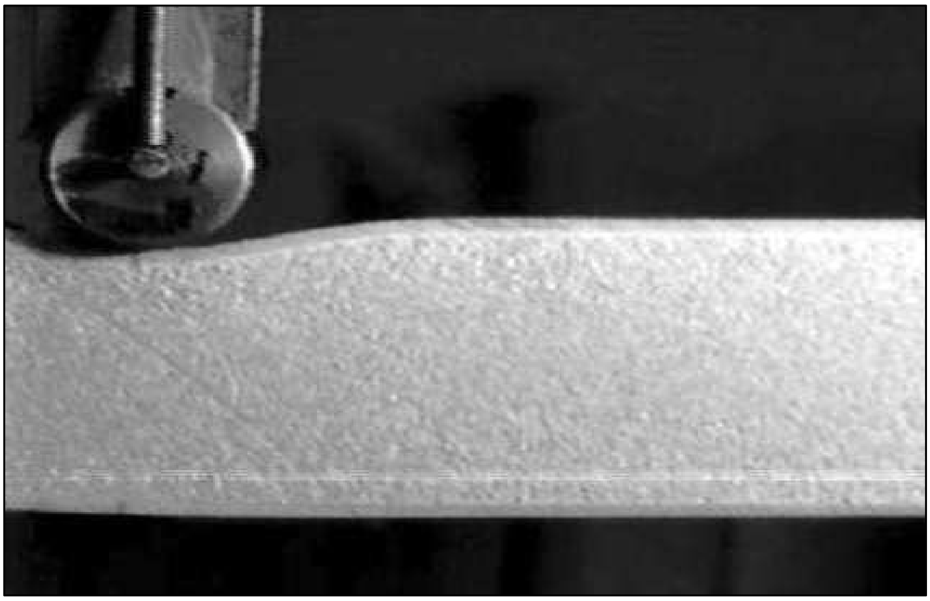


Figure 2.4: Panel Failing due to Indentation (Steeves et al. 2004)

2.4 Analytical and experimental studies

A good deal of research has been carried out on sandwich panels examining their behaviour under different types of loading, dimensions and material properties. Of particular interest has been the use of aluminium cores and faces; and how these panels perform under load.

Mohan et al. (2005) used analytical formulae to estimate the failure loads of a number of samples comprising aluminium core and skin and found the failure modes to be core shear, indentation and face sheet cracking. Samples were constructed and tested under four point bending in order to compare the analytical results to actual results. The results found good agreement between analytical and experimental for cracking and indentation; however the core shear results deviated from the analytical by around 20%. A study by McCormack et al. (2001) using sandwich beams with metallic foam cores and aluminium skins also compared analytical results to experimental testing on samples with varying thicknesses of skin and core.

The effects of the core thickness on the flexural behaviour of aluminium foam structures were examined by Styles et al. (2007). Three thickness of aluminium foam core were used with a thermo plastic composite face and tested under four point bending. Results found that each structure failed by a different mechanism depending on the thickness of the core; 5 mm core failed by skin wrinkling, 10 mm core failed in compression with skin wrinkling and the 20 mm failed due to indentation. It follows that a thicker sample would fail by indentation as the thicker core provides greater stiffness and resistance to bending. Similar results to Styles et al. were found by Chen et al. (2001). This study used an aluminium face and core with varying face and core thickness and found that indentation was the dominant failure mechanism in the thicker cores.

Pollien et al. (2005) performed a study using aluminium skins and layers of graded porous aluminium foam to form the core. Sandwich beam theory was used to predict deflection under load in three point bending and samples were constructed to test these analytical results. Differences between the calculated deflection and measured deflection were found to be least for samples with the densest core, with measured results being between 2 and 20% less than calculated.

A different approach to sandwich panels was taken by Mamalis et al. (2008) which studied the effects of using a thin inner layer of either glass fibre or plywood between the metal face and PVC core (see Figure 2.5). It was found that this inner layer being stiffer than the core allows for the use of thinner face sheets and cheaper, less robust, cores. This approach not only saves money on material, it reduces the overall weight of the panels and improves structural performance and rigidity when compared to similar panels without the inner layer.

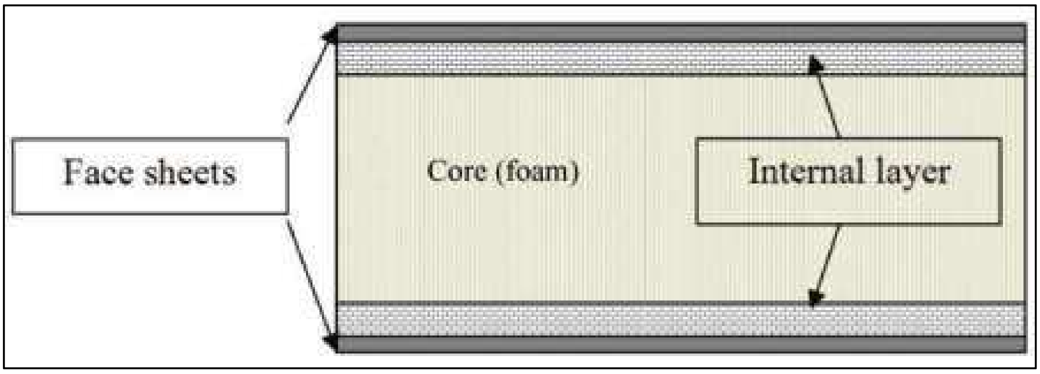


Figure 2.5: Sandwich Panel with Inner Layer (Mamalis et al. 2008)

There has been much work done on the use of plastic foam cores and fibre composite cores and their performance under load. Kim et al. (2001) constructed samples using a high density polyurethane core of varying density and thickness with a Carbon/Epoxy face of four ply laminate. Three point bending tests were conducted and the results for core shear compared to that of the plastic manufacturer, with mixed results. The maximum core shear stress supplied by the manufacturer is within 5% for the two thinnest core samples however the difference between the expected and experimental results for the thickest core was around 25%. This suggests caution should be used when relying on manufacturers figures and that it may be prudent to conduct in-house testing on materials to ascertain its properties.

In this same vein Steeves et al. (2004) examines the behaviour of sandwich beams with a glass fibre-epoxy skin and a closed cell PVC core with relative densities of 2.6%, 6.6% and 13.3%. Six specimens were constructed for each density of foam, with varying skin thickness and length, and the predicted failure modes and loads were calculated as either chore shear, face yield, wrinkling or indentation. Tests were carried out under three point bending and in all instances where core shear was the predicted mode of failure, failure occurred by this method. One of the main conclusions proposed by this study, and may prove useful in future research, is the existence of a critical length were the failure mode changes from core shear to indentation.

Konsta-Gdoutos (2005) also finds the presence of a critical beam span where failure method changes from core shear to face wrinkling. In a numerical study examining beams with foam cores, rectangular cross sections of sandwich beams with faces of equal thickness were subjected to bending and shear, with the bending taken up by the face and the shear stress mainly taken up by the core. The study compared the ratio of face strength in compression and core shear strength (F_f / F_{cs}) to beam length and face thickness (L / h_f). As shown in Figure 2.6 if these variables are known then the failure mode can be predicted. Whilst this is a useful tool for predicting failure modes it should not replace constructing and testing actual samples.

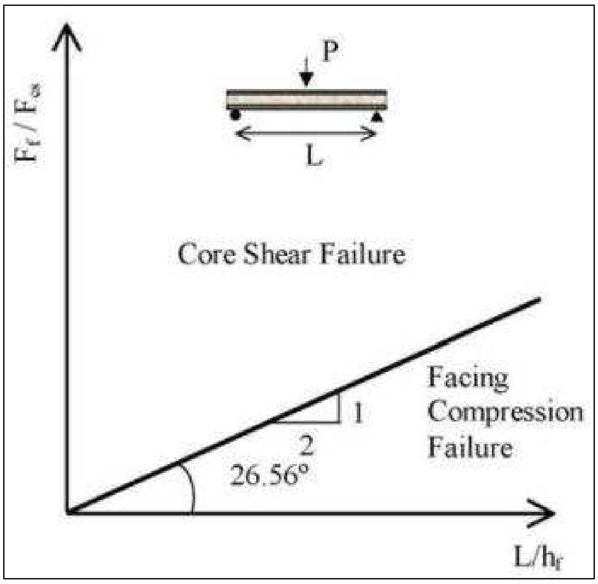


Figure 2.6: Predicting Failure Mode (Konsta-Gdoutos 2005)

An interesting study by Manalo et al. (2010) utilised sandwich beams with phenolic cores and glass fibre composite skins in a flatwise and edgewise position. Beams were constructed in two spans, 300 and 400 mm, and two depths, 18 and 20 mm. The failure modes were predicted numerically and the samples tested under four point bending with results finding the predicted failure load for core shear 25-40% higher than the actual and predicted failure load due to tensile failure 5% lower than the actual. These results are reassuring as they show the beams function as good as and better than what was expected. This provides some comfort when designing a sandwich member knowing it will function as intended.

Islam et al. (2010) conducted a study using glass polymer reinforced fibre skins with a modified phenolic core being used as floor slabs. They studied the behaviour of these panels with reference to the main fibre orientation in order to determine the effect of erroneous orientation during installation. Two and four point edge systems with different fibre orientations and fixity were tested under point and uniformly distributed loads. The panels were found to behave similarly under both load conditions and that fixity does not have a major effect on failure mode and deflection.

Structural Insulated Panels (SIP) are becoming a popular construction material in the northern hemisphere comprising a sandwich of a thick polystyrene core and an Oriented Strand Board (OSB) skin. SIP are primarily used in roofs and walls and offer structure, sheathing, insulation and air tightness (Hairstans et al. 2007). OSB is European made flat hardboard comprising three layers of oriented distributed strands or micro veneers (Figure 2.7). The strands are plantation softwoods, thus renewable, and are glued together to make boards ranging from 6 to 25 mm (Egger 2012). OSB has begun to penetrate into the Australian construction market however the use of SIP continues to be more common in the Northern Hemisphere

Figure 2.7: Oriented Strand Board (Egger 2012)

Kermani et al. (2006) tested the suitability of SIP under axial loads and bending to the point of failure. Their study found that panels with stiffeners performed better than unstiffened, as would be expected. It was concluded by this study that the panels behave effectively as a composite material and the polystyrene was effective in transferring shear forces and providing stiffness and strength to sustain the applied loads. Kermani et al. (2006) undertook a similar study on SIP, this time taking into consideration the structural performance under racking loads as well as bending and axial loads. This study was mostly interested in the possibility of replacing timber framed bracing walls in housing with SIP however it does provide good insight into the types of panel that can be made with new materials.

The use of SIP as roof panels was investigated by del Coz Diaz et al. (2008). One side of the panel consisted of OSB and the other side a waterproof agglomerate which formed the finished external face of the roof. Two span continuous panels with foam cores of both 40mm and 80 mm were tested to determine failure load, failure mode and defection/load graphs. Finite Element Analysis (FEA) was used to simulate bending and good agreement was found between FEA and actual test results. These results further show the practicality and value of sandwich panels as construction materials.

2.5 Natural Fibre Composites

Fibre reinforced polymer composites (FPRC) made with synthetic fibres such as carbon and glass provide high strength to weight ratio and chemical inertness when compared to conventional construction materials i.e. wood, concrete and steel. Despite these benefits they have seen limited use due to their higher cost, non-efficient structural forms and adverse environmental impact.

Recently, natural fibre reinforced composites (NFRC) have emerged as an environmentally friendly and cost effective alternative. Bamboo in particular has been studied as it has the highest mechanical strength and lowest density of the natural fibres. While possessing inferior mechanical properties to glass fibres, it is up to ten times cheaper and is the fastest growing, highest yielding, natural construction material (Huda et al. 2012).

Burgueno et al. (2004) undertook a study looking at beams and plates made from industrial hemp and flax fibres impregnated in unsaturated polyester (UPE) resin and compared their performance to chopped E-glass fibre and UPE composites. Beam samples were manufactured to 24.5 x 24.5 x 508 mm long and square plates were made 304.8 mm by 12.7 mm thick. Both of the samples had 9.5 mm diameter strands of fibre running laterally through them (Figure 2.8).

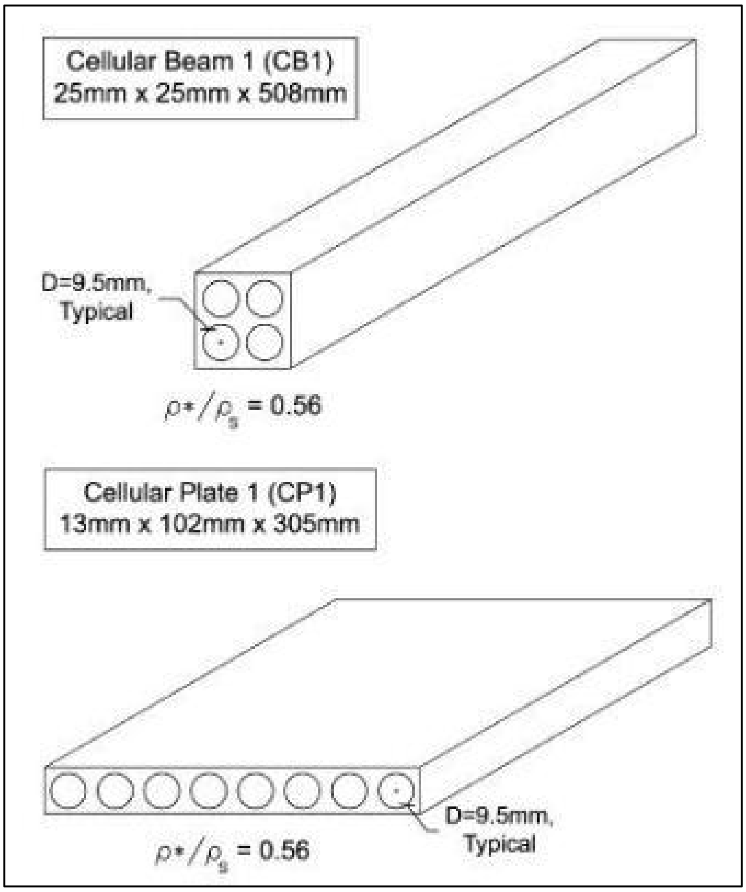


Figure 2.8: Natural Fibres in Beams and Plates (Burgueno et al. 2004)

Beams were tested in four point bending and the plates were tested in three point bending in order to determine modulus of elasticity, and tensile strength. Thermal expansion and moisture absorption were also tested. The results showed that depending on the composition NFRC can outperform traditional FRPC and there is the potential for use as primary loadbearing components. The study also found that in deflection tests the NFRC panels performed just as well as two commercially available E-glass/UPE sandwich panel systems.

Glass fibre reinforced plastics (GFRP) have been widely used in industry however they are not environmentally friendly to produce and difficult to recycle. The result has seen a move towards bamboo based polymer composites, or bamboo fibre composites (BFC), with the benefits being the bamboo is an abundant natural resources in Asia and South America and only needs several months to maturity.

Fujii et al. (2003) studied BFC by constructing 150 x 150 x 2 mm plates of bamboo fibres set in polypropylene. Strips were cut from these plates and tested in tension, with the results compared to the typical mechanical properties of GFRP. The results showed a significantly lower tensile strength, about 80%, and a Young's modulus approximately 50% lower than GFRP. The density of the BFC was much less than the GFRP. These results are promising as they show the potential for the use of bamboo in composite materials. If the density of the BFC was increased, this may lead to an increase in mechanical properties while still realising the renewable benefits of using bamboo.

Huda et al. (2012) also studied BFC in order to determine the ideal concentration of bamboo in the composite material. Webs of bamboo strips and polypropylene were made into thin sheets and then pressed together in varying orientations to make 3.2 mm thick sheets (Figure 2.9).

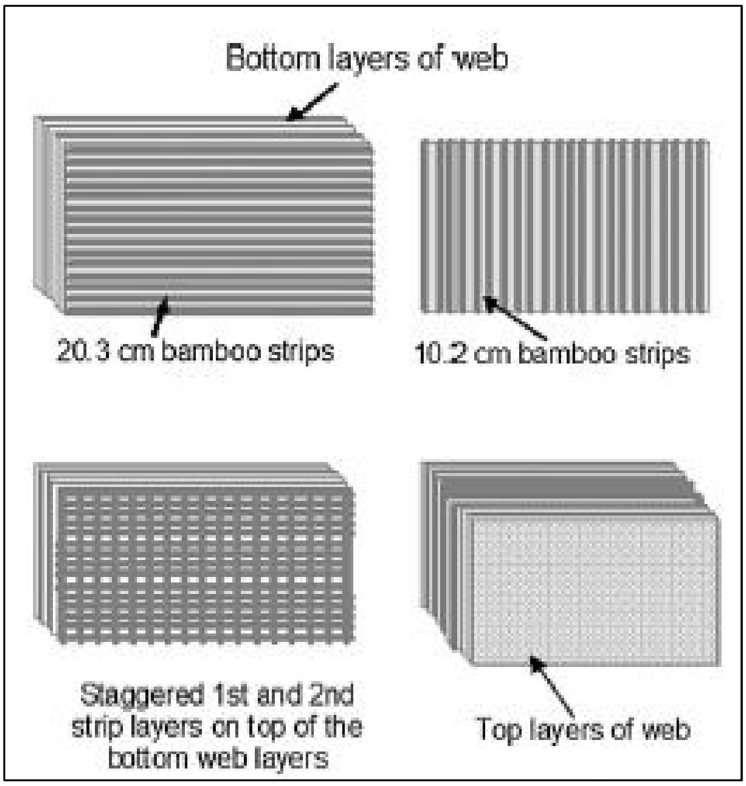


Figure 2.9: Oriented Strands of Bamboo to make 3.2mm Sheets (Huda et al. 2012)

The sheets were made with four different concentrations of bamboo, 40, 50, 60 and 70%, and samples were tested in three point bending to 100 N in order to determine the flexural strength, modulus of elasticity and yield load. Results showed that the 50 and 60% concentrations performed the best, with the 50% concentration outperforming 60% in flexural strength and yield load while the 60% concentration had a superior elasticity modulus. A chart comparing the test results is shown below in Figure 2.10.

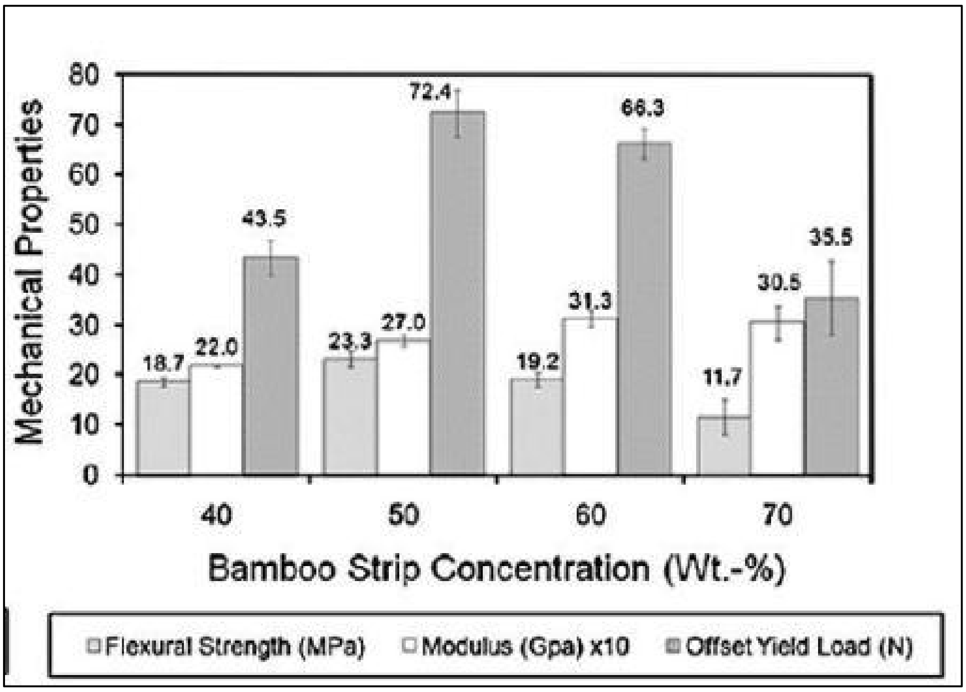


Figure 2.10: Strength Properties for Four Concentrations of Bamboo Fibres (Huda et al. 2012)

Ashheim et al. (2010) examined the use of bamboo in making an engineered timber I-joist similar to the joists commonly used in residential construction. The flanges of the I-joists were constructed out of a solid single strand of bamboo in two laminations while the web of the I-joist was either three-ply bamboo plywood or OSB. In order to achieve the long lengths required, the flanges were finger jointed together. Figure 2.11 shows the dimensions of the joist and one of the manufactured joists.

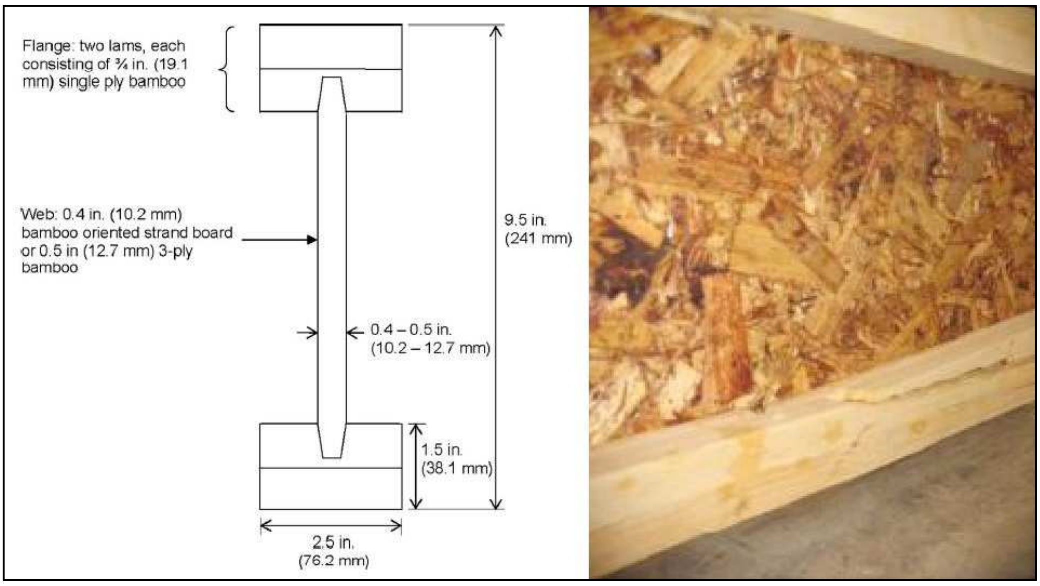


Figure 2.11: Bamboo I-joist (Ashheim et al. 2010)

Tests were carried out on the web material in order to determine the elasticity modulus and shear modulus. Results gave an elasticity modulus of 14 GPa for both the OSB and ply webbed joist which is on par with the plywood used in this study (16 GPa) and considerably higher than that for regular OSB (5 GPa). Shear modulus for the bamboo OSB was 1.7 GPa, higher than the 1.08 GPa for regular OSB. For bamboo plywood shear modulus was 0.94 GPa compared to 0.62 GPa for regular plywood. These results indicate that materials can be made using the plentiful, renewable bamboo that are as good as, if not better than, common construction materials.

Traditional polymer composites are typically non-biodegradable and pose environmental problems. Charry et al. (2003) examined the concept of “green composites”, polymer composites that are reinforced with natural fibres which in turn makes them partially degradable at the very least. In this study short bamboo fibres were used to reinforce styrenated polyester composites with varying fibre content and the density, void content, weight reduction, tensile and flexural strength were determined.

Fibres 0.2 mm thick and 10 mm long were randomly mixed throughout a mixture of polyester resin and styrene and made in 80 x 30 x 10 mm samples. Tensile strength increased by 68% when the bamboo ratio was increased from 10 to 40%. Flexural strength increased 75% when bamboo was increased the same. These results are promising and show just another used for the versatile bamboo fibre composite with the potential being to manufacture large sheets of this material to use as sandwich panel faces.

3 Materials and Methodology

3.1 Introduction

To ensure an effective and efficient study it is sound practice to formulate a methodology and to plan how the project will take shape. The first part of this chapter will describe the materials for the sandwich panel faces, core and adhesives while the second part of this chapter will discuss the methodology used to construct, test and analyse the panels. Finally, the formulae used to determine the optimum thickness core will be discussed.

3.2 Material Properties

The respective properties of the face and core materials are discussed below along with the four types of adhesive that were considered to construct the panels.

3.2.1 Face Material

Allen (1969) suggested one way of designing sandwich panels is to choose the thinnest face which can be used and then find the thinnest core which can be used with it. This approach has been adopted for this project as the face materials have been selected based on what is readily available at local suppliers and the thinnest available material. Thus the face materials selected are steel, aluminium, OSB and plywood Figure 3.1. Their relevant properties are shown below in Table 3.1.

Figure 3.1: Face Materials – Steel, Aluminium, OSB and Plywood

Table 3.1: Face Material Properties

Material	**Plywood**	**OSB**	**Aluminium**	**Steel**
Grade	F22	Type 3 EN300	5005 H34	G250
Thickness (mm)	4.5	6	1.2	1.6
Compressive Strength (MPa)	45	15.9	530	250
Modulus of Elasticity (MPa)	16	5	68.9	200
Density (kg/m^3)	620	638	2700	7850
Poisson's Ratio	0.22	0.25	0.334	0.287

All of the properties except the density of plywood were available through Australian Standards, manufacturers or suppliers. The density of plywood varies according to the species of timber used in the laminates and the adhesive used. Samples of plywood from the same batch as used in the sandwich panels were weighed and the density established from this data.

3.2.1.1 Anisotropic Materials

Steel, aluminium and EPS are isotropic materials as their properties are the same in all directions. On the other hand plywood and OSB are classed as anisotropic; its properties are directionally dependent. For example a sheet of plywood and OSB would exhibit different characteristics depending on which axis was being loaded. The major axis of the plywood sheets runs with the grain of the top laminate while OSB typically has the direction of the major axis stamped on the face on the material (Figure 3.2).

Figure 3.2: OSB Major Axis

Structural applications for 4.5 mm plywood and 6 mm OSB in Australia are generally as bracing panels in timber framed construction. These panels are used to resist raking loads on buildings with the sheets being attached to the framing with the major axis in the vertical direction (Figure 3.3). The panels will be constructed with the major axis lengthwise along the panel and as such the plywood and OSB will be treated as isotropic. The material properties of the major axis will be used in calculations.

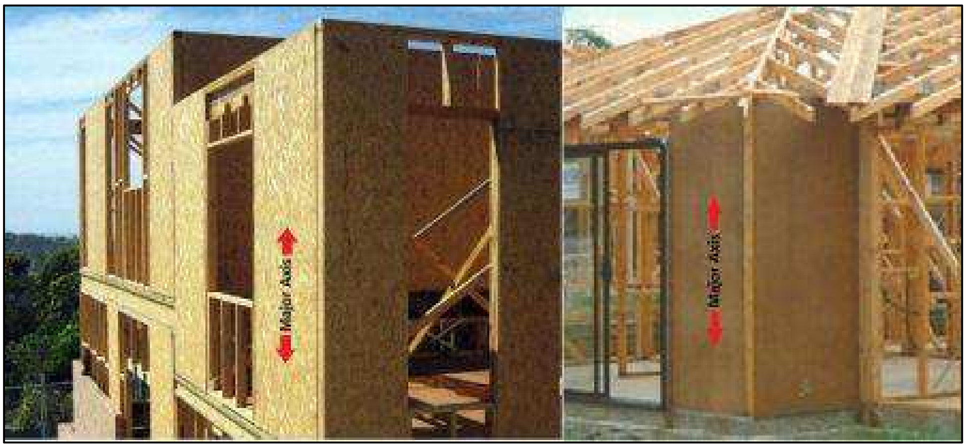


Figure 3.3: OSB and Plywood bracing panels with major axis in vertical direction

3.2.2 Core Material

Expanded polystyrene (EPS) was the core material selected for the test samples and FEA. In addition to this, a test panel was made using layers of a bamboo fibre mat for the core.

3.2.2.1 Expanded Polystyrene

EPS was chosen for the core material because of its good mechanical and thermal insulation properties and the low cost of procuring the materials. EPS is produced by extruding plastic in closed moulds where the plastic is mixed with a blowing agent which then expands at an elevated temperature (Zenkert 1995). AS1366.3 – Rigid Cellular Plastic Sheets provides a range of classifications for EPS, with class H foam being suitable for applications in insulated floors and roofs subjected to constant traffic of people and equipment. Class H foam has a nominal density (ρ) of 24 kg/m^3 and this can be used to determine other structural properties of EPS.

Horvath (1995) proposed formula to estimate the Modulus of Elasticity (E) and Poisson’s ratio (υ) based on the initial linear range of the stress-strain curve and are as follows:

$$E = 0.45\rho - 3 \tag{4}$$

$$v = 0.056\rho + 0.0024 \tag{5}$$

where E is in MPa and ρ is the density of the EPS in kg/m^3.

Modulus of Elasticity and Poisson’s ratio can then be used to calculate Shear Modulus G:

$$G = \frac{E}{2(1+v)} \tag{6}$$

where G is MPa.

This gives the following theoretical properties of EPS shown in Table 3.2.

Table 3.2: Theoretical EPS Core Properties

Grade	Density (kg/m^3)	Modulus of Elasticity (MPa)	Shear Modulus (MPa)	Poisson’s Ratio (ν)
H	24	7.8	3.43	0.137

Rather than rely solely on theoretical properties for the core materials it is prudent to gather additional information on the actual properties of EPS. The American Society for Testing and Materials (ASTM) in their publication C578: Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation provides information on the required properties of EPS.

By ASTM classification Type II foam has a nominal density of 1.5 lb/ft^3 which equates to 24 kg/m^3, the same nominal density of H grade foam. Modulus of Elasticity falls into the range of 320 to 360 psi so taking a conservative value of 320 psi this equates to 2.206 MPa. Shear modulus falls into the range of 460 to 500 psi, again taking a conservative approach, 460 psi equals 3.172 MPa. Poisson’s ratio is calculated using Equation 6 and the actual properties of EPS according to ASTM are shown in Table 3.3.

Table 3.3: ASTM Properties of EPS

Type	Density (lb/ft^3 : kg/m^3)	Modulus of Elasticity (psi : MPa)	Shear Modulus (psi : MPa)	Poisson’s Ratio (ν)
II	1.5 : 24	320 : 2.206	460 : 3.172	-0.65

The shear modulus doesn’t vary greatly between the theoretical properties and the ASTM while the modulus of elasticity according to ASTM is significantly less. Another important thing to note is the negative value for Poisson’s ratio. This unusual phenomenon is discussed further.

3.2.2.1.1 Negative Poisson’s Ratio

Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Generally speaking, when a material stretches in one direction it contracts in the other direction to give a positive Poisson’s ratio, although this is not always the case.

A study by Lakes (1987) found that while normal polymer foams have a positive Poisson’s ratio, re-entrant polymer foams such as EPS have a negative Poisson’s ratio. Atmatzidis et al. (2001) studied EPS foams of varying densities to obtain the Poisson’s ratio values based on triaxial compression tests and the results indeed indicated a negative Poisson’s ratio for EPS. Horvath (1995) proposed the formula in Equation 5 which calculates the Poisson’s ratio from the initial linear range of the stress-strain curve however further study found that this value could in fact be a negative value in the post elastic range of the stress-strain curve (Negussey et al. 1993; Preber et al. 1994).

3.2.2.2 Bamboo Fibre Mat

A panel was made using a bamboo fibre composite material produced by Maat & To Environmental Engineering Co Ltd of Hong Kong. These mats range in thickness from 20 to 50 mm and contain 50% polyester and 50% bamboo fibres. The appearance and the composition of the mat is that of an insulation batt (Figure 3.4) however the bamboo mat appears stiffer and denser than an insulation batt. There were no mechanical properties given for the bamboo material as it is intended for non-structural use.

Figure 3.4: Bamboo Fibre Mat

3.2.3 Adhesives

Four different adhesives were considered from which the sandwich panel adhesive would be selected, namely Aquadhere Durabond, SikaBond Techgrip, Parfix 2-part epoxy resin and Parfix Maxi Nail construction adhesive Figure 3.5.

Figure 3.5: Adhesives

Both the Aquadhere Durabond and the SikaBond Techgrip are polyurethane adhesives that came highly recommended by the EPS supplier due to their high strength and because they do not react with the foam, unlike solvent based adhesives. Parfix 2-part epoxy resin is a typical epoxy adhesive consisting of a tube of epoxide resin and a tube of tertiary amines mixed together in equal proportions. Parfix Maxi Nails is a general purpose construction adhesive that provides a high strength and workability and is safe to use on polystyrene. This type of adhesive is commonly used in the construction industry to glue particleboard flooring to floor joists.

3.3 Project Methodology

This study will look at sandwich panels constructed with various materials for the face and different thicknesses of the same core material. This process will occur in order to find the optimum size panel for slab applications. The first objective is to conduct a background study and literature review into sandwich panels to get a better idea of the science behind how they work and to see what other research has been conducted, particularly in their use as beams/slabs and performance under bending.

To begin with, four samples will be constructed and tested under three point bending on a SANS material testing machine. The four panels will each be constructed using a different face material, these being plywood, oriented strand board (OSB), steel and aluminium, while the core will be 50 mm EPS. Overall the panels will be 1.2 m long by 250 mm wide. This width has been chosen to fit into the testing apparatus and the length has been chosen so that the panel can be seated with a 100 mm overhang each end and an effective span of 1 metre (Figure 3.6).

Figure 3.6: OSB Faced Sandwich Panel under 3-point Bending

A fifth panel will be constructed using multiple layers of a 25 mm bamboo fibre mat for the core and plywood for the face. This core material is quite soft and will not be tested on the SANS machine although observations will be made on its appearance and robustness.

The four panels will be tested to failure in order to determine the failure mode/load and deflection versus load. Analytical formula will be used to calculate the theoretical failure load and this will be compared to the test results. Strand7 software will then be used to model the four panels under three point bending to create a load/deflection curve which can then be compared to the test results. If the FEA results are within an acceptable range it can be said with confidence that the computer model is accurately predicting sandwich panel behaviour under bending loads.

Once it has been determined that the Strand7 model is working correctly a more thorough analysis can be carried out on the suitability of sandwich panels as slabs. Formulae exist to calculate the core thickness with respect to three different failure modes, core shear, indentation and excess deflection under a uniformly distributed load. A core thickness will be calculated that satisfies each failure mode for the face material and the thickest core will be adopted. This core thickness represents the optimum thickness for the panel span that will also achieve minimum weight.

Panels of varying length, breadth and thickness will be modelled using Strand7 FEA software by applying a uniform pressure and concentrated load consistent with domestic floor loading. The performance of these panels will be compared to what was predicted using the formulae. In addition to this, the panels will be modelled with the addition of shear connectors, a screw of nailed connector between the faces, to see if this markedly improves the panel’s performance.

3.4 Determining Core Thickness

The key to this project is to find the optimum thickness panel that maximises strength while minimising the weight of the panel. Zenkert (1995) proposed a way of determining the core thickness under a uniform load with respect to wrinkling/yield of the face, core shear and deflection. The following formulae represent the core thicknesses for these failure modes where the thickest of the three values is selected for the core.

For face wrinkling:

$$t_c \geq \frac{qL^2}{8t_f \partial_f} \tag{7}$$

For core shear:

$$t_c \geq \frac{qL}{2\tau_c} \tag{8}$$

For deflection:

$$t_c \geq \frac{qL^2}{16G_c\Delta}\left[1+\sqrt{1+\frac{20\Delta G_c^2}{3qE_f t_f}}\right] \tag{9}$$

where Δ is the limiting deflection (Span/400), σ_f is the compressive strength of the face and q is the imposed uniformly distributed load.

4 Experimental Investigation

4.1 Introduction

An experimental investigation was carried out that involved testing the four adhesives to find the most suitable, constructing a number of samples and then testing them under three point bending. Data was collected for load and deflection and the failure load for each panel was recorded. The results were then used to validate a FEM using the Strand7 software package. This chapter describes the setup and procedure for constructing and testing the adhesives and sandwich panels. Test results are presented and the observations made during testing are discussed.

4.2 Adhesive Testing

Four adhesives were considered to make the test panels with the initial criteria being that they wouldn't react with the EPS core. Adhesives containing strong solvents are generally not suitable to be used with polystyrene as they melt the foam. To ensure the adhesives were safe to use with polystyrene a small amount of each adhesive was applied to a piece of foam from the same batch of foam as the EPS cores. Figure 4.1 shows the adhesive samples after seven days. All of the adhesives appeared not to have any adverse effect on the EPS as such their suitability for constructing the panels could be based purely on their shear strength.

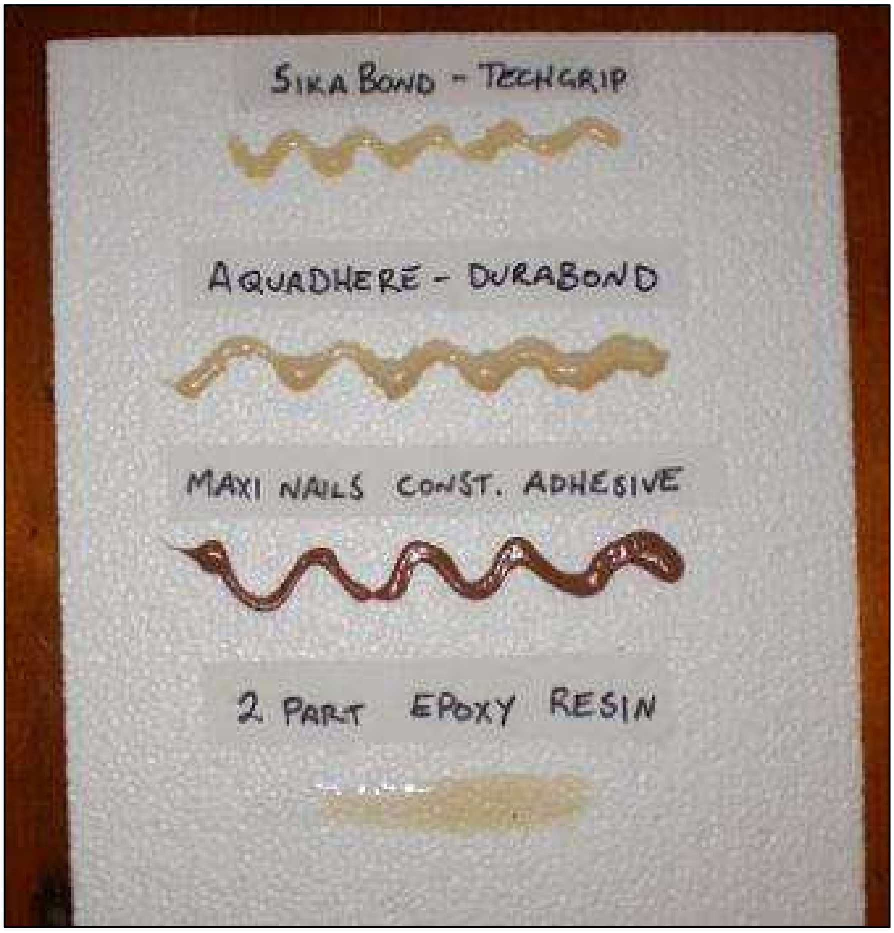


Figure 4.1: Adhesive samples on EPS after seven days

4.2.1 Setup and Procedure

A fairly rudimentary testing process was used to gauge the strength of each adhesive and its suitability to be used with the different face materials. Test rigs were constructed by gluing small cubes of EPS, roughly 50 x 50 x 50 mm, between two pieces of plywood, OSB or sheet steel. These specimens were held together overnight with clamps to allow for the glue to set, as seen in (Figure 4.2). Four test rigs were made for each of the three face materials, one for each type of adhesive, making 12 test rigs in total. The test rigs were denoted according to the type of adhesive used, AD for Aquadhere Durabond, SB for SikaBond Techgrip, CA for construction adhesive and 2P for 2-part epoxy. Figure 4.3 shows the 12 assembled rigs ready for testing.

Figure 4.2: Clamping adhesive test rigs to allow glue to set.

Figure 4.3: Assembled rigs ready for testing

In turn, each rig was hung from a hook using a piece of wire threaded through the top of the rig. To prevent the hanging wire from pulling the top of the rig together a small timber blocking piece was placed between the face sheets. This ensured the faces were not pulling away from the EPS and the only action on the rig was the EPS shearing way from the face. Figure 4.4(a) shows a plywood rig assembled with Aquadhere Durabond (AD) hanging awaiting testing. Note the timber blocking piece keeping the two faces separated.

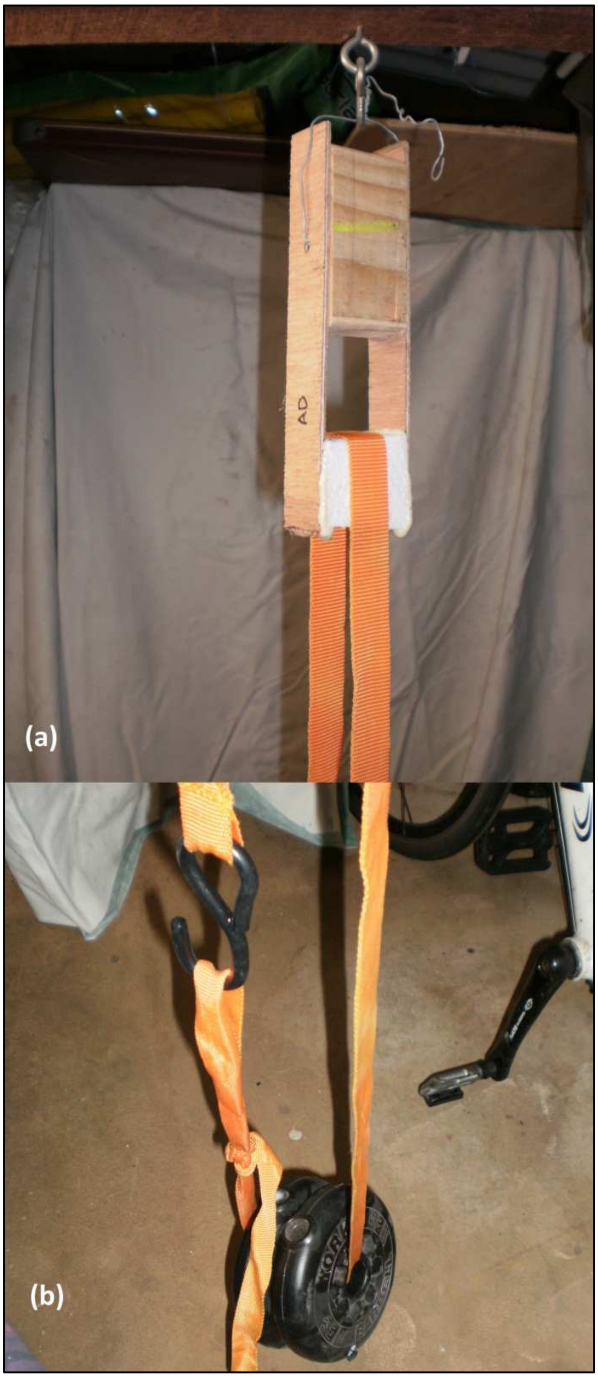


Figure 4.4: A plywood and AD test rig

Weights of 1.1, 2.3 and 4.5 kg were hung from an orange cargo strap which was wrapped over the top of the EPS cube (Figure 4.4b). The weights were added, beginning with 4.5 kg, in increasing increments with 1 minute allowed between the adding of weight to observe the effect the weight was having on the test rig. Once failure occurred the weight was recorded as was the contact area of the EPS to the face material as there was some variance in the size of the EPS. This kg/mm^2 force was converted to kilopascals (kPa) which represents the shear pressure at which failure occurred.

4.2.2 Observations and Discussion

Failure of the test rigs occurred in one of three ways, foam, adhesive or combination and these are discussed further. With foam failure the weight compressed the foam to the point where the foam began to tear and could not sustain the weight anymore. As a result the EPS was ripped out of the rig. Figure 4.5a shows a steel rig with AD adhesive where the EPS has begun to compress and tear. In Figure 4.5b failure has occurred and the EPS has torn out of the rig.

Figure 4.5: (a) EPS compressing and tearing, (b) EPS failure

Adhesive failure resulted in the EPS core being pulled out of the rig relatively unharmed. Failure began to occur at the top of the foam as it began to peel away from the face and the adhesive gave out. Figure 4.6a shows a plywood rig with CA where the EPS is beginning to peel away from the plywood. In Figure 4.6b the EPS has been cleanly pulled out of an OSB faced rig after failure, leaving no trace of the foam on the rig and the EPS cube intact

Figure 4.6: (a) CA beginning to fail, (b) Adhesive failure

In one instance where 2-part epoxy (2P) was used with an OSB face, one side appeared to show signs of foam failure and the other side of adhesive failure. This is referred to as a combination failure. The results of the testing are shown in Table 4.1 indicating the failure load, contact area of the EPS and the pressure at failure.

Table 4.1: Adhesive Testing Results

Face Material	Adhesive	Weight (kg)	Area (mm^2)	Pressure (kPa)	Failure Mode
Plywood	AD	22.6	2430	91.24	Foam
	CA	19.1	3112	60.21	Adhesive
	2P	23.7	2854	81.46	Foam
	SB	24.8	2863	84.98	Foam
OSB	AD	20.3	2970	67.05	Foam
	CA	11.3	3010	36.83	Adhesive
	2P	20.3	2992	66.56	Combination
	SB	20.3	2985	66.71	Foam
Steel	AD	21.4	2640	79.52	Foam
	CA	9	2914	30.30	Adhesive
	2P	15.8	2580	60.08	Adhesive
	SB	21.6	2745	77.19	Foam

In every instance where CA was used, failure was via the adhesive and the pressure at failure was well below that of the other adhesives thus CA was not given any further consideration. There was very little difference between AS, CA and 2P for the OSB rigs although the 2P rig failed due to a combination of foam and adhesive failure. For the steel rigs AD was marginally better than SB and for the plywood rigs AD was the standout performer. Figure 4.7 shows the dismantled rigs which show evidence of the failure modes for each type of adhesive

The adhesive tests were conducted to provide a guide for selecting the sandwich panel adhesive. AD and SB performed almost identically and when either of these adhesives were used in the test rigs, neither of them failed due to the adhesive. Either one of these two adhesives could have been used to construct the sandwich panels however the AD was ultimately selected because of its high strength and because it could be purchased in a larger bottle providing more value for money.

Figure 4.7: (a) Plywood, (b) OSB, (c) Steel

4.3 Constructing Test Panels

Once a suitable adhesive had been chosen the test panels could be built. Each panel was constructed 1.2 metres by 250 mm wide, wide enough to still fit into the SANS machine and long enough to give an effective span of 1 metre with sufficient bearing each end. Four panels were constructed using a 50 mm thick EPS core and one panel was constructed by layering three 25 mm thick bamboo fibre mats between a plywood face. The procedure to construct these panels is discussed as follows.

4.3.1 EPS Core

Four sandwich panels were constructed with an EPS core using plywood, OSB, aluminium and steel as the face materials. In accordance with the manufacturer's instructions each of the faces were cleaned prior to applying the adhesive. The steel and aluminium were first cleaned with a wire brush to remove and surface rust (Figure 4.8a) and then roughed up with sandpaper in order to improve adhesion (Figure 4.8b). Next the metallic surfaces were cleaned with solvents (Figure 4.8c) and then dried with a clean paper towel (Figure 4.8d)

Figure 4.8: Preparing the metal faces.

The plywood and OSB faces were free from any grime or grease so only needed to be wiped down with a damp cloth which not only cleaned the surface but moistened it in preparation for the adhesive. Aquadhere Durabond and Sikabond Techgrip are moisture cure adhesives which means they use moisture on the surface and from within the substrate to cure. Both the plywood and OSB were quite dry and porous so by wetting the surface ensured there was sufficient moisture for the glue to cure.

To assemble the panels the bottom face was laid down on the work surface on top of a sheet of grease proof paper to prevent the face becoming stuck to the ground. The grease proof paper could easily be torn or scraped off from wherever the glue spilled over and stuck to the paper. Next, the adhesive was applied in a zigzag pattern and spread out with a paint scraper to ensure even coverage.

The EPS core was laid on top of the bottom face and then more adhesive was applied in the same fashion before the top face was laid over the core. More greaseproof paper was placed on top before two heavy timber planks and 60 kg of weights were added to help provide an even contact between the core and face. Figure 4.9 shows the steps taken to assemble the steel panel; (a) applying adhesive to the bottom face, (b) spreading the adhesive, (c) laying the EPS core over the face, (d) applying adhesive to the core, (e) spreading the glue on the core, (f) laying the top face on the core, (g) greaseproof paper over the panel and (h) weighting the panel to promote better adhesion.

Some observations were made for each face material. The plywood was slightly cupped and bowed making it hard to get a flat surface to evenly spread the glue. When finished there was some separation at the edges which were filled with glue and clamped shut. OSB contains strands of timber and the surface is undulating with many imperfections which made it hard to spread the glue evenly although total coverage was achieved. The aluminium was quite soft and easy to roughen up prior to gluing. A cupped surface made it difficult to spread the glue and again some edge separation needed to be repaired. Surface rust was present on the steel and it was slightly oily in places. It was very difficult to roughen up which may affect adhesion.

Figure 4.9: Assembling an EPS core panel

4.3.2 Bamboo Fibre Composite Core

To assemble the BFC cored panels a different adhesive was used, partly due to financial constraints and partly the BFC material. The BFC is quite a porous material and when samples of the adhesive were applied Figure 4.10 both the AD and 2P seemed to seep into the fibres and disappear, while SB and CA remained on the surface of the material. The CA was by far the cheapest adhesive, $1.56/100 mL compared to $4.78/100 mL for 2P, so it was decided that CA would be used to construct the panel, which proved a very wise decision considering the amount of adhesive that was eventually used.

Figure 4.10: Adhesive samples of the BFC material

Plywood was used as the face as there was a sufficient amount left over from making the EPS core panel and is strength properties were superior to OSB. An entire 320 mL tube of CA was used between each of the three layers of BFC, this proved very difficult to spread evenly on the fibrous material, and left a very uneven application of the adhesive. The material was very soft so timber blocks were nailed in each end to prevent crushing at the bearings and the nails stopped the face slipping relative to the core. Figure 4.11 shows the three-layered panels with bearing blocks nailed in at the end.

Figure 4.11: BFC core panel with timber bearing block

4.4 Test Setup and Procedure

The four EPS core panels were tested under three point bending consisting of two roller supports 1000 mm apart on which the panel rests and another roller above the panel in the centre (Figure 4.12). This creates three points of contact with the panel with the mid-span deflection under load being measured.

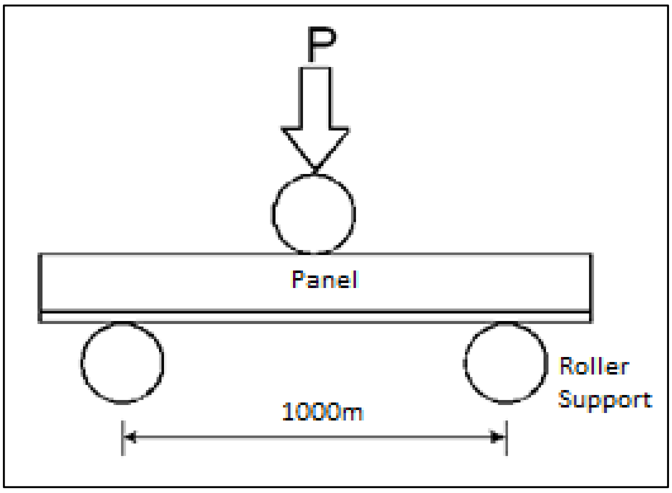


Figure 4.12: Three-point bending

The rollers supporting the panel rose at a rate of 1.5 mm/minute while the testing machine's computer measured load and deflection, with data points being recorded every 0.033 seconds. An enormous amount of data was collected for each of the four panels with the OSB panel alone recording 23839 readings for load and deflection. Figure 4.13 shows the OSB panel positioned in the machine. As mentioned earlier the panels measure 1200 mm overall giving an effective span of 1000 mm with 100 mm overhang at each roller support. For this test a metal bar 25 mm in width was placed under the middle roller to prevent localised indentation. This metal bar was used for the following tests.

Figure 4.13: OSB panel positioned in the bending machine

4.5 Predicted Failure Loads

The predicted failure loads for the three most common failure modes, core shear, wrinkling and indentation, were calculated using Equations 1, 2 and 3 respectively. These are shown below in Table 4.2 and were compared to the actual failure load during testing.

Table 4.2: Predicted Failure Loads for the EPS panels

Panel	Failure Load (kN)		
	Core Shear	Wrinkling	Indentation
Plywood	5.5	5.41	7.32
OSB		4.9	6.3
Aluminium		2.35	2.09
Steel		4.46	5.49

Naturally all four panels have the same failure load under core shear as they all have the same core. According to the formulae the plywood, OSB and steel faced panels should fail via face wrinkling while the aluminium faced panel should fail via indentation.

4.6 Test Observations and Discussion

The four EPS panels were tested until failure while data was recorded for load and deflection (Table 4.3). Observations were made on the behaviour of each panel during the test and load deflection curves have been presented. The BFC panel wasn’t tested in the SANS machine as it appeared very weak and unable to withstand any significant load.

Table 4.3: Test results for the four EPS panels

Panel	Time (secs)	Failure Load (kN)	Maximum Deflection (mm)
Plywood	580.54	1580.21	14.51
OSB	794.88	2125.24	19.85
Aluminium	516.84	1485.76	12.9
Steel	993.18	2323.09	24.81

4.6.1 Plywood Panel

The plywood panel test ran for 580.54 seconds (9 minutes and 40 seconds) failing at 1580.21 N with a maximum deflection of 14.51 mm. The mode of failure appeared to be an indentation of the middle roller although the roller seemed to crush and indent the face rather than push into the core. In Figure 4.14 (a) the roller is shown indenting the plywood and in (b) and (c) the panel has been removed for the machine and the indentation can be seen more clearly.

The load versus deflection curve for the plywood panel is shown in Figure 4.15. Deflection is almost linear up to around 800 N / 5 mm. From 1400 N onwards failure is quite rapid with the deflection increasing much quicker for smaller increase in load.

Figure 4.14: (a) Plywood panel at failure, (b) & (c) roller indentation in the panel

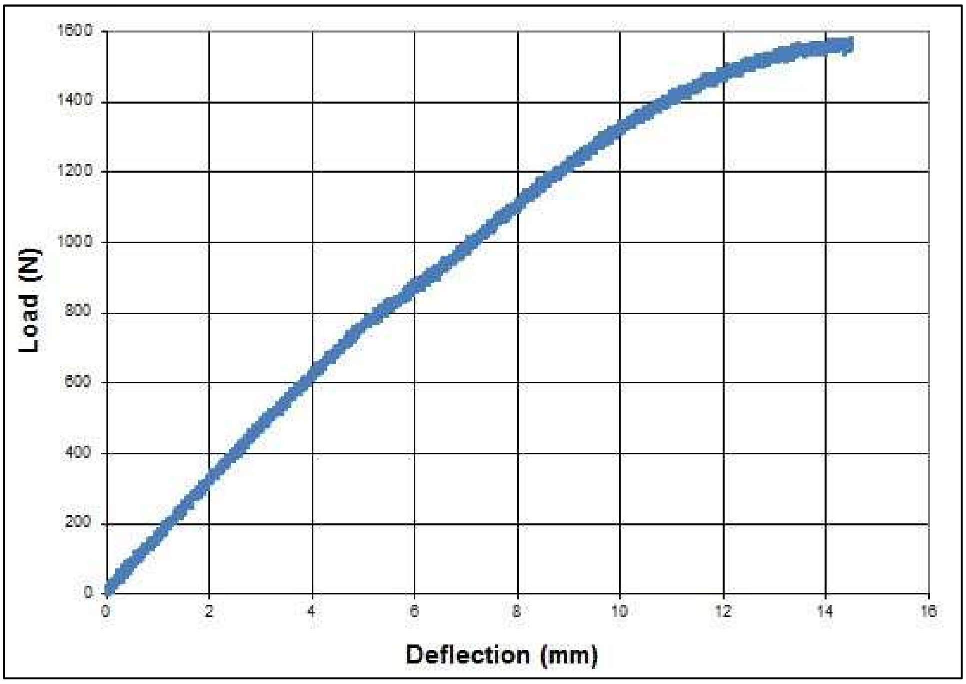


Figure 4.15: Load /Deflection - Plywood

4.6.2 OSB Panel

Next to be tested was the OSB panel. This test ran for 794.88 seconds (13 minutes and 14 seconds) with failure occurring at 2125.54 N and 19.85 mm deflection. To prevent a local indentation failure in this test a 370 x 25 x 5 mm thick plate was placed under the centre roller to try and distribute the load better. As with the plywood the failure was by indentation albeit much less than the predict 4900 N failure due to wrinkling. In Figure 4.16(a) the OSB panel is shown on the SANS machine with bearing plate indenting the panel and in (b) removed from the machine so the failure can be seen more clearly.

Figure 4.16: OSB panel failing

The load/deflection curve generated from the tests show linear results until 1200 N / 8 mm where the deflection begins to increase at a quicker rate (Figure 4.17). These results indicate that the OSB panel is performing better than the plywood panel.

Figure 4.17: Load / Deflection - OSB

4.6.3 Aluminium Panel

The aluminium panel was tested using the bearing plate as per the test for the OSB panel with the test lasting 516.84 seconds (8 minutes and 36 seconds), failing at 1485.76 N and 12.9 mm deflection. Failure was again by indentation however this was to be expected considering aluminium is the thinnest of the faces and the most malleable. Figure 4.18(a) shows the panel on the SANS machine with the bearing plate indenting the face and (b) removed from the machine to better see the indentation.

The aluminium panel is the only of the four panels to fail by the predicted failure mode, albeit at a load less than predicted. It was predicted the panel would fail at 2090 N when failure occurred at 1485.76 kN. The load/deflection curve from the test results, shown in Figure 4.19 indicate a linear range up until 1000 N / 7 mm deflection before the deflection begins to increase quickly to a rather low failure load. So far the test results have indicated a similar performance of the plywood, OSB and aluminium panels in the linear range with deflection of 7 mm at 1000 N for all three panels.

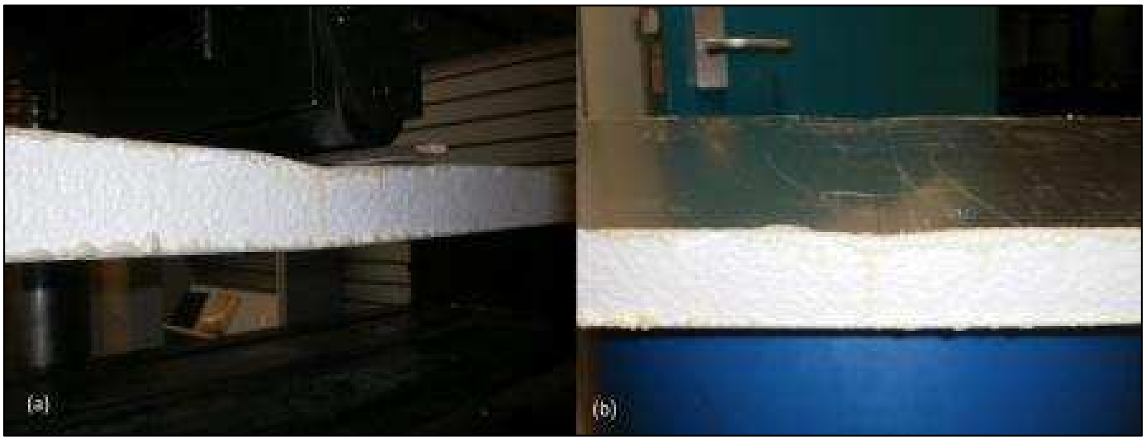


Figure 4.18: Aluminium panel failing

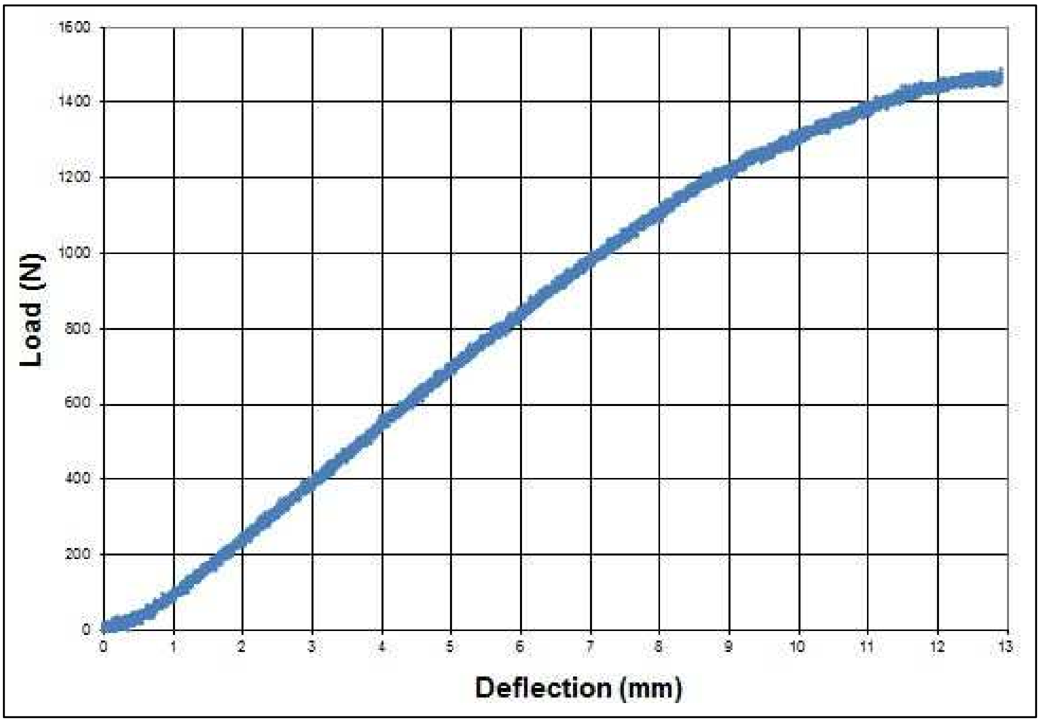


Figure 4.19: Load/ Deflection - Aluminium

4.6.4 Steel Panel

The fourth and final bending test was on the steel faced panel with the test running for 993.18 seconds (16 minutes and 33 seconds), the longest of the four tests. This panel was also able to sustain the greatest load, failing at 2323.09 N and 24.81 mm deflection, again failing due to indentation. In Figure 4.20(a) the large deflection of the panel can be seen while in (b) the resulting indentation failure can be seen.

Figure 4.20: Steel Panel Failing

It was predicted the steel panel would fail due to core shear at 5500 N however it failed at a much lower load under indentation. In Figure 4.21 the load/deflection curve indicates a linear range up to 1300 N and 8 mm deflection which makes the steel panel by far the best performing panel in the linear range and overall.

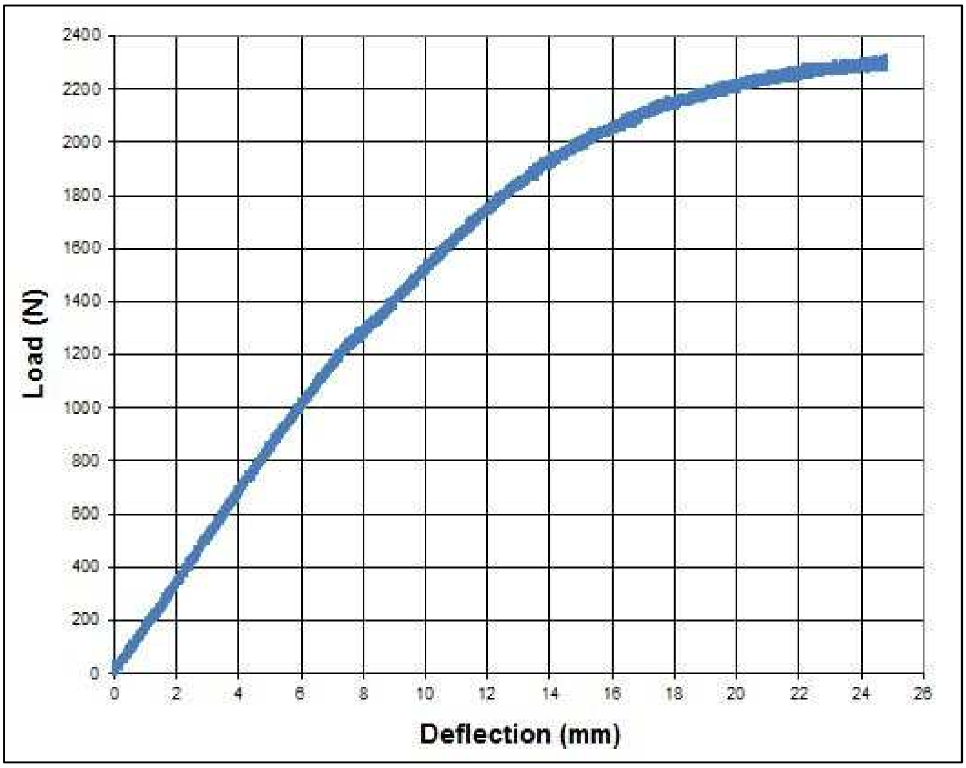


Figure 4.21: Load/ Deflection - Steel

4.6.5 BFC Panel

The BFC panel appeared very flexible and exhibited noticeable deflection even when compressed by hand. As a result, it was decided not to test the panel in the SANS machine as the results would no doubt be disappointing. In order to get an idea of just how flexible the panel is a very simple test was conducted outside of the laboratory. The panel was positioned with a 35 mm thick timber block under each end to achieve a one metre span. Measurements were taken in the middle of the panel from the work surface to the underside of the panel (35 mm) and to the top of the panel (117 mm), as shown in Figure 4.22.

Figure 4.22: Measuring the BFC Panel prior to loading

On top of this was added four 4.5 kg weights giving a load of 176.52 N, much less than the EPS core panels, and the height of the panel from the work surface was again measured in the middle of the panel (Figure 4.23). The bottom of the panel measured 29 mm meaning the panel had deflected 6 mm. At the top the panel measured 107 mm which indicates the panel had deflected 6 mm and compressed the core a further 4 mm. In its current form the BFC is unsuitable for load bearing applications however it does show the various applications of composite fibres.

Figure 4.23: BFC Panel deflecting under load

5 Finite Element Analysis

5.1 Introduction

At the completion of the laboratory experiments the next step was to replicate the tests using the FEA software package Strand7 to see how well the FEA results match the test results. Models were created in Strand7 that are comprised of the same dimensions and material properties as the test samples and subjected to the same loads. If the Strand7 model performed similar to the experimental tests then the conclusion could be drawn that the model is an accurate prediction of real life loading scenarios. FEA could then be used to model sandwich panels in slab applications and see how they perform at different spans and core thicknesses.

Four sandwich panel models were created in Strand7, one for each of the panels tested in the laboratory. This chapter describes the process taken to develop these models using the software and how the loads were applied and the results from the analysis. These results are compared to the experimental test results which will hopefully validate the accuracy of the model.

5.2 Finite Element Modelling

Strand7 has the ability to create full, half or quarter length models depending on the size of the model and the computational requirements. A full length model is input using the actual dimensions of the test specimen while half and quarter length models scale down the dimensions in order to make the model more manageable. As seen in Figure 5.1 a half-length model uses either half the length (L/2) or half the breadth (B/2) while the quarter length model uses both L/2 and B/2. Conditions are imposed on the boundaries of the half and quarter length models that tell the software the model is symmetrical about these edges.

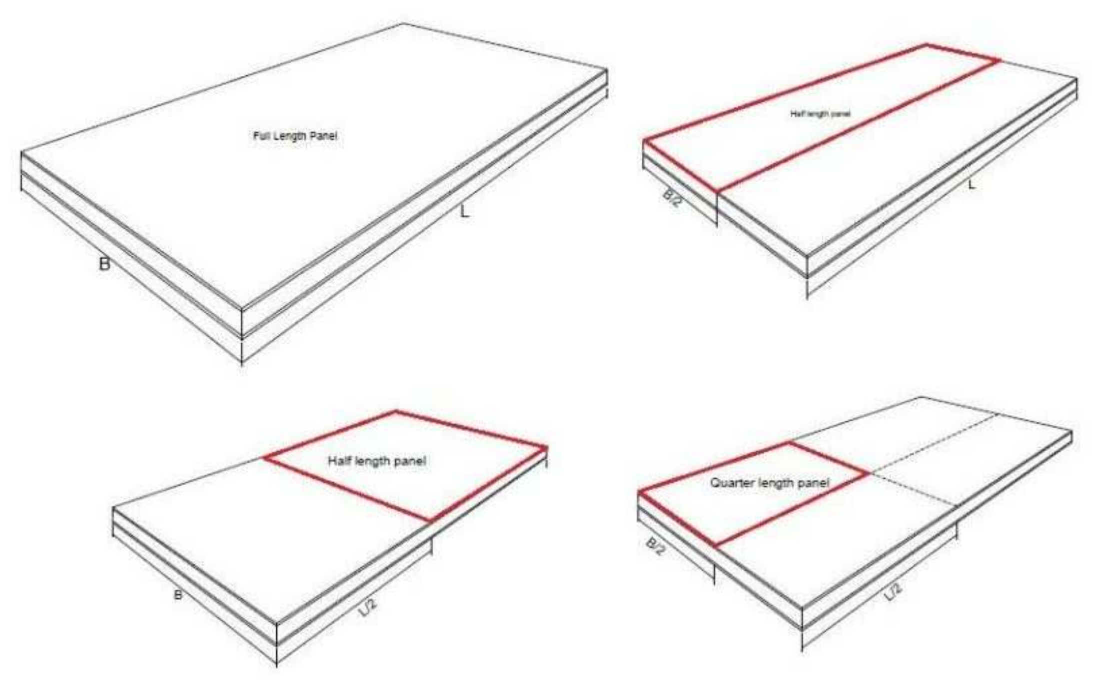


Figure 5.1: Full, half and quarter length models

The benefit using half or quarter length models is that they improve the efficiency of the software by reducing computational time while improving the accuracy of the model. For example, a full length model may be subdivided in 100 smaller elements for analysis. If this model was scaled down to a quarter-length and subdivided into 50 elements computational time would be quicker and the symmetrical boundary conditions would mean 200 elements were analysed, increasing accuracy. As the test specimens being modelled were small, 1200 x 250 mm, a full length model was deemed sufficient.

5.3 Constructing the Model

The four EPS core panels, plywood, OSB, aluminium and steel were modelled in Strand7 as full length models with the same dimensions as the test panels. The following describes how the model was built and subdivided into smaller elements, the restraints that were applied to the model and the properties of the materials.

5.3.1 Geometry and Mesh Size

Table 5.1 shows the input dimensions of the panels into Strand7

Table 5.1: Dimensions of the panels (mm)

Panel	Length	Breadth	Core	Face
Plywood	1200	250	50	4.5
OSB				6
Aluminium				1.2
Steel				1.6

Nodes were defined for the corner points of the bottom of lower face and then copied by increment to form the corner points of the top and bottom faces and the core. The panel faces and core were input as Hexa8 brick elements which means the brick element has eight corner nodes with the corner nodes being selected in sequence until the brick element is formed. Different properties are nominated for the face and core at this stage, hence the different colour on the model, though the actual properties are input at a later stage prior to solving the model.

Next the brick elements are subdivided into a number of smaller finite elements. The greater the number of finite elements the more accurate the solution and more computational time required. In this instance the geometry of the panel allows it to be divided up into 24 elements in the X direction and 5 elements in the Z direction. Faces were not divided in the Y direction while the core was divided into three. Thus the faces were comprised of 50 x 50 mm elements the depth of the material and the core comprised 50 x 50 x 16.67 mm elements. Figure 5.2 shows the panel being created from node input (a) to element creation (b) and subdivision (c).

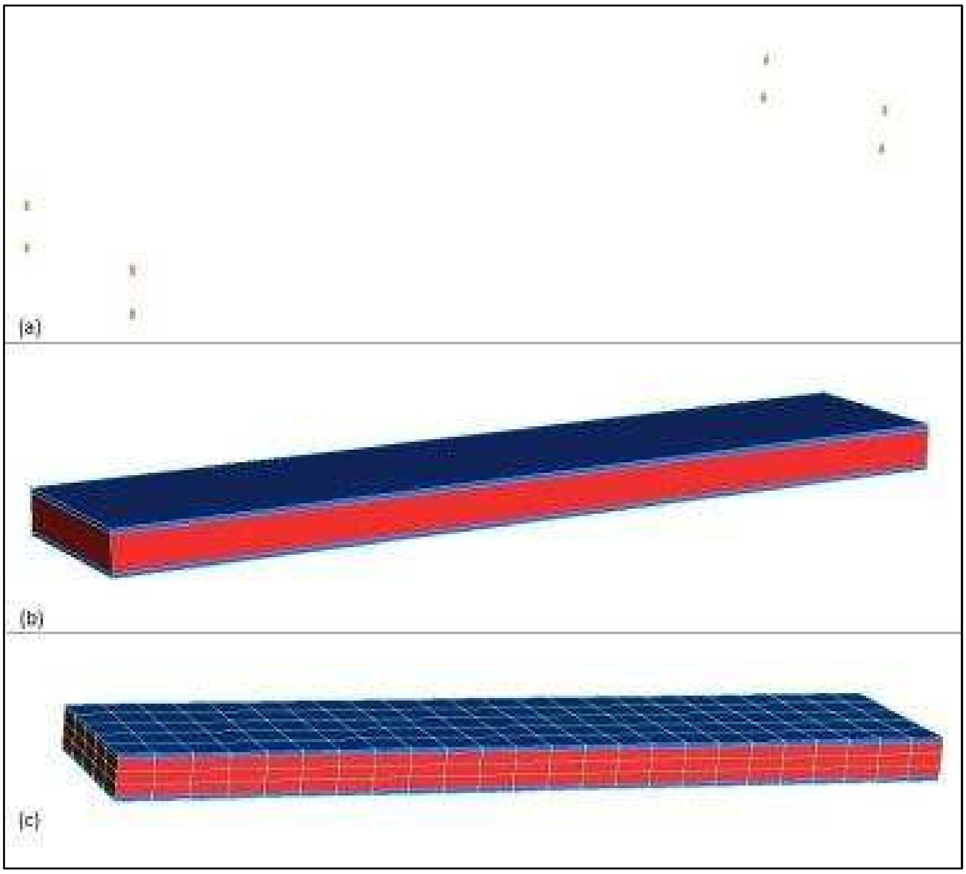


Figure 5.2: Creating a panel in Strand7

5.3.2 Restraints

To create an accurate model, conditions need to be applied that mimic the restraints on the panel during the laboratory tests. The restraints were applied 100 mm in from each end of the panel across six nodes to give a clear span of 1 metre. DY was restrained for all six nodes at each support to prevent vertical movement, in effect creating the roller supports of the SANS machine.

At the left hand end, all six nodes representing the support were restrained in the DX direction to prevent rigid body motion in the long direction. At each of the supported edges the outermost node was restrained in the DZ direction to prevent rigid body motion in the transverse direction. Strictly speaking, during laboratory testing there was no mechanical restraint preventing movement in the DX or DZ directions. The pressure of the rollers bending the panel would have provided the physical restraint to prevent movement of the panel during testing. Table 5.2 below summarises the restraint conditions imposed on the Strand7 model.

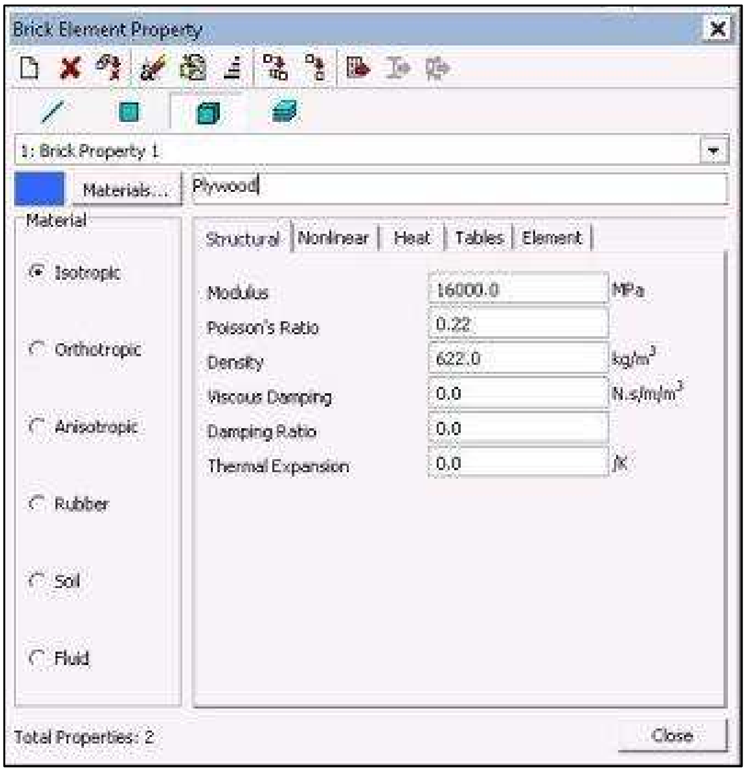
Table 5.2: Restraint Conditions

Direction	Restraint
DY	6 nodes each end
DX	6 nodes left hand end
DZ	1 node each end

5.3.3 Properties

Once the model was constructed and restraint conditions applied the next step was to input the material properties. It is easiest to treat the face and core materials as isotropic when entering their properties into Strand7 as the only material information required is the modulus of elasticity (E), poisons ratio (ν) and density (ρ). Strand7 uses E and ν to calculate shear modulus (G) using Equation 6.

The properties of the materials were discussed in Chapter 3 with the plywood and OSB being treated as isotropic materials for the purpose of this study, even though they are anisotropic. Figure 5.3 shows a screenshot from Strand7 where the material property data is input for plywood as an isotropic material. Viscous Damping, Damping Ratio and Thermal Expansion are not required for this study; as such these properties are not input.



1: Brick Property 1

Plywood

● Isotropic
○ Orthotropic
○ Anisotropic
○ Rubber
○ Soil
○ Fluid

Modulus 16000.0 MPa
Poisson's Ratio 0.22
Density 622.0 kg/m^3
Viscous Damping 0.0 N.s/m/m^3
Damping Ratio 0.0
Thermal Expansion 0.0 /K

Total Properties: 2

Figure 5.3: Entering material properties into Strand7

5.4 Load Application and Results

The load applied to the test panel by the SANS machine was divided up and applied to the centre six nodes of the finite element model. Instead of dividing the load by six and applying 1/6th of the load to each node 1/10th of the load was applied at the two outer nodes and 1/5th applied to the inner four nodes, still equating to 5/5th of the applied load. This was considered a more realistic approach to applying the load rather than apply 1/6th at each node due to the arrangement of the testing machine.

The centre roller of the SANS machine is attached to a single ram in the middle so it is possible that a greater proportion of the load is being applied at the middle of the roller than at the edges (Figure 5.4). A number of trial runs were completed in Strand7 where the load was applied both ways. In actuality this had little effect on the results but in the interest of accuracy the load was applied with a greater proportion of the load in the centre of the panel.

Figure 5.4: SANS Machine centre roller and ram

Load was applied in increments of 100 N and solved using Strand7's linear static solver. This was repeated up until the failure load for each panel with the mid-span deflection recorded each time. In Figure 5.5 the Strand7 output for a plywood panel is presented as a contour diagram showing the deflection changes throughout the panel. 1000 N has been applied to this panel, 100 N to the outside two nodes and 200 N to the inner four, with the greatest deflection in the blue area in the centre of the panel.

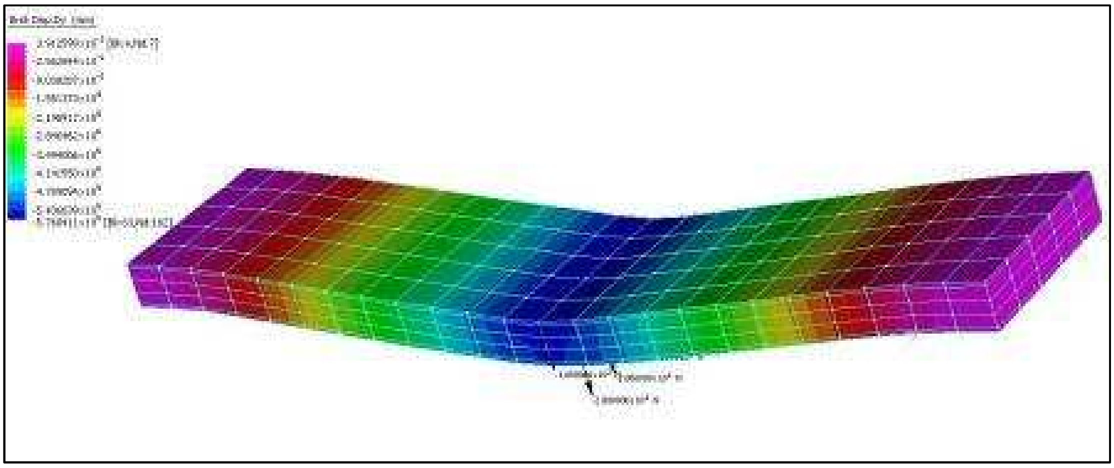


Figure 5.5: Strand7 linear static solver for a plywood panel

As the name suggests, Strand7 solves the model in a linear fashion and when plotted the load/deflection results will always be a straight line passing through the origin. To save time only one load/deflection case could have been solved and plotted through the origin with other data points calculated from this line. However each load case was solved in turn to ensure the Strand7 solver was operating properly. The results from the finite element modelling are presented below in Figure 5.6.

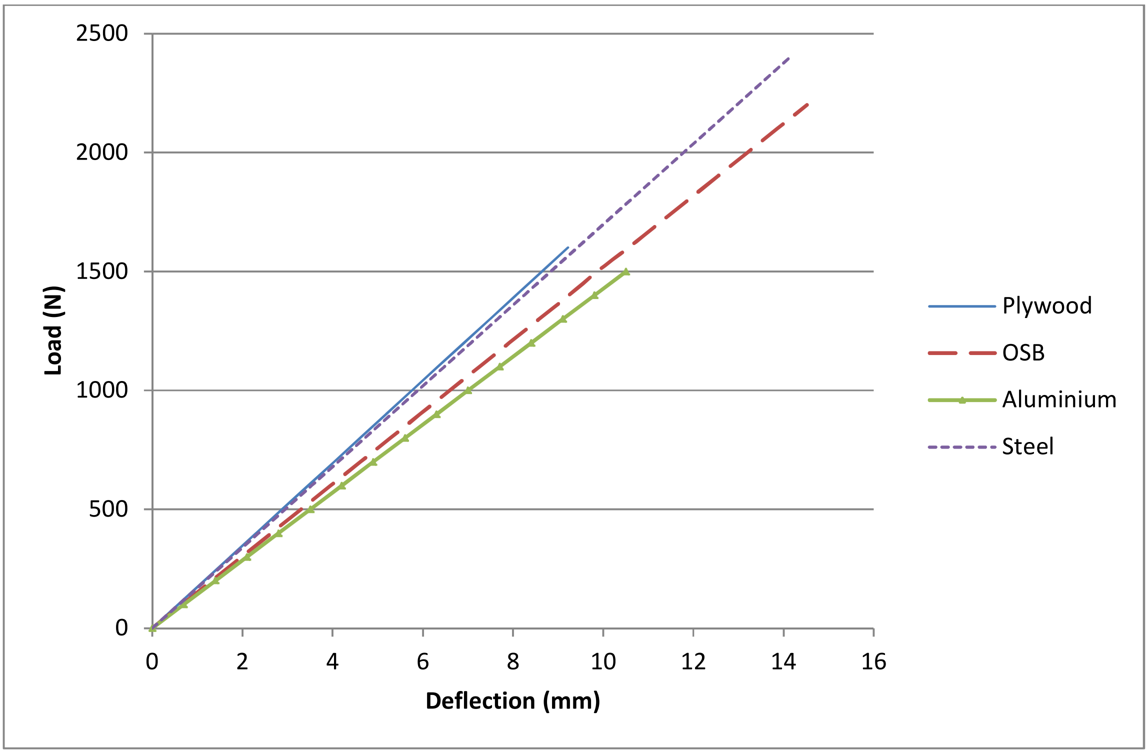


Figure 5.6: Linear static solver results from Strand7

As expected the results from Stand7 are linear thus the model is operating properly. It is interesting to note at this point that Strand7 has the plywood faced panel as the best performing panel as it is deflecting the least out of the four panels for a given load. Deflection at 1500 N for the plywood, OSB, aluminium and steel panels was 8.64, 9.87, 10.5 and 8.84 mm respectively.

5.5 Comparing FEA Results to Experimental Results

Plots of the test results show a linear response until deflection begins to increase exponentially while the FEA results remain linear. To compare these results it is important to consider the kind of load being applied to a domestic floor slab. Usually this load is in the order of 2 kPa which for a panel measuring 1000 x 250 mm equates to 500 N. As long as the Strand7 results are within 10% of the test results in the lower linear range then it can be said with confidence that the FEA is an accurate portrayal of the sandwich panel's behaviour. All of the load/deflection curves for the experimental test appear to be linear at least until 800 N so the Strand7 results will be compared to the test results at 800 N and the percentage difference compared. It stands to reason that the percentage difference between the two values will decrease as the load approaches zero.

In Figures 5.7, 5.8, 5.9 and 5.10 the load/deflection curves are presented for plywood, OSB, aluminium and steel with the experimental test results shown as a curve and the Strand7 results as squares with a straight line connecting the data points. It can be seen in these figures that the FEA results and experimental results are in reasonably good agreement in the linear range.

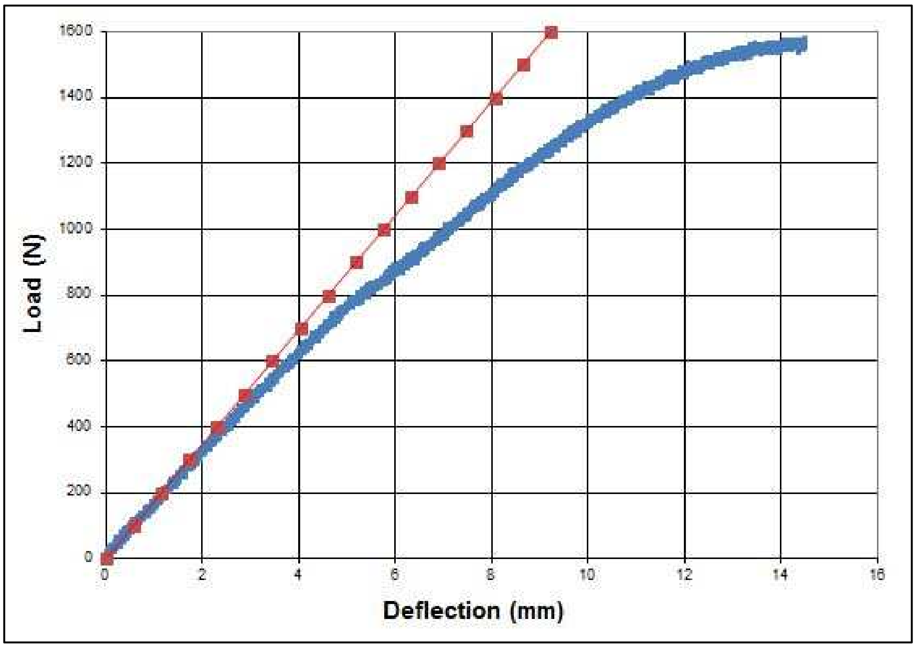


Figure 5.7: Load/Deflection - Plywood

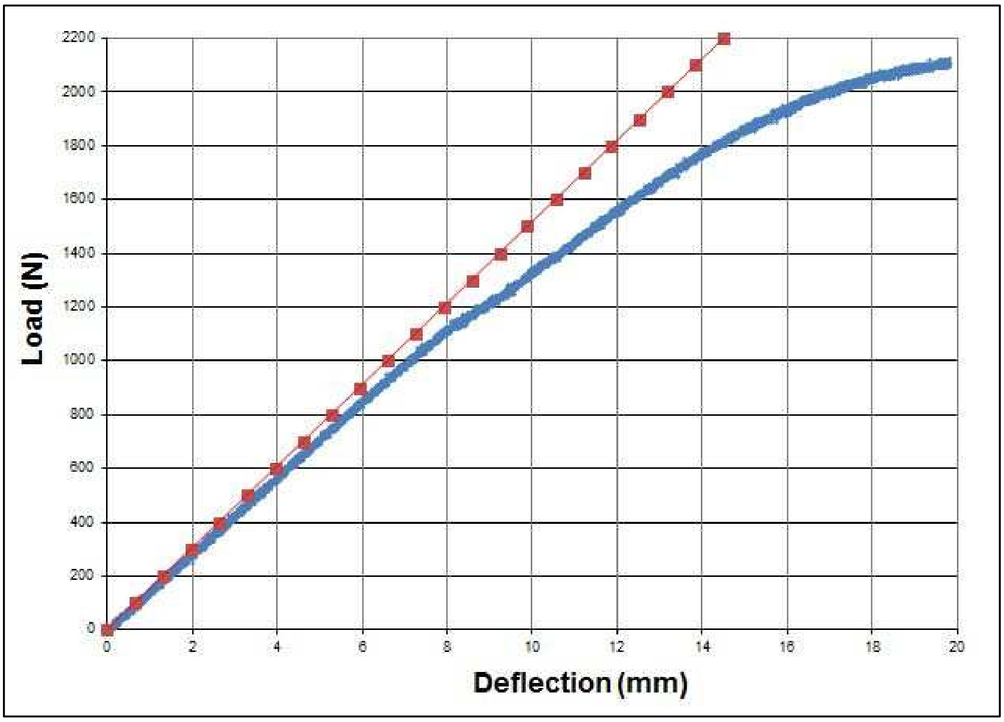


Figure 5.8: Load/Deflection - OSB

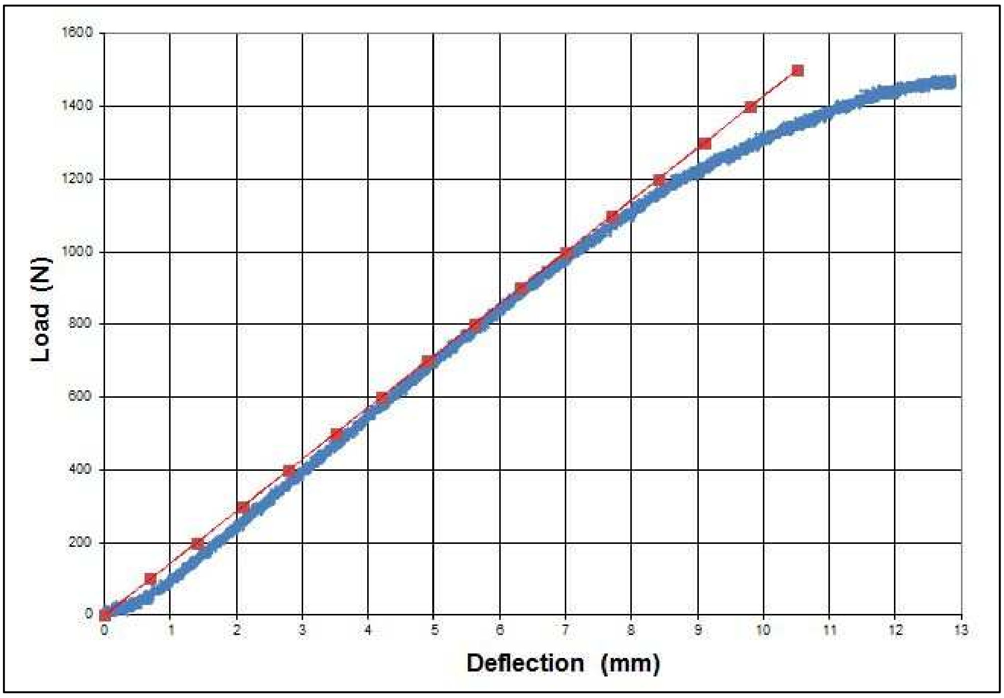


Figure 5.9: Load/Deflection - Aluminium

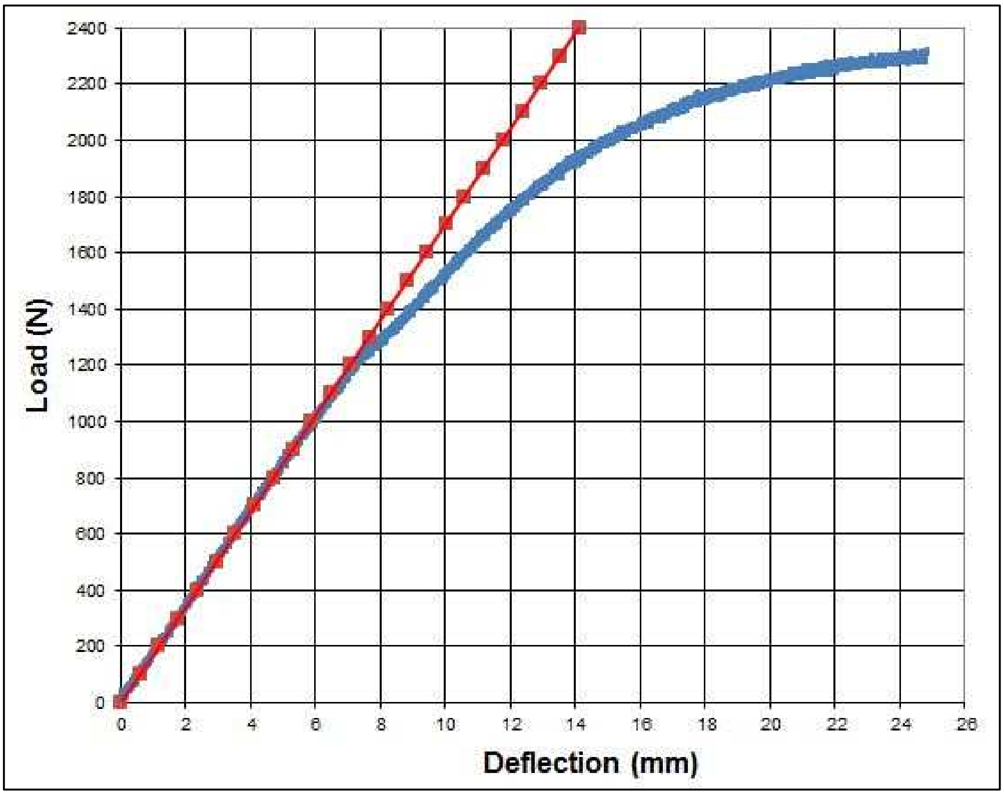


Figure 5.10: Load/deflection - Steel

For both the plywood and OSB panel the FEA and experimental results are on parity until around 400 N for the plywood panel and 300 N for the OSB when the two results begin to diverge. The aluminium panel displayed somewhat different characteristics to the previous two panels. Initially the test results diverge quickly away from the Strand7 results before converging at around 600 N and maintaining the same load/deflection rate until 1000 N. The steel panel by far showed the best agreement between the test and FEA results with the results maintaining parity until 1200 N when deflection in the experimental tests began to increase rapidly. Table 5.3 has a breakdown of the experimental and Strand7 results with the percentage difference between them.

Table 5.3: Comparing Test and Strand7 Results

Panel	Deflection at 600N			Deflection at 800N		
	Test Results (mm)	**Strand7 Results (mm)**	**% difference**	**Test Results (mm)**	**Strand7 Results (mm)**	**% difference**
Plywood	3.79	3.46	9.54	5.21	4.61	13.02
OSB	4.17	3.96	5.3	5.59	5.28	5.87
Aluminium	4.31	4.2	2.62	5.58	5.6	-0.36
Steel	3.4	3.53	-3.82	4.62	4.71	-1.95

5.6 Discussion

When comparing the test and Strand7 results, for the most part signs are positive. In both instances when the steel panel results were compared Strand7 gave a slightly higher value for deflection, 3.83% at 600 N and 1.95% at 800 N. The computer model is predicting greater deflection than actually occurred during testing. From these results the conclusion can be drawn that the Strand7 model for the steel faced panel will be giving an accurate prediction of how a panel would perform in service conditions.

In the 0-600 N load range for the aluminium panel the test results for deflection were higher than the Strand7 results, while from 600-1000 N the results were on par with each other. At 600 N Strand7 results were 2.62% less than the test and at 800 N 0.36% higher. The rapid initial deflection of the test panel is difficult to explain and could be the fault of some kind of flaw or fatigue in the face material. If the test panel displayed linear characteristics initially like the other three panels the results would match the Strand7 output quite well. Further testing would be required to see if this initial behaviour could be replicated, however the fact that results became linear and comparable to the Strand7 results gives cause to conclude the finite element model of the aluminium panel is operating correctly.

Both of the Strand7 models for OSB and plywood modelled performed quite well until around 500 N. After this the test panel began to deflect greater than the finite element model. At 600 N the Strand7 results for the OSB panel was 5.3% less than the test and at 800 N 5.87% less. These results are still under the acceptable limit of 10% thus is can be assumed that Strand7 for OSB is operating as it should and can be used to further study sandwich panels.

After initially showing good agreement between the finite element and test results up to 500 N the results for the plywood panel begin to differ markedly. At 600 N the Strand7 output is 9.54% less than the actual, which is still acceptable, while at 800 N the Strand7 results are 13.02% less. At face value it would seem that this finite element model is unsuitable for predicting the actual behaviour of the sandwich panels.

It is worth referring back to Figure 5.8 to see that in the lower range of the load/deflection curve the Strand7 model is working very well and it is only under higher load that it becomes unsuitable. The sort of loads applied to a sandwich panel are governed by Australian Standards (discussed later) and do not change for domestic applications. These loads will be in the vicinity of 500 N for panel of this size and Figure 5.8 shows very little difference between the results at this point. It can be concluded that while the finite element model would be unsuitable under higher loading, in the range of loading that would be expected to be applied to a domestic floor the Strand7 can be used to model a plywood sandwich panel.

6 Sandwich Panels as Slabs

6.1 Introduction

Laboratory tests and finite element analysis have shown that the Strand7 model can accurately predict the performance of sandwich panels and can be used to study how sandwich panels would perform as slabs. Computer modelling was then employed to determine the minimum core thickness required for a given span, thus optimising its performance by giving the thinnest possible core for maximum possible deflection, while minimising the weight of the panel and material costs.

The slabs investigated in this study were considered to be for domestic and residential activities and a number of different computer models were created using the loads prescribed in the relevant Australian Standard. Different spans and thicknesses of panels were modelled in order to determine the optimum core thickness and to create span/thickness charts which allow the required thickness for a given span up to 6 metres to be read directly from the chart.

Further to this study was the examination on whether adding shear connectors between the two faces of the panel would increase the load bearing capacity of the panel. Plywood panels utilising the shear connectors were modelled in the same fashion as the plywood panels without the connectors and the results compared. Finally bamboo materials are discussed along with their potential to be used in sandwich panels as either face or core materials.

6.2 Loading and Serviceability Requirements

The loads and serviceability requirements applied to these slabs were taken from Australian Standard AS1170.1: 2002: Structural Design Actions – Permanent, imposed and other actions. In this project the panels were subjected to domestic and residential floor loading as these loads are the smallest when compared to other load cases like commercial and industrial floors. This serves to keep the size of the panel down which will minimise size of the Strand7 model, yet leaves the door open to future research with different loading if the results of the project are positive. Table 3.1 of AS1170.1:2002 provides reference values of imposed floor actions broken down into six categories A through F depending on the activity/occupancy of the structure. Table 6.1 below explains the category and type.

Table 6.1: Imposed Floor Action Categories

Category	Activity/Occupancy
A	Domestic and residential activities
B	Offices and work areas not covered elsewhere
C	Areas where people may congregate
D	Shopping areas
E	Warehousing and storage areas
F	Light vehicle traffic areas

This study assumed the panels will be used in self-contained dwellings; general areas, private kitchens and laundries. The Australian Standard requires a uniformly distributed load (UDL) of 1.5 kPa and a concentrated load of 1.8 kPa applied at its known position or where its position is not known, a position giving the most adverse effect.

AS1170.0:2002 requires for normal floor systems the applied actions to be permanent load G and long term imposed load $\psi_L Q$, where Q is the imposed load and ψ_L is a reduction factor for long term loads. Table 4.1 of AS1170.0:2002 states that for residential and domestic floor $\psi_L = 0.4$. Therefore for ultimate limits states for strength the permanent and imposed actions (dead and live loads) are:

$$E_D = 1.2G + \psi_L 1.5Q \qquad (12)$$

where E_D is the design action effect.

Serviceability requirements for mid span deflection requires noticeable sag be limited to Span/400 thus a 4000 mm span floor system would be allowed 10 mm deflection. It is not uncommon for floor systems to span up to 6000 mm which would be allowed quite a large deflection based on Span/400. An arbitrary decision has been made that any deflection over 10 mm was unacceptable and as such allowable mid span deflection was taken to be Span/400 or 10 mm, whichever is less.

6.3 Optimum Core Thickness

The aim of this study is to try and find the optimum core thickness that minimises the thickness of the panel while still satisfying strength and serviceability requirements. This was done two ways, first by using Equations 7 to 9 by Zenkert presented in Chapter 3, and second by using Strand7 to create span/thickness tables.

6.3.1 Verifying the Formula

The three equations from Chapter 3 are used to calculate the thickness of the core with respect to the mode of failure; face wrinkling, core shear and excess deflection. Each formula is used to calculate a core thickness that would prevent the panel failing in that mode and the thickest of the three values is adopted as the core of the panel. A problem with this approach is that it uses only a UDL, not a UDL and concentrated load as prescribed by AS1170.1: 2002.

In order to check these formulae are giving accurate results the 1.8 kN concentrated load was treated as a 1.8 kPa UDL and added to the 1.5 kPa UDL being applied to the panel. By using Equation 12 the load becomes 1.98 kPa. This load was then used in the core thickness equations based on a 1 m^2 panel to give the core thicknesses shown in Table 6.2. In all instances deflection was the governing factor in determining the core thickness with serviceability requirements allowing a maximum deflection of Span/400 i.e. 2.5 mm.

Table 6.2: Core Thickness Calculations

Failure Mode	**Core Thickness (mm)**			
	Plywood	**OSB**	**Aluminium**	**Steel**
Face Wrinkling	0.93	1.97	0.29	0.47
Core Shear	3.41	3.41	3.41	3.41
Deflection	38.8	46.27	37.98	33.35

These four panels, plywood, OSB, aluminium and steel, were modelled in Strand7 with core thicknesses of 39, 47, 38 and 34 mm respectively. Restraint conditions were the same as used for verifying the test panels with a mesh size for the face and core of 50 x 50 mm. When applying the 1.98 kN UDL the maximum deflection was recorded and if less than the 2.5 mm the model was deemed to be operating properly. Figure 6.1shows a 1 m^2 plywood faced panel with 39 mm core being after being solved in Strand7.

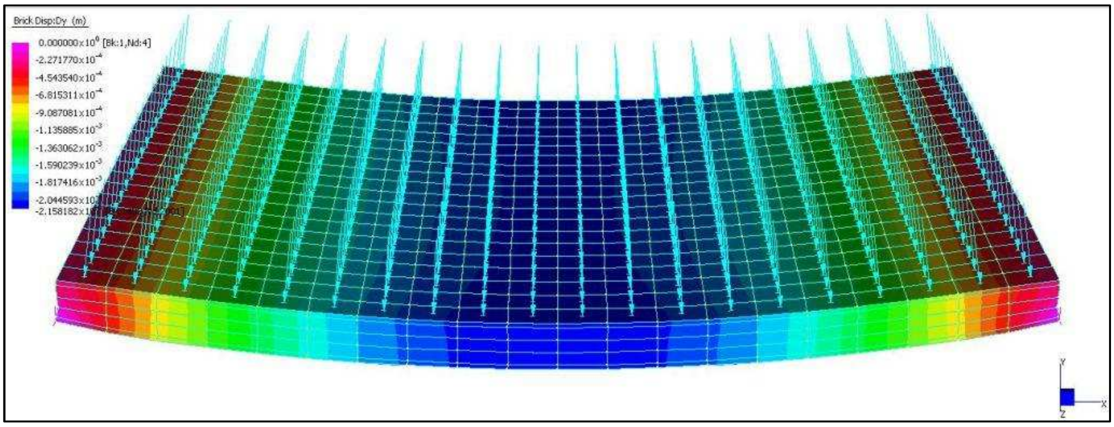


Figure 6.1: Strand7 output of plywood panel with UDL

The same panels were modelled again, this time with a UDL and concentrated load on the centre node, the position giving the most adverse effect. Using Equation 12 the UDL becomes 0.9 kPa and the concentrated load 1.08 kN. Once the four panels were modelled using this different load arrangement the results were compared as shown in Table 6.3.

Table 6.3: Strand7 Deflection Results

Panel	Deflection (mm)	
	UDL	UDL & Conc. Load
Plywood	2.16	4.02
OSB	2.16	4.46
Aluminium	2.48	5.22
Steel	2.33	4.59

Results show that the formulae can accurately predict the panel’s behaviour when the load is applied as a UDL. For all four panels the deflection taken from Strand7 is below the limit of 2.5 mm. However, when the load is applied as a UDL and concentrated load as dictated by Australian Standards the deflection is almost double the allowable limit. Whilst the formulae are useful for determining the thickness of the core accurately under UDL they cannot be used when determining thicknesses of sandwich panel slabs.

6.3.2 Span/Thickness Tables

A different approach was considered that used an iterative method to determine optimum core thickness. Four spans of panel were modelled for the four different types of face materials at 1, 2, 4 and 6 metres. Each span was modelled in Strand7 four times with an increasingly thicker core and for each core thickness the mid-span deflection was recorded.

In the interests of computation time and efficiency the 1 and 2 metre spans were modelled with core thickness increments of 25 mm and the 4 and 6 metre spans were modelled with 50 mm core thickness increments. This served to keep the number of nodes and brick elements down in the finite element model and sped up the time taken to solve the model for the larger, thicker panels. For the models, mesh sizes were 50 x 50 mm by face material thickness and 50 x 50 x 25 mm or 50 x 50 x 50 mm for the core, depending on the spans.

Figure 6.2 shows a 1 metre span panel with 100 mm thick core and a 6 metre span panel with a 300 mm core. The 1 metre span is comprised of four 25 mm thick layers and the 6 metre span six 50 mm thick layers. The panels were analysed with the results shown below in Table 6.4.

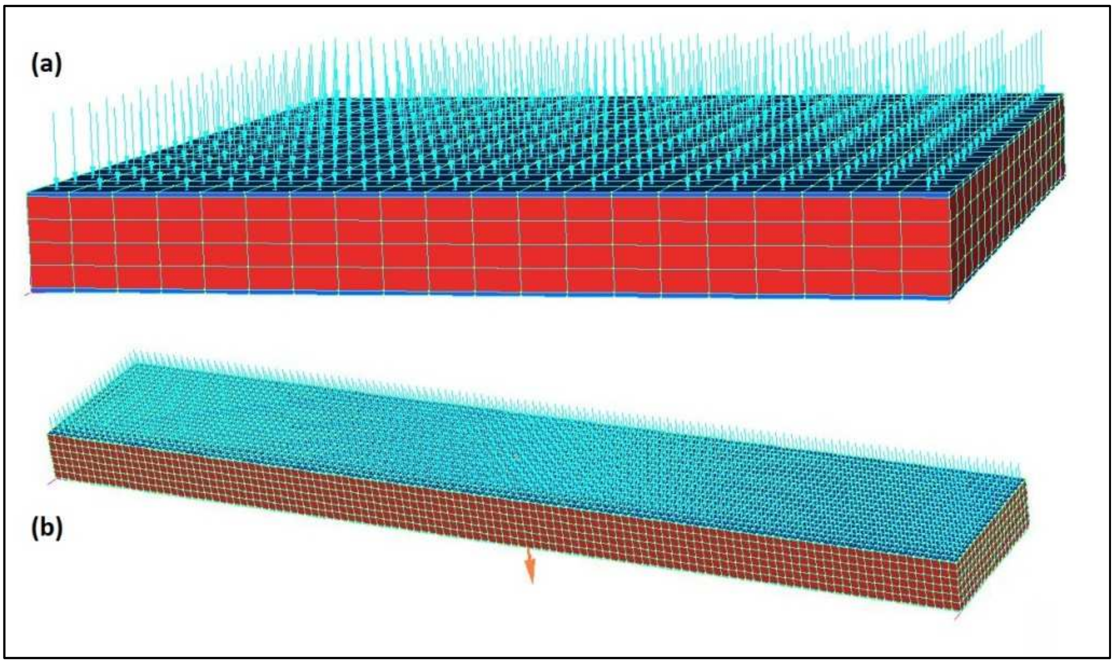


Figure 6.2: (a) 1 x 1m and (b) 6 x 1m panel in Strand7

Table 6.4: Thickness/Deflection

Length x Width	Plywood		OSB		Aluminium		Steel	
	Core (mm)	Deflection (mm)	Core (mm)	Deflection (mm)	Core (mm)	Deflection (mm)	Core (mm)	Deflection (mm)
1 x 1m	25	5.43	25	6.77	25	7.84	25	5.91
	50	3.26	50	3.62	50	4.00	50	3.31
	75	2.34	75	2.52	75	2.76	75	2.37
	100	1.87	100	1.98	100	2.17	100	1.9
2 x 1m	75	6.16	75	8.12	75	6.74	50	7.77
	100	4.6	100	5.76	100	5.01	75	5.31
	125	3.73	125	4.51	125	4.07	100	4.13
	150	3.17	150	3.75	150	3.49	125	3.45
4 x 1m	100	20.59	150	18.84	150	12.15	50	28.53
	150	12.02	200	12.53	200	8.77	100	12.63
	200	8.59	250	9.41	250	7.09	150	8.41
	250	6.85	300	7.65	300	6.12	200	6.56
6 x 1m	300	13.94	300	22.12	300	13.92	200	13.81
	350	11.75	400	14.96	350	11.85	250	11.18
	400	10.30	500	11.57	400	10.48	300	9.62
	450	9.23	600	9.71	450	9.54	350	8.6

Four plots for each type of panel were created with this data, one for each length panel. On each, the core thicknesses were plotted against the deflection to which a polynomial trendline was fitted that allowed the required core thickness at the limiting deflection to be read from the plot. Figure 6.3 shows the thickness/deflection data for the plywood panel plotted with the core thickness highlighted at the 2.5 mm deflection limit. Incidentally the required core thickness to achieve a maximum 2.5 mm deflection is 69 mm.

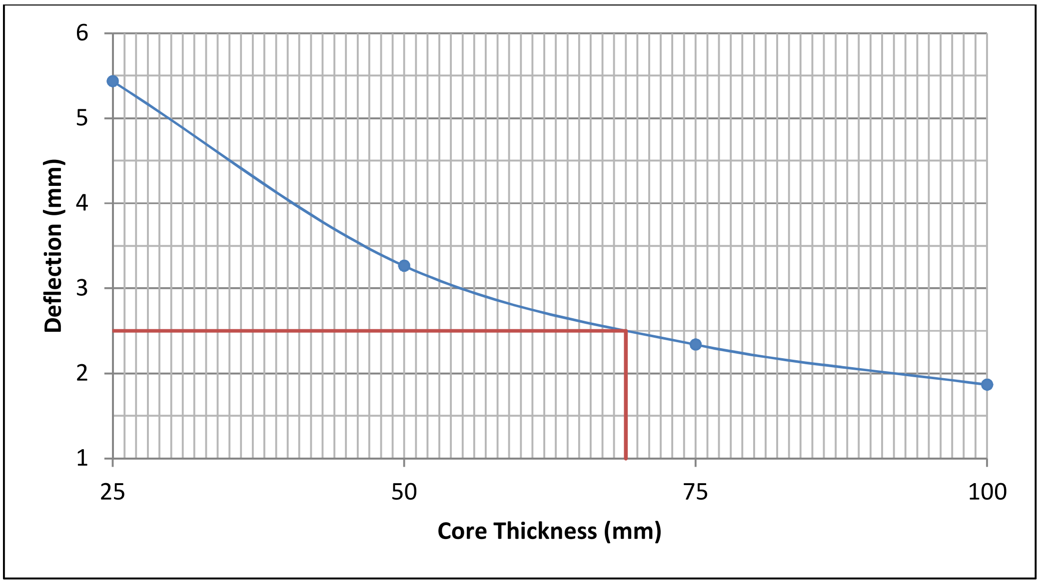


Figure 6.3: Thickness/Deflection plot for 1x1m Plywood Panel

16 plots were created in total to give the optimum core thickness for the given span as shown in Table 6.5.

Table 6.5: Optimum Core Thicknesses

Length x Width	Deflection (mm)	Core Thickness (mm)			
		Plywood	**OSB**	**Aluminium**	**Steel**
1 x 1m	2.5	69	76	84	70
2 x 1m	5	91	113	100	79
4 x 1m	10	173	238	180	120
6 x 1m	10	410	583	424	284

With the required core thickness for a range of spans now known, it was possible to plot this data for each panel. The resultant curve allows the optimum core thickness for any span between 1 and 6 metres to be read from the chart with ease. The decision to terminate at 6 metres was one of convenience from a manufacturing point of view as such length materials would be difficult to fabricate. Analysis using Strand7 for a plywood panel 8 metres long indicated a core thickness in excess of one metre which from a construction and cost point of view would be prohibitive if not impossible.

Figures 6.4, 6.5, 6.6 and 6.7 below show the span/thickness tables for the plywood, OSB, aluminium and steel panels developed using Strand7

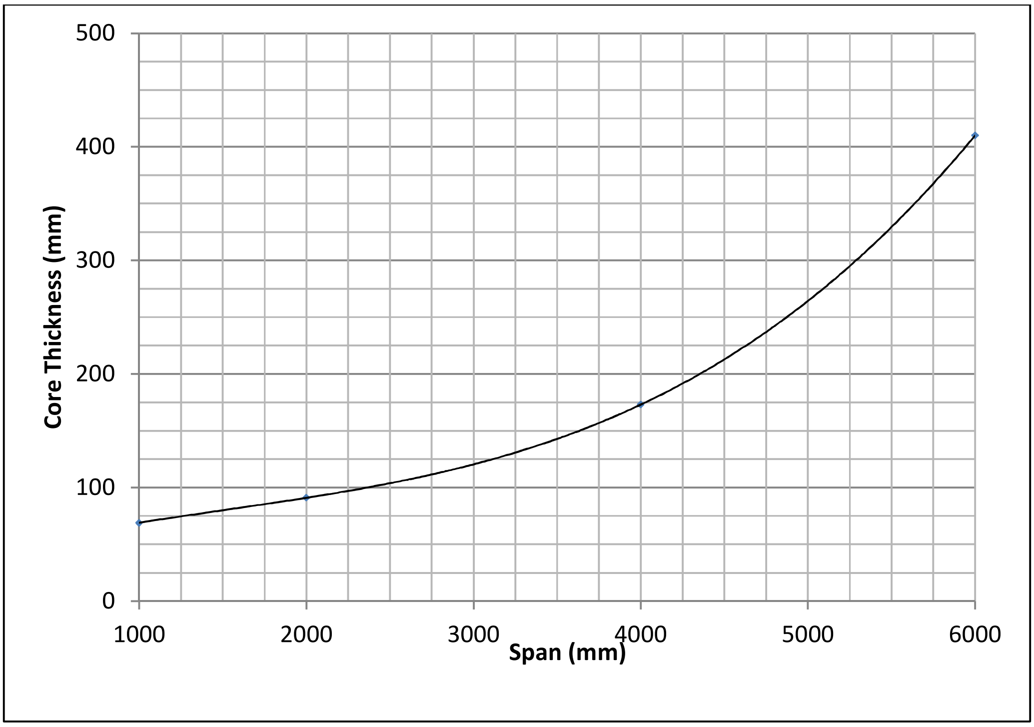


Figure 6.4: Plywood Span/Thickness Table

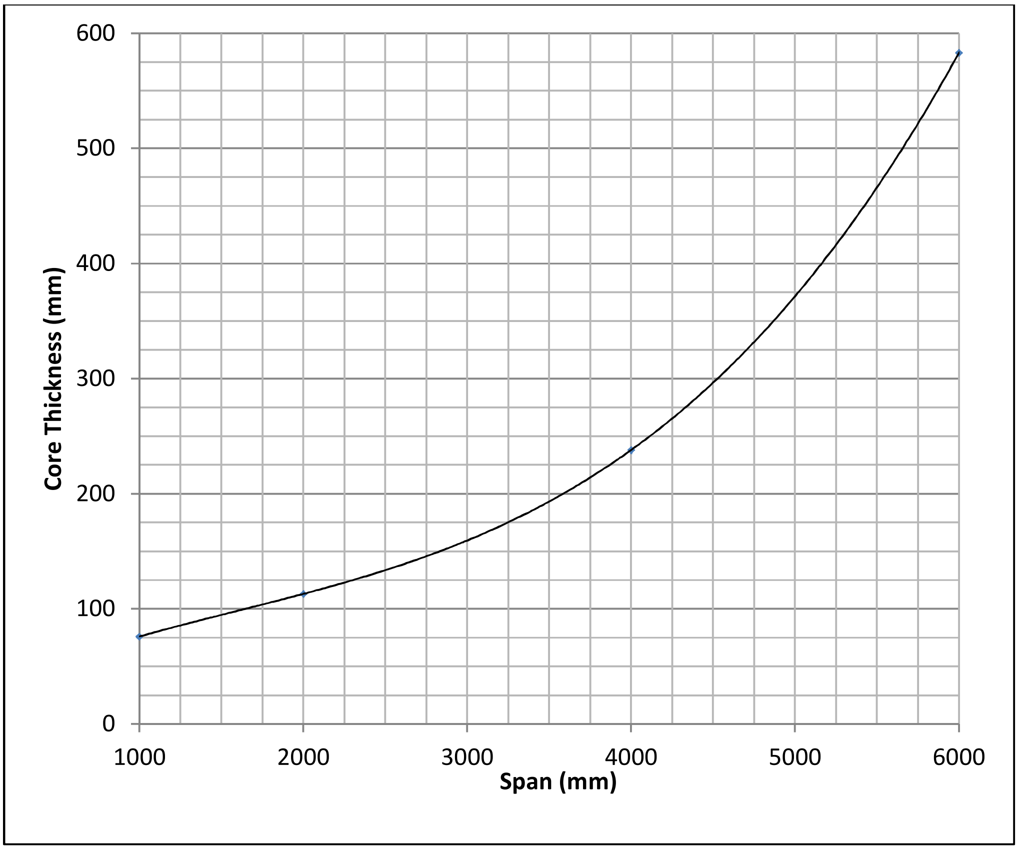


Figure 6.5: OSB Span/Thickness Table

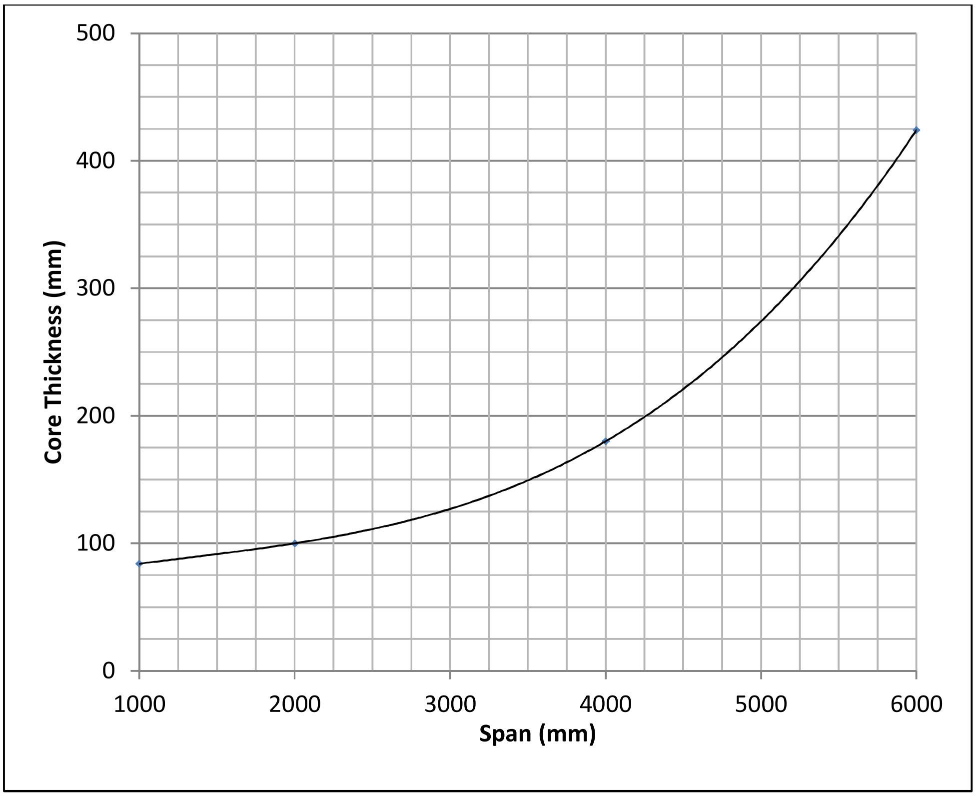


Figure 6.6: Aluminium Span/Thickness Table

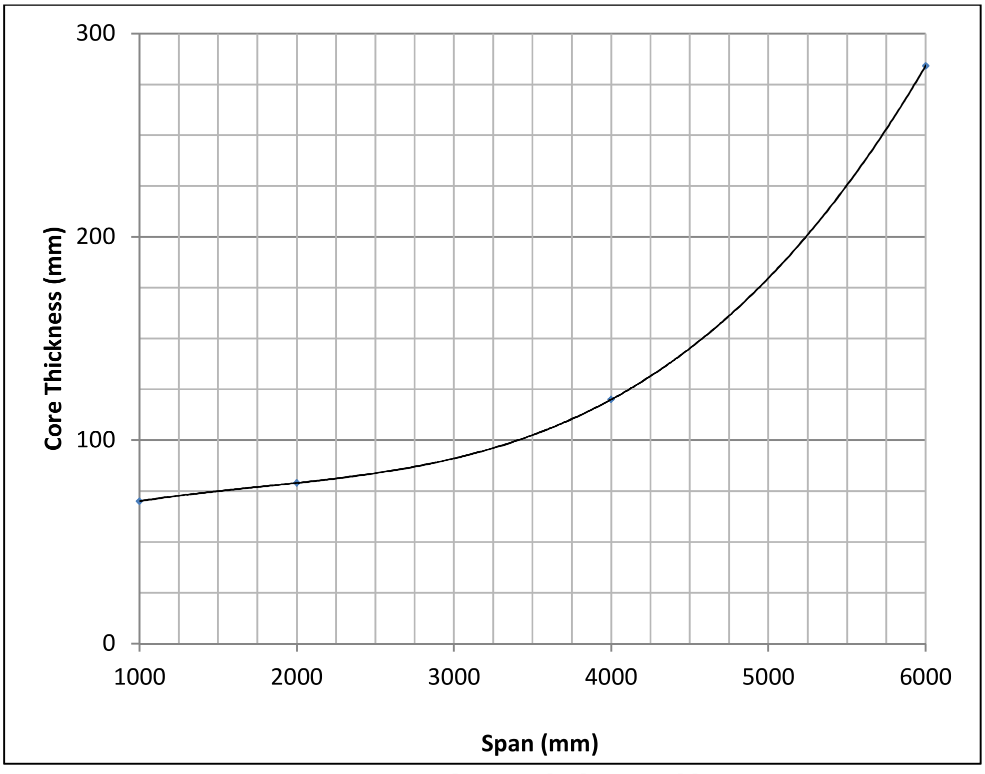


Figure 6.7: Steel Span/Thickness Table

6.4 Panels with Shear Connectors

Shear connectors were considered as a way of increasing the load bearing capacity of the panels, or to decrease the required core thickness for a given span. The idea behind the shear connector is a small rod or bar that connects the two faces of the panel through the core to reduce the shear between the face and the core. For the purpose of the Strand7 modelling the shear connector was treated as a 5 mm diameter steel rod.

Without spending considerable time reanalysing all of the panels created thus far, four of the plywood panels were selected, their dimensions shown in Table 6.6. These results should provide a good insight into whether the addition of shear connectors makes a significant difference to the performance of the panels and if the extra cost and effort to install the connectors is offset by the improved performance. Presumably, installing these shear connectors would involve a considerable amount of labour so the increase in panel performance would need to justify this.

Table 6.6: Dimensions for the Plywood Panels with Shear Connectors

Length x Width	Core Thickness (mm)
1 x 1m	100
2 x 1m	100
4 x 1m	200
6 x 1m	300

The 5 mm thick steel shear connectors were placed 50 mm in from the edge of the panel and spaced at 100 mm intervals in each direction. In Strand7 this was simply a matter of creating a beam element and defining the end node on each of the outer faces. Once the first beam element was created it could be copied in the x and z direction with ease. In Figure 6.8 a 1 x 1 m panel is shown with the core switched of so the shear connectors can be seen in green.

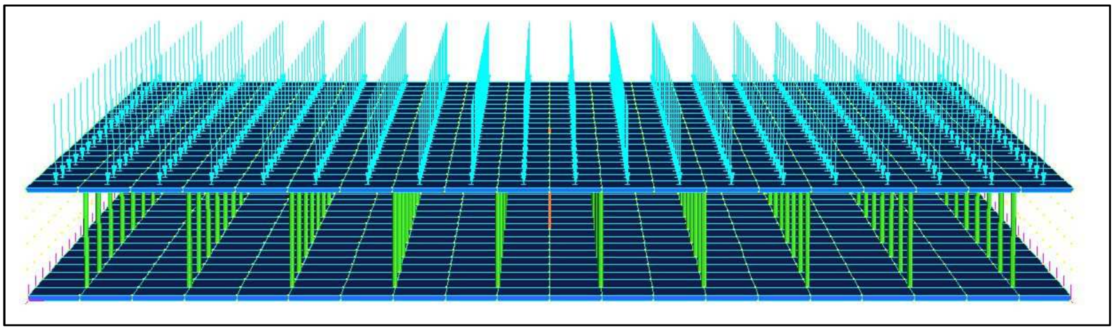


Figure 6.8: Sandwich Panel with Shear Connectors

These four panels were modelled the same way as the panels without the shear connectors and the deflection measured and compared. Figure 6.9 shows a comparison of the results.

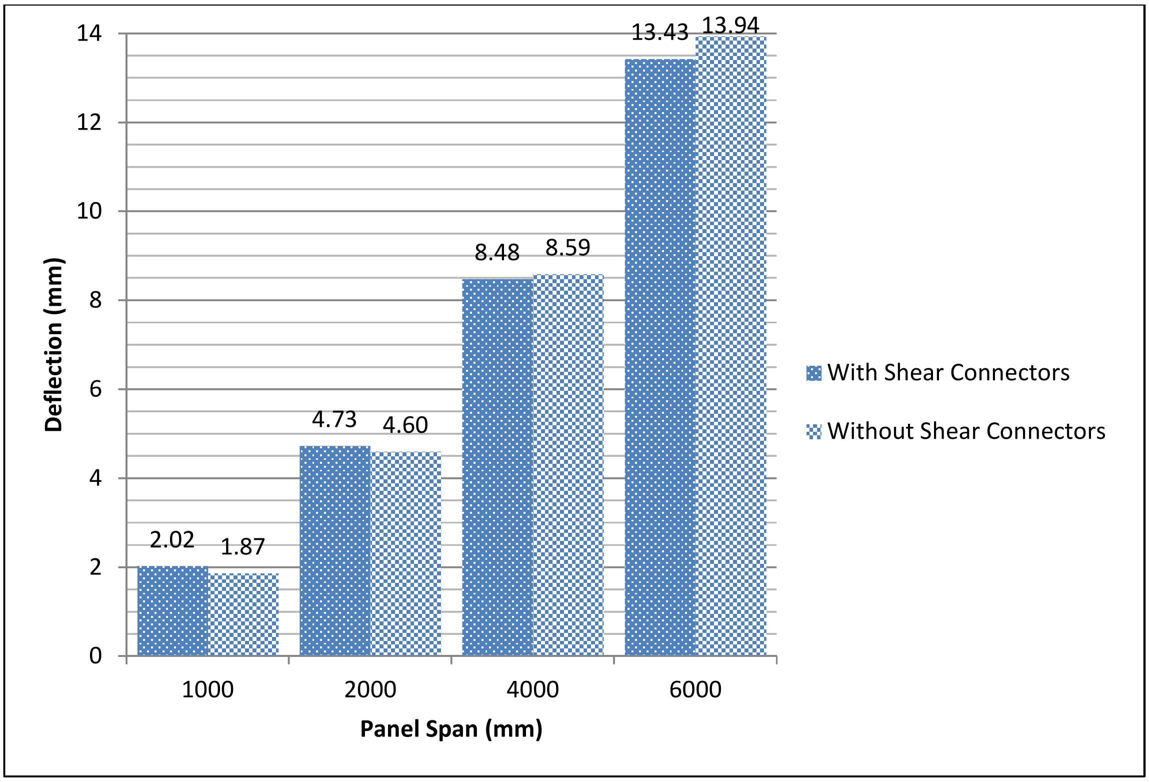


Figure 6.9: Shear Connectors

The results in Figure 6.9 seem to show very little difference between the panels with and the panels without shear connectors. For the 1 and 2 metre panels with shear connectors, deflection was higher, albeit marginally, than the panels without shear connectors so the addition of shear connectors is definitely not justified.

Deflection was less for the panels with shear connectors in the 4 and 6 metre panels when compared to the panels without connectors. In fact, it appears the panels with shear connectors perform better as the span increases. Realistically though, even at 6 metres, the shear connectors only reduce deflection by 0.51 mm. Half a millimetre less deflection hardly seems to make a solid case for the addition of shear connectors, so based on the analysis of the four plywood panels it can be concluded that adding shear connectors to sandwich panels provides no significant benefit.

6.5 Bamboo Materials Used in Panels

Chapter 2 discussed the use of bamboo fibre composites (BFC) as a construction material. There is much potential for the future development of BFC particularly as non-renewable resources spiral in cost and decrease in availability, as is happening with concrete, steel and old growth hardwood. An increased move towards sustainability in construction materials will require further discussion about the potential for BFC to be used as sandwich panel faces and cores.

6.5.1 Bamboo Faced Panel

Ashheim et al. (2010) carried out a study where a BFC I-joist was manufactured utilising either bamboo OSB or bamboo plywood as the flange material of the joist. In this study the researcher tested the materials to determine the modulus of elasticity which is presented below in Table 6.7 compared to those of the conventional OSB and plywood used in this study.

Table 6.7: Modulus of Elasticity values for OSB and Ply

Material	E (GPa)
Bamboo OSB	14
Conventional OSB	5
Bamboo Plywood	14
Conventional Plywood	16

The results for the conventional and regular plywood are on par however the bamboo OSB displays a markedly better modulus of elasticity than the conventional OSB. In Strand7 the modulus of elasticity for the conventional OSB was changed to that of the bamboo OSB and re-analysed to see how this affected deflection with the 1 m^2 panels. The values for poisons ratio and density were assumed to be similar to the conventional OSB as they could not be determined from the results presented by Ashheim et al.

Table 6.8: Comparing the deflection of Conventional and Bamboo OSB

Core Thickness (mm)	Deflection (mm)	
	Conventional OSB	Bamboo OSB
25	6.77	4.69
50	3.62	2.85
75	2.52	2.09
100	1.98	1.69

The results in Table 6.8 indicate that bamboo OSB should perform better than conventional OSB as a sandwich panel face although this would need to be confirmed by determining poisons ratio and density and performing laboratory tests. The fact the bamboo plywood displays very similar strength properties to conventional plywood is promising as it indicates that it would give similar results if used in sandwich panel slabs.

6.5.2 BFC Cored Panel

A BFC material consisting of 50% polyester and 50% bamboo fibre was used as the core in a sandwich panel as discussed in Chapter 4. This material was very lightweight, with a consistency slightly denser than an insulation batt, and appeared very soft to touch. Testing showed that the panels constructed with this BFC as the core material deflected significantly under very low loads making them unsuitable for use in sandwich panels in their current form.

Although this material is unsuitable it does present some interesting opportunities for the development of new materials and highlights the versatility of BFC. Perhaps if a denser material could be manufactured, or a resin injected to stiffen the materials, a more rigid material could be developed that would prove useful.

6.6 Discussion

As a quick check to see if the span/thickness tables are accurate a three metre span plywood panel was modelled in Strand7. From the table, the panel requires a 120 mm thick core and an allowable deflection of 7.5 mm. Modelling this panel in Strand7 gives a deflection of 7.628 mm which is very encouraging. It shows the tables are accurate and that the core thicknesses provided in these tables will give a sandwich panel that will perform as required.

The span/thickness curves for the four types of panel were combined to compare performance (Figure 6.10). Not surprisingly the steel faced panel is the best performer as steel is the strongest, most rigid, of the face materials and gives the thinnest cores. Plywood and aluminium show very little between their performances with plywood only slightly better. In this instance plywood panels might be considered the superior, not only for its smaller overall core thicknesses but a cheaper material and the fact the plywood is a quarter the weight of aluminium. OSB panels require the thickest cores for a given span which will increase the cost and weight of the panels and may make them an unattractive option.

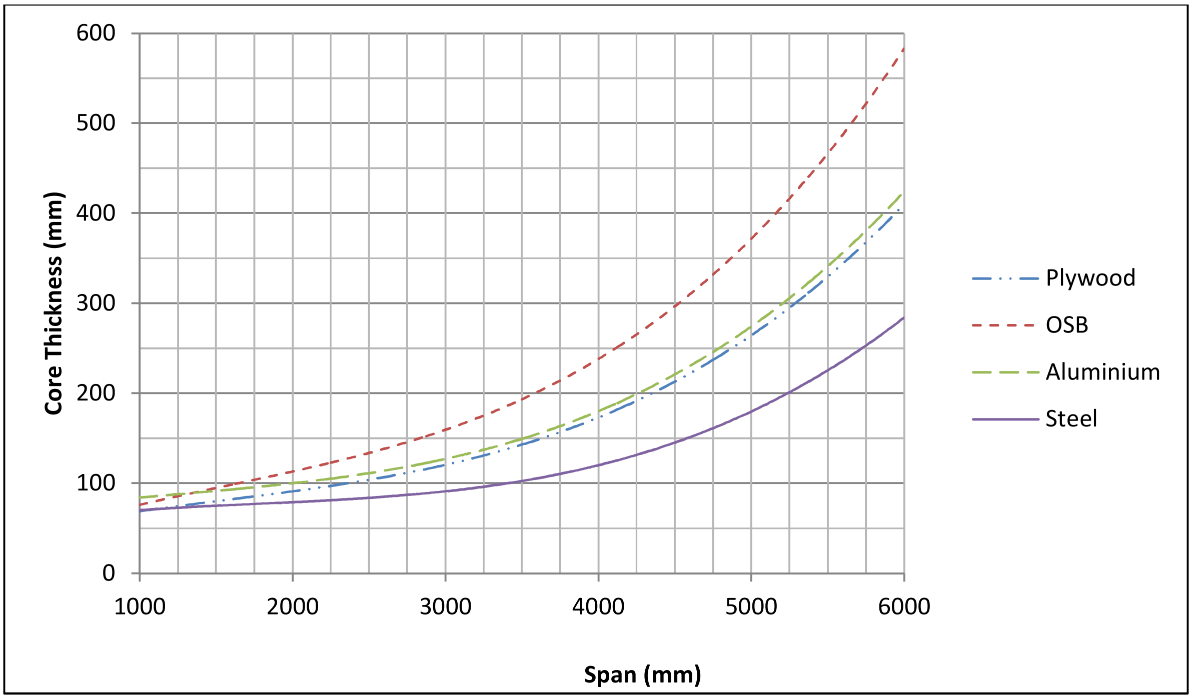


Figure 6.10: Combined Span/Thickness Curves

As discussed, there is a great potential for BFC to be used in sandwich panels. Currently research has shown very little difference between the strength properties of bamboo plywood and conventional plywood, while bamboo OSB performs better than conventional OSB. The key to ensuring the industry wide adoption of such materials is reliant not only on its strength abilities and its sustainability merits but also the cost of the material.

Construction firms would be unwilling to adopt new materials, regardless of its benefits, if the cost was significantly higher than conventional materials. While the cost of the bamboo materials are unknown it can be safely assumed that if they are only produced in small quantities then the cost of manufacturing these materials would be quite high when compared to mass produced OSB and plywood. Encouraging demand for the BFC would see cost savings achieved through mass production and economies of scale, allowing these new materials to compete with existing materials and allow the benefits of BFC to be realised.

7 Practicality of Sandwich Panel Slabs

7.1 Introduction

Previous chapters have shown the Strand7 modelling of sandwich panels as slabs to be valid and that FEA can be used to predict how sandwich panels perform when subjected to domestic floor loading. Further to this Strand7 has been used to develop span tables that provide the optimum thickness core for a given span and to show that formulae used to predict core depth under UDL are inadequate when a UDL and concentrated load is applied.

This chapter aims to discuss the practicality of sandwich panels as slabs and their potential uses. Firstly, the approximate cost of constructing a sandwich panel system will be compared to a conventional timber joist floor system. Situations where a sandwich panel system would be beneficial will be discussed as will the potential problems and drawbacks of using sandwich panels as slabs.

7.2 Panel Floor VS Conventional Floor

Typically, a conventional floor system in domestic Australian construction consists of timber joists 450 mm apart, spanning between timber bearers, with floor sheeting overlaid consisting of either particle board or plywood. In recent times, as timber resources become scarcer and new construction materials introduced, there has been a move towards engineered timber I-joists. These comprise of two laminated timber flanges separated by a 10 mm thick structural plywood web, with depths ranging from 200 to 400 mm and flange widths 45 to 90 mm (Dindas Australia 2012). If sandwich panel slabs were to be a viable alternative to conventional floor systems they would need to be price competitive and a lighter weight material to reduce labour costs and build time.

Material costs for the conventional floor system were provided by Trusstec Pty. Ltd. and comprise of 200, 240 and 360 mm joists, construction adhesive and 19 mm thick particleboard flooring. The material costs for the sandwich panels were based on the purchased price of the materials. On a larger scale these prices would be inaccurate as it would be expected that there would be some economy in purchasing in bigger quantities. These prices have been used however to give an indication of whether sandwich panels could compete with conventional floors based on price. Table 7.1 below shows the calculated cost of the materials.

Table 7.1: Material Costs

Item	**Cost (\$/m^2)**
Steel - 1.6 mm thick	\$38.19
Aluminium – 1.2 mm thick	\$34.38
Plywood – 4.5 mm thick	\$4.27
OSB – 6 mm thick	\$5.51
Particleboard Flooring – 19 mm thick	\$11.27
Particleboard Adhesive	\$1.05
Sandwich Panel Adhesive	\$14.00
Item	**Cost (\$/m^3)**
EPS Foam	\$613.00
Item	**Cost (\$/LM)**
200x45 Joist	\$7.50
240x45 Joist	\$8.74
360x63 Joist	\$14.34

Three spans of floor were analysed to determine the square metre cost of construction using the conventional method and the four kinds of sandwich panel. The spans considered were 2, 4 and 6 metres. In addition to this the weight of the floors were calculated as kg/m^2 to see if sandwich panel construction presented any significant weight savings over the conventional method of construction. Tables 7.2, 7.3 and 7.4 present the cost and weights of the 2, 4 and 6 metre span floors respectively.

Table 7.2: 2m Span Floor Cost and Weight

Material	Thickness (mm)	Cost ($/m^2)	Weight (kg/m^2)
Conventional	200	$33.15	21.95
Plywood	100	$80.17	8
OSB	150	$112.36	11.26
Aluminium	100	$110.28	10.08
Steel	100	$114.09	21.24

The conventional floor system is by far the most cost effective even at this small span being around a third to a quarter of the cost of the sandwich panels. At this span the plywood, OSB and aluminium panels are half the weight of the conventional floor system. Not only is the steel panel excessively expensive it presents little in the way of weight saving.

Table 7.3: 4m Span Floor Cost and Weight

Material	Thickness (mm)	Cost ($/m^2)	Weight (kg/m^2)
Conventional	240	$36.60	22.39
Plywood	200	$142.07	10.4
OSB	250	$174.26	13.66
Aluminium	200	$172.18	11.28
Steel	150	$145.04	22.44

Little has changed for the conventional floor system as the span increases to 4 metres. As the depth of the joist has only increased by 40 mm in the plywood flange of the joist the cost and weight increase is almost negligible. The remainder of the sandwich panels have almost doubled in price due to the expensive EPS core. Plywood, OSB and aluminium panels remain less than half the weight of the conventional floor while the weight of the steel panel has not changed drastically as the major weight component is the steel face not the lightweight core. The steel panel has become price competitive with the plywood panel and the aluminium competitive with the OSB panel due to the stronger metal faced panels requiring less of the expensive EPS for the core.

Table 7.4: 6m Span Floor Cost and Weight

Material	Thickness (mm)	Cost ($/m^2)	Weight (kg/m^2)
Conventional	360	$52.12	26.45
Plywood	450	$296.82	16.4
OSB	600	$390.91	22.06
Aluminium	450	$326.93	17.28
Steel	300	$237.89	21.24

At the six metre span the sandwich panels are not even close to being price competitive with the conventional floor. The cheapest panel, steel, is nearly five times more expensive than the conventional floor while the most expensive OSB panel approximately seven times more expensive than a conventional floor. As the steel panel requires the thinnest core, the least of the most expensive component, it is by far the cheapest sandwich panel option. Plywood remains the lightest of the panels coming in at 10 kg/m^2 lighter than the conventional floor. Steel once again is the heaviest although 5 kg lighter than the conventional floor.

It is easy to see from these calculations that the most significant cost of the sandwich panels is the EPS foam core. This becomes more apparent as spans increase and larger amounts of EPS are required to construct the panel. These cost comparisons are fairly basic and based on the costs of small amounts of materials purchased in one off transactions. Simple economics suggests that if EPS were manufactured in commercial quantities and purchased in bulk by sandwich panel manufacturers that the cost would reduce.

Testing and FEA has shown that sandwich panels can be used as floors and the many benefits of sandwich panel have been discussed at length throughout this research paper. To be a viable alternative to conventional floor systems they need to be price competitive otherwise there would be little chance of widespread adoption. A way of reducing the cost of the EPS foam core needs to be investigated if sandwich panels are realistically going to be used as floors.

7.3 Construction Uses

While the cost of manufacturing the panels may not make them an attractive construction material as yet there are still many benefits to using sandwich panels. This section discusses these uses and also introduces the concept of the “lookup chart”, a quick reference guide that allows the panel thickness to be quickly read from a chart.

It is important to remember when discussing the construction uses of sandwich panels that they are currently used for roof and wall construction with great success. Construction of entire dwellings out of sandwich systems is not an unrealistic proposal.

7.3.1 Lookup Charts

From a manufacturing point of view it would be difficult to produce every different thickness core for every different span of panel. This would involve time consuming and costly retooling or adjustment of manufacturing equipment and these capabilities may not exist. A more sensible approach would be to create a standard increment to which the panels could be manufactured which would reduce the number of different core thicknesses required. If possible the foam could be glued together in layers to make the thicker cores.

The following charts consider the core being manufactured in 50 mm increments. The previously developed span/thickness tables were used to create these charts with each chart giving a range of spans that are suitable for the core thickness. If sandwich panel slabs were to achieve industry wide adoption, charts similar to these could be distributed to builders and contractors so they would know the required panel dimensions and order them without requiring any design work.

Figures 7.1, 7.2, 7.3 and 7.4 show the lookup charts for the four types of panel. 100 mm was selected as the smallest core panel and would be used for anything under a 1 metre span. For the most part the core increments are 50 mm except in the large span OSB panels were the core increased at a greater rate for the span increase. For these panels the core increased from 300 mm to 600 mm in 100 mm increments.

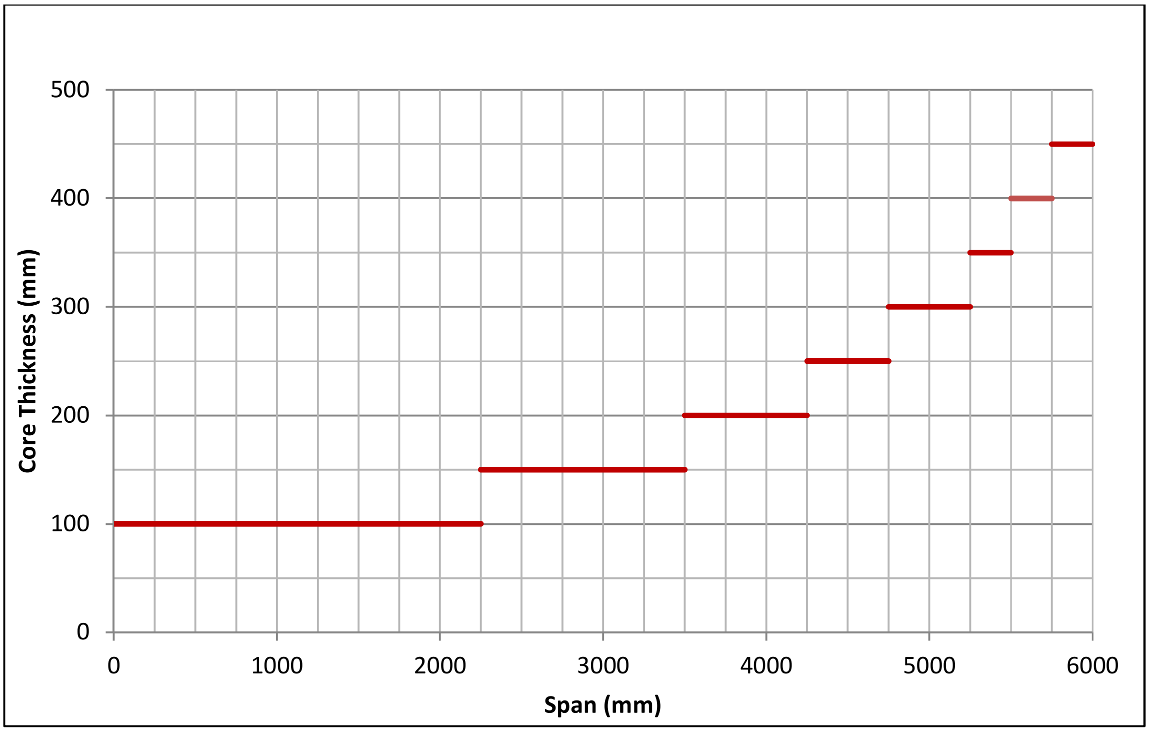


Figure 7.1: Plywood Panel Lookup Chart

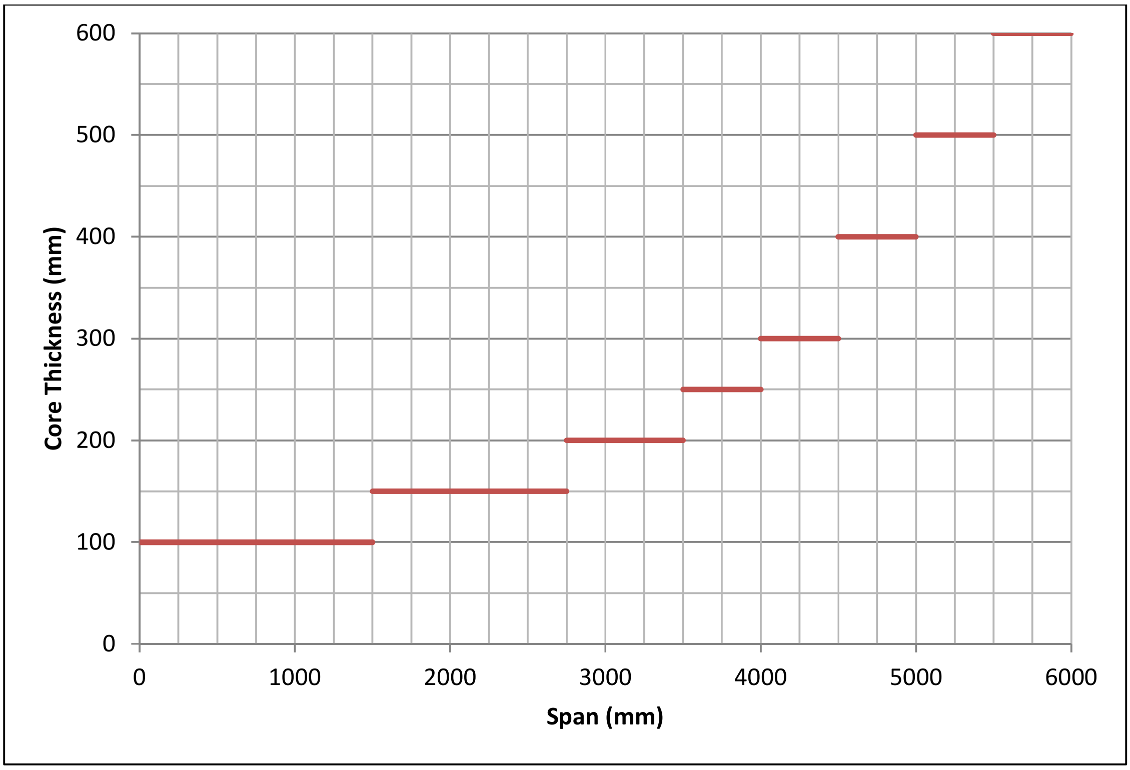


Figure 7.2: OSB Panel Lookup Chart

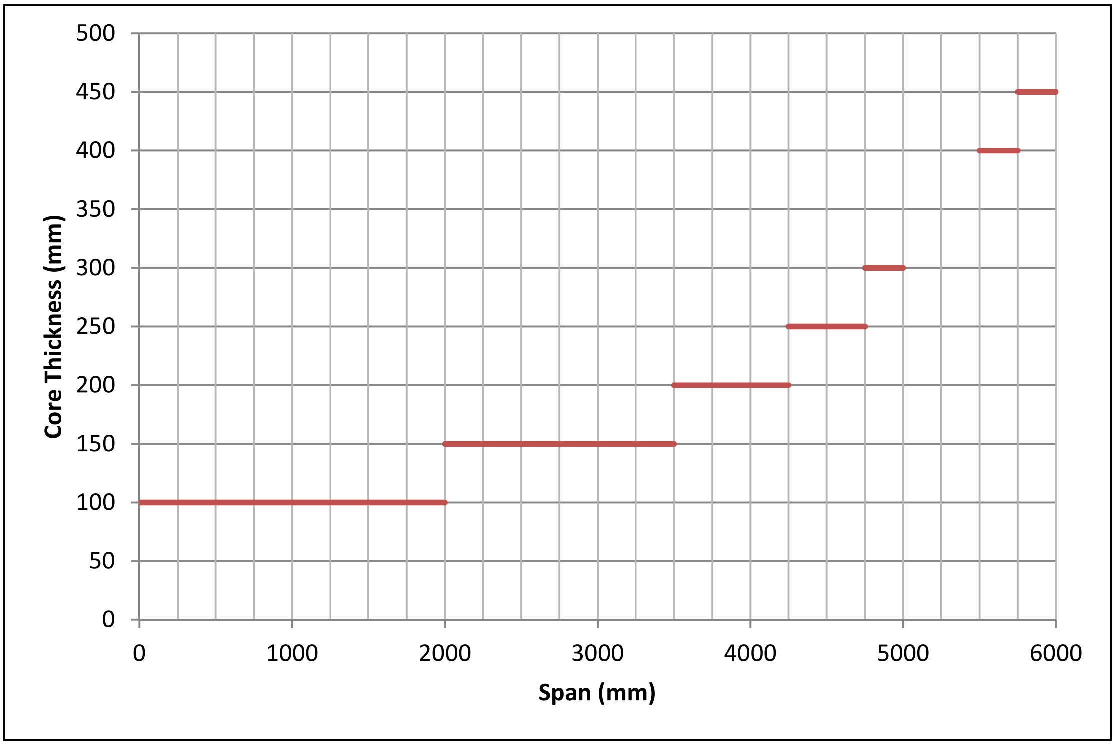


Figure 7.3: Aluminium Panel Lookup Chart

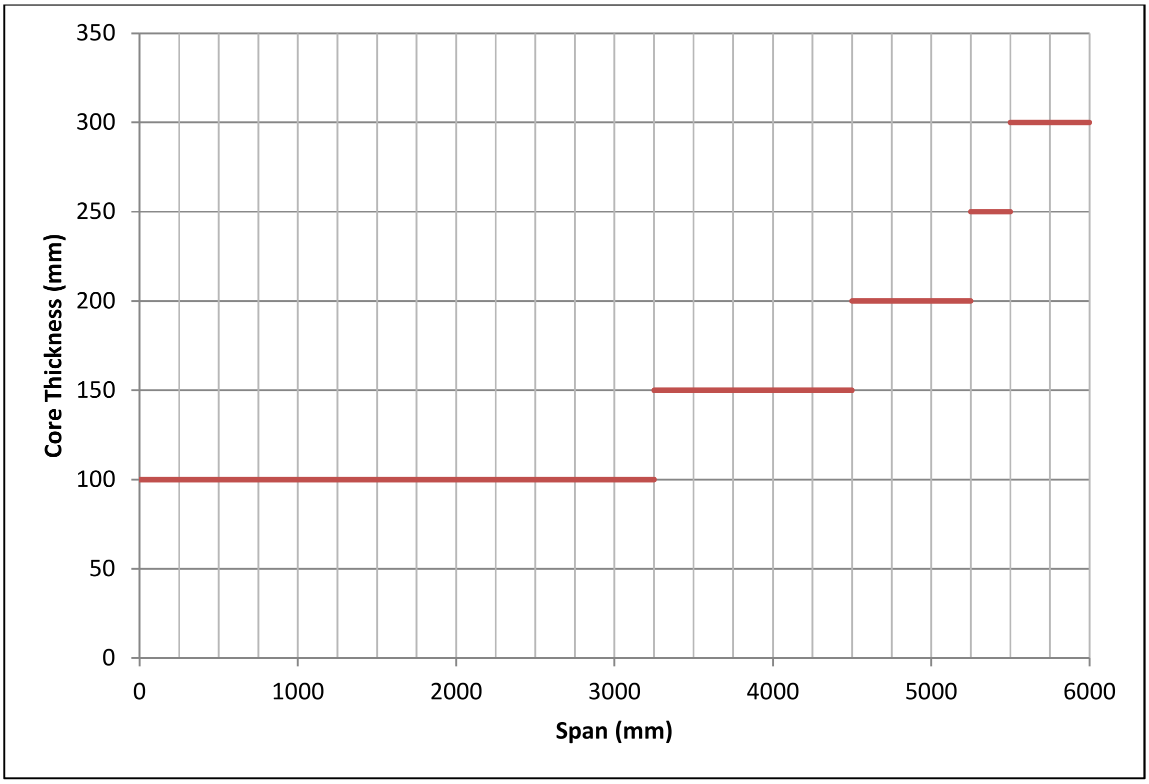


Figure 7.4: Steel Panel Lookup Chart

7.3.2 Low Cost Housing

Based on the cost calculations done in this study, sandwich panels are not an attractive option however this has not considered the already commercially available floor and wall systems. If a way was found to reduce the cost of materials to below conventional materials there could be a market for low cost sandwich panel houses. Cost savings could be achieved in labour and erection as well. The panels are lightweight which would help with materials handling onsite and the internal and external finishes could be applied in the factory. If a timber faced panel were being used, such as the plywood or OSB, a light oiling or protective coating may be the only surface finish required.

Sandwich panel construction could potentially be used to quickly erect shelter in post disaster situations. Sandwich panels could be assembled to provide basic shelter for those in need and would be particularly useful in overpopulated areas in developing countries where there may be large amounts of affected people and little other options available for shelter or relocation. In these situations no floor or wall finishes need be applied, the materials could be sent as is from the manufacturer.

7.3.3 Remote Mining or Indigenous Communities

The same benefits outlined above apply to housing in remote mining camps or indigenous communities where the functionality of the dwelling may be the priority rather than the aesthetics or “street appeal”. Simple, functional dwellings could be designed and mass produced to be sent to these remote locations and erected without requiring a large labour force to travel to these locations. In fact, sandwich construction may present employment opportunities for indigenous communities where local labour could be used to assemble these kit style homes with relative ease and supervision from a qualified tradesperson.

A major benefit in using sandwich panel construction in remote locations is the weight of the material, particularly the timber faced panels. Lighter material means more can be sent per truckload reducing the number of trips and saving on freight charges. A lighter load would also mean less fuel is used per load which not only reduces the cost of the trip but has positive environmental implications as well.

7.3.4 Flood Prone Areas

Sandwich panels could also be used in flood prone areas. They are well sealed off units providing an inherent vapour barrier and are not really susceptible to water damage if a suitable finish is applied to the face. In flood damaged properties, when the water subsides, the interior of the dwellings needs to be stripped and the structure repaired. This would not be the case with sandwich panels as there would not be any water penetration into the structure. Once the flood waters subside it may simply be a matter of clearing out and hosing down any remaining mud and debris

7.3.5 Developing Countries

All of the above mentioned reasons make sandwich panel construction suitable for developing countries. The materials could be sent to remote regions of the country were housing and suitable materials are in short supply. These homes could be constructed in factories as kits ready to be assembled and then transported to areas where there is less infrastructure and skills available to build housing. Local labour could be employed to assemble the kit homes.

Flood prone areas in developing countries are typically more populated than in developed countries with a good example of this being the 2010 floods in Pakistan where 20 million people were directly affected by flooding (Wikipedia 2012). If sufficiently robust sandwich panel housing could be constructed to withstand the force of the flood waters then the dwellings could be quickly cleaned out and put to use as the panels would not be damaged by water absorption. Again, panels could be easily transported and erected in the affected areas to assist the displaced.

Employment opportunities exist in every facet of manufacturing sandwich panels from the manufacturing of the face material, to the assembling of the panel and the distribution and erection of the structure. This could greatly benefit developing countries particularly as the labour cost would be much less than if produce in a developed country which would reduce the cost of the panels. There is potential here to utilise cheaper labour costs to open up an export market for the panels which could boost the economy in developing countries.

Using timber to construct the face materials could also help stimulate the manufacturing and timber plantation industry in developing countries and carry with it all of the environmental benefits that come with using a sustainable resource. Again the cheaper labour costs would make an attractive export option so even if the panels were to be assembled in developed countries the face materials could be sourced from developing countries. The abundance of bamboo in Asia and its incredible replenishment rate makes bamboo plywood and OSB ideal materials to be used in sandwich panels and the growth of these industries in Asia should be encouraged. It is important though to ensure timber sources in developing countries are renewable and not harvested from rainforest or habitats for endangered animals

7.4 Problems

Despite the benefits of using sandwich panels as slabs there are a number of issues that limit their practicality. This is most evident in the construction of large span panels. Current manufacturing setups may not be able to produce long lengths of the materials and may need costly reconfiguring before continuous long lengths of the face and core materials can be produced. Currently structural plywood and OSB used in the construction industry are supplied in up to three metre lengths so there would need to be some consideration as to how these larger spans could be manufactured.

The sandwich panel slabs may not be sufficient to withstand other loads from the structure. If the external walls of the house are built over the sandwich panel supports, as is the case with conventional floor construction, there may be some crushing of the panels at the bearing. This would be more apparent if the roof of the structure was made of concrete or terracotta tiles rather than metal sheeting. It would require some sort of bearing block or spacer at the support to prevent crushing and to protect the panel.

No dead load for floor finishes was applied to the panels in this study. Tiled floor finishes may not be possible due to the extra load from the tiles and grout as this extra weight would increase core thickness and may make sandwich slabs impractical. As an alternative to tiled flooring a lightweight alternative like carpet or vinyl maybe required. It is possible that a timber face could be oiled or stained to make an attractive floor finish although this may allow undue wear and tear on the surface and reduce the life span of the panel.

Metallic surfaces probably wouldn’t be suited to slab application despite their strength properties. Steel is prone to rust and aluminium is very soft and can dent easily, not very useful for floors which receive a lot of traffic. Metal conducts electricity which also makes these panels quite unsafe. An electrical fault would have the potential to liven up a large area of the floor which is dangerous and potentially life threatening.

Getting construction firms to adopt this way of building over conventional methods may be difficult as there would be some reluctance to change; as the old saying goes “if it isn’t broke don’t fix it”. There would need to be as significant advertising or education programme within the industry to broadcast the benefits of this method of construction.

Another drawback is that this method is suited to mass produced, standardised housing, not bespoke, architecturally designed housing. Typically plumbing, electrical and mechanical services are contained within the floor structure however with sandwich panel slabs they would need to run below it. This would not be a problem for single storey houses however with two storey houses the services would need to be hidden somehow. Also it is yet to be seen what happens to the structural integrity of the panel if holes were cut through to allow these services to run up into the dwelling. That being said there is definitely a niche market for sandwich panel slabs that could be exploited in time if the cost of the panels were reduced.

8 Conclusion and Recommendations

8.1 Summary

This study has examined the use of sandwich panels as slabs, particularly sandwich panels with EPS foam cores. An in-depth literature review was conducted that identified previous analytical and experimental studies and assisted in determining the direction for the rest of the study. After selecting steel, aluminium, plywood and OSB for the face materials the thinnest available sheets of these materials were obtained and four small sandwich panels were made using a 50 mm EPS core.

These four panels were tested under three-point bending in the laboratory with the applied load and mid span deflection recorded. This data was plotted to create load/deflection curves. Using the Strand7 software package, finite element analysis was carried out whereby the sandwich panels used in the laboratory test were modelled to see if the physical test results could be simulated. Results from the computer model were in agreement with the test results, so the conclusion was drawn that Strand7 could be used to simulate different spans and thicknesses of panel subjected to actual floor loading as stipulated by Australian Standards.

Three formulae were used to determine the thickness of the sandwich panel core with respect to the method of failure. For these formulae to work the load needed to be applied as a uniformly distributed load, however AS1170 requires a UDL and a concentrated load which rendered these formulae unsuitable with results from the computer modelling confirming this. Further iterative finite element analysis was undertaken which allowed span/thickness charts to be generated using the required load of the UDL and concentrated load. These charts can be used to look up the optimum core thickness for a given span for any of the four types of sandwich panel.

The remainder of this chapter discusses the achievements of the objectives, conclusions made from the research and analysis and some recommendations for further work.

8.2 Achievement of Objectives

Chapter 1 listed the specific objectives this project was trying to achieve. Each of these objectives is discussed below with the extent to which the desired outcomes were met.

1. *Research various types of sandwich panels to establish a number of different parameters involved in making different types of sandwich panel.*

The main outcome of this objective was to learn what sandwich panels were and their function. This was achieved through an in depth literature review where research identified the outcomes of previous experimental studies. This led to EPS foam being adopted for the core and plywood, OSB, steel and aluminium being selected for the face materials. The literature suggested when designing sandwich panels to select the thinnest available face materials and designing the core thickness to suit.

Part of the literature review involved researching and understanding the ways in which sandwich panels can fail. Research found different formulae that calculate the load at which sandwich panels should fail and formulae to determine the core thickness which were tested in the experimental study and finite element analysis. Natural fibre composites were researched with a view to potentially using a bamboo fibre composite as a sandwich panel core.

2. *Select four skin materials from available resources, construct these panels and test them for structural behaviour*

Chapter 4 describes the experimental study where sandwich panels were constructed and tested under three point bending. Prior to constructing the panels, four adhesives were tested to determine the strongest and most suitable for constructing the panels. Before the tests the expected failure loads were calculated for each panel. During the tests however neither the failure load nor the panel behaviour were as expected and the actual failure mode was also unexpected.

Despite these differing results data was successfully gathered for each panel. This enabled the load and deflection to be compared using computer models of the panels later in the study. In addition to this, a panel was constructed using plywood for the face and layers of a bamboo fibre mat as the core. This panel was not tested in a machine as it did not appear structurally sound. Basic testing was successfully done by adding weights to the panel and measuring deflection using a tape measure. This gave a very good indication of the structural behaviour of this panel.

3. *Perform a Finite Element Analysis (FEA) on these panels in Strand7,* and
4. *Compare experimental results to FEA in order to validate the Strand7 model.*

The same panels that were tested in the laboratory were modelled using finite element analysis in Strand7. Chapter 5 describes the steps taken to create these models and to generate an output. Results from Strand7 were plotted against the results from the laboratory tests to see if the deflection of the panels was similar for the same applied load. This comparison of results found that in the linear range results were within 10% which is satisfactory. The computer models were validated which meant Strand7 could be further used to model sandwich panels in floor slab scenarios.

5. *Carry out a FEA analysis to determine the optimum core thickness for each skin material for a range of spans*.

In Chapter 6, AS1170 was used to determine the required load for a domestic floor which was applied to the four sandwich panels in Strand7. AS1170 required a limiting deflection of Span/400 which was used when calculating the optimum core thickness. Three formulae found in the literature review were used to calculate the core thickness for a number of panels and these were modelled in Strand7. The results of these tests showed the formulae were unsuitable to model panels under floor loading so a different approach was taken.

For each of the four types of panel different core thicknesses were modelled for spans of 1, 2, 4 and 6 metres and the deflection recorded. The deflection data for each span was plotted against core thickness so that the minimum span for the limiting deflection at each span could be determined. This data was successfully used to create span/thickness charts for the four sandwich panels.

6. *Make recommendations on use of these panels in actual slab applications based on weight, cost and structural performance.*

In Chapter 7 conventional floor systems consisting of I-joists and particle board flooring were compared to sandwich panel floor systems. The aim was to determine which had the least cost and weight. Information on the weight, cost and structural performance of conventional floors was obtained from a timber supplier and the cost of the sandwich panel materials was based on the actual retail costs of the materials.

Naturally as a floor system spans further it costs and weighs more so the square metre costs and weights of the floor systems spanning 2, 4 and 6 metres were calculated. Results found the conventional floor system to be much more cost effective than the sandwich panels and the weight savings from sandwich panels was much more for smaller spans, although still quite good at larger spans.

7. *Suggest using these panels in developing countries and make recommendations for further research.*

Chapter 7 discusses the practical construction uses for sandwich panels slabs and in particular their use in developing countries. The main benefits of sandwich panels in this situation lie in their ability to be easily erected and to be transported quickly to where they are required. This chapter also highlights the potential to develop manufacturing and export markets in developing countries which would provide employment opportunities and stimulate economies.

8.3 Conclusions

A broad conclusion that can be drawn from this research project is that all four of the sandwich panels built, tested and modelled could be used for slab applications. Sandwich panels provide an alternative to conventional timber floors and suspended concrete slabs and have many inherent weight and thermal benefits. Although the steel faced panels performed best in the study, plywood faced panels should be given the most consideration because of their sustainability merits and the fact it can be easily produced from renewable plantations. Cost comparisons done in this study found sandwich panel floor systems to be much more expensive than convention floor systems mostly due to the cost of the EPS foam core. It could reasonably be expected that widespread adoption of this system would see cost reductions in the materials due to economies of scale achieved by mass production.

8.4 Recommendations for Further Work

This research project has shown that sandwich panels can indeed be used for slab applications and highlighted the potential for them to become a mainstream building product used in a wide range of projects. The scope of this paper was fairly narrow and leaves room for further work into studying the benefits and uses of sandwich panels as slabs. Some recommendations for further work are as follows:

- Conduct further tests in three-point bending to further verify the validity of the Strand7 model. The validity of the model was based on testing only one of each type of panel. More panels should be made and tested to see if the results can be replicated. These tests should aim to find out if the method of failure is the same for further tests.
- Testing under real life loading should be conducted if possible. Instead of testing panels under three-point bending panels should be tested with a UDL and concentrated load as required by AS1170. Results from these tests would verify, or disprove, the Strand7 models under this loading arrangement.

- More could be done to test the outputs of the span/thickness tables. Spans and thicknesses could be randomly selected from the charts and modelled to see if these results are accurate. This would involve a serious investment in time and resources not available during this study.
- Study further the use of shear connectors. Only a small number of panels were analysed with shear connectors to compare their deflection to that of the panels without shear connectors. Different size and spacing arrangements for the connectors could be trialled using Strand7 to see if their addition created a significant reduction in deflection.
- Create a finite element model using a smaller mesh to improve accuracy. The mesh size in Strand7 could be reduced which would improve the accuracy of the results however even with a mesh size of 50 x 50mm computation time was upwards of 5 minutes for the larger panels. If a smaller mesh size was to be used a half or quarter sized model would be needed to ensure computational time and efficiency is not reduced.
- Investigate different loading scenarios. AS1170 provides loading requirements for commercial and industrial applications. Further research could be conducted to find out how this loading affects the core thickness of the panels.
- Find alternative suppliers and research material costs. When investigating the cost of different panels in the study, the prices were based on what was actually paid for the small amount of materials used to build the four test panels. Further work could be done to find alternative suppliers with cheaper prices and also to find out the benefits of mass producing EPS and if this would reduce the cost enough to make sandwich panels price competitive.
- Model sandwich panel slabs by applying a dead load for floor finishes e.g. tiles or carpet to see what effect the extra load has on the thickness of the panel.

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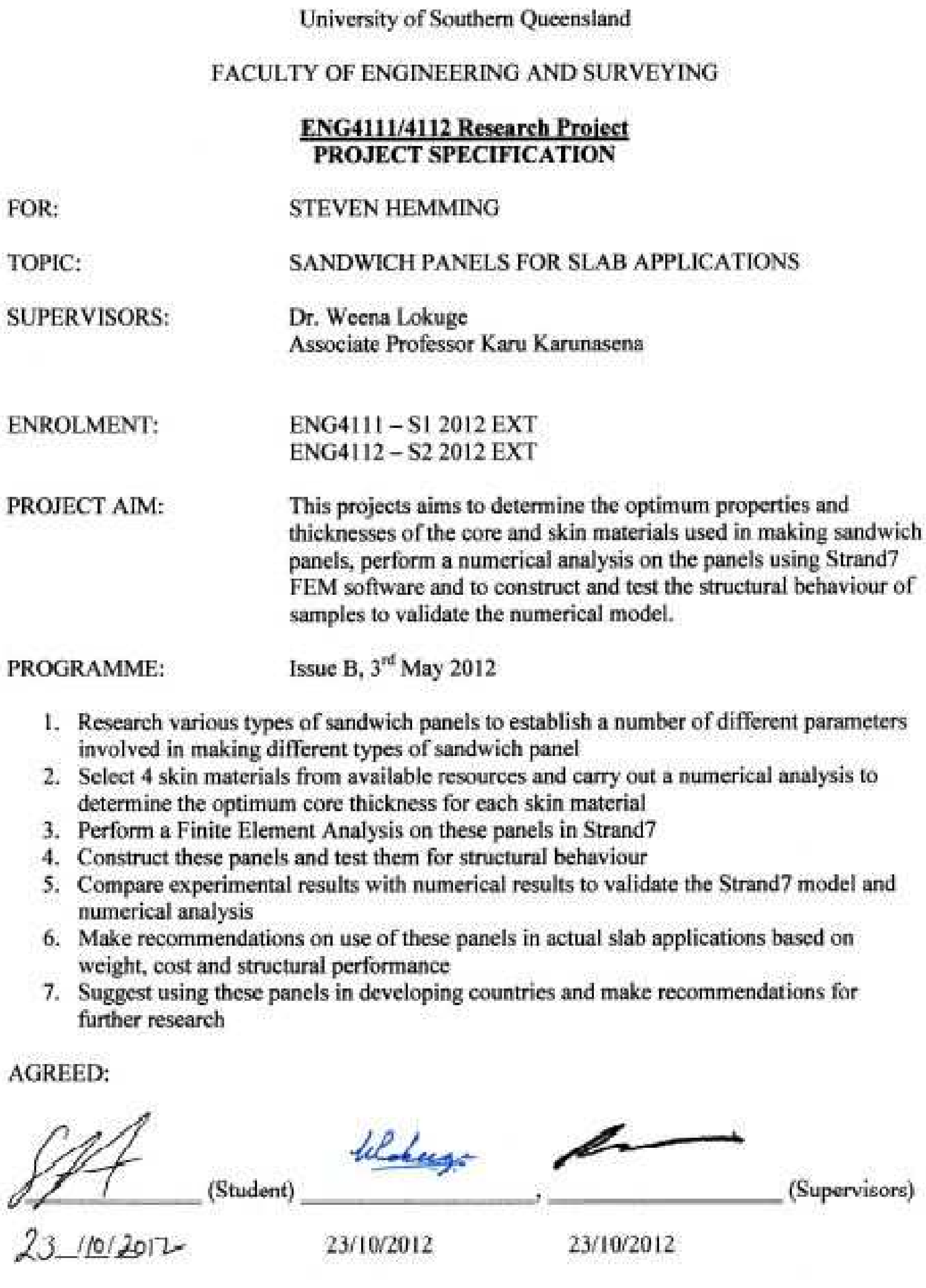
Appendix A – Project Specification



University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR:	STEVEN HEMMING
TOPIC:	SANDWICH PANELS FOR SLAB APPLICATIONS
SUPERVISORS:	Dr. Weena Lokuge Associate Professor Karu Karunasena
ENROLMENT:	ENG4111 – S1 2012 EXT ENG4112 – S2 2012 EXT
PROJECT AIM:	This projects aims to determine the optimum properties and thicknesses of the core and skin materials used in making sandwich panels, perform a numerical analysis on the panels using Strand7 FEM software and to construct and test the structural behaviour of samples to validate the numerical model.
PROGRAMME:	Issue B, 3rd May 2012

1. Research various types of sandwich panels to establish a number of different parameters involved in making different types of sandwich panel
2. Select 4 skin materials from available resources and carry out a numerical analysis to determine the optimum core thickness for each skin material
3. Perform a Finite Element Analysis on these panels in Strand7
4. Construct these panels and test them for structural behaviour
5. Compare experimental results with numerical results to validate the Strand7 model and numerical analysis
6. Make recommendations on use of these panels in actual slab applications based on weight, cost and structural performance
7. Suggest using these panels in developing countries and make recommendations for further research

AGREED:

_______________ (Student) _______________, _______________ (Supervisors)

23/10/2012 23/10/2012 23/10/2012

Appendix B – Risk Assessment

This study required panels to be manufactured and tested in a laboratory and as such there was a risk involved from the power tools, material handling, adhesives and machinery. Also there was a risk from frequent computer use when compiling this report. These risks are described in terms of how significant the risk is and how frequently there was exposure to the risk during the study. Measures used to control and mitigate the risks are discussed

Hazard: Computer Use

Hazard Description	People at Risk	Injury	Risk / Exposure	Control
Overuse of computer	Computer user	Fatigue, eyesight strain, wrist injury, back/neck soreness	Significant risk, frequent exposure	Frequent breaks, stretching

Hazard: Power Saw

Hazard Description	People at Risk	Injury	Risk / Exposure	Control
Splinters, spinning blades, cut power lead, noise	Operator	Equipment damage, minor personal, major personal	Slight risk, very rarely exposure	Operate in a safe manner, wear PPE

Hazard: Adhesives and Solvents

Hazard Description	People at Risk	Injury	Risk / Exposure	Control
Fumes, skin irritation	Operator	Inhalation, nausea, minor soreness	Significant risk, very rarely exposure	Use as directed, wear PPE

Hazard: Laboratory Testing

Hazard Description	People at Risk	Injury	Risk / Exposure	Control
Flying debris, Crushing	Machine operator, observers	Minor to major personal	Slight risk, rarely exposure	Wear PPE, Stand behind safety screen, keep hands clear

Hazard: Materials Handling

Hazard Description	People at Risk	Injury	Risk / Exposure	Control
Back injury, Splinters	Person handling	Minor Personal	Slight risk, frequent exposure	Correct procedure, wear gloves

Hazard: Disposal

Hazard Description	People at Risk	Injury	Risk / Exposure	Control
Incorrect disposal	Environment	Environmental - pollution	Minor	Waste taken direct to landfill

Appendix C – Resource Analysis

Item	Supplier	Availability	Purchasing Arrangement	Cost
Aluminium Sheet	Millers Steel	Stock	Student to purchase	≈ $70 per sheet
Steel Sheet	Millers Steel	Stock	Student to purchase	≈ $50 per sheet
OSB	Trusstec	Stock	Donated by Trusstec	Nil
Plywood	Trusstec	Stock	Donated by Trusstec	Nil
Adhesive	Hardware Store	Stock	Student to purchase	≈ $10 small pot ≈ $40 large pot
Tools	Student	Student owns tools	N/A	Nil
Workshop	Trusstec	After business hours	N/A	Nil
Laboratory	USQ	Booking Required	N/A	Nil
Computers & Software	Student & USQ	All times	N/A	Nil
Staff Services	USQ	Depends on staff	N/A	Nil

Appendix D – AS1170.1 Floor Loading

Below is an excerpt of the imposed floor actions as per AS1170.1 showing the type of activity / occupancy and the required loading used in the study.

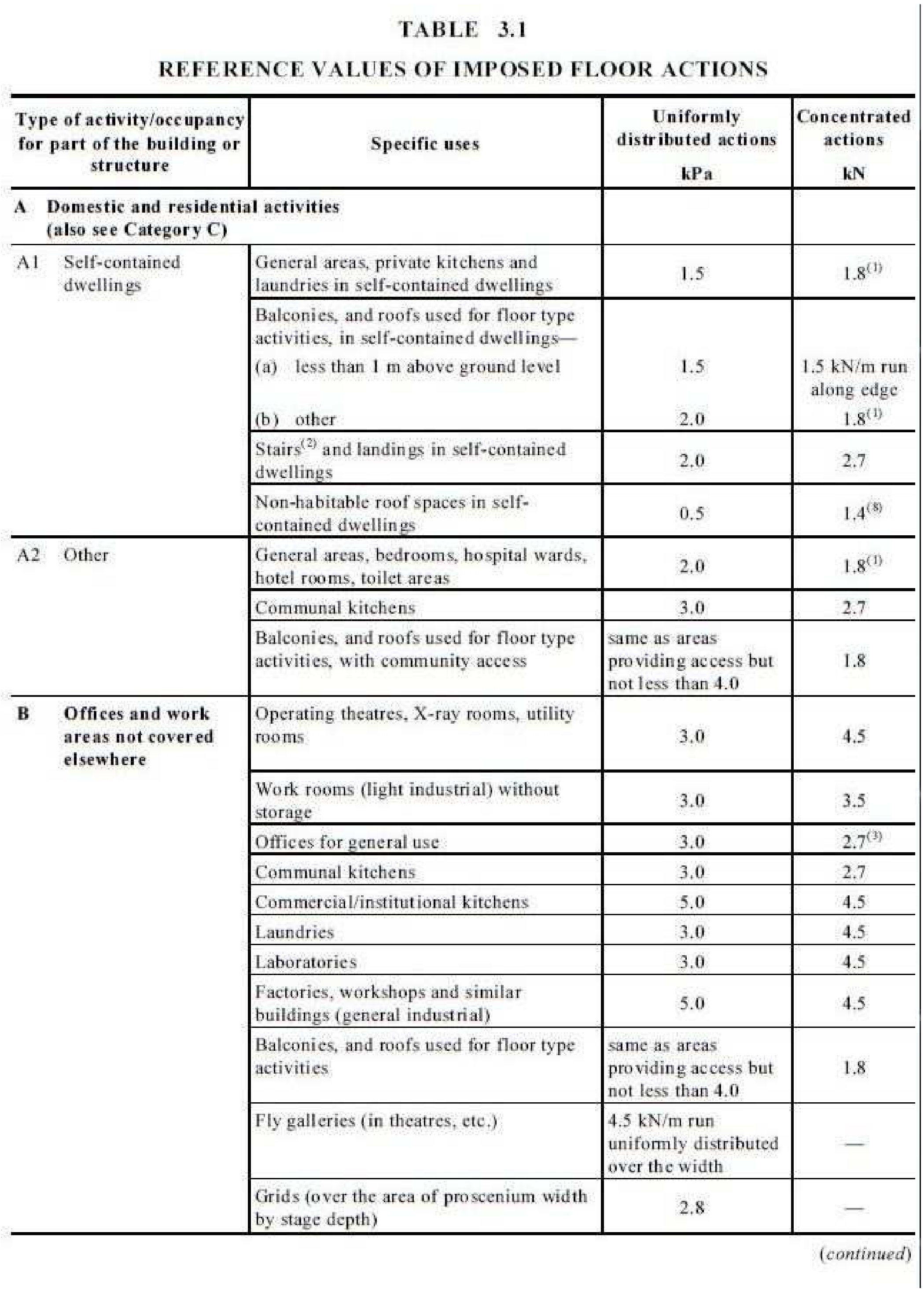


TABLE 3.1

REFERENCE VALUES OF IMPOSED FLOOR ACTIONS

Type of activity/occupancy for part of the building or structure	Specific uses	Uniformly distributed actions kPa	Concentrated actions kN
A Domestic and residential activities (also see Category C)			
A1 Self-contained dwellings	General areas, private kitchens and laundries in self-contained dwellings	1.5	1.8(1)
	Balconies, and roofs used for floor type activities, in self-contained dwellings— (a) less than 1 m above ground level (b) other	 1.5 2.0	 1.5 kN/m run along edge 1.8(1)
	Stairs(2) and landings in self-contained dwellings	2.0	2.7
	Non-habitable roof spaces in self-contained dwellings	0.5	1.4(8)
A2 Other	General areas, bedrooms, hospital wards, hotel rooms, toilet areas	2.0	1.8(1)
	Communal kitchens	3.0	2.7
	Balconies, and roofs used for floor type activities, with community access	same as areas providing access but not less than 4.0	1.8
B Offices and work areas not covered elsewhere	Operating theatres, X-ray rooms, utility rooms	3.0	4.5
	Work rooms (light industrial) without storage	3.0	3.5
	Offices for general use	3.0	2.7(3)
	Communal kitchens	3.0	2.7
	Commercial/institutional kitchens	5.0	4.5
	Laundries	3.0	4.5
	Laboratories	3.0	4.5
	Factories, workshops and similar buildings (general industrial)	5.0	4.5
	Balconies, and roofs used for floor type activities	same as areas providing access but not less than 4.0	1.8
	Fly galleries (in theatres, etc.)	4.5 kN/m run uniformly distributed over the width	—
	Grids (over the area of proscenium width by stage depth)	2.8	—

(continued)

Appendix E – Raw Data from Laboratory Tests

The amount of raw data collected for each panel in the laboratory test is vast and reproducing this data in this dissertation is impractical. A full copy of the raw data will be provided as a separate attachment on the submission CD.

Appendix F – Linear Static Solver Results

Presented below are the linear static solver results for the panels modelled in Strand7. The laboratory test results were compared to these results to validate the finite element model.

Load (N)	Strand7 Deflection Results (mm)			
	Plywood	OSB	Aluminium	Steel
0	0	0	0	0
100	0.58	0.66	0.70	0.59
200	1.15	1.32	1.40	1.18
300	1.73	1.98	2.10	1.77
400	2.30	2.64	2.80	2.36
500	2.88	3.30	3.50	2.95
600	3.46	3.96	4.20	3.53
700	4.03	4.62	4.90	4.12
800	4.61	5.28	5.60	4.71
900	5.18	5.94	6.30	5.30
1000	5.76	6.60	7.00	5.89
1100	6.34	7.26	7.70	6.48
1200	6.91	7.92	8.40	7.07
1300	7.49	8.58	9.10	7.66
1400	8.06	9.24	9.80	8.25
1500	8.64	9.87	10.50	8.84
1600	9.22	10.56		9.42
1700		11.22		10.01
1800		11.88		10.60
1900		12.54		11.19
2000		13.20		11.78
2100		13.86		12.37
2200		14.52		12.96
2300				13.55
2400				14.14