University of Southern Queensland

Faculty of Health, Engineering and Sciences

Finite Element Analysis of a Hybrid Natural Fibre Sandwich Wall Panel Loaded with In-Plane Shear

A dissertation submitted by

Shane Michael Collier

Supervised by Y. Zhuge

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Abstract

The world is rapidly growing and the need for sustainable materials is increasing. This project analysed a newly developed hybrid sandwich panel with in-plane shear loading in Strand7, finite element analysis software. The objective was to determine if adding natural fibre composites as intermediate layers between the core and skins would decrease the shear stresses within the core as well as reviewing the extension caused by the loading.

This was completed by the creation and use of 2D and 3D models within Strand7. These models were validated by comparing the linear results against Dr. Fajrin's experimental testing results. The 2D models used the classic laminate theory and tested the diagonal extension as well as the overall shear stress within the panels. The 3D models used extruded plates and tested for the diagonal extension as well as shear stresses within each layer of the model. A convergence study was also done within Strand7 to determine the optimal mesh when considering accuracy, computational time and workability. It was found that an 80x80 mesh was suitable for the analysis and offered the best results based on the testing criteria.

Four natural fibre composites were analysed and tested to see if they could aid in strengthening the sandwich wall panels mechanical properties. These fibres were jute, medium density fibres, hemp and sisal. The results were compared to the control panel which consisted of just an expanded polystyrene core and aluminium skins.

Overall the results found that the jute and medium density fibres were viable whilst the hemp and sisal fibres increased the shear stress within the core making them redundant. Jute in both analysis' showed better results. The 3D results were able to provide a more detailed and in-depth analysis of likely real world results compared to the 2D laminated models. Non linear analysis was also trialed however due to time constraints could not be finalised. It was found that the models were not transitioning to a non linear state because the skins were absorbing more than 99% of the loading thus not putting enough strain on the core to allow for deformation. Further analysis of this section is recommended as future work.

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Certification of Dissertation

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

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

S. Collier

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1.0 Introduction

As global development occurs the demand on sustainability increases and so composite materials must be researched and developed as a solution to this ongoing problem. As the competitive construction market grows, so does the need for cost efficient and adequate materials. Currently the materials needed for the highly demanded housing is lacking behind and so the price of these materials increases which doesn't promote sustainability and a solution to this situation. This stands as a key challenge of today's engineer to meet these criteria in the industry. Composite sandwich wall panels aim to be cost efficient, sustainable and structurally adequate. They are an upcoming solution to the current problems as they offer low self weight and easy construction allowing for mass distribution and use of the composite structures.

1.1 Project Background

Composite panels were originally used in aerospace structures and aircraft because of their easy construction and engineering properties that they offered compared to their self weight. This would make aircraft cost less as the turbine requirements would be less and thus smaller motors installed. However today research is being conducted to try expand the use of composite panels into other industries and uses. Sustainability has always been of a highly contested nature as manufacturers look to produce materials that offer high supply, easy construction and low weight with high structural properties. The ongoing development of composite panels has enabled it to become a viable economic material in other fields than aerospace engineering as it is now used in construction and civil fields.

The ongoing challenge within composite panels is to find the optimum hybrid panel that offers low weight, uses lesser resources (and possibly environmentally friendly resources), good insulation and high engineering properties. Such developments are only recent and this project will aim to create a finite element model, validated by Dr. Fajrin's experimental tests, of a possible hybrid panel.

1.2 Project Aims

The aim of this project is to research the effects of in-plane shear on a new hybrid sandwich panel using Strand7, a finite element analysis software. Dr. Fajrin experimentally tested several iterations of possible hybrid sandwich panels and found an ideal combination of materials which was tested via bending and in-plane shear.

The major objective of this project is to develop a finite element model (FEM) of a sandwich panel under in-plane shear. Dr. Fajrin's testing results will be used to validate the model so analysis on it can be completed as well as allowing for a parametric study. This study will aim at finding the optimum configuration of layers of the sandwich panel.

1.2.1 Requirements

This project requires the following requirements:

- Reproduce a 2D model of the panel
- Test the 2D model to ensure correct Strand7 use
- Reproduce a 3D model of the panel
- Test the 3D model based off experimental hybrid panel
- Compare the experimental results and the Strand7 results
- Analyse the results and perform a parametric study on the optimal configuration

1.3 Constraints

This project is completed via Strand7 which is accessible 24 hours 7 days a week at the University of Southern Queensland Springfield Campus. As an undergraduate project this project will be completed under the supervision of Assoc. Prof. Yan Zhuge. Due it this project being an undergrad project then a full Strand7 analysis including bending cannot be completed and as time permits a parametric study of the optimal design can be included.

1.4 Project Objectives

The project objectives have been specified in the project specification in Appendix A and listed as followed:

1. Research background information on composite wall panels under in-plane shear load.
2. Design a basic 2D model of the composite wall panel while continuing research.
3. Develop the complex 3D model and compare to experimental results.
4. Validate the model.
5. Analyse the finite element model for its materialistic properties and results.
6. Evaluate the results and produce a conclusion.

As time permits:

7. Undertake a parametric study to find the optimum design of the sandwich panel.

2.0 Literature Review

2.1 Sandwich Panel Background

Composite sandwich panels were initially designed and used for aerospace construction. It served as a good structure due to its engineering properties and low weight to strength ratio. Over the past few decades the composite sandwich panels have been recognised as a suitable alternative to many other construction materials and now have a wide set of uses and applications (Marshall, 1998). Composite sandwich panels are now used in a diverse range of fields such as aircraft, both military and space, boats and also the construction industry as doors, windows and other components that don't carry loads. Recently however structural insulated panels (SIP) have been used in the construction as structural components. Sandwich composite panels are today starting to be used for urban housing however further research and testing is required to find out the optimal compositions.

When composite structures initially became used in the construction industry, as stated above, they were primarily used for non structural members such as doors and windows. This limitation was primarily due to the limit adhesives available at the time which featured casein glue and urea-formaldehyde with wooden cores and skins (Marshall, 1998). As Marshall's research suggested, as new adhesives were developed they became more diverse and functional leading to the recent advancements of using sandwich panels as structural components. The advancement of adhesives allowed for more combinations of materials and allowed composite structures to support loads, specifically in walls and roofing.

As mentioned above, SIPs have recently gained popularity for use as structural components in construction. Tracy (2000) described a SIP as, in its most basic form, two facings covering a core which are bonded via a industrial grade adhesive. The most common core materials are extruded polystyrene (XPS), polyurethane and expanded polystyrene (EPS). The facings or skins are generally a form of metal, wood or oriented strand boards (OSBs) with the OSBs comprising of the vast majority of SIPs (Kelly, 2009). An OSB can be defined as layers of bi-directional small rectangular strips of wood bonded together via resin and wax adhesives. Combinations of vast materials are a possibility for SIPs as long as the facings or core do not have a negative chemical reaction with the adhesive that could compromise the mechanical properties of the composite. Another benefit of SIPs is their construction cost, time and labour required (Tracy, 2000). Arguably, the greatest advantage of using a SIP is the fact that the structural component as well as the insulation are included in the composite which allows an achievable higher amount of structural support and thermal effectiveness (Kermany, 2006).

2.2 Sandwich Panel Structure

The structure of a composite sandwich panel is generally slim but strong skins with a thick and lightweight core. This general set up is also accustomed to the core having a high stiffness in the direction normal to the skins of the panel (Davies, 2001). The skins material are typically a metal however can be a broad range of materials such as wood, aluminium, plastic, concrete and steel (Engineered Materials, 2012). Additionally the cores are very diverse in the fact they can be wood, plastics, foams or cheaper metals. There are however multiple types of core structures, Davies (2001) listed a few key successful ones as being expanded plastic, honeycomb and mineral wool cores. These individual structures have their advantages and disadvantages.

The most basic structure of a sandwich wall panel is outer skins covering a core material bonded via adhesive. Figure 2.1 shows a very basic set up of a sandwich panel using a honeycomb core. There are many materials and core structures available in many combinations, in fact almost any material in the form of a thin sheet can act as a skin for the panel (Zenkert, 1995), which is a key factor of why composite structures are so advantageous in multiple situations and hence their increase in popularity and usages. However on the contrary Zenkert (1995) also found that certain combination of cores and adhesives were not compatible as certain plastics can have chemical reactions to certain adhesives.

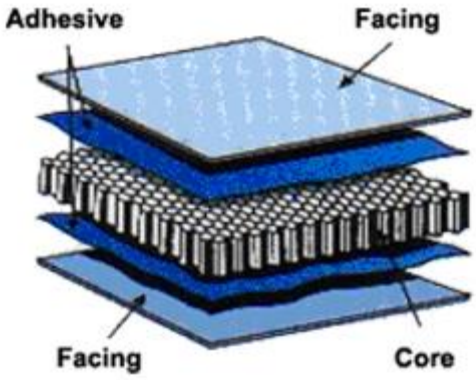


Figure 2.1: General structure of sandwich panel (Engineered Materials, 2012)

Davies (2001) noted that the general configuration of composite structures lies in its high stiffness and strength to low weight ratio. Along with this several advantages include cost, transportation ease, construction ease, good insulation and low requirement of resources. Sandwich panels in terms of construction have several advantages including low maintenance cost, rapid construction, easy to repair and replace as well as easy to mass produce. Sandwich panels, as explained earlier, are recently being expanded and used in the construction industry for buildings and houses. It has been found that the ideal combination of materials for walls or roofs is thin steel or aluminium facings engulfing a low density plastic core (Davies, 2001). These materials produce ideal mechanical properties that are suitable in a housing environment as they contain protection from vapour, corrosion, weathering and human induced accidental damage.

The three main components of any sandwich structure is the core, adhesive and facings, also known as skins. Each component serves an important task in the composite as a whole (Davies, 2001). The core will help enforce the skins against buckling and more importantly resist shear loading. The core also attributes to the structures high section modulus and is the thickest component. The adhesive helps transfer the shear loading between the skins and core as well as increase shear resistance and to prevent slipping. The facings act simultaneously under external bending moments.

Sandwich panels configuration however does have its limitations. Due to the nature of having multiple components joined together this can cause some complications. As Zenkert (1995) stated, some combinations of materials and adhesives are not compatible and this causes more extensive research required in order to find ideal combinations. The failure mechanisms of sandwich panels are also quite complex as extensive knowledge of the base materials are required in order to try predict the strength, stiffness and other elements. The biggest problem composite panels suffer from is shear failure and wrinkling (Mostafa et al. 2013) due to the configuration nature however alternatives such as shear keys, various adhesives, fibre orientation (Zhou and Stronge, 2005) and increased skin quality (Grenestedt and Reany, 2007) are all being researched to try to aid in solving this problem. As further research is conducted and the failure criterion of sandwich panels are understood better than the wider usage of sandwich panels will occur.

This section explained the basis of the sandwich panel configuration. Sandwich panels generally have three layers which are two facings, or skins, and a core which are all bonded via adhesive. As sandwich panels develop there is a new concept of hybridisation, which can include introducing new layers or elements to the composites however this will be discussed in detail in section 2.4. The possibilities and combinations of materials in sandwich panels is very diverse and with the right modifications the future of sandwich panels for use as structural components in houses and buildings is a certainty.

2.3 Natural Fibre Composites in Sandwich Panels

With growing attention to sustainable building, research has begun investigating the use of green construction within composite structures. Specific focus has gone into the use of natural fibre composites (NFCs) however there are other alternatives available such as wood plastic composites (WPCs) and glass fibre reinforced polymers (GFRPs). NFCs and WPCs make up the vast bulk of sustainable composites currently in use or being researched.

NFCs are composites of synthetic/bio resins mixed with natural fibres to form a composite that is environmentally better than other options. Natural fibres, defined as animal and vegetable bio-based fibres, are made out of four possibilities, these are hemp, jute, sisal and bamboo. These materials can be found plentifully in developing countries and therefore produce good candidates for use in sandwich panels in developing areas. In addition to being environmentally beneficial than other alternatives they contain many advantages such as having high toughness, noise reduction, low energy requirement in construction, easy altercation and production, low density, decent strength properties and high toughness (Suddel and Rosemaund, 2008).

According to Suddel and Rosemaund (2008) NFCs already have several applications in the construction industry such as floor, wall and roof covers, light structural walls and can act as insulators. Currently NFCs are challenged in several attributes such as low moisture, stiffness and impact resistance, thermal sensitivity, bio-fibre properties and unavertable bio-degradation over time (Drzal et al, 2004). Further testing is currently undergoing to try improve on the NFCs weaknesses such as altering the natural fibres with chemical agents (Reddy et al. 2010). The use of NFC's as described above make them a suitable candidate for use in hybrid composite structures, this terminology will be discussed in the following section.

NFC are a relatively recent addition to sandwich panels and from research it is clear that it is very beneficial in the development of composites. Green construction is a present issue which the building industry must cater towards and NFC are a great candidate for this. The natural-based materials in NFCs meet the requirements as a sustainable material and aid in increasing multiple mechanical properties of sandwich panels. They do have their disadvantages however are being introduced to chemical agents for altercation to improve some of their weaknesses and will only become a better option in the future.

2.4 Hybrid Sandwich Panels

A hybrid sandwich panel can be described as a composite structure which has had an altercation applied to it to try increase a certain characteristic. Fajrin (2013) tested hybrid sandwich panels with an intermediate layer between the facings and core. His research focused on the introduction of a NFC to act as the intermediate layer. Predominantly Fajrin (2013) focused on the idea of a hybrid sandwich composite containing EPS foam core with aluminium facings and NFC acting as the intermediate layers. Hybrid composite structures allow the use of sustainable green material in building structures and so creating sandwich panels with NFC layers to act as a viable solution and therefore allowing this advancement in the building industry. There has been a lot of researches who have tried to create various forms of hybrid composites to try improve their mechanical properties and failure criterion.

The work of Mostafa (2013) and Mitra (2009) attempted to create a hybrid sandwich panel using shear keys in the core. Mitra (2009) tested the shear keys inserted into a PVC core to try increase the shear performance within the structure. These shear keys were placed in the core along the facings. Using an experimental approach within the guidelines of ASTM C 273 (ASTM,2007) the results proved that the introduction of shear keys increase the in-plane shear stiffness and panel strength.

Mamalis et al (2002) inserted reinforced tubes into the core in an attempt to strengthen the core properties. This was done by placing these tubes within the core such that they connected with the facings as well as longitudinally placed tubes of smaller diameter along the core. The sandwich panel was placed under compressive loading which was applied in turn to both along the edge and against the faces of the skins. The research concluded that the addition of the reinforced tubes drastically increased the crash energy absorption and stiffness of the sandwich panel.

2.5 FEM Research on Sandwich Panels

As the popularity of sandwich panels increase and the idea of hybridisation comes into play, many researchers use finite element analysis (FEA) programs such as Strand7, ABAQUS, Calculix and many more to explore possibilities that may prove beneficial to the advancement of sandwich panels and composite structures. Some research is directed at finding new altercations to improve the mechanical properties of sandwich panels. This work aims at testing modifications to composite structures such as shear keys and additional layers. Other finite element modelling aims at testing existing or experimental sandwich panels using finite element analysis such as checking the experimental values and replicated numerically to validate models and allow for further testing and alternative iterations. The main benefits of using FEA software are the cost reduction, environmental factors such as pollution and accurate testing. A drawback of FEA is the complexity of building the models which can cause delays in the research. This section will explore such research for both hybrid sandwich panels and the analysis of existing basic composites.

Jiang and Shu (2005) experimented with the addition of an internal sheet. This internal sheet would be placed at the centre of the structure with the core broken into two components on either side of the internal sheet. This addition was to try strengthen the sandwich panels resistance of impact loading. This research was carried out via a numerical approach using a finite element software. The model aimed to determine the local displacement of the core (honeycomb core in this analysis) under a three-point impact load. The results showed that the core was significantly less displaced along the direction of the local loading however the internal sheet provided no effect on the total deflection and contact forces in the structure.

Mostafa (2013) tried integrating semi-circular shear keys into the PVC core of a sandwich panel. The shear keys were placed between the skin and foam core on both sides as shown in Figure 2.2. Mostafa's research was performed numerically using a finite element model (FEM). The model was validated from experimental results and such a parametric study of the effect of shear keys diameter in relation to the in-plane shear performance. All configurations of the FEM showed that the addition of shear keys produced the results of stopping skin-core de-bonding and significantly improving the overall shear performance.

The research concluded that the shear keys proved to be a great method of reducing shear however it did raise issues. The failure mode turned out to be issues with the key-core de-bonding where tension proved to be the largest with diagonal shear failure in the foam core. Solutions to this problem are still being researched however it is noted that shear keys did help increase the shear performance and was described as having perfect bonding with the skins.

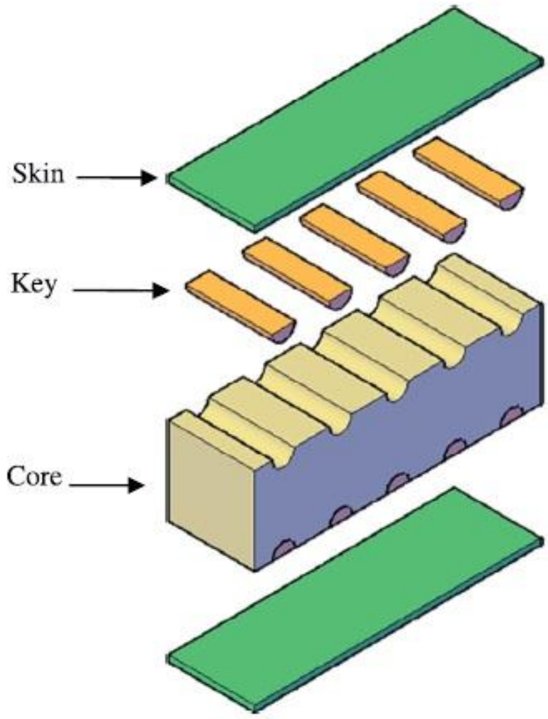


Figure 2.2: FEM of shear keys in sandwich structure (Mostafa, 2013).

Goswami (2005) tested the effect of cross-sectional warping on sandwich panels in a state of flexural response. This was conducted via finite element analysis using a higher-order shear deformation theory (HOST). Multiple thick and thin panels were subjected to warping in the analysis. A total of seven sandwich structure possibilities were analysed which varied in thickness and material composition. The research proved that cross-sectional warping was much more dominant and present in thick laminates and such higher-order stress theory was required when analysing thick sandwich plates for more realistic stress and deformation computation. Goswami also tested classical lamination theory (CLT) and first-order shear deformation theory (FOST) however the results found that these theories were not as effective in producing accurate results compared to HOST. This research is an example of the development of FEA on sandwich panels which benefited future researches who conducted their testing in this area to receive more accurate results using HOST.

Mamalis et al (2008) introduced a new type of hybrid which included an intermediate layer between the core and facings using wood. Originally glass fibre/epoxy was used in the experiment however it was found that plywood was the ideal material. The idea was to maximise the benefits of the panel by using metal skins and an extremely lightweight core. The research was tested using finite element software and yielded very promising results. Mamalis et al (2008) noted that the configuration prevented failure of face wrinkling of the facings and results showed that the configuration minimised the major disadvantages of each material. The research concept was developed because of the cost for high performance cores. The analysis was undertaken on the hypothesis of the possibility of using a low cost core with intermediate layers to reduce costs without lowering performance. The results showed that the introduction of an intermediate layer performed greatly as an alternative of using a high performance core and reduced the cost significantly. If an intermediate layer is included then it is highly recommended that the intermediate layer is stiffer than the core of the composite and thicker than the facings.

2.6 In-Plane Shear Sandwich Panels

Testing of a sandwich panel for in-plane shear is measuring the properties of the composite structure such as in-plane shear modulus and/or in-plane shear strength. There are multiple tests available in which to do so such as the racking test, direct shear test, diagonal shear test, picture-frame test and many others. Currently there is no universally accepted shear test method however the most used is the racking test (Tissel, 1993). The racking test has been noted as being the most reliable test however it's time and cost associated with it limit its use. A more efficient test alternative is the diagonal in-plane shear test which is more efficient in resources and cost. The main advantage of the diagonal shear test is its versatility. Due to its simple nature and easy set up, it is possible to use other basic testing machines with simple modifications and can be tested via compression and tension.

Kuenzi et al (1962) found that a compressive diagonal shear test would cause higher initial eccentricities and a lower result of accuracy because of this. It is highly recommended that for this purpose and nature of testing a sandwich panel, that a tension load be applied. The research also concluded that the tension based test produced higher buckling loads than its alternative of compression testing. Kuenzi et al (1962) tested the elastic stability of sandwich panels and used a diagonal tension in-plane shear test set up with a frame encompassing the sandwich panel. A hydraulic machine was used with the sandwich panel placed between the arms of the machine with pinned connections. The failure of the panels occurred at just above the buckling load due to high stress in the core.

Although generally diagonal in-plane shear testing is carried out on square members, De-Iorio (2002) performed experimentation using rectangular panels with four rigid rods attached at each end to form a frame mechanism. The results showed that the racking stiffness of the specimens increased with the framed specimens as well as creating a uniform shear stress distribution within the panel. This research allowed the advancement of the diagonal tension testing rig to include frames for the members being tested.

Overall there is two possible diagonal shear tests, compression and tension however compressive tests are used more for concrete and masonry structures whilst tensile tests are more suitable for panels. The tests may use two pin connections or four pinned corners as used in the frames. Research has proven that the frames increase the accuracy and allow for more evenly distributed shear stress within the panel. The general size of panels used in experimental tests using a diagonal tension shear test rig are 300-850mm which are a lot more resource conservative than the popular racking test. Some of these factors may not directly affect the FEA testing however it is important to develop an appreciation of why certain test characteristics such as tensile forces should be used.

2.7 Conclusions

Composite structures have existed for quite some time however only recently has the popularity for sandwich panels increased drastically. Originally used in aerospace structures, composites are now widely used and beginning to be used as a structural component in houses and buildings. Recent advancements such as the idea of hybridisation have allowed further development and research into further refining and improving sandwich panels to allow for further applications and a wider range of uses. Material combinations are nearly limitless however it is important that certain cores and adhesives specifically don't mix and all materials should be catered towards the designs required performance. Sandwich structures are relatively cheap to produce however the introduction of hybrid panels can cause significant increases in costs as they offer better mechanical properties.

Sustainable building is a present day issue which engineers must always be aware of when designing. NFCs offer significant advantages for sandwich panels when used as an intermediate layer compared to other alternatives. NFCs do have their limitations however considering its wide availability and low cost efficiency they act as the best possible solution to enable further development of sandwich structures. Hybrid panels incorporating intermediate layers have shown great success at maintaining or increasing mechanical properties while reducing the cost significantly. The use of intermediate layers and a low performance lightweight core as opposed to a high performance core is a great alternative and proven to work as efficiently with a lower cost.

FEA software has proven to be a good alternative to experimental testing. A number of researchers have developed tests using FEMs as opposed to using laboratory equipment. It has the benefits of being cost and resource effective, better to the environment and high accuracy results. This is achieved through validating models, comparing the analytical data to the experimental data, and then performing modifications which would require additional resources and time if done experimentally. The problem with FEA is the complexity of the models which can take time to develop as errors and unexpected problems arise however once these issues are addressed then FEMs become ideal to conduct experiments.

It is important however before trying to create FEMs that an appreciation to the current experimental tests is developed to fully understand the processes. It is apparent through multiple sources that the diagonal shear test is much more beneficial to the racking test due to cost and time benefits. Recently the diagonal shear test has gained popularity in two forms, the compression and tension shear tests. Tension shear tests are ideal for panels and a metal frame is usually employed to develop a uniform distribution of shear allowing for greater loading.

3.0 Methodology

This section aims to explain how the project is planned to be completed. As mentioned above this project aims to replicate the work of Dr. Fajrin in Strand7 for in-plane shear testing. This will be completed through a simplified 2D model of the testing rig and a more complex 3D model, the method in which these are created and will be tested will be explained below. However it is first important to understand how Dr. Fajrin carried out his experimentations and so his testing rig and other relevant information will be covered.

It will include the procedure in which the project is to be carried out. An explanation of the creation of both the 2D and 3D finite element models (FEM). The advantages and disadvantages of both of these models and a basic review of Dr. Fajrin's testing rig.

3.1 Procedure

The procedure of completion of the project as outlined in the project specification is shown in Appendix A. This procedure is fairly standard and a simplified outline is listed below;

1. Researching background information to build up an appreciation and understanding of the topic of this project and of Dr. Fajrin's dissertation.
2. Develop a simplified 2D model of the composite wall panel and validate the model by comparing to experimental results.
3. Develop a more complex 3D model of the composite wall panel and validate the model by comparing to 2D model.
4. Analyse the 3D model and produce results.
5. Make conclusions based on the 3D models results.

Steps for each specific model will be detailed in future chapters.

3.2 Theoretical Diagonal Tension Shear Testing

As discussed earlier the Strand7 model analysis will be completed via simulating a tensile shear test. This section will aim to explain the theoretical concepts behind using a diagonal shear test as the basis of the analysis. Mohammed et al (2000) is an example of a relevant literature which utilised the diagonal tension shear test to analysis the micro mechanics and shear deflection of fabric composites. This background literature did not test sandwich composite panels however it serves as an example of the theoretical concepts behind diagonal tension shear testing.

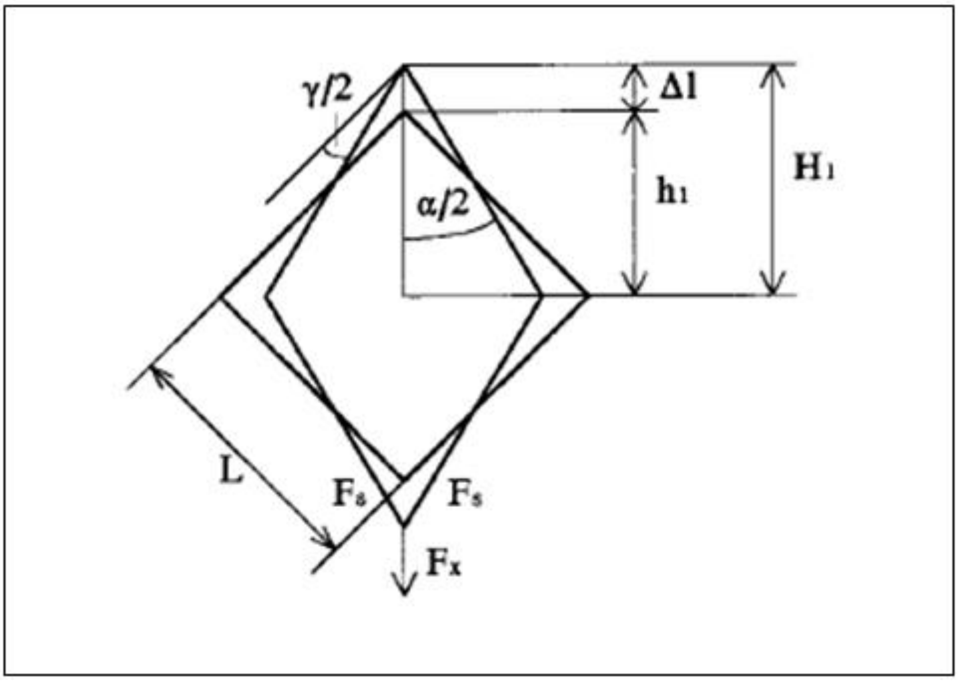


Figure 3.1: Mohammed et al (2000) picture frame

The geometric set up of Mohammed et al tests are shown above in Figure 3.1 where a tensile force, F_x, is applied to the bottom of the composite and the deflection of the shape is noted. The original height is noted by h_1 and the height after loading is denoted by H_1. The angles are also shown in the figure. To transform the tensile force into a shear force the following equation can be applied;

$$F_s = \frac{F_x}{2\cos\left(\frac{\alpha}{2}\right)} \qquad 3.1$$

Then assuming that the thickness does not change after loading the shear stress can be found;

$$\tau_s = \frac{F_s}{LH} \qquad 3.2$$

This then yields the shear stress within the composite. This is the general concept that Dr. Fajrin applied to his work so it is important when comparing results to understand how his methodology was undertaken and how he analysed his results. Dr. Fajrin's experimental testing rig will be explained in detail in section 4.1. For this thesis the computations will be completed by Strand7 which has the ability to output a wide range of information such as stress, strain and deflection. These outputs will be used and analysed and then compared to Dr. Fajrin's results.

3.3 Introduction and Testing of Intermediate Layers

Following onto 3.1 procedure, the point of this project is to test and analyse the effects of adding intermediate layers made out of NFC. This means that the four NFCs (JFC, MDF, hemp and sisal) will have to be modelled and then tested, analysed and compared to each other as well as Dr. Fajrin's experimental results. The method in which this will be completed is as listed;

1. Add intermediate layers in 2D via laminate dialog box
2. Test and analyse the 2D models
3. Model 3D models with intermediate layers
4. Test and analyse the 3D models
5. Discuss and compare results

This process will be completed after all initial models are completed as discussed in section 3.1. It is greatly important that the NFCs be investigated to see how they hand in-plane shear and displacement. It is expected that these results will indicate which NFCs are suitable for practice, if any, and which ones are redundant.

4.0 Development of the 2D Model

A very important part of this study was to develop a 2D model and validate it via the experimental results conducted by Dr. Fajrin. This 2D model would then be used to compare against and aid in the development of the 3D non linear model. The 2D model would also be used in a convergence study to determine the required number of subdivisions required to produce accurate results. To develop the 2D model an understanding of the procedure completed by Dr. Fajrin is required and is explained in the section below.

4.1 Experimental Testing Rig

Dr. Fajrin created a testing rig based on Kuenzi et al (1962) apparatus. They concluded that as opposed to using a compressive load to find the in-plane shear that a tensile load would be more beneficial. They found that using a compressive arrangement caused higher initial eccentricities and therefore lower accuracy and less concluding results. Figure 4.1 shows a schematic illustration of Dr. Fajrin's testing rig.

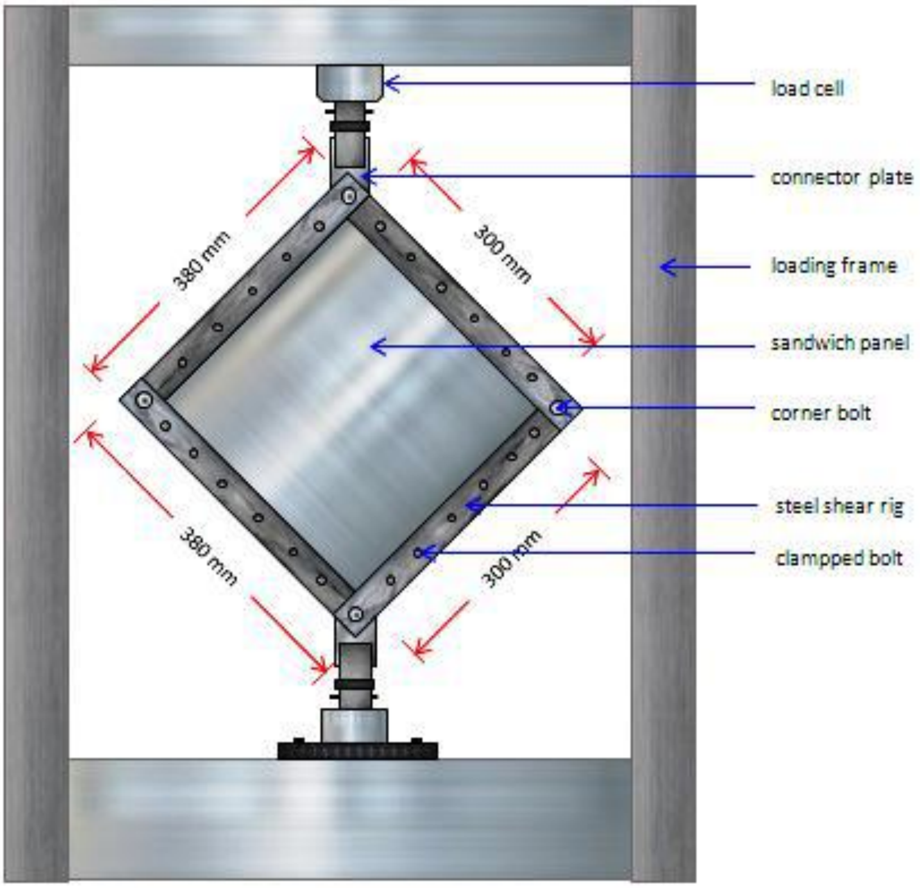


Figure 4.1: Theoretical illustration of Dr. Fajrin's diagonal tension shear test (Fajrin 2013)

As can be seen in Figure 4.1 a composite panel is bolted at its lower end and a tensile load is applied at the top to create in-plane shear stress. The panels dimensions are 300mm by 300mm however the steel frame shown in the illustration is 380mm by 380mm. Thickness of the panel was a total of 26mm with the outer skins being 0.5mm each and the core having a thickness of 25mm. Note that these values are for the current control panel (represented as the 2D model) and for the 3D model other parameters may have to be used. The load was applied until failure and the diagonal displacement was measured using a computer system incorporated in the testing rig. Using Dr. Fajrin's testing rig the Strand7 models could be made both 2D and 3D.

4.2 Beginning the 2D Model

Factors in the 2D model that had to be considered was the global load and freedom cases, the material properties, loading, support reactions, stress and strain distribution as well as the diagonal extension of the model. Initially the model was created by using three plates. These plates were layered on each other and the process is noted below;

1. Create outer plate element and assign plate property (aluminium) to it
2. Create overlapping inner plate element and assign plate property (EPS foam core) to it
3. Create overlapping outer plate element and assign plate property (aluminium) to it
4. Input thicknesses in the plate properties
4. Assign loading conditions and global load and freedom cases
5. Assign support restraints
6. Assign loading
7. Test via linear static solver

Before any successful model was created, the material properties had to be determined. The material properties used were extracted from Dr. Fajrin's work and these values were used in the development of the 2D model. The materials for aluminium skins and EPS foam core can be found in Figures 4.2 and 4.3 respectively, the thicknesses were also included in these property dialog boxes. Another factor required to determine was the global load and freedom cases. After analysing the model it was clearly determined that due to no bending occurring that setting the parameters as a 2D-beam would suffice. The loading conditions could easily be applied at the top node and the support restrictions could also be applied at the foot of the panel. The support reactions, at the foot of the model, used in all alterations and developments of the model was translational X and Y and rotational Z

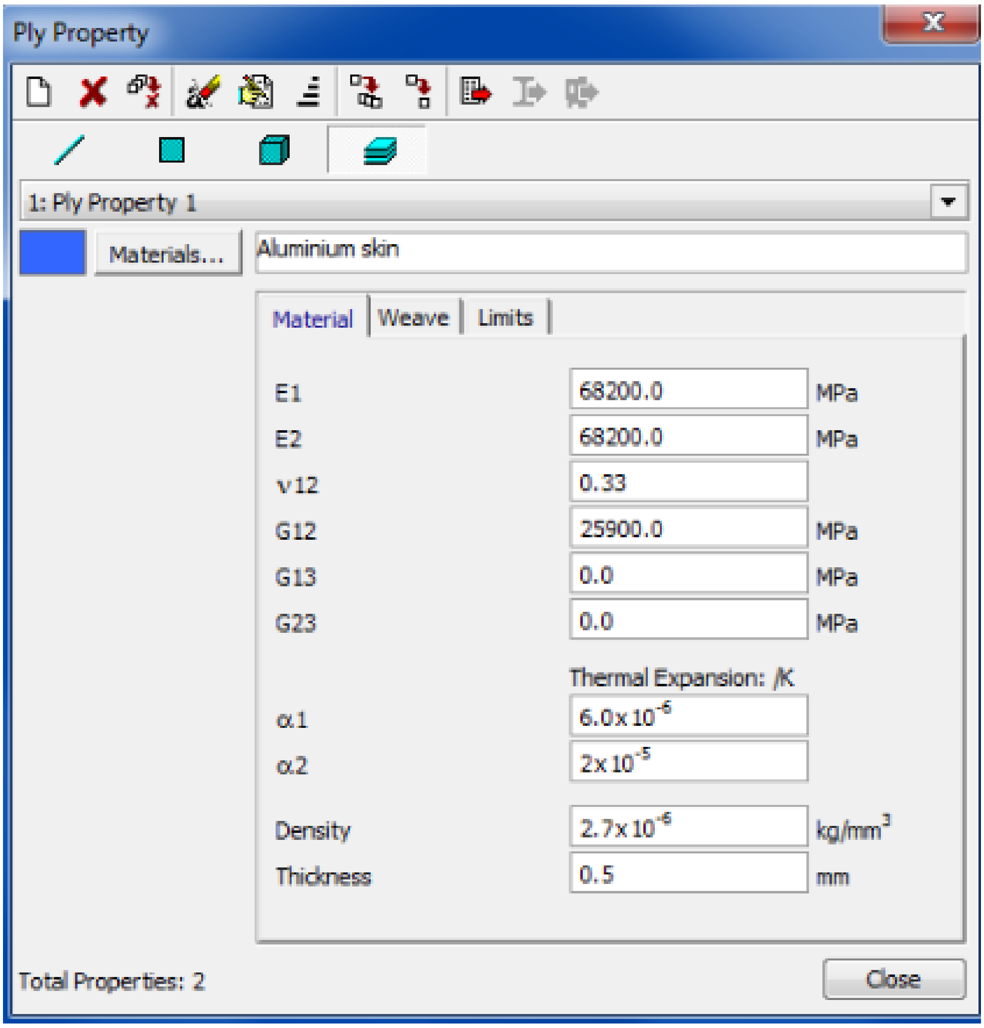


Figure 4.2: Aluminium properties

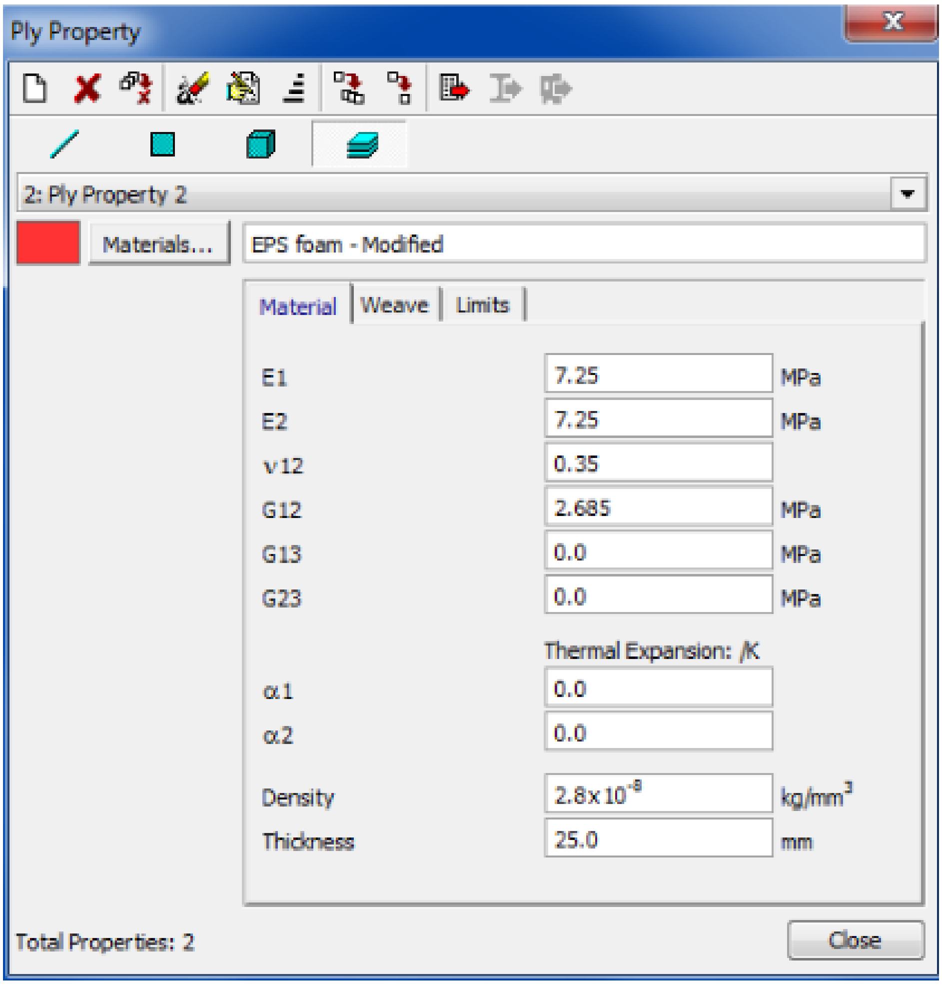


Figure 4.3: EPS foam core properties

This initial model appeared to work fine however after analysing the results it was determined that the computer was only analysing the over lapping aluminium skin. Since the core and other aluminium skin were not bonded in any way the computer only tested one skin so in order to fix this, link elements were investigated. A wide variety of link elements were trailed, such as rigid, master-slave, 2-point and sector symmetry. However it was found through trial and error that these link elements were used for other purposes that were not related to this issue. Because of the nature of the model, being 2D, link elements could not exist within plates. Essentially the whole idea of overlapping plates was incorrect in the 2D model as each plate override the previous one and link elements could only create relationships within that plate, such as the top node linking with an internal node. This caused a long halt in the development in the 2D model as research had to be completed to try find another solution.

4.3 Laminate Model

Dr. Muni Rami Reddy assisted in the development of the model by providing direction and analysing the models results and behaviour. It was through his help that the development of the 2D model was possible. After the failure of overlapping skins Dr. Muni suggested testing the use of laminate properties and ply properties in Strand7. The laminate property dialog feature allows for the user to assign a plate laminate values. So instead of creating layers of plates, a single plate consists of layers of ply which form the laminate. This new model was created by the following process;

1. Create plate element and assign laminate property
2. Assign material properties to ply properties
3. Create the laminate consisting of layers of ply
4. Input thicknesses in the ply properties
5. Assign loading conditions and global load and freedom cases
6. Assign support restraints
7. Assign loading
8. Test via linear static solver

As noted above the procedure was similar to the old model however instead of multiple plates a single plate with laminate properties was used. This allowed easy alteration of the model structure for future variations (such as including natural fibre composites). The laminate function contained three plies, namely the aluminium skins and EPS foam core. The properties of the materials were applied to the plies and the rest of the model was completed with no new alterations. The end result is shown in Figure 4.4. This model was very simplistic and easy to use and allowed for quick and effective alterations. Since only one plate was used the problem of the computer analysing only the forward most plate was solved so analysis and testing could occur. The rest of the process such as the global load and freedom cases, support restraints and loading all followed the same method described previously.

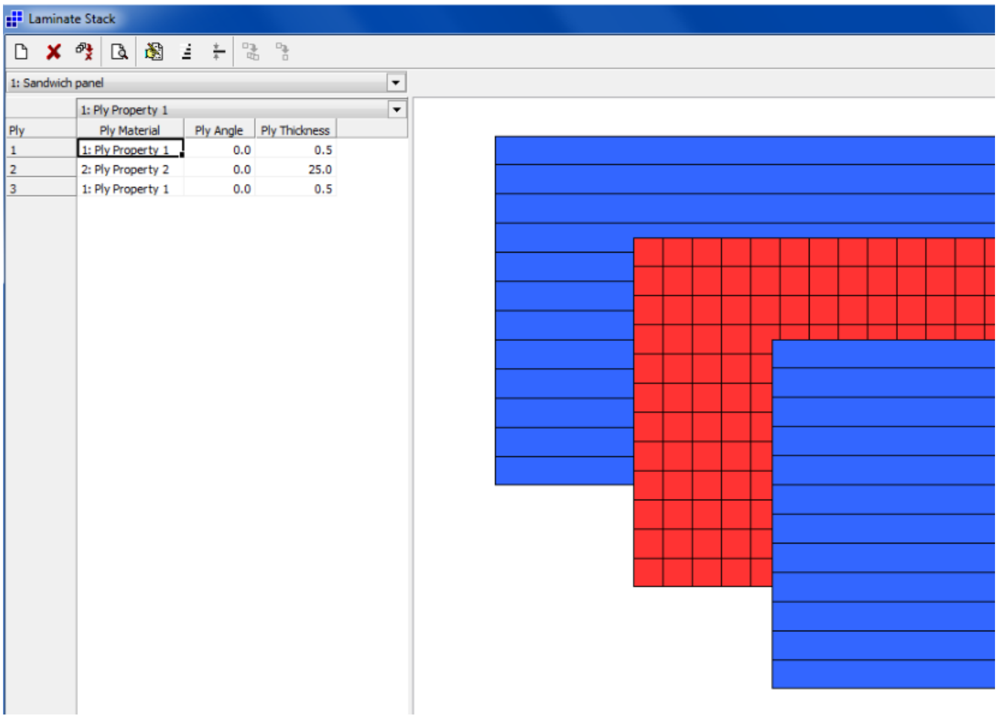


Figure 4.4: Laminate stack dialog

As can be seen in Figure 4.4 making changes to the composition of the panel can be made easy and fast. The laminate stack dialog box allows for simple addition or subtraction of ply layers as well as their orientation. In this study the E1 values are equivalent to the E2 values so ply angle is not applicable. The final parameter this dialog box offers is the ply thickness which for this case was 0.5mm for the aluminium skins and 25mm for the EPS foam core.

To assign the laminate to a plate is very simple, instead of using an isotropic material the material is set as the laminate option shown in Figure 4.5. This is this plate dialog box and after assigning the laminate created earlier in Figure 4.4 to the plate the engineering properties are automatically calculated and applied to the model. In this instance Ex is equal to Ey which was expected as E1 values were equivalent to E2 values. With this complete testing began on the model. However the results were showing an X direction displacement. The model only had a positive Y axis load applied to the top as will be shown in Figure 4.6. This result caused one final alteration to the model which was adding a X translational support at the top of the model. This restricted its X axis movement and didn't affect the Y axis results. The model was now finalised and shown in Figure 4.6. The advantages of using a laminate material plate is the quick and simple alterations that can be made to restructure the entire panel such as thicknesses, plies and ply orientations. One modification yet to be determined was a convergence study on the 2D model to determine the necessary subdivisions within the mesh to produce the ideal accuracy, computation time and workability.

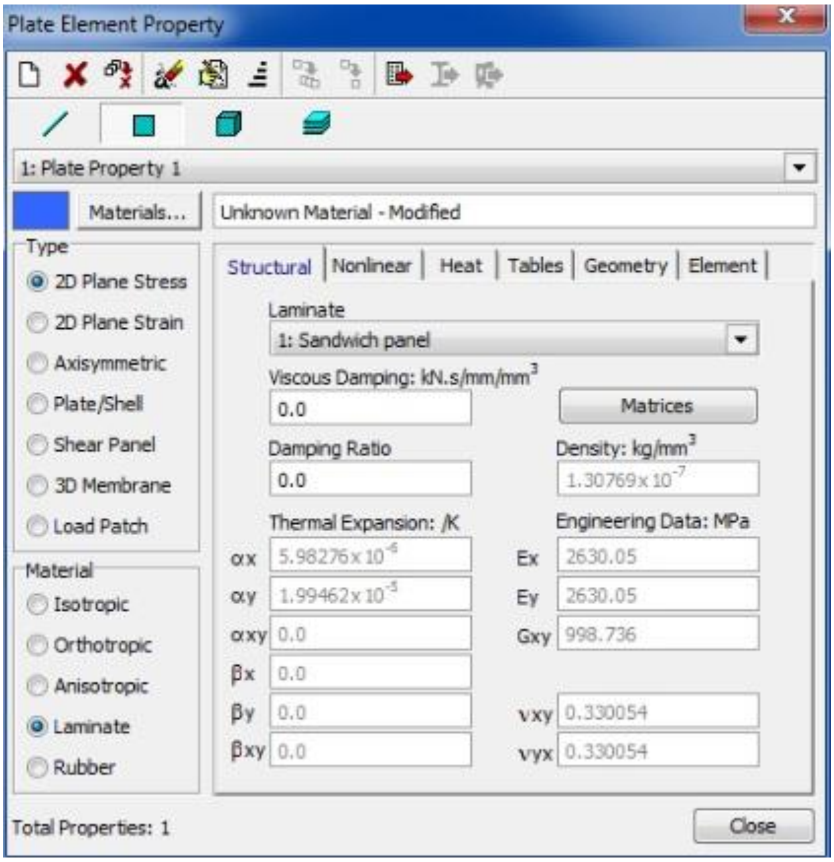


Figure 4.5 Plate element dialog

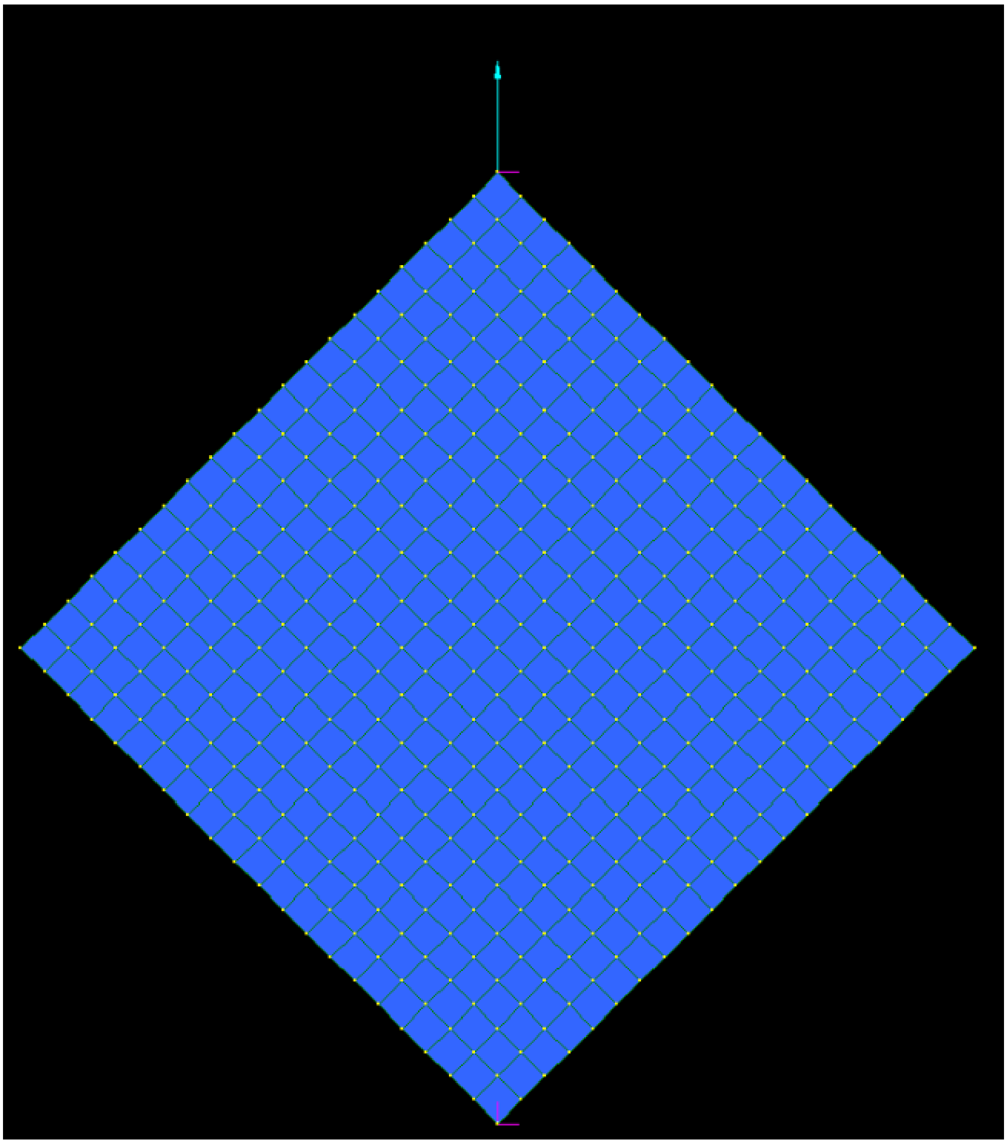


Figure 4.6: 2D model 20x20

4.4 Addition of Intermediate Layers and NFC Materials

After the model was validated it was time to start testing the 2D laminate models. These models included the control panel (no intermediate layer), jute (JFC) model, medium density fibre (MDF) model, hemp model and sisal model. These models were all constructed in the same manner as the control panel however with additional intermediate layers applied within the laminate dialog box. The material properties of each material was used from Dr. Fajrin's analysis and are shown below in Table 4.1.

Table 4.1: Mechanical properties of used NFCs

NFC	Young's Modulus (MPa)	Poisson's ratio
JFC	4592	0.361
MDF	2603	0.253
Hemp	3048	0.391
Sisal	3505	0.471

As shown in Table 4.1, the four NFCs used in this project have their Young's Modulus and Poisson's ratios listed. First is JFC which has the highest Young's modulus of all NFCs used with a fairly average Poisson's ratio. The next material is MDF which has the lowest Young's modulus as well as lowest Poisson's ratio. This does mean however that any strain that is applied longitudinally via the tensile force will be much less severe in the lateral direction because of such a low Poisson's ratio making MDF a more brittle material. Hemp and sisal both had average Young's modulus values with 3048MPa and 3505MPa respectively. However their difference is certainly shown in their Poisson's ratio values with 0.391 for hemp and a very high value of 0.471 for sisal. Based on this it shows that sisal is a very ductile material and a lot of the strains caused in the longitudinal direction will be carried into the lateral direction. This suggests a possible failure due to skin de-bonding. Another restriction of the model was the isotropic assumption due to limited information given in Dr. Fajrin's project. Due to not knowing the E2 values as well as the orientation in which he placed the intermediate layers it must be assumed that the NFCs are all isotropic so the orientation does not affect results.

The method in which the NFCs were added was to simply add an extra ply within the laminate dialog box. As shown in Figure 4.4 the laminate stack dialog acts as a very easy method to modify and alter any changes to the sandwich panel. This makes it extremely easy for the user to test and evaluate the addition of new layers or changing existing parameters such as thicknesses and orientations. Figure 4.7 below shows the new laminate stack with the addition of intermediate layers.

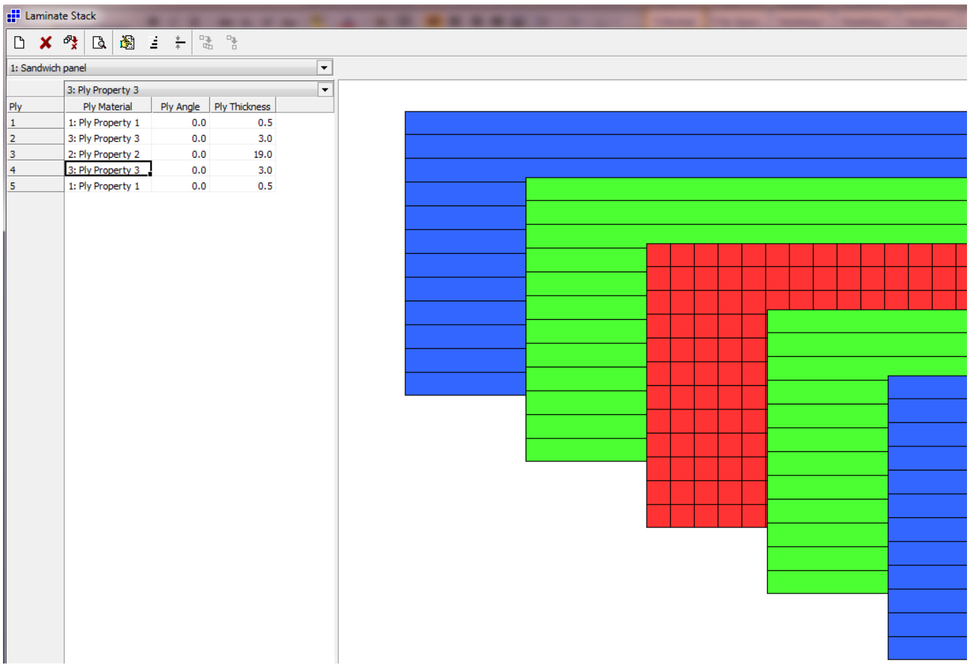


Figure 4.7: Laminate dialog box with intermediate layer

The laminate dialog box is shown above in Figure 4.7 and shows the addition of an intermediate layer. It is important to note that the because the intermediate layers are 3mm thick each the core has been reduced from 25mm to 19mm to keep the total width of the models 26mm. As can be seen the intermediate layers have been assigned ply property 3 which means that variations of the model can be made and instead of changing the configuration the user simply has to change the ply properties to those of the specified NFC.

5.0 Convergence Study

It is common in FEM studies to undertake a convergence study to analyse the benefits and costs to using particular parameters. A convergence study tests the accuracy of a mesh, or plates, through subdividing an element. However the workability and computational speed is also considered. As the element is subdivided the number of computations increases and so the time required for Strand7 to analyse the model also increases. The workability similarly also decreases and subdivisions are added. These issues will be analysed and the ideal number of subdivisions will be selected.

This convergence study will test the 2D linear model created in Strand7 for the parameters of accuracy, computation time and workability of the model. The accuracy will be measured against the limited information given via the experimental results. Computation time will be noted down and it is important to consider this effect when moving onto the 3D model analysis. The workability will be tracked with screenshots and personal experience of altering the model.

The first parameter considered will be the accuracy of the model. This accuracy is directly affected by the number of subdivisions on the plate and past studies have generally concluded that an increase of subdivisions will also increase accuracy. However to check if the accuracy has been met then it must be compared to the linear section of the experimental results. Unfortunately in this case, the experimental results linear phase occurred whilst the machine was settling and therefore making it unreliable to compare to, however results did show a similar result in the linear phase. The model was validated, as discussed in Chapter 7 through the help of Dr. Muni Rami Reddy and Dr. Yan Zhuge as well as continuous testing.

The next parameter is computation time. This is simply the amount of time required for Strand7 to run its computations and produce the results. It is a trade off for increasing the subdivisions in the mesh, as the subdivisions increase so will the computation time. With 2D models this computation time will not be exceedingly long however when considering the transition to 3D and the affect that it may cause then precaution is necessary when considering the ideal number of subdivisions.

The final parameter to be considered is the workability of the model. In essence this is how easy or difficult the user finds using the model as well as how understandable the model is. As subdivisions are increased then the amount of nodes and elements increase however there comes a point where the model becomes flooded and making alterations to the model requires introduction of new steps to ensure surrounding nodes are not being used as well. With the increase of new nodes and elements the model may become overly complex to viewers and cause problems in understanding exactly how the model is being tested. This parameter will be compared via the use of screenshots listed in Appendix B.

This study has been carried out using the following meshes; 1x1, 5x5, 10x10, 20x20, 40x40, 80x80, 100x100 and 160x160. Each mesh was tested using the linear solver in Strand7 with a set load of 2kN. The results and models were recorded and are listed in Appendix B. The results were used to build a graph showing how the increase in subdivisions affected the accuracy. The models themselves will be used to judge the workability and the computational time was noted down from the linear solver results file.

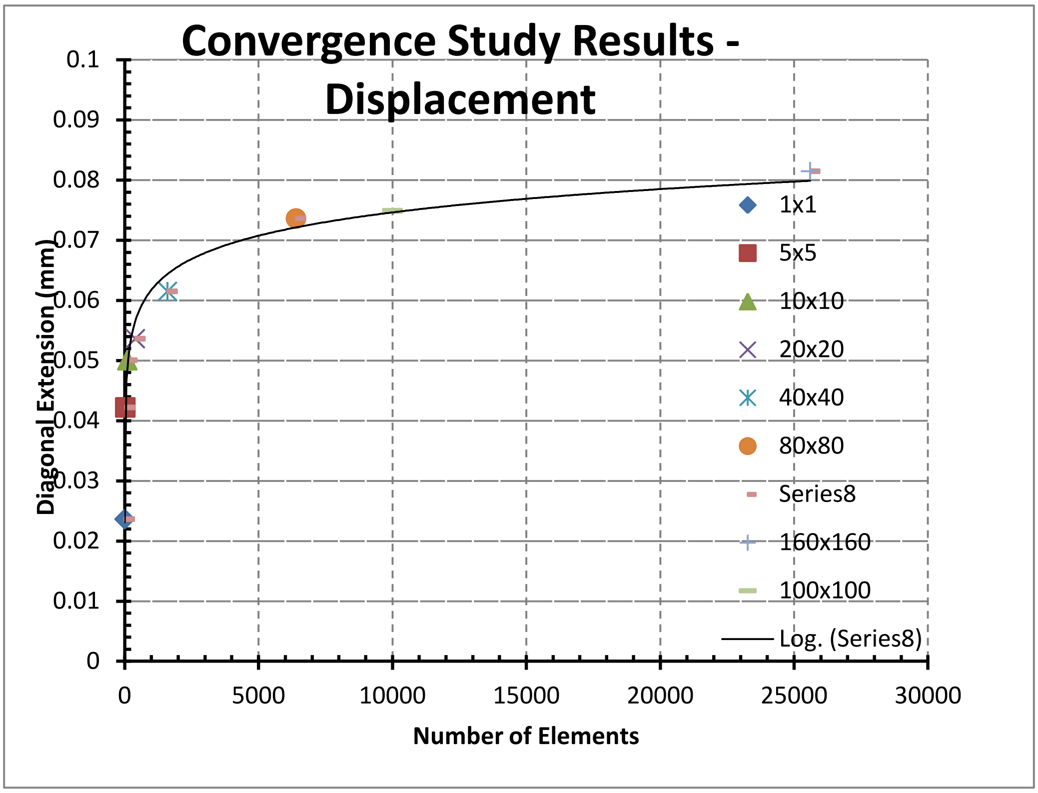


Figure 5.1: Convergence study results

Figure 5.1 shows us the results of each mesh with comparison to a logarithmic line of best fit. As mentioned before, the experimental linear phase occurred during settling of the machine so unfortunately it cannot provide an accurate comparison. The x axis represents the number of elements in the model and the y axis represents the diagonal extension in millimetres. Each mesh was colour coded as can be seen in the legend. These meshes were tested using linear static solver in Strand7 with a 500N load applied.

The results of Figure 5.1 show us that as the subdivisions are increased then so does the diagonal displacement. As expected the 5x5 mesh produces a greater diagonal extension than the 1x1 mesh. This is applied for all increases in subdivisions however as subdivisions get greater the spacing between them minimises. For example take the 80x80 mesh and compare it to the 160x160 mesh, the difference in these is only 0.007mm. However if we look at the 5x5 mesh compared to the 10x10 mesh the difference is 0.008mm. This number is reasonably close to the difference in 80x80 and 160x160 however a major factor to note is that the 10x10 mesh had only 75 more elements included than the 5x5 mesh while the 160x160 mesh had 19,200 more elements included than the 80x80 mesh. As mentioned before, as the subdivisions increase then so does the accuracy however the reason why the difference in the 160x160 and 80x80 meshes didn't significantly rise is due to the accuracy limit being reached. If another mesh was included, a 320x320 mesh, then the diagonal extension between itself and the 160x160 mesh could be assumed to be much smaller than the 100x100 and 160x160 mesh difference. It is also worth noting that a 320x320 mesh would include a very long computation time and extremely clunky and confusing model due to the results of the 160x160 mesh which will be discussed below.

If we look at the line of best fit in Figure 5.1 we can see that it follows an exponential pattern with an approaching limit of 0.08mm. Because the meshes all have relatively low number of elements, excluding the higher ones such as the 80x80, they appear to all be grouped together at the start. The last three meshes all approach the limiting factor. 80x80 and 100x100 meshes both provide a very close result of less than 0.001mm difference while compared to the 160x160 mesh they have a difference of 0.007mm. With this in mind the 80x80 or 100x100 prove ideal in terms of accuracy however once considering other factors a selection can be made.

Table 5.1: Mesh element differences

Mesh	Difference
5x5 and 1x1	24
10x10 and 5x5	75
20x20 and 10x10	300
40x40 and 20x20	1200
80x80 and 40x40	4800
160x160 and 80x80	19200

An interesting concept in regards to the graph to consider is that as the subdivisions increase then we can expect the accuracy limit to be reached exponentially however if we look at the graph we notice that the difference in the 10x10 and 20x20 meshes is actually very small. This however is caused by the number of element increasing exponentially as well. To explain this Table 5.1 shows us the difference in elements between each mesh increase. As can be seen this increase is exponential and as noted earlier, more elements leads to greater accuracy. Now if we look at the diagonal extension difference in the 10x10 and 20x20 meshes and compare this to the 20x20 and 40x40 meshes whilst looking at the difference in elements we can explain why Figure 5.1 shows us this behaviour. The difference in plates between the 20x20 and 10x10 meshes is only 300 whilst the difference between the 40x40 and 20x20 meshes is 1200. As the accuracy limit is reached then the diagonal extension is expected to only get smaller with each increase so using these factors it is understandable that the graph produces this behaviour.

Table 5.2: Computation time of meshes

Mesh	Computation time (s)
1x1	3
5x5	3
10x10	3
20x20	3
40x40	4
80x80	8
100x100	10
160x160	17

The next parameter mentioned was computation time which is shown above in Table 5.2. These times were manually recorded through the Strand7 results files of each mesh. An important factor to keep in mind is the increased complexity of the 3D models which will highly affect the computation times. Table 5.2 shows us that all meshes up to the 40x40 mesh had the same computation time of 4 seconds however when the mesh was subdivided again to become the 80x80 mesh the computation time was 8 seconds. The 100x100 mesh requires only 2 more seconds to compute than the 80x80 model which for a slight increase in accuracy is validated. The 160x160 model showed an even larger jump in computation time with more than double the time required, 17 seconds, than the 80x80 mesh. These computation times are within reasonable limits however considering the 3D model in mind it is unreasonable to use the 160x160 mesh.

The final parameter analysed is workability. The pictures of several meshes can be found in Appendix B. The criteria used to determine which meshes are ideal is complexity to the viewers and the ability for the user to alter or use the model. The first mesh to be reviewed is the 10x10 mesh, it shows a very easy to understand model and is also very easy to configure. The 20x20 mesh provides a solid idea of what an ideal mesh would look like. It is very simple to view and easy to use and has a good number of elements and nodes. The next mesh, 40x40, shows a bit more of a complex model however it is still moderately easy to understand and use. 80x80 shows a much more complicated mesh however is still relatively simple to configure. The next mesh is the 100x100 where the workability starts becoming compromised. This mesh has become so crowded that some information is now covered such as viewing the number of plates, their orientation and the support restriction. The final mesh, 160x160, is overly complex and confusing. Looking at it does not grant information to the user and required additional difficulty to make changes.

While considering all of these parameters a conclusion of the ideal mesh can be made. In terms of accuracy the 80x80, 100x100 and 160x160 meshes were all reasonable to use. Computational time of these meshes were 8, 10 and 17 seconds respectively. While considering the effects of transitioning to the 3D model the 160x160 model can definitely be ruled as out inefficient. The final parameter considered was workability which found that the 80x80 model was just borderline acceptable however once transitioned to the 100x100 model then the workability drops slightly and the 160x160 model was completely overcrowded and confusing to use and view. When considering all of these factors it is clear that the 80x80 mesh is ideal as it provides a good level of accuracy, computation time and workability when compared to the other two meshes.

6.0 Development of the 3D Model

After the 2D model was completed the next focus of this thesis was to develop a 3D non linear model. The 3D non linear model was heavily dependent on the completion of the 2D model due to the complex nature of making a non linear model. Once the 2D model was completed and tested, work on developing the 3D model began which followed a somewhat similar procedure to that of the 2D model however was much more complex as non linear properties were included. The experimental conditions were the same as that explained in section 4.1.

6.1 Beginning the 3D Model

Just like the 2D model, factors that had to be considered included the global load and freedom cases, the material properties, loading, support reactions, stress and strain distribution, diagonal extension, non linear properties, load increments and convergence. Similar to the beginning of the 2D model, the model was first started by creating three layered plates as listed in the process below;

1. Create outer plate element and assign plate property (aluminium) to it
2. Create overlapping inner plate element and assign plate property (EPS foam core) to it
3. Extrude inner plate by 25mm to transition to 3D
4. Create overlapping outer plate element and assign plate property (aluminium) to it

This process began the 3D model where it looked similar to the initial 2D model (see section 4.2) however in this instance the inner plate, the core, was extruded to make the model 3D. The 3D model has been created such that the core is 3D however the aluminium skins are 2D, this was recommended by Dr. Muni. This extrusion allowed the plates to be stacked on each other without the use of the laminate feature. As noted, an initial problem within the 2D development was stacking plates as Strand7 would only analyse the top overlayed plate however in the 3D model the program was able to analyse each node and element.

The next steps in the development was to assign the global load and freedom cases as well as the loading conditions. The loading conditions were slightly different from those used in the 2D model. Because of the 3D models nature, having a Z direction thickness, the loading had to be applied at the front and back of the tip of the model. In other words the load was split up into two and assigned at the top of the two outer plates which can be seen in Figure 6.1. The support restraints were also applied like the loading, two pin connections located at the bottom of the outer plates as opposed to one in the 2D model. The support reactions used in the model was translational X and Y and rotational Z. The material properties used for the EPS foam core and aluminium skins was the same as the materials used in the 2D model, to view specific properties refer to Figure 4.2 for the aluminium and Figure 4.3 for the EPS foam core.

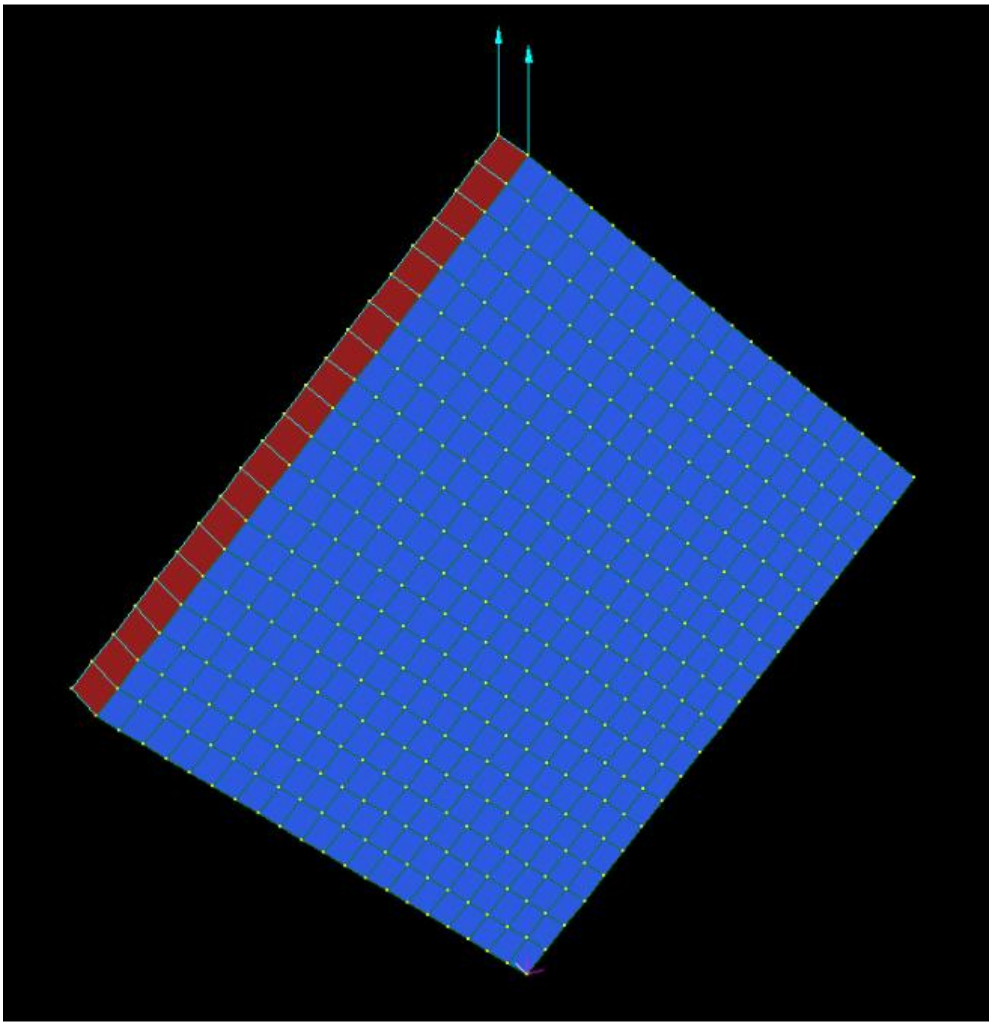


Figure 6.1: 3D model with 2D skins

Figure 6.1 gives an angled view of the 3D model. As can be seen the loading has been applied in two points at each end and the support restraints are also replicated with this behaviour. The core is shown as red and the skins as blue which are 2D in the model with thicknesses applied to them via their material properties. As can be seen it is very similar to the 2D model at this stage in the development however as non linear properties, load increments and convergence is introduced the model becomes more complicated although the physical appearance will remain constant.

6.2 Initial Testing

At this stage in development no non linear attributes had yet been included however it was important to test the model and compare it to the completed 2D model whilst the 3D model was still in a linear state. This test was carried out to ensure the properties and model fundamentals such as global load and freedom cases were all correct so further development of the model could confidently be completed. It was also important to see how the linear results would vary, if any, using a 3D model compared to a 2D model.

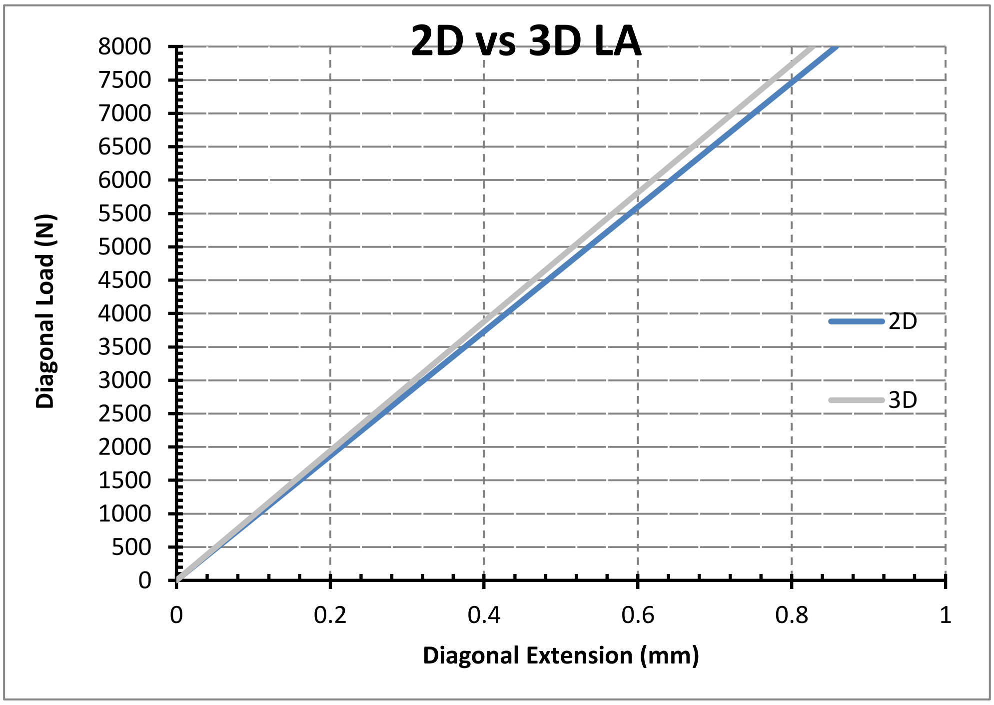
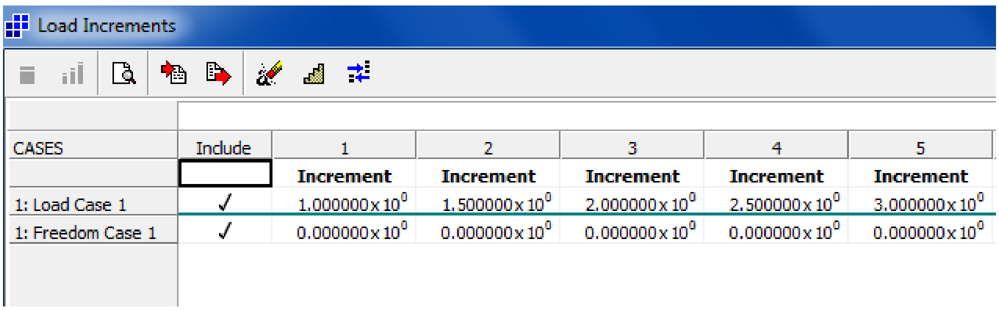


Figure 6.2: Linear comparison of 2D and 3D models

Figure 6.2 shows the results of the 2D verses 3D linear results. The results were obtained by testing both models with linear static and then extracting the results at two locations on both models to develop the linear function. These functions were then created in excel and yielded the results shown in Figure 6.2. The x axis shows the diagonal extension in millimetres and the y axis shows the tension load applied in Newtons. The 2D results are shown in blue and the 3D in grey. As can be seen the results are very similar. At the highest load applied, 8kN, the difference in diagonal extension is only 0.015mm and gets progressively smaller as the load is reduced. Overall these results show good consistency within the models and allows confirmation that the 3D model fundamentals are all in check so that further development can be completed.

6.3 Non Linear Development

The next stage in the 3D model development was to start including non linear properties and start the transition to a non linear model. For this to be completed the non linear properties, load increments and convergence factors must be considered. The first step was to include load increments. This was done through the non linear solver and allows the set up of increasing loads. This can be viewed in Figure 6.3, this shows how the load increments were implemented and as can be seen they are increased by 0.5kN at a time.


Load Increments

CASES	Include	1	2	3	4	5
		Increment	Increment	Increment	Increment	Increment
1: Load Case 1	✓	1.000000×10^0	1.500000×10^0	2.000000×10^0	2.500000×10^0	3.000000×10^0
1: Freedom Case 1	✓	0.000000×10^0	0.000000×10^0	0.000000×10^0	0.000000×10^0	0.000000×10^0

Figure 6.3: Load increment table

The next step was to include the non linear properties to the materials. Due to the nature of a sandwich panel, the EPS foam core is obviously going to fail much earlier than the aluminium skins. This meant that the stress-strain curve was only applicable to the core as the skins would not need one. The stress-strain curve was implemented into the cores material properties and is shown in Figure 6.4. This curve shows the relationship of stress against strain and allows the model to act non linearly and is based off a typical EPS foam (Ozturk, 2011).

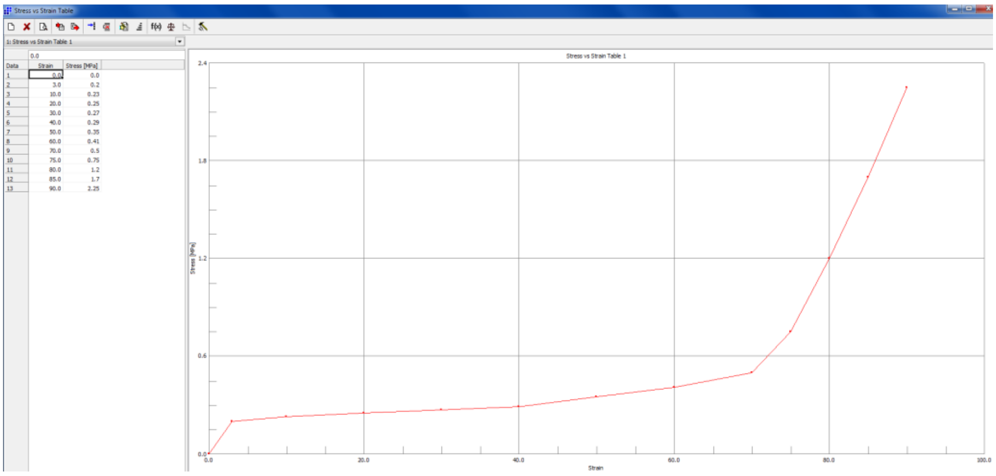


Figure 6.4: Stress vs. strain graph

Finally the convergence was considered which is determined via two criteria in Strand7. The first criteria is the displacement norm which tests to see if the iterative displacement has reached near zero to determine if the total displacement has converged. The second criteria is the residual forces norm which is tested in a similar manner. If the unbalanced iterative forces has reached near zero then the structure is deemed to be in equilibrium and the model is considered converged. These criteria determine if a model has converged or not, if it has not converged then the iterations and calculations will cease and the model will not produce results. Figure 6.5 shows the convergence for the non linear static tests using the load increments in Figure 6.3. Initially load increments of 1kN were used and the convergence criteria were not being met so in order to achieve a converged model the increments were changed to the current 0.5kN. The graph shows displacement norm in blue and residual force norm in red. For each iteration to be considered converged the curve must reach underneath the constant blue and red lines. As can be seen this is achieved in every iteration and such the 3D non linear model has been correctly developed and is ready for further testing and investigation.

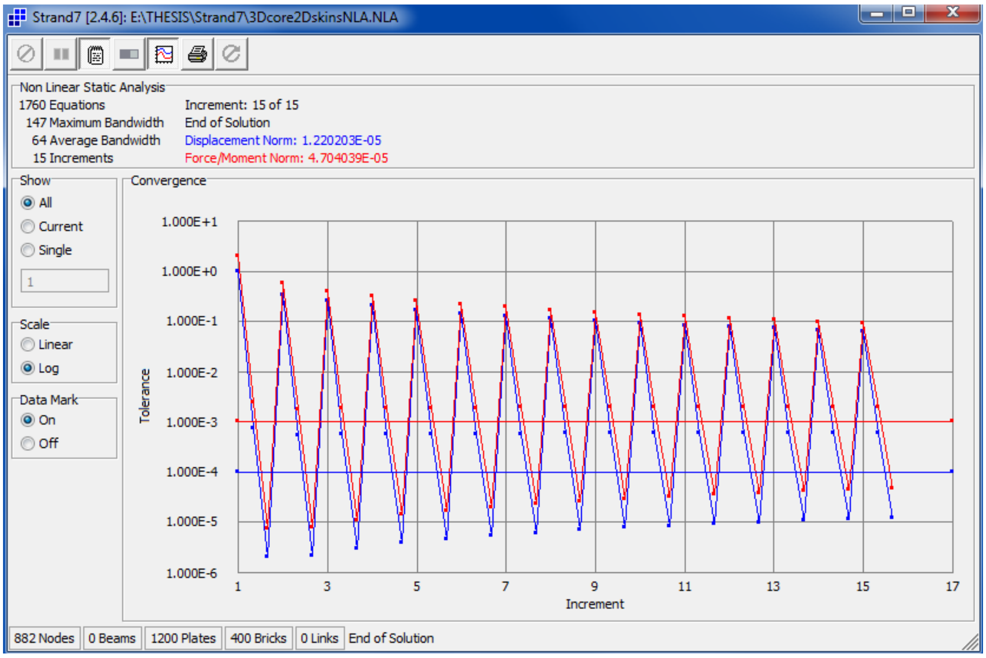


Figure 6.5: Convergence graph

6.4 Addition of 3D Intermediate Layers

Another important portion of developing the 3D model was to include and create models that catered for the addition of the intermediate layers. This process was a lot more complicated than the 2D laminate version. In the 2D version the laminate dialog box could simply be configured however this was not the case for the 3D model. Because actual 3D layers were used it meant the model had to be recreated. The process followed was very similar to that of creating the 3D control base panel (no intermediate layers).

Firstly the core was created as a plate element and extruded to 19mm using the same process as before. However instead of assigning 2D plates to cover the core now 3mm thick brick elements were created over the core. This was done by the same process for creating plates and extruding them however the core and intermediate layers now made up the same thickness of 25mm as the core did in the original control model. Next the 2D aluminium skins were applied. The support reactions were placed on the skins and where the intermediate layers met the core at the bottom of the model for a total of 4 supports. The global load and freedom cases were not changed. The intermediate layer was assigned brick property 2 and so this could be easily modified within the material properties depending on which natural fibre composite was undergoing testing.

The addition of using a beam element over the top of the model to apply the loading as a uniformly distributed load (UDL) as opposed to two point loads. This result found that the displacement and stresses within the layers were all the same and had no effect whatsoever. The 3D NFC models were tested using a UDL as will be discussed in section 8.0. Because the layers are not expected to fail before the core there is no need to add stress-strain curves to the NFCs. To transition to the non linear phase then the same process as explained in section 6.3, apply the load increment table and test if the model converges.

7.0 Analysis and Results of 2D Models

In this section of the thesis the testing and results of the 2D models will be analysed. This will range from the base control model, laminated NFC models and comparing these results to Dr. Fajrin's findings. For discussion relating to the development of the models refer to section 4.0. It is important to test the behaviour of the developed hybrid sandwich panels both in their displacement/diagonal extension as well as their ability to handle shear strength as it is a critical factor when using a sandwich panel for wall purposes. By introducing an intermediate NFC layer it is expected that the displacement and shear stresses are reduced overall. This chapter investigates if this assumption or expected result is correct or if NFC do not aid in this purpose.

7.1 2D Control Model Validation

The control model was simply a replica of Dr. Fajrin's testing sandwich panel. It was a simple model consisting of only a 25mm thick EPS foam core and 0.5mm thick aluminium skin. The development of this model was discussed in section 4.0 and was finally completed via the use of the laminate function within Strand7. Figures 4.2 and 4.3 show the mechanical properties of the materials used. It should be noted that due to restraints the core was assumed to be isotropic. This was used because lack of data given in Dr. Fajrin's analysis as well as orientation. The results would be varied greatly if the core had various orientations so for this analysis the core will be isotropic to eliminate this restriction.

As discussed in the convergence study, it was found that the 80x80 mesh was the ideal one to be tested due to accuracy, computation time and workability. To ensure the model was validated, it was compared against the linear phase of Dr. Fajrin's control panel. This control panel was constructed and tested in the same manner as the Strand7 file. Figure 7.1 shows the results of comparing all meshes against Dr. Fajrin's CTR-1-12 specimen. Note that the CTR-1-12 specimen results were picked because this control panel in particular gave the most average results compared to the control panels tested.

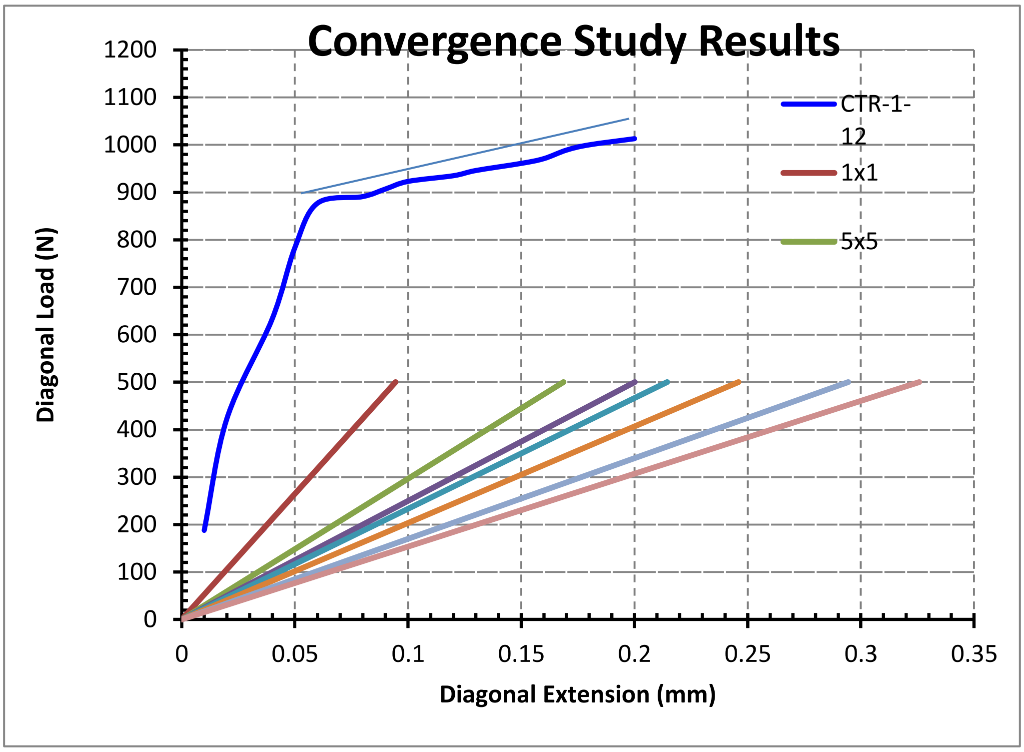


Figure 7.1: Meshes against CTR-1-12

As can be seen in Figure 7.1 the load was shown on the y axis as N and the displacement shown on the x axis in mm. The linear phase of CTR-1-12 was hard to determine due to characteristics of the test. This is because the initial section from 200N to 850N is assumed to be the machine settling and thus causing strange and incomparable results. However the section that occurs between 900N to 1000N shows the largest phase of the linear phase in a level of accuracy needed. Post 1000N the graph for CTR-1-12 transitions to a non linear state where the slope is constantly changing. This slope, shown in blue in Figure 7.1, is comparable to both the 160x160 and 80x80 meshes.

Although it is more steeper than the 160x160 slope it is not greatly different, which is also true about the 80x80 slope. Unfortunately due to machine settling it is hard to validate the model in terms of comparing it to Dr. Fajrin's control panel CTR-1-12 however this similarity in slope shows the similarity in the linear phase. The model was also thoroughly checked by Dr. Muni at USQ Springfield and he could spot no flaws with the 2D linear models. Figure E.1 lists all the developments as well as models used within the analysis of this report.

7.2 Linear 2D Analysis

The 2D analysis in this project was completed by using the laminate function in Strand7. Each model is tested for its diagonal extension as well as maximum in-plane shear stress and stress distribution. The results will be collected for each model and explained with a summation at the end of the section. The applied load for each model is 1kN and this will be used to keep results consistent. Due to the large amount of visuals and data please refer to Appendix B for this section.

The first panel to be tested was the control panel which had no intermediate layers however to compensate and keep it consistent the core was set as 25mm to keep the thicknesses of all test specimens 26mm total. This panel is viewable in Figure 7.2 and it shows the maximum stress as well as the stress distribution. Note that the stress distribution for these laminates are determined as if the sandwich panel was one solid plate, or laminate. Hence the stress distribution and maximum stresses for each individual layer are not able to be considered in the 2D models however in the 3D models the individual layers can be analysed. For this control panel shown in Figure 7.2 it shows a maximum stress of 5.023MPa and an even stress distribution with the stress all focused at the support and loading points. There is some minor stress occurring as the distance from the support and loading points increase but it rapidly reaches 0. The diagonal extension was found to be 0.139mm.

The next panel tested was the JFC model which had a 19mm core, 3mm intermediate NFC layers and 0.5mm thick aluminium skins. All up again for a total of 26mm with the same loading and support conditions. The configuration is the same as shown in Figure 4.7 and the visual can be found in Appendix B Figure B.1. As can be seen the stress distribution is much the same as the control panel. The shape and behaviour is the same however the maximum stress has been reduced to 3.625MPa which is approximately only 72% compared to the control panel. The diagonal extension of this plate however was only 9.8963*10^{-2}mm. This is a 29% reduction in diagonal extension.

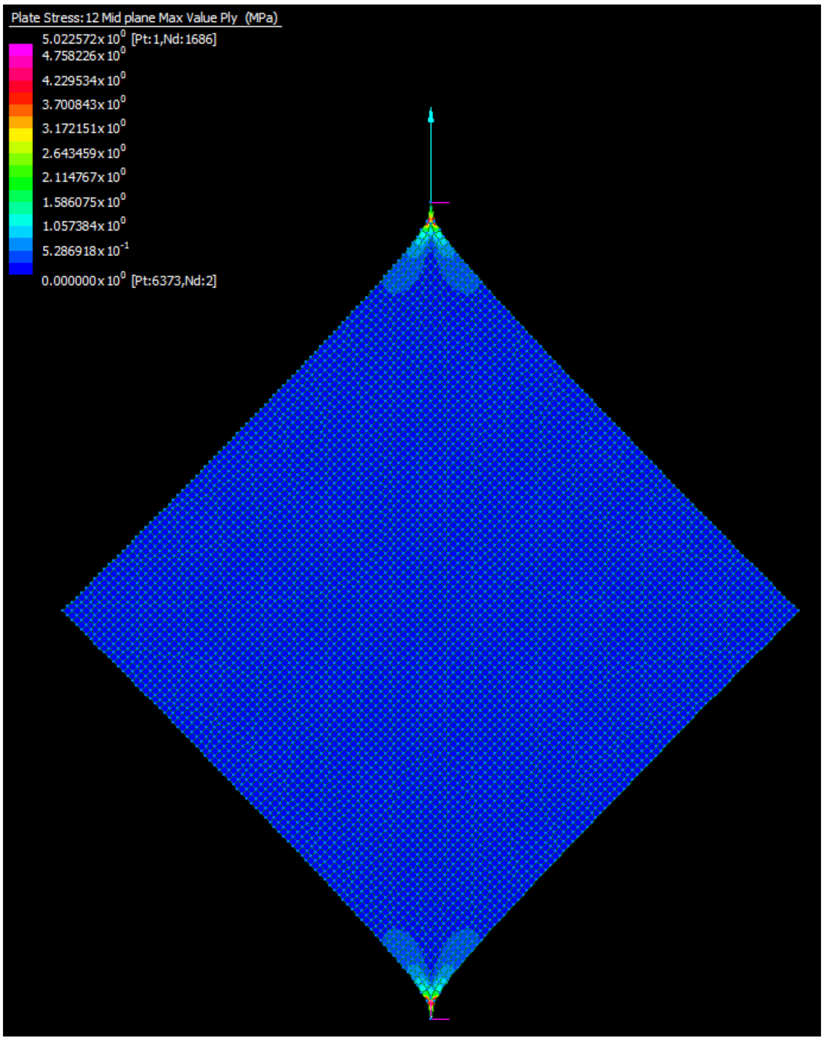


Figure 7.2: 2D control panel laminate shear stress

The medium density fibre (MDF) panel was then tested. It was tested by using a model that was identical to the JFC model however with altered material properties for the intermediate layer. Again the thicknesses were the same as the JFC model and a visual can be seen in Figure B.2 which also shows the stress distribution. The stress distribution again takes the same form as expected with it all being concentrated at the loading and support. The stress rapidly decays to 0 and shows the same pattern. The maximum stress achieved on the MDF model is 4.045MPa. This stress is 80% of the control panel's maximum however it is 111.5% larger than the stress found in the JFC model. The diagonal displacement was found to be 0.113mm. This value is less than the control panel however more than the JFC panel. This is a 19% reduction in the diagonal extension when compared to the control panel.

The next intermediate layer to be tested was the hemp fibre. Again the ply properties were altered to match the hemp mechanical properties whilst the model remained with the same configuration and parameters. The model and stress distribution is shown in Figure B.3. Again the stress distribution as expected followed the same pattern as the other test specimens. The maximum stress reached was 4.022MPa which is very similar to that of the MDF panel. Overall again it is 80% of the maximum shear stress reached in the control panel. This value was larger than the value from the JFC by 115%. The diagonal extension found on this material was 0.109mm which was similar to the MDF model. The diagonal extension was only 78% compared to the original control panel or a 22% reduction in diagonal extension. This value was a bit more than the MDF panel whilst maintaining the same maximum shear stress. Overall this material had surprising results as the Young's modulus and Poisson's ratio were very different when compared to the MDF. These values can be seen in Table 4.1. The Young's modulus are 400MPa apart however the Poisson's ratios are vastly different with the MDF having only 0.253 and hemp fibre having 0.391.

The final NFC to be tested was the sisal fibre. The sisal fibre model was created and tested in the same process as explained before with only the mechanical properties of the intermediate layer altered to match up with the sisal properties. This method of course meant consistent and accurate results could be obtained. The sisal fibre model and stress distribution is shown in Figure B.4 which shows the same pattern as all other models. The maximum shear stress reached was 3.969MPa which is very similar to the MDF and hemp fibre models. The maximum stress reach was only 79% of the control panel's maximum so there is a big improvement in this regard. The diagonal extension was found to be 0.1056mm which is similar but smaller than the MDF and hemp fibre models. This is a total of 24% reduction from the original diagonal extension of the control panel. Overall the sisal fibre had similar Young's modulus to the MDF and hemp fibre materials however the Poisson's ratios are greatly different with sisal fibre having 0.471 compared to MDFs 0.253 value. The results are expected to be fairly similar to that of hemp but the high similarity between the results was not expected.

Table 7.1: Diagonal extension and maximum shear stress of laminate models

Panel (2D)	**Load applied (kN)**	**Diagonal extension (mm)**	**Maximum stress (MPa)**
CTR	1	0.138688	5.0226
JFC	1	0.088963	3.6246
MDF	1	0.113007	4.0449
Hemp	1	0.109435	4.0221
Sisal	1	0.105589	3.9687

Table 7.1 shows a summation of the results including the diagonal extension and the maximum shear stress in each model. Each model had a tensile load of 1kN load applied, this was then analysed by the Strand7 linear static

solver and produced the results listed in Table 7.1. The original control panel had a diagonal extension of 0.139mm and a maximum stress of 5.023MPa. This yielded the highest values for all panels tested. The next panel, JFC, produced the most ideal results of 0.08896mm for diagonal extension and 3.6246MPa for maximum stress. This specimen showed the best results when compared to the other NFCs tested. This was expected due to its Young's modulus value of 4592MPa.

The next panel tested was the MDF composite which also showed very promising results. The results weren't quite as good as the JFC composite, however with a much lower Young's modulus of 2603MPa this was an acceptable result. The next panel tested was the hemp fibre panel. These results lined up very closely to the MDF results with less than 1% difference however referring back to Table 4.1 it is vastly different in mechanical properties. The hemp fibre had a much higher Poisson's ratio and moderately higher Young's modulus than the MDF panel. Finally the Sisal panel was tested and had a lower diagonal extension and maximum shear stress than both the MDF and hemp fibre composites. This was expected due to the sisal fibres high Young's modulus.

Overall JFC was found to be the best material for a NFC intermediate layer followed by sisal and then more closely followed by MDF and hemp fibre composites. Because this testing was completed by linear analysis then higher loads such as 10kN could have been applied however the results would still yield the same with JFC being the optimal NFC. The other materials are all promising too and all are viable when compared to the control panel. All panels showed stress distribution in the same pattern, the magnitude of this stress was simply dependant on the NFC used as such the JFC showed the smallest stress distribution and the control panel showed the largest.

7.3 Dr. Fajrin's Results

Dr. Fajrin performed experimental tests on the control panel, JFC and MDF composites to see how they handled the tensile load applied in both diagonal extension and in-plane shear stress. His results and workings are shown in Appendix C and should be referred to for the remainder of chapter 7. As can be seen in Table C.1 are the list of results from his experimental tests. He found that the control panel withstood a diagonal load of 10kN and extended to 14mm before failing. The shear stress within this panel was found to be 23.36MPa. The next panel he tested was the JFC which reached a loading of 49.8kN and a diagonal extension of 18.27mm before it failed. The shear stress within this composite was found to be a much higher, 80.4MPa. Finally he tested a composite with MDF as the intermediate layer which did not fail until a 22.4kN load was applied and a total of 26.5mm diagonal extension. The shear stress in this composite was found to be 40.68MPa at failure. These values are the averages of multiple testing specimens, due to the nature of this project utilising Strand7 only one test was required as no deviation in the results would occur.

Dr. Fajrin then plotted his results shown in Figure C.1. The first specimen to fail was the control panel followed by the JFC composite and finally the MDF composite. However it is important to note that the JFC was able to withstand a much greater load than the MDF composite. The failure mechanisms Dr. Fajrin found were de-bonding for the control panel and MDF specimens and shear cracking failure for the JFC. The load deformation comparison graph shown in Figure C.1 shows how the addition of a JFC or MDF composite can alter the behaviour of the sandwich panel.

7.4 2D Results Discussion and Comparison

The experimental results completed by Dr. Fajrin also showed similarities to the Strand7 computations. The Strand7 models could not predict the failure modes however they do give valuable information on the expected behaviours of adding NFC intermediate layers. Dr. Fajrin did not test the hemp or sisal fibre composites. The control panel was the worst in handling stress and diagonal extension in both experimentally and computationally. Dr. Fajrin found that the control panel could not handle the shear and diagonal extension as well as the JFC and MDF composites. He found that the JFC was much more capable of handing higher loads and hence higher forces than the MDF and control panel. This falls in line with the results found using Strand7. He found the MDF composite to be viable and better than the control panel although not quite as good as the JFC intermediate layer. This also is shown within the Strand7 results as shown in Table 7.1. The JFC had the highest load carrying capacity in both analyses followed by MDF and finally the control panel. The JFC behaved differently to the MDF and control panel as found in Dr. Fajrin's results. This is because the JFC specimens acted more as a single integrated panel as opposed to a standard sandwich panel (hence the failure due to shear cracking as opposed to skin de-bonding).

The results showing the stress capabilities are shown in Figure C.2 where Dr. Fajrin has plotted his load against strain results for each specimen. This graph shows how each panel reacted to the strain and how much it could handle before failure. Figure C.2 shows that the control panel was first to fail, followed by the MDF panel and finally the JFC panel. It is easily visible that both the NFC intermediate layer additions performed better than the control panel by quite a margin. This is reflected in the results shown in Table C.1 where it was discussed that the shear stress capability of the JFC model was greatly higher than both the MDF and control panel.

The Strand7 results showed the maximum shear stress in each model depending on which NFC was used. All results showed panels with a NFC had a minimum 20% reduction in maximum shear stress when compared to the control panel. The JFC showed the best reduction in stress by a total of 28%. These results line up with Dr. Fajrin's experimental results as shown in Figure C.2. The Strand7 computation found that JFC was the ideal NFC for reducing stress followed by MDF and finally the control panel. Dr. Fajrin found that the JFC was able to withstand a much higher force with reduced strain because it was better at handling the shear stress and deflection. This is evident in Figure C.2 as when JFC is compared to MDF it is visible that at 20kN loading the JFC has approximately -500 micro strain and the MDF panel has approximately -650 micro strain. The control panel does not reach 20kN loading before failing however this trend can still be applied at 10kN loading where JFC handles it better than MDF which handles it better than the control panel. The Strand7 results showed the same relationship. The other two NFCs tested in the Strand7 analysis, sisal and hemp fibre, were not covered by Dr. Fajrin's experimental testing, however they both showed to produce results very similar to the MDF fibre. This is shown in the summation Table 7.1. Based off the identical behaviours shown in both analysis's it is safe to assume they would also be viable NFCs.

Overall the 2D laminate testing has shown that all NFCs tested are viable. The JFC is the best material possible followed by sisal, hemp and MDF. All NFCs tested showed that they are all possible and viable modifications for making a hybrid sandwich panel. The NFCs all showed a reduced diagonal extension as well as a reduced maximum shear stress. The failure modes are undetermined as this was a limitation of the 2D linear model. The JFC panel had the best reduction in both diagonal extension and maximum shear stress. For a further detailed conclusion on Dr. Fajrin's results refer to Figure C.3.

8.0 Analysis and Results of 3D Models

This section of the report will analyse and discuss the 3D model results. This will include showing how the models were tested, their results and discussion. The validation of the 3D models will also be briefly looked at. The discussion will focus on determining the trends and behaviours within the models and to provide reason as to why the NFC intermediate layers are or are not a viable addition to produce a sustainable hybrid sandwich panel. The development of the models can be found in section 6.0 which includes development of the base model, NFC incorporated models and the non linear development. Much like the 2D analysis the conclusions will be drawn based on the diagonal extension and maximum shear stress within the models. The 3D analysis will also include looking at the shear stresses in the core, intermediate layers and skins. Comparisons will be made based on the 2D results as well as Dr. Fajrin's experimental results. Appendix C will be referred to when Dr. Fajrin's results are being discussed and Appendix D will be for raw data and visual models (for purposes such as stress distribution) for the 3D analysis. Similar results to the 2D analysis are expected however since the models are now in 3D it is also more likely that the results show much more accurate representations of real life behaviours.

8.1 3D Control Panel Validation

Before any analysis of the 3D models could be conducted a validation test had to occur. This validation test would aim to compare the 2D laminate model against the 3D linear model. Similar to how it was carried out in section 7.1 for the 2D model however this time since the 2D model was validated it can be compared to that model. Thus eliminating the need to compare to Dr. Fajrin's experimental results for validation. The 3D non linear control panel was made as explained in section 6.0 and then tested with the same loading as the 2D laminate control panel to see if the results were similar. Figure 8.1 shows the 3D control panel model as created in Strand7.

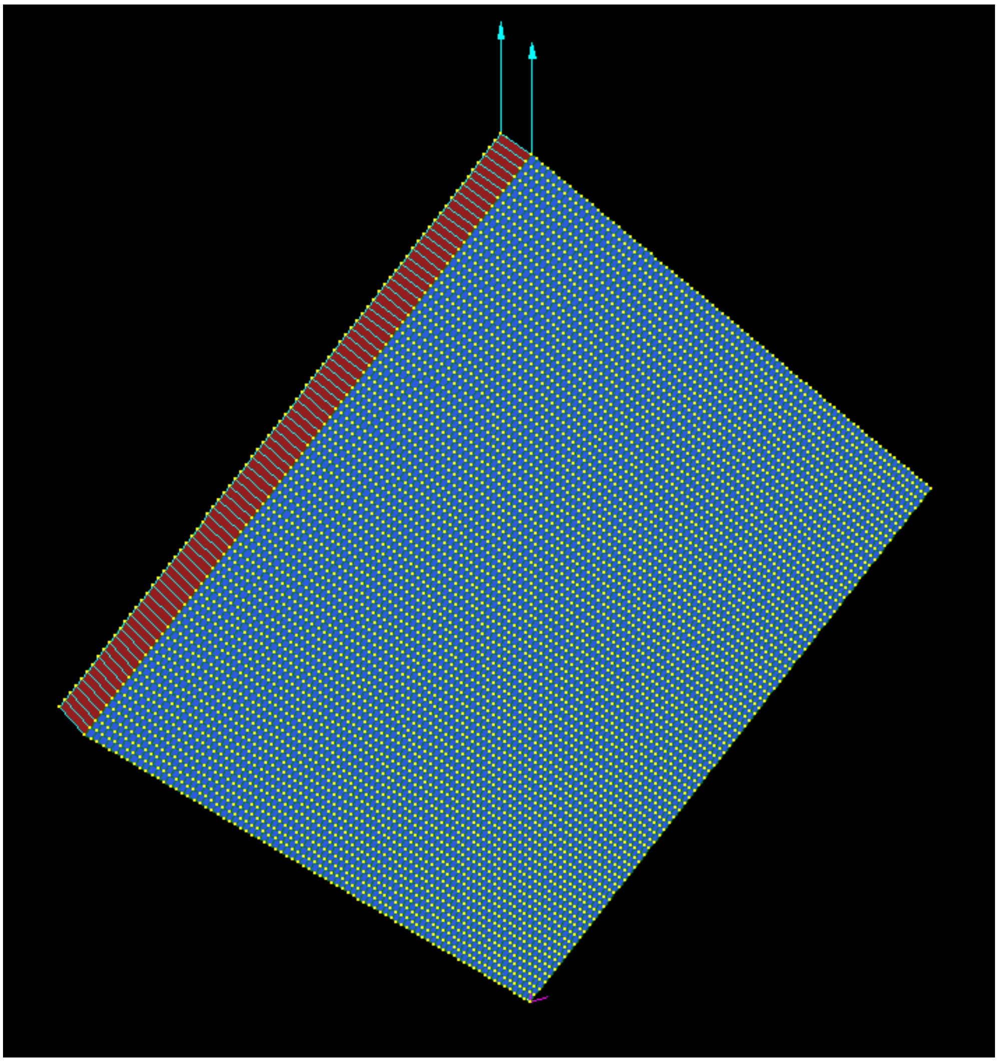


Figure 8.1: 3D control panel

The 3D control panel is the same as the 2D laminate model however the differences lay in the transition to 3D. The loading is now applied at two points as well as being supported by two points at the bottom. The layers are all 80x80 meshes and this increases the computation time moderately. The forces, global load and freedom cases are all the same as the 2D model however the transition to the 3D model is expected to give a more reasonable answer relating specifically to shear. This is because the 2D models act as one integrated material, being a laminate, and the 3D model treats each layer individually. Because of this the diagonal extension is not expected to vary much however the in-plane shear stress in each layer is expected to produce more accurate and viable results.

The model was tested in the same manner as the 2D model by using the linear static solver in Strand7. No other parameters have been changed and the diagonal extension results are shown below in Figure 8.2. This figure shows the linear analysis of the 2D model against the 3D model by plotting the diagonal extension for the diagonal load applied. These lines show the similar expected results of each model. As can be seen the 3D results follow a very similar slope to that of the 2D results. At 8kN loading the difference between the two results is only 0.04mm. This value decreases as smaller loads are applied and increases as larger loads are applied. The differences within the results are expected to be caused due to the nature of one being analysed as a laminate and the other as a layered 3D panel. Overall the results indicate that the 3D model has been fundamentally built correctly. This allows for further analysis with additional NFC intermediate layers which can then be compared to Dr. Fajrin's results as well as the 2D results. Note that a beam element was created along the top of the panel to allow the force to be distributed as a UDL as opposed to two point load forces on each skin however the diagonal displacement as well as stress distribution did not change.

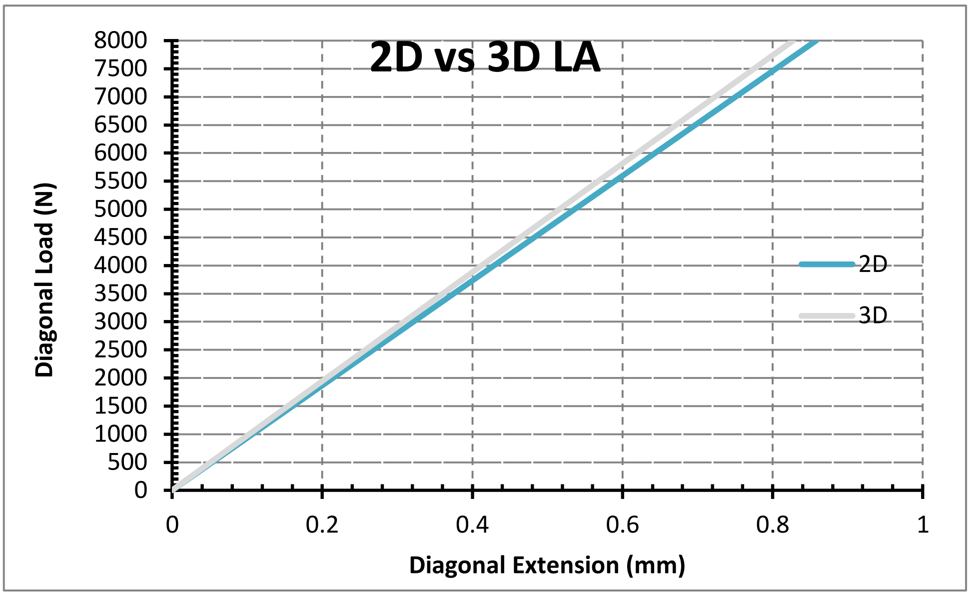


Figure 8.2: 2D vs. 3D linear results

8.2 Linear 3D Analysis

Testing of the linear 3D analysis followed the same procedure as the 2D analysis. The development of the models used has been explained in chapter 6. Each model was tested linearly using Strand7's linear static solver with a 1kN load applied. The models tested was the control panel, JFC, MDF, hemp and sisal NFC panels. The testing conditions were the same as the 2D analysis in that a 1kN load was applied and the displacement and shear stresses were recorded. The 3D analysis will analyse the shear stress in each layer of the sandwich panel including core, NFC intermediate layers and skins. The results will be compared to the 2D results as well as Dr. Fajrin's and conclusions will be drawn to determine the viability of NFCs in a hybrid sandwich panel. The results are expected to be similar in the diagonal extension however vastly different in the shear stresses because now the model may analyse the model as a layered structure as opposed to a single integrated panel like the 2D analysis did. Due to the large amount of visuals and data please refer to Appendix D during this section.

The first model tested was the control panel which can be seen in Figure 8.1. There was no intermediate layers so the core was made 25mm to keep testing consistent. The control panel was slightly different in the 3D model not only with the core thickness but also only using 2 supports since extra ones were not needed where the intermediate layers connect to the core. The loading was applied as shown in Figure 8.1, using two point loads. Note that using a UDL was tested to see if it affected results, specifically the shear stress within the core however it did not change any results. The control panel was found to have a diagonal extension 0.1338mm which was an expected result and is very similar to the 2D control panel extension. The in-plane shear stress of the skin was found to be 241.3MPa and the core 0.01289MPa. These values are shown in Figures 8.3 and 8.4. These results are very different from the 2D and basically show that all of the force is being carried within the skin and nearly none is being transferred into the core. The shear distributions are different for both the core and skins. The skins show a distribution that is very unique, the shear stress is again concentrated at the top and bottom points however now it acts directly along the central y-plane of the plate. The core shear stress distribution is similar to the 2D models where there are forces on either side of the y-plane but this time the shear stress is focused around only one side. This is possibly due to how small the shear stress actually is.

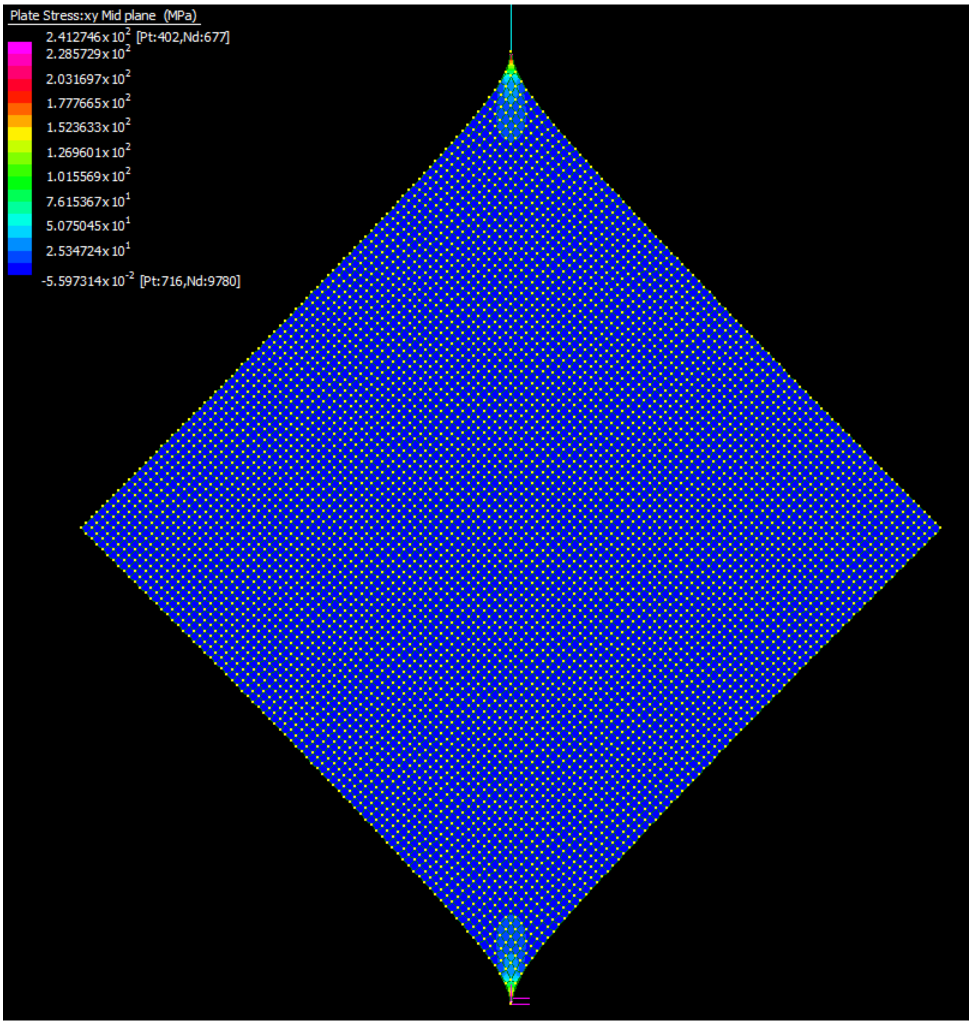


Figure 8.3: 3D control panel skin shear stress

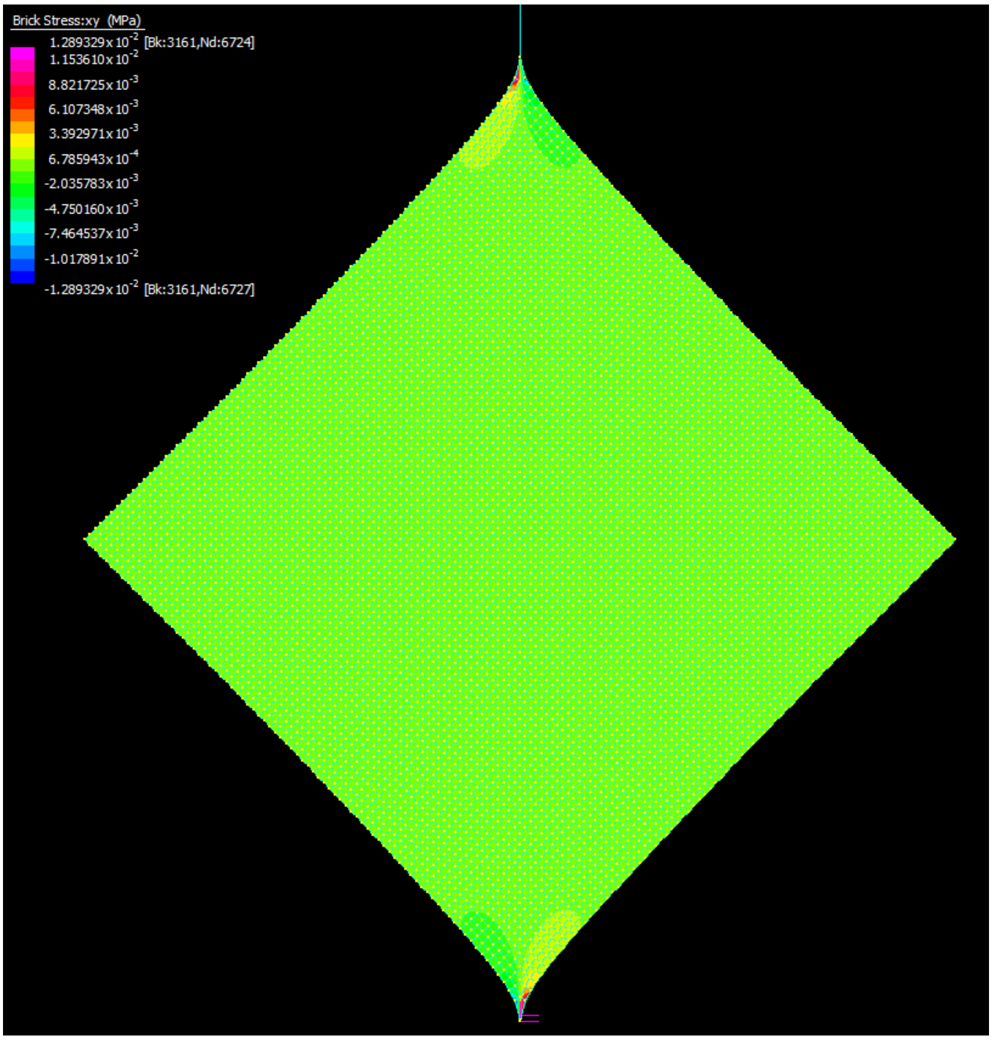


Figure 8.4: 3D control panel core shear stress

The next model tested was the jute fibre composite (JFC) model. The visuals and data for all models containing a NFC intermediate layer are listed in Appendix D. This model was similar but different to the control panel. This is because with the addition of the 3mm intermediate layers the core was reduced to 19mm to keep the total thickness, 26mm, consistent with the control panel. As explained in section 6.4 the NFC 3D models had 4 supports at the edges and where the intermediate layers connected to the core. The loading was applied as a UDL however this did not alter the results. The diagonal extension for the JFC panel was found to be 0.0711mm which is a significant reduction, 46.9%, when compared to the control panel. The shear stress distribution in the skin was found to very similar to the control panel. The shear distribution in the intermediate layer acted the same way as the core did in the control panel and the shear distribution in the core of the JFC model acted the same way as the NFC intermediate layer. However it was found that the core did not extend fully with the intermediate layer and skins as can be seen in Figure D.4. The cause of this is unknown and it occurs in all of the 3D NFC models. This behaviour is also replicated at the bottom of the model in the same manner.

The models were built with perfect bonding so this result is very unexpected and further testing is needed. The total shear stress in the plate was found to be 207.3MPa, the shear stress in the intermediate layer was found to be 7.296MPa and the shear stress in the core was found to be 0.0115MPa. These distributions and maximum shear stresses for the plates, intermediate layers and cores can be found in Figures D.1, D.2 and D.3 respectively. The skins are expected to withstand most of the loading and the intermediate layers are there to reduce the stresses within the core. Based on these results the JFC panel showed very promising results. A possible conclusion as to why the core doesn't extend the entire way is possibly due to the model not producing much stress within the core and so no extension is required.

The next model tested was the MDF panel which was tested and analysed the same way as the JFC however with the mechanical properties of the intermediate layer altered so that it matched the MDF properties. The supports, thicknesses, global load and freedom cases all remained the same. The stress distribution in the skins, intermediate layers and core are all the same shown in Figure D.5, D.6 and D.7. They show the same behaviour and the patterns all follow suit. The maximum shear stress within the plate was found to be 220.8MPa which was lower than the control panel although higher than the JFC. This is expected due to JFCs high Young's modulus. The shear stress in the intermediate layer was found to be 4.078MPa which is significantly lower than the shear stress in JFCs intermediate layer. This was a total of only 55% of the shear stress found in the JFC intermediate layer. Finally the core was found to have 0.0126MPa which is very slightly smaller than the original control panel. This shows how the core is not receiving much stress in any model but it is still reduced. The diagonal extension was 0.0864mm which again showed that the MDF panel had very promising results with an overall decrease in shear stresses and diagonal extension. More in-depth comparison will be made in the following section 8.3.

The next NFC tested was the hemp fibre which was tested in the same manner as the JFC and MDF panels. Hemp had a higher Poisson's ratio and Young's modulus than the MDF fibre so expected results were that the overall diagonal extension and maximum shear stress in the skins were lower. These results were confirmed with testing as it was found that the maximum shear stress in the skin was found to be 217.4MPa which is only a 1.5% reduction compared to the MDF panels shear stress in the skin. The maximum shear stress in the NFC intermediate layer was 5.729MPa. Again this result was expected as the Poisson's ratio was higher in the hemp fibre than the MDF. Again the core was found to produce very negligible results as the shear stress was found to be 0.0133MPa. Overall the shear stress in the core has slightly increased. This is a very strange result as it is expected that the shear within the core should decrease with the addition of an intermediate layer. Further analysis will be included in section 8.3. The results for the hemp fibre found that the maximum shear stress in the skins and core had decreased when compared to the control panel however the maximum shear stress within the NFC intermediate layer was much higher (40%) than the MDF specimen. The diagonal extension was found to be 0.0780mm which is only 58% of the total diagonal extension found within the original control panel. Also important to note is that although the hemp fibre and MDF models shared similar stress results within the skin, the diagonal extension of the hemp panel was only 90% of the MDFs diagonal extension. The shear stress distribution is shown in Figures D.8, D.9 and D.10. Again there is not very much difference at all, the skins show the same pattern as expected. The intermediate layer and core also show the same behaviours and patterns. The hemp fibre showed great results in terms of diagonal extension and shear stress within the intermediate layer however due to the increase in shear stress within the core it ultimately concludes that hemp fibre was found in this study to be an unviable NFC.

The final NFC tested was the sisal fibre which was tested and modelled the same way as explained for the other NFC hybrid panels. The sisal fibre had a fairly high Young's modulus and extremely high Poisson's ratio as shown in Table 4.1. Sisal in particular had concerning expectations due to its mechanical properties. The transverse shear was going to be somewhat high due to the high Poisson's ratio and this could cause additional stress onto the core. Testing found that the maximum shear stress distribution for the skin, intermediate layers and core were all the same as expected and are shown in Figures D.11, D.12 and D.13. These shear stress distributions are the same as all other panels containing a NFC intermediate layer. The diagonal extension was found to be the best reduction of 50%, compared to the control panel, yielding only 0.0668mm. This result was not anticipated as the expected results were that the JFC panel had the lowest extension due to its high Young's modulus value however these results can be explained due to the very high Poisson's ratio within the sisal fibre. This reduced diagonal extension must then mean some stresses have been carried transversally throughout the structure. This hypothesis was then confirmed as the maximum shear stresses of each layer were found. The maximum shear stress in the skin was found to be 209.5MPa, this value was roughly expected as sisal had the second highest Young's modulus. The intermediate layer however had a maximum shear of 7.360MPa which was the value of any NFC model. Finally the core had a shear stress of 0.0141MPa. This value was a 9% increase in shear stress within the core compared to the control panel. This as explained previously was due to the high Poisson's value making this panel unviable. Although this panel showed extremely promising results when analysing the diagonal extension and skin stress, the fact that it increases shear stress within the core makes the sisal fibre fail as a possible NFC.

Table 8.1: Diagonal extension and maximum shear stress of layers in 3D

Panel (3D)	Load applied (kN)	Diagonal extension (mm)	Maximum stress skin (MPa)	Maximum stress NFC (MPa)	Maximum stress core (MPa)
CTR	1	0.13378776	241.2746	0	0.0128933
JFC	1	0.07110381	207.3096	7.296076	0.0114603
MDF	1	0.08643856	220.7874	4.078289	0.0125705
Hemp	1	0.07796697	217.4453	5.729188	0.0133192
Sisal	1	0.06680553	209.5025	7.359621	0.0140929

The list of results of diagonal extension and shear stresses within each layer for each model is shown in Table 8.1. Overall the shear stress distributions shown in Appendix D are all roughly the same with very minor differences depending on the intensity of the stresses involved. These behaviours and patterns were all expected to be very similar as the same models were used with altered mechanical values to suit the values of the NFC intermediate layers. As can be seen the control panel had the largest diagonal extension as expected with 0.1338mm. The addition of any NFC intermediate layer dramatically reduced the diagonal extension by at least 35% for the MDF and up to 50% for the sisal fibre. The MDF fibre showed the least amount of reduction and compared to the other NFC panels it was well below the average. The JFC had the largest Young's modulus by far with 4592MPa so the great reduction in diagonal extension was expected with 0.0711mm. The MDF had the lowest Young's modulus of 2603MPa and as expected had the lowest reduction in diagonal extension with 0.0864mm. Hemp fibre had a Young's modulus of 3048MPa and so as expected had a diagonal extension of 0.0780mm. Finally sisal fibre had the second largest Young's modulus of 3505MPa, it was expected to have a reduction in diagonal extension laying somewhere between the JFC and hemp fibre although it was found that the introduction of a sisal fibre intermediate layer reduced the diagonal extension the greatest with a result of 0.0668mm. This was very unexpected as JFC had the largest Young's modulus so one could predict this NFC to have the greatest effect on reducing diagonal extension.

All panels were tested using a 1kN loading and this force caused 241.3MPa of shear stress in the skins of the control panel. Every NFC intermediate layer helped reduce the maximum shear stress in the skins by increasing the overall strength of the panel. The maximum reduction in shear stress within the skin occurred when using the JFC model with a 14% reduction. The MDF panel again showed the least improvement in shear stress reduction compared to the other NFC models. The control panel had a total of 241.3MPa of shear stress within the aluminium skins. The JFC as expected had the lowest value of 207.3MPa largely due to its very high Young's modulus. As expected the MDF panel yielded the lowest reduction in shear stress within the aluminium skins due to its very low Young's modulus. The MDF found to have a total of 220.8MPa of shear stress within its skins. The next specimen was hemp fibre which had a total of 217.4MPa of shear stress as expected. Finally sisal was tested and having the second largest Young's modulus was found to have the second largest reduction in shear stress with 209.5MPa. Overall all NFC intermediate layers added a good reduction of shear stress within the aluminium skins when compared to the control panel however the JFC and sisal fibre panels showed the greatest increase in reduction.

The shear stress within the NFC intermediate layer was also analysed for each panel and as can be seen in Table 8.1 the sisal fibre had the largest shear stress of 7.36MPa followed closely by JFC with 7.30MPa. Naturally as the control panel did not include intermediate layers there is nothing to compare these with but themselves. Sisal showed a very large maximum shear stress within its NFC layer however this was expected due to its high Poisson's ratio of 0.471, as listed in Table 4.1. JFC however had a Poisson's ratio of 0.361 and a slightly smaller maximum shear stress within the aluminium skin. This would lead the expected results to have a much lower value for shear stress within the intermediate layer however this was not the case. MDF had the lowest Poisson's ratio of 0.253 and as expected had the lowest shear stress within the intermediate layer with 4.08MPa even though it had the highest shear stress value in the skins of any NFC model. This value was considerably lower than the JFC and sisal fibre panels as well as moderately reduced compared to the hemp fibre model. The hemp fibre had the second largest value for Poisson's ratio with 0.391 and with such a high shear stress within the aluminium skins was expected to carry the second largest shear stress within the NFC layer. This however was not the case as the hemp fibre maximum shear stress in the NFC layer was found to be only 5.73MPa. A value much smaller than expected.

The final criteria that was analysed was the maximum shear stress within the core of each model. The control panel was found to have 0.0129MPa of shear stress within the core which showed how much force the aluminium skins were handling. The JFC model found the largest reduction within the core with only 0.0115MPa acting within it, this was a total reduction of 11.1%. This is quite large considering the failure mechanisms of sandwich panels generally occur due to skin de-bonding or core failure due to the shear forces within it. The next panel, MDF, also showed a reduction of shear stresses within the core. As seen in Table 4.1 the MDF panel had a maximum shear stress within the core of 0.0126MPa, yielding a total reduction of 2.6%. Although this value was significantly smaller than the JFC it still shows improvement within the core thus concluding MDF as a suitable and viable NFC but not as potent as the JFC model. The hemp fibre and sisal fibre found maximum shear stresses within the core as 0.0133MPa and 0.0141MPa respectively. The addition of NFC layers within these two models have actually increased the shear stress within the core. The whole idea to add intermediate layers is to reduce in-plane shear stress within the core and these results show that hemp and sisal actually increase it thus these two materials are unviable. Although sisal actually found the greatest reduction in diagonal extension as well as a very large reduction in the shear stress within the aluminium skins the fact that it increases shear stress within the core rules it overall as a failure. Hemp, with much less impressive results, still reduced the diagonal extension and shear within the skins however it too is a failure due to increase within the cores shear stresses.

Overall it was found that the addition of any NFC intermediate layer reduced the diagonal extension and maximum shear stress within the skins however hemp and sisal were found to actually increase the shear stress within the core. The concludes that in the 3D analysis only the JFC and MDF intermediate layers are viable. Out of these two options it was determined that JFC yielded the best results however MDF remains a viable alternative. JFC had a massive reduction in the diagonal extension and maximum shear stress in both the skins and core. MDFs results were also very impressive in terms of reducing diagonal extension and reduction in the shear stress of the skin however not the greatest reduction in the core with only a 2.6% total reduction.

8.3 Discussion and Comparison of 3D Results

This section aims to compare and discuss the 3D results against those found the in 2D analysis as well as Dr. Fajrin's experimental results. Dr. Fajrin's results and discussion can be found in section 7.3 as well as Appendix C. The 3D analysis showed a lot of similarities to both the 2D analysis and Dr. Fajrin's work. As previously noted Dr. Fajrin carried out his experiments with a control panel and two panels incorporating NFC intermediate layers, JFC and MDF.

The 3D and 2D results both showed a reduce in diagonal extension with the addition of any NFC. The 2D analysis found that the greatest reduction in diagonal extension was with the use of the JFC however the 3D analysis found that sisal yielded the best reduction. The values between the models in 2D and 3D are not very similar and this is believed to be due to the fact that the laminate models treated the panel as one integrated structure where as the 3D model did not. The 2D analysis was limited to testing only the maximum stress where as the 3D analysis was able to test for maximum stress within the skins, NFC intermediate layers as well as the core. In the 2D analysis JFC was found to have the largest reduction to the maximum shear stress where as in the 3D JFC was found to have the best reduction in the skins and core. JFC however was found to carry a high proportion of the stress in its intermediate layer (when compared to the other hybrid panels). In both analyses the MDF panel showed the least improvement in both diagonal extension as well as maximum shear stress. This is true to some extend however the MDF panel was also receiving the smallest stress within its intermediate layer. The sisal and hemp panels in the 2D analysis were found to reduce diagonal extension and overall stress in the models. This was found true also in the 3D analysis however the shear stress was transitioned into the core raising it to endure a greater amount than the control panel. This in-depth analysis found that although sisal and hemp did reduce stresses it did not reduce the core stresses which are most vital.

The 3D results also showed similarities with Dr. Fajrin's experimental results. The experimental results as discussed in sections 7.3 and 7.4 showed that the addition of JFC as the intermediate layer significantly increased the capability of the plate in both diagonal extension and shear stress reduction. The MDF panel also reduced the diagonal extension and shear stress within the panel but not nearly as well as the JFC intermediate layer did. These results coincide with the 3D analysis. The 3D analysis found that the JFC significantly improved the shear stress resilience and decreased the diagonal extension by a large margin. The MDF also improved these properties but not to the extent of the JFC. Dr. Fajrin did not test the hemp or sisal fibres however based off of the findings, these fibres actually increasing the strain within the core, they are not viable.

Overall the 3D analysis results were in line with Dr. Fajrin's experiments. Both the JFC and MDF increase the mechanical properties of the sandwich panels when compared to the control panel. The 3D results found that the hemp and sisal fibres actually increased the stress within the core making these materials not viable regardless of how well they reduced the diagonal extension or shear stress within the skins. The JFC was found to be the idea material with a diagonal extension of only 0.0711mm compared to the control panels 0.1338mm. The maximum shear stress in the skins and core was found to be 207.3MPa and 0.0115MPa respectively. The control panel had a shear stress of 241.3MPa within the skin and 0.0129MPa within the core. The MDF panel also had promising results with a diagonal extension of 0.0864mm and a shear stress of 220.8MPa within the skin and 0.0126MPa within the core.

8.4 3D Non Linear Analysis

This study as explained in section 6.3 also experimented with the use of non linear models. However after testing was completed it was found that the results were the same as the 3D linear results. Hence the models were not transitioning to a non linear phase regardless of how large a load was applied to the models. This failure can be determined from the 3D linear results where the shear stresses were all concentrated within the skins and NFC layers and the cores remained relatively unaffected. Since the models did not transition into the non linear phase no conclusions can be made on these testings. The non linear analysis tested for both nonlinear geometry (GNL) as well as nonlinear material (MNL). It was expected that MNL would yield results similar to Dr. Fajrin's however this was not the case as the models failed to transition. Figure 8.2 showed the linear 2D vs linear 3D plots however the non linear 3D plot followed the linear plot exactly. This trend did not change as loads increased as expected. Overall this area can lead to further study as the results will show a more in depth and realistic expectations of real world behaviours.

9.0 Conclusions and Recommendations

This study has tested and analysed a development of a new possible hybrid sandwich panel by introducing an intermediate layer made from NFC. The 2D and 3D analysis both showed similarities in results when compared to Dr. Fajrin's experimental testing. The 2D analysis found that every addition of an intermediate layer made from NFC decreased the diagonal extension and shear stress within the panel. The best result in this section was JFC with a reduction of 35.8% in diagonal extension and 21.9% in overall maximum shear stress compared to the control panel (which had the composition of a EPS foam core and aluminium skins). Dr. Fajrin also found the JFC to best the best NFC in his analysis. The 2D analysis found all NFCs to be viable.

The 3D analysis was able to take this analysis one step further by investigating the shear stress in each layer. The panels were tested again however this time using layers and it found that all NFCs decreased the diagonal extension significantly compared to the control panel. The shear stress within the aluminium skins was also decreased in each NFC model however hemp and sisal fibres actually increased the shear stress within the core making these materials unviable. The 3D analysis again found JFC to be the best NFC with a total reduction of 46.9% in diagonal extension, 14% shear stress reduction in the skins and 11.2% reduction in the cores shear stresses. Dr. Fajrin's experimental results as noted found JFC to be the best candidate followed by the MDF composite.

Non linear 3D analysis was also attempted and trialled for many months however due to time constraints the models could not be finalised and tested. However it was found in the non linear analysis that the skins were absorbing almost the complete loading applied in both the point load models and UDL models.

9.1 Further Work

Non linear 3D analysis could provide more accurate and in depth results on the behaviour of the new hybrid sandwich panels. It is recommended that further work is undertaken to try to develop the non linear 3D models into a suitable condition by validating a control panel model against Dr. Fajrin's. Then adding the NFC layers to test and analyse the behaviours to compare with Dr. Fajrin's experimental results. A more in depth analysis can be concluded due the realistic real world non linear behaviour patterns. As it currently stands the models have been altered for 3D testing with the addition of the cores stress-strain curve, loading increments and ensuring convergence however the models are not entering non linear phase due to the aluminium skins absorbing over 99% of the load. It is recommended to trial link elements in the non linear 3D models to simulate de-bonding within the skin and core. This is a common failure mechanism of sandwich panels and must be investigated due to the core not failing under high shear loadings.

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Appendix A - Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **SHANE COLLIER**

TOPIC: FINITE ELEMENT ANALYSIS OF A NEWLY DEVELOPED HYBRID NATURAL FIBRE SANDWICH WALL PANEL LOADED WITH IN-PLANE SHEAR LOADING

SUPERVISORS: Assoc Prof Yan Zhuge, USQ

ENROLMENT: ENG4111 - S1, D, 2015;
ENG4112 - S2, D, 2015

PROJECT AIM: This project seeks to develop a finite element model for a composite wall panel using Strand7 where EPS foam core and natural fibre indeterminate layers will be modelled using 3D element and the aluminium skins will be modelled as 2D layered element. The project aims to test and analyse the economic and materialistic properties of the wall panel.

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

1. Research background information on composite wall panels under in-plane shear load.

2. Design a basic 2D model of the composite wall panel while continuing research.

3. Develop the complex 3D model and compare to experimental results.

4. Validate the model.

5. Analyse the finite element model for its materialistic properties and results.

6. Evaluate the model for economic factors.

As time permits:

7. Undertake a parametric study to find the optimum design of the sandwich panel.

AGREED:

__________ (Student) __________ (Supervisor)

17/3/2015 16/3/2015

Appendix B

This appendix shows data and visuals from the 2D laminate analysis.

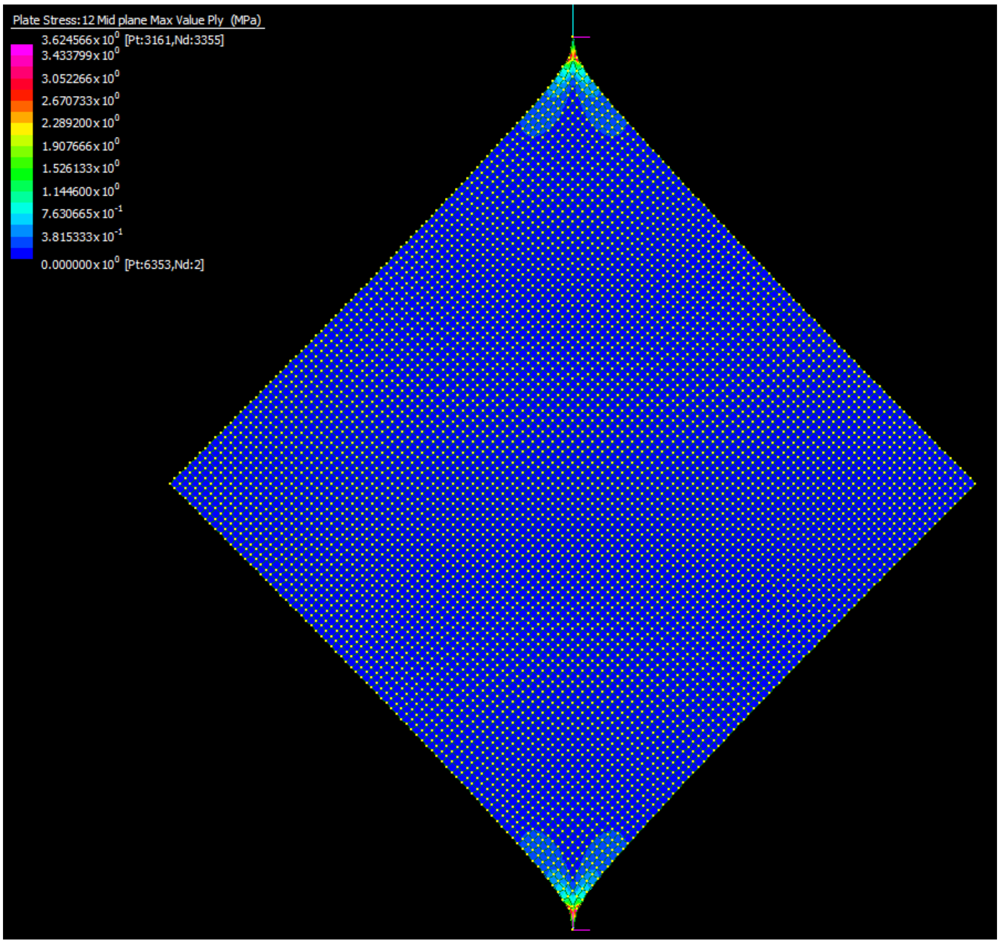

Figure B.1: JFC 2D laminate shear stress

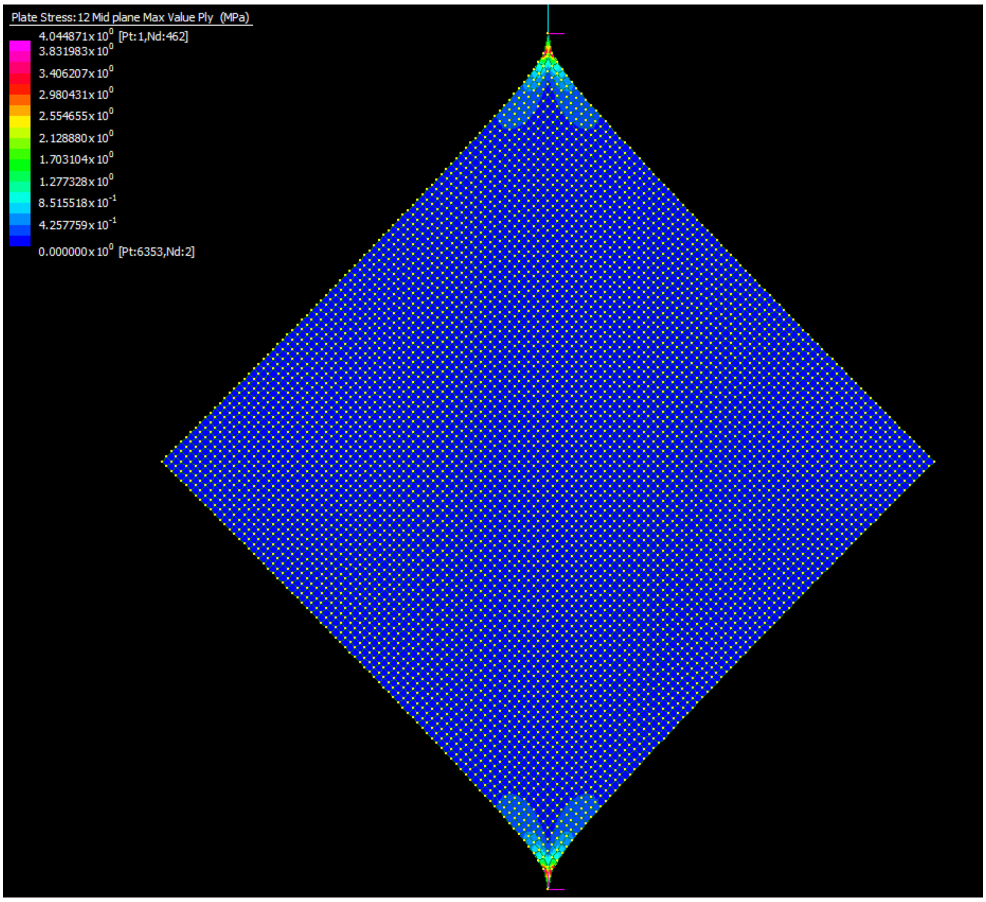

Figure B.2: MDF 2D laminate shear stress

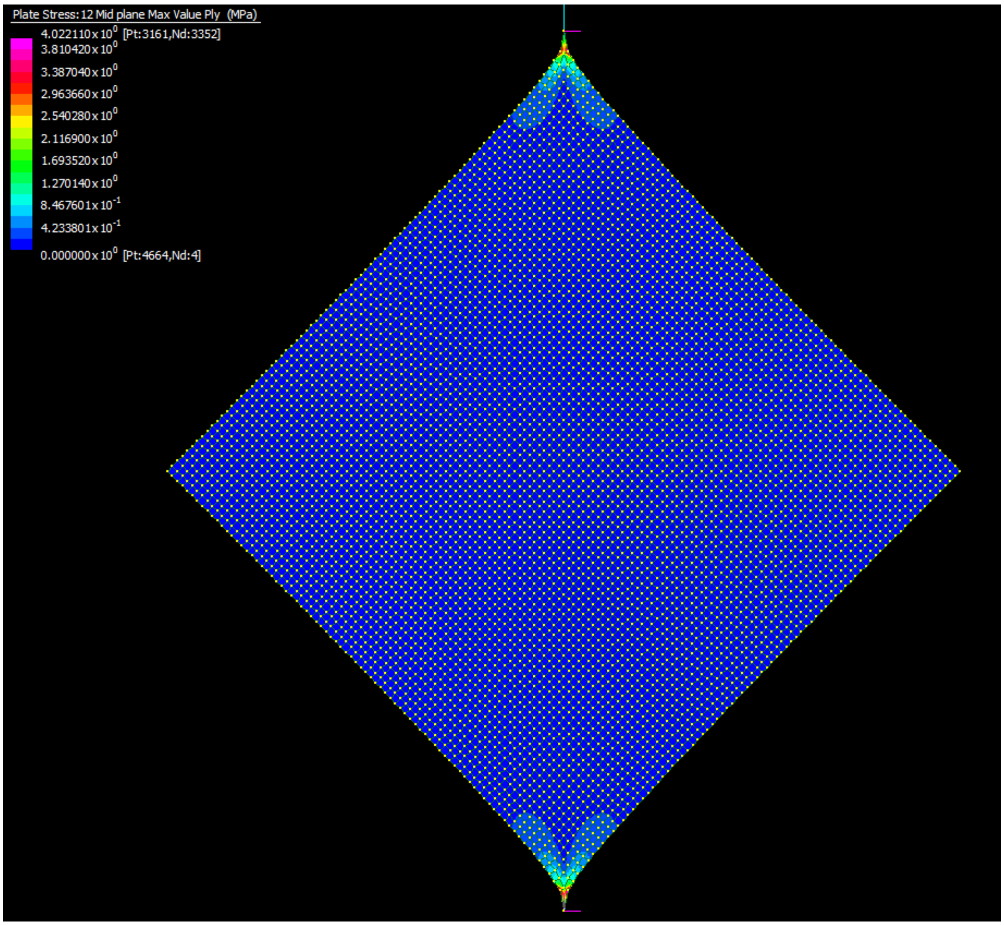

Figure B.3: Hemp fibre 2D laminate shear stress

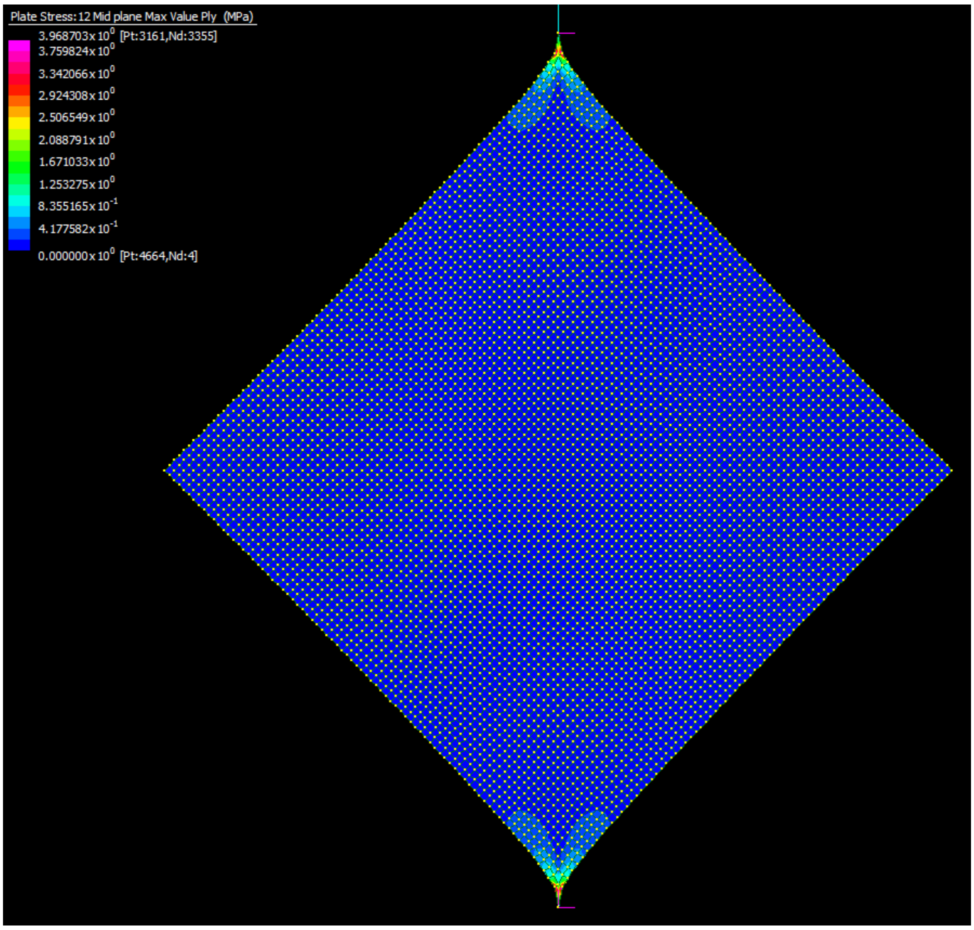

Figure B.4: Sisal fibre 2D laminate shear stress

Appendix C

This appendix shows the results of Dr. Fajrin's tests on utilising NFCs as an intermediate layer for in-plane shear stress behaviour.

Table C.1: Diagonal extension results

Table 7.2. Diagonal tension shear test results

Specimen Group	Specimen	Diagonal Load (F_s)	Extension (δ)	Shear Load (F_s)	Shear Stress (τ_s)	Shear Angle (γ)	Shear Displ. (Δ)
		(N)	(mm)	(N)	(MPa)	(^{0})	(mm)
				Eq. 7.3	Eq. 7.4	Eq. 7.7	Calculated
1	2	3	4	5	6	7	8
CTR	CTR-1	9228	7.73	6409.37	21.36	2.09	10.95
	CTR-2	10043	14.48	6868.10	22.89	3.96	20.78
	CTR-3	13575	22.75	9111.76	30.37	6.30	33.14
	CTR-4	9051	13.17	6208.24	20.69	3.60	18.86
	CTR-5	9367	12.05	6441.49	21.47	3.28	17.22
Average		**10252**	**14.04**	**7007.79**	**23.36**	**3.85**	**20.19**
Stdev		**1894.74**	**5.49**	**1200.45**	**4.00**	**1.54**	**8.12**
CV		**18.48**	**39.11**	**17.13**	**17.13**	**40.03**	**40.24**
JFC	JFC-1	49006	15.52	33434.46	79.61	4.25	22.32
	JFC-2	47921	19.73	32384.16	77.11	5.44	28.59
	JFC-3	53834	26.98	35795.47	85.23	7.52	39.61
	JFC-4	51127	14.72	34945.09	83.20	4.03	21.14
	JFC-5	47192	14.42	32277.60	76.85	3.95	20.69
Average		**49816**	**18.27**	**33767.36**	**80.40**	**5.04**	**26.47**
Stdev		**2692.38**	**5.31**	**1560.75**	**3.72**	**1.51**	**8.00**
CV		**5.40**	**29.09**	**4.62**	**4.62**	**30.00**	**30.23**
MDF	MDF-1	21809	23.38	14617.95	39.94	6.48	34.10
	MDF-2	22324	25.97	14877.05	40.65	7.23	38.06
	MDF-3	22442	29.38	14843.25	40.56	8.22	43.34
	MDF-4	22366	23.73	14979.57	40.93	6.58	34.63
	MDF-5	22908	29.92	15133.44	41.35	8.38	44.18
Average		**22369.8**	**26.48**	**14890.25**	**40.68**	**7.38**	**38.86**
Stdev		**390.99**	**3.07**	**189.51**	**0.52**	**0.89**	**4.73**
CV		**1.75**	**11.59**	**1.27**	**1.27**	**12.08**	**12.18**

The above experimental results of diagonal in-plane shear testing were plotted as the average of ultimate diagonal load, vertical deformation, in-plane shear load, shear displacement, shear stress and shear angle against the type of intermediate layer. As expected the experimental data for the MDF was the most consistent with a CV of only 1.75% (for F_s). The JFC data was also very good with a CV of 5.4% while the CV for CTR was surprisingly high at 18.48%, but it remained within acceptable levels. Figure 7.10 presents the average of ultimate diagonal load and vertical deformation against the type of intermediate layer of sandwich panel. As it can be observed from the figure, the average ultimate diagonal load for hybrid sandwich panels with JFC and MDF

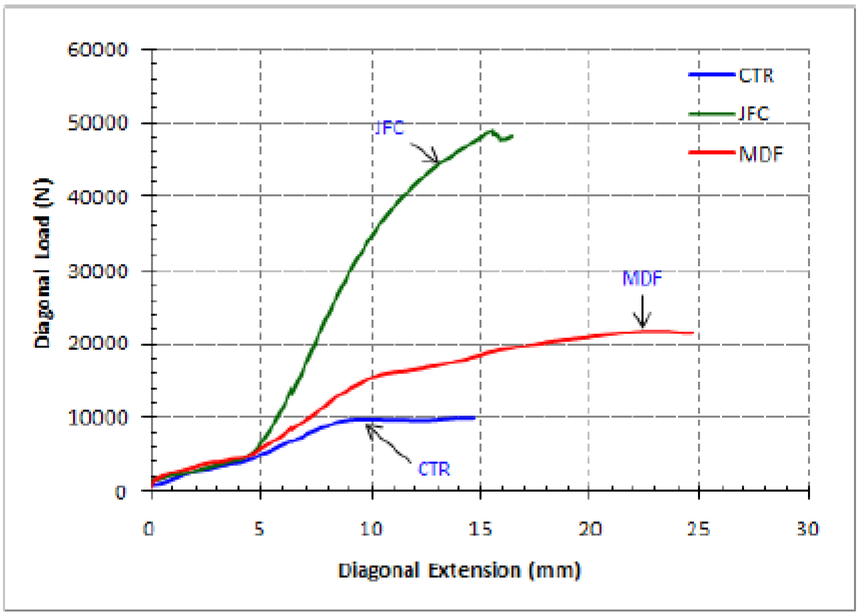

Figure C.1: Diagonal extension results

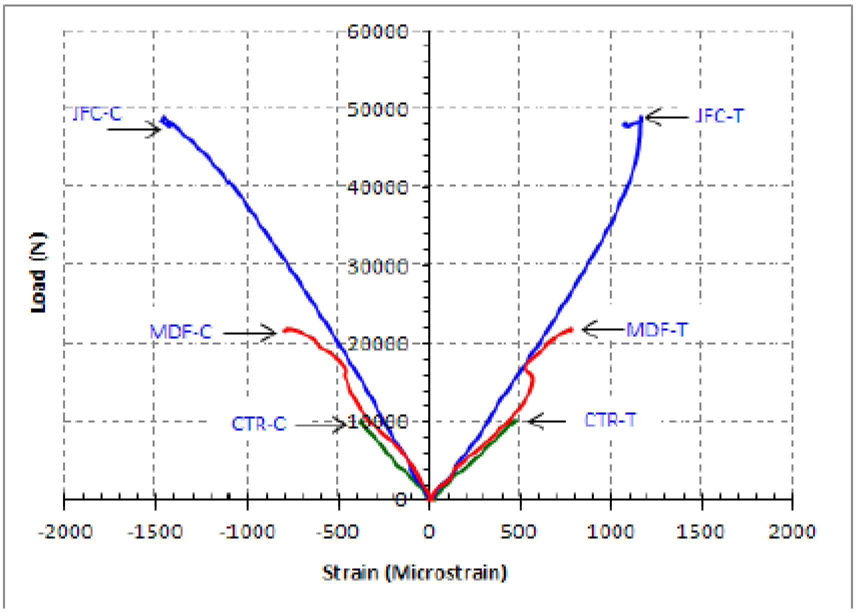

Figure C.2: Load vs. strain results

7.6. Chapter Conclusions

The in-plane shear behaviour of hybrid sandwich panels with an intermediate layer had been examined under a tension diagonal shear test. The in-plane shear behaviour and failure mechanisms of the hybrid sandwich panels have been compared to the conventional sandwich panels. The results of experimental investigation showed that incorporating intermediate layer within a sandwich structure significantly enhanced the in-plane shear behaviour of the hybrid sandwich panels developed in this thesis. More specific findings are outlined as follows.

1) The incorporation of JFC and MDF intermediate layer within sandwich panel has increased the diagonal load carrying capacity of sandwich panels by 385.9% and 118.2%, respectively. The average in-plane shear load of sandwich panels with JFC and MDF intermediate layer was about 381.9% and 112.5% higher

than such value of the sandwich panels without intermediate layer. While the improvement of shear stress given by the introduction of intermediate layer was about 384.9% for JFC and 118.3% for the MDF.

2) Hybrid sandwich panels with the JFC intermediate layer show excellent strength and stiffness. The panels with MDF intermediate layer behaved less stiff than the panels with JFC intermediate layer. The introduction of the intermediate layer, especially the one that made of JFC, has shown a significant contribution to the enhancement of the load carrying capacity of the sandwich panels.
3) Hybrid sandwich panel with either MDF or JFC intermediate layer has a better deformation capability than the conventional sandwich panels. Based upon the tension strains measurement, the deformation capability of hybrid sandwich panels with MDF intermediate layer is 1.6 times higher than the conventional sandwich panels, and 2.4 times for the panels with JFC intermediate layer. The enhancement is even more significant when the analysis uses the compression strain. The deformation capability of hybrid sandwich panels with MDF intermediate layer is 2.1 times higher than the conventional sandwich panels, and 3.8 times for the panels with JFC intermediate layer. If the comparison is made under a same load, the hybrid sandwich panels with JFC and MDF intermediate layers deform less than the conventional sandwich panel providing better deflection serviceability.
4) The results of the experiments were analysed as per Mohammed et al (2000) and Kuenzi et al (1962). The two methods provided comparable results. The difference between the average results was only about 3.5% for the CTR specimens, 4.6% for the JFC specimens and 5.5% for MDF specimens
5) Modified Kuenzi Model and Modified Hoff-Mautner Model have reasonably predicted the strength of hybrid sandwich panels with the JFC intermediate layer that collapsed under a buckling mechanism. The Modified Mamalis Model has successfully predicted the strength of hybrid sandwich panels with MDF intermediate layer that failed due to face wrinkling or delamination between intermediate layer and core. The strength of sandwich panels without an intermediate layer (CTR) has reasonably predicted with the Classical Euler shear equation.

Figure C.3: Dr. Fajrin's shear behaviour conclusions

Appendix D

This appendix shows data and visuals from the 3D analysis.

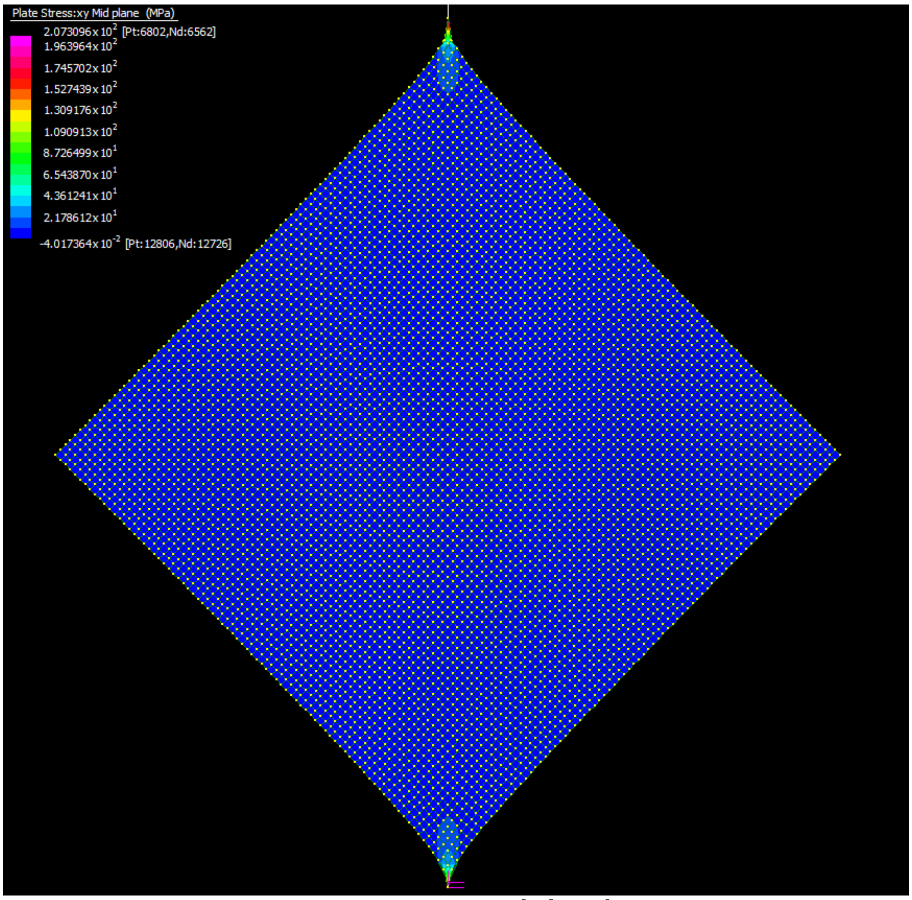

Figure D.1: JFC panel plate shear stress

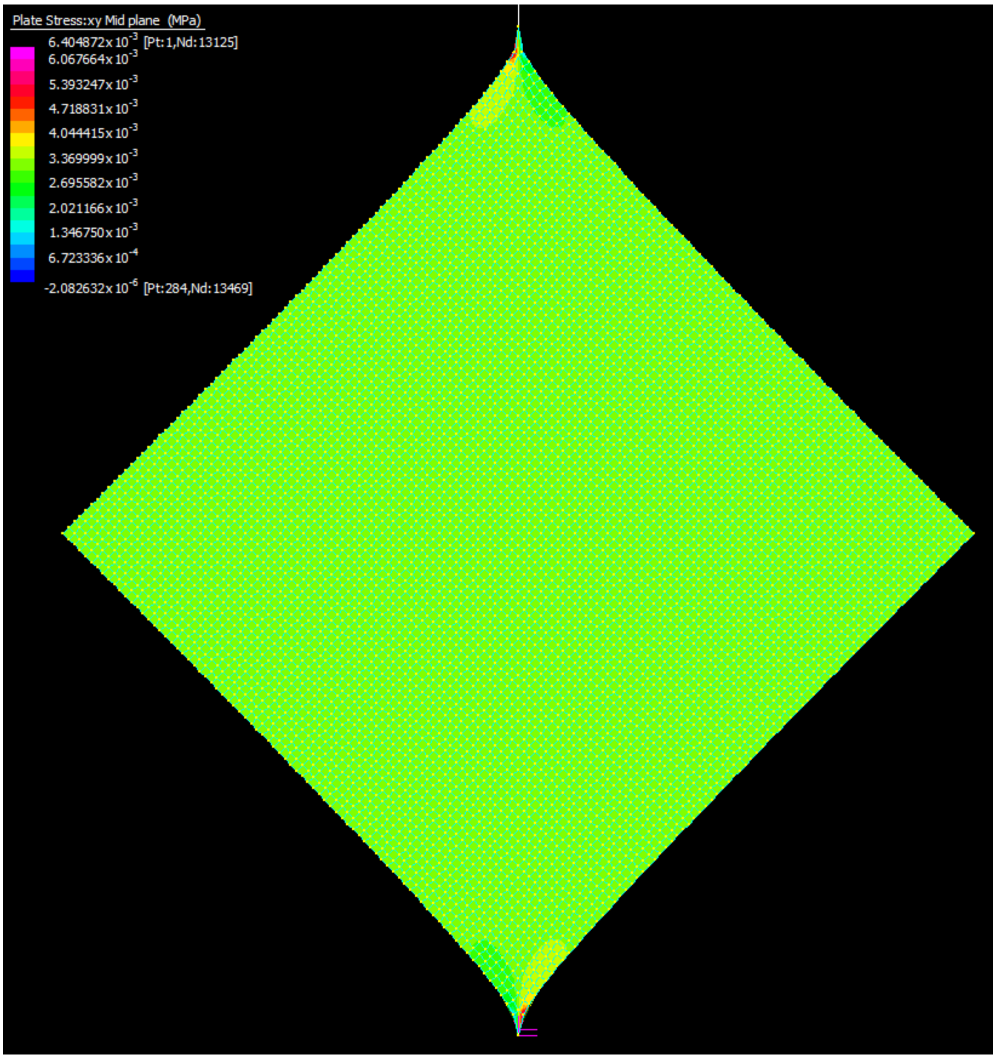

Figure D.2: JFC panel intermediate layer shear stress

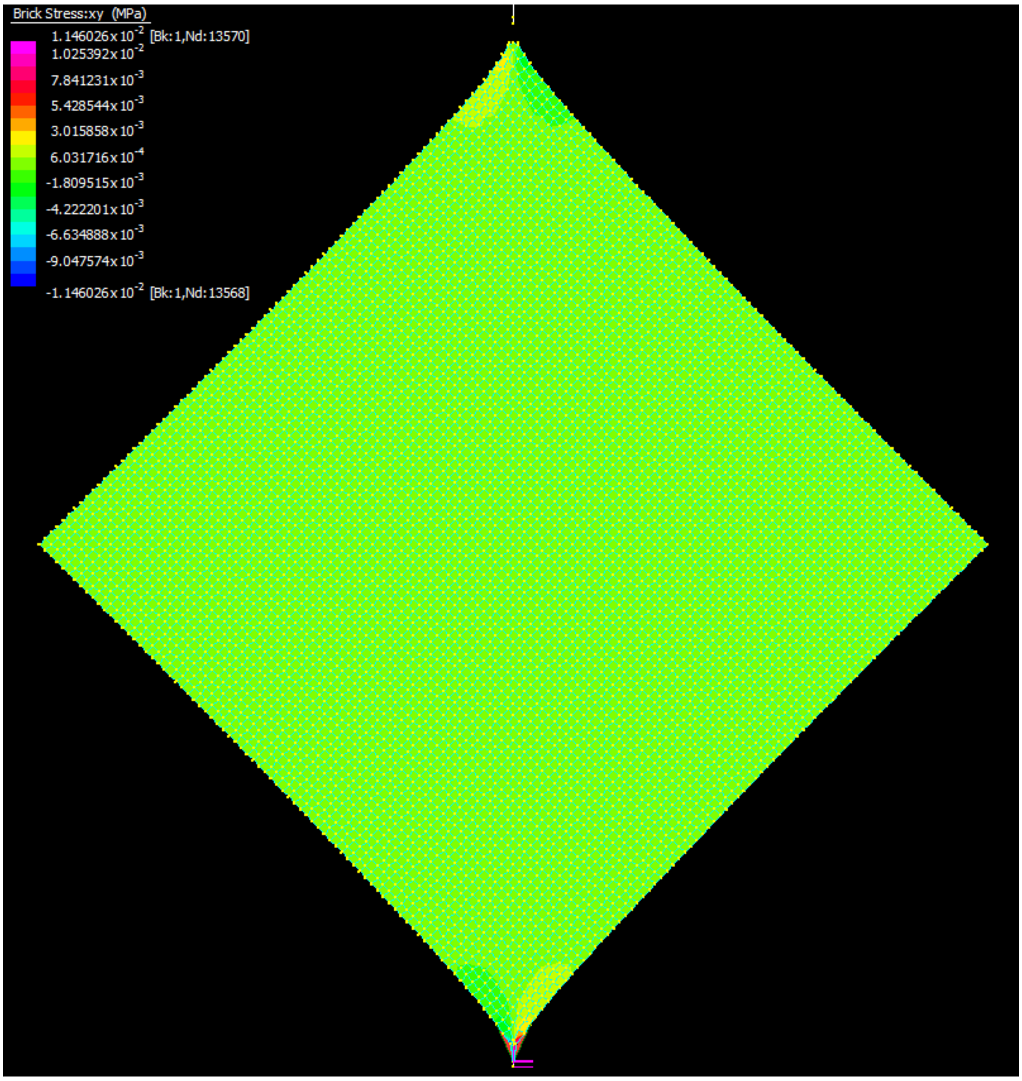

Figure D.3: JFC panel core shear stress

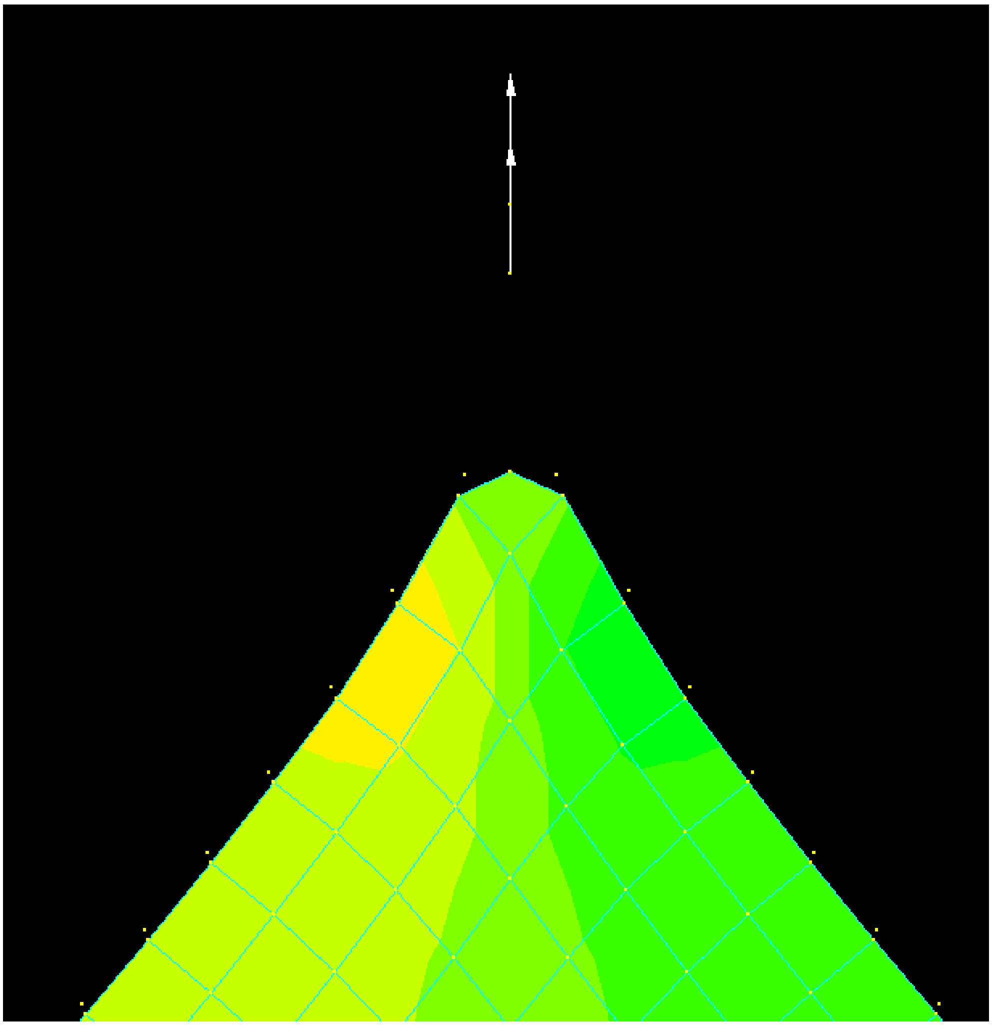

Figure D.4: JFC panel core failure

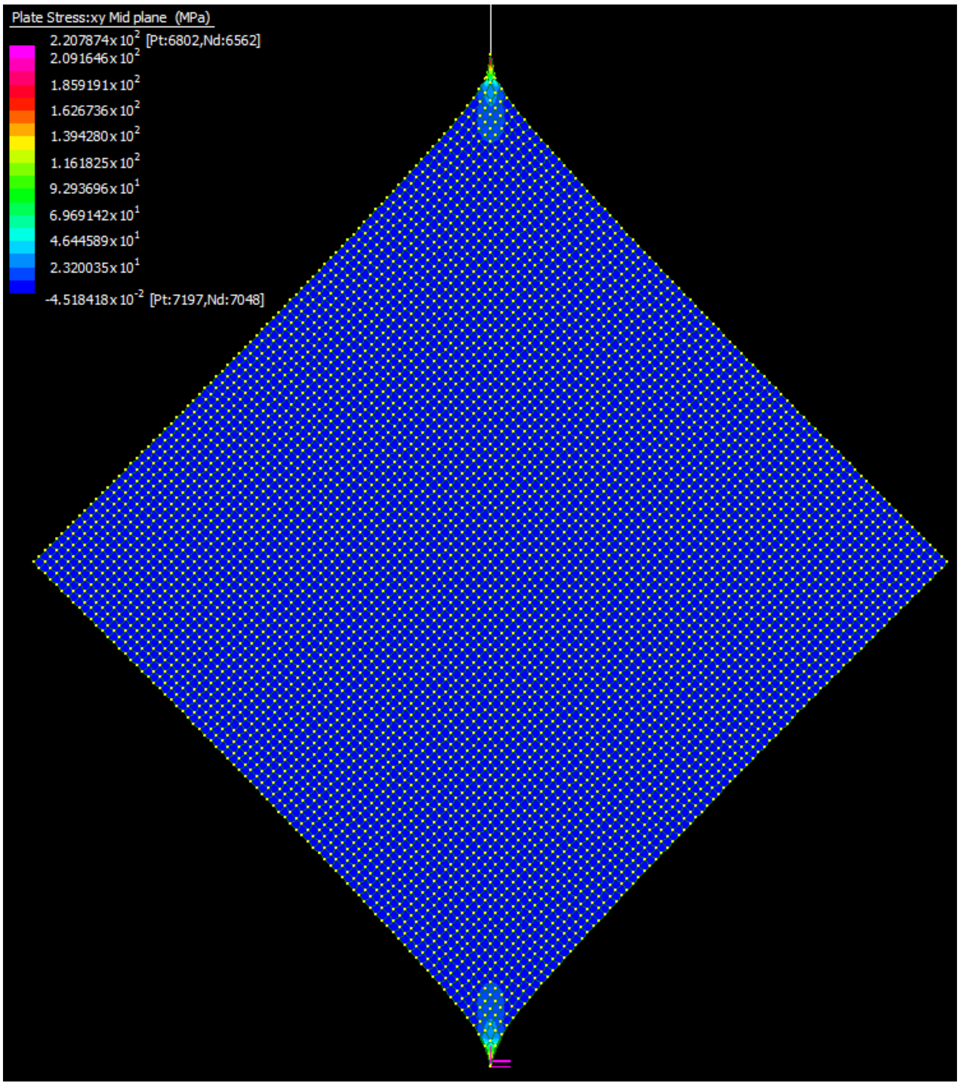

Figure D.5:MDF panel plate shear stress

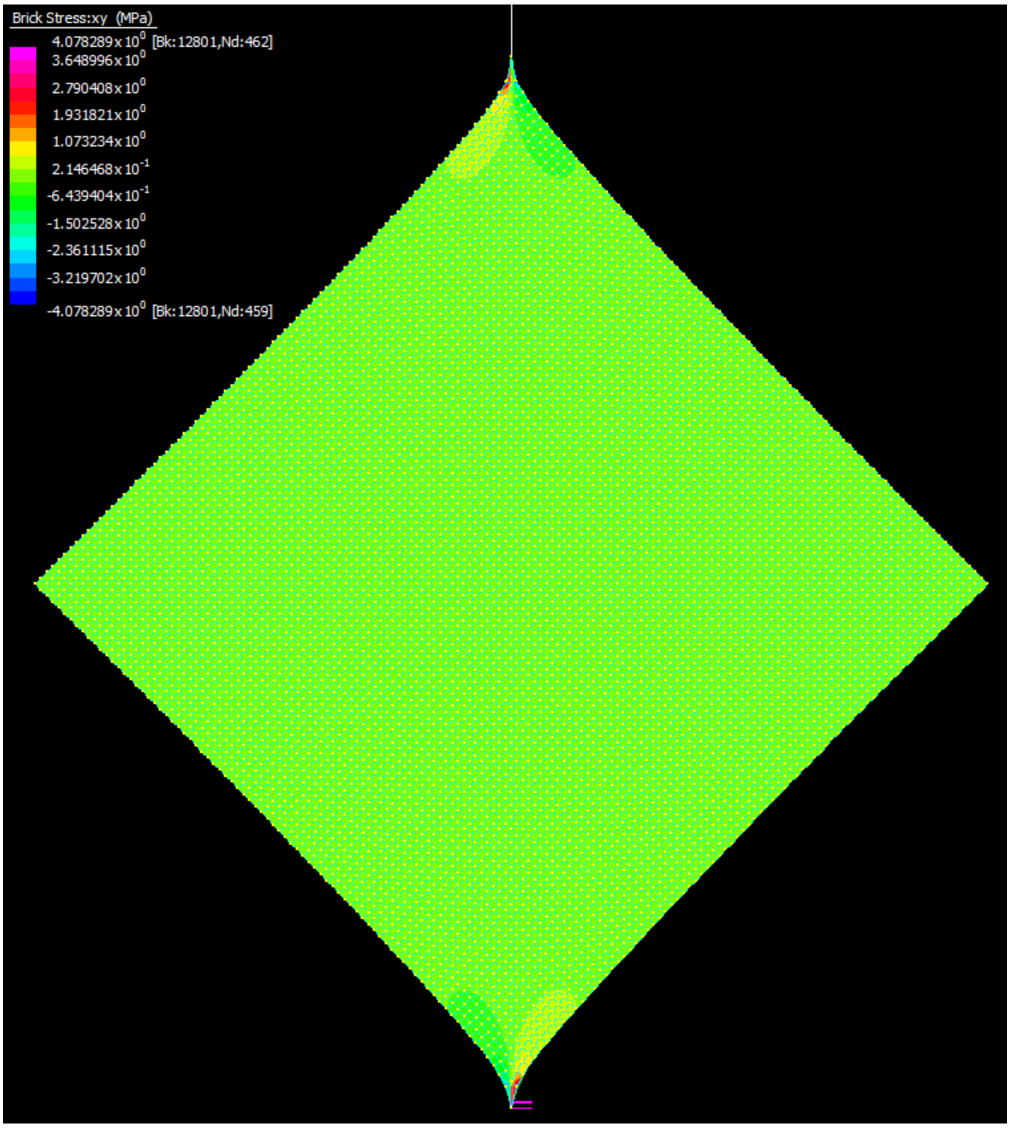

Figure D.6: MDF panel intermediate layer shear stress

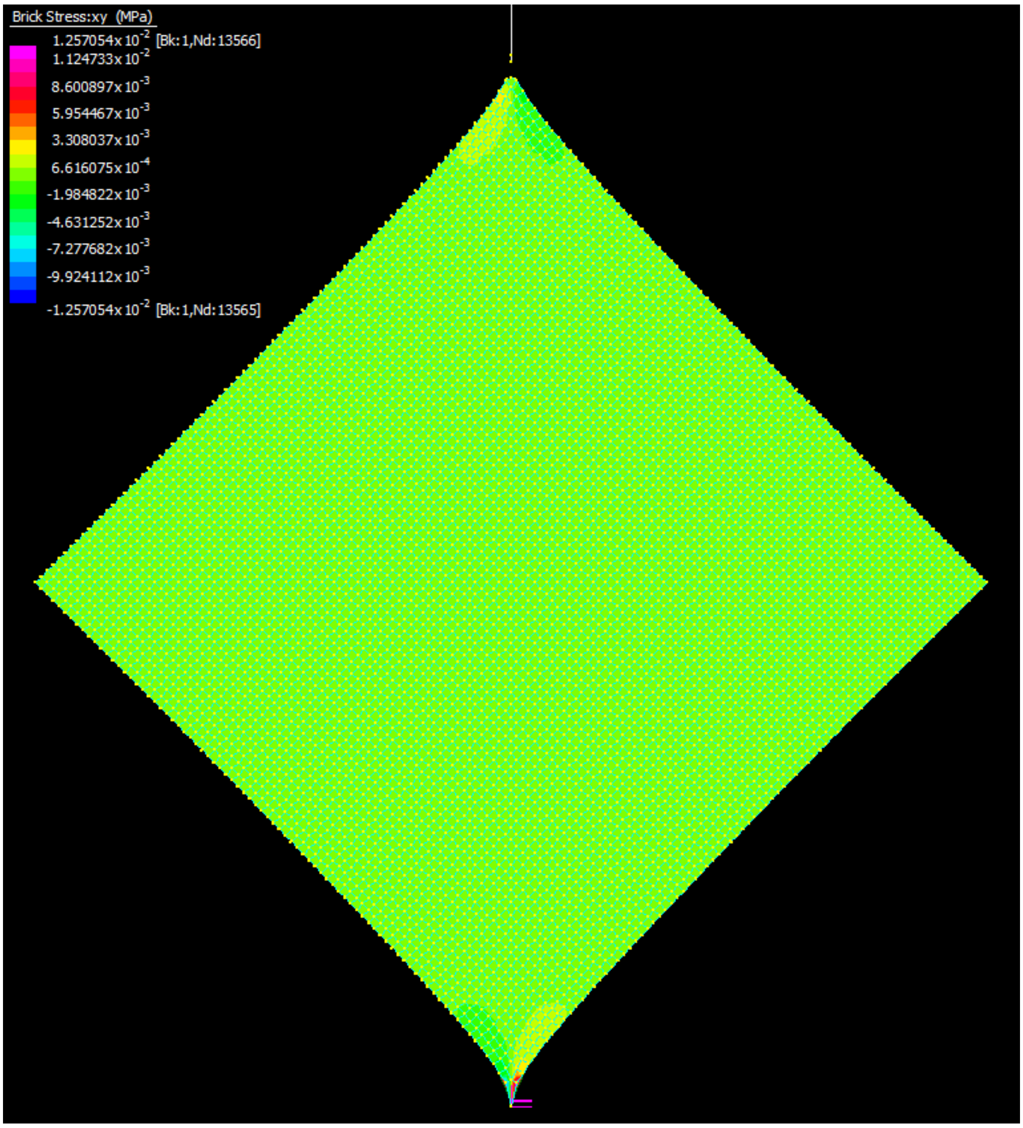

Figure D.7: MDF panel core shear stress

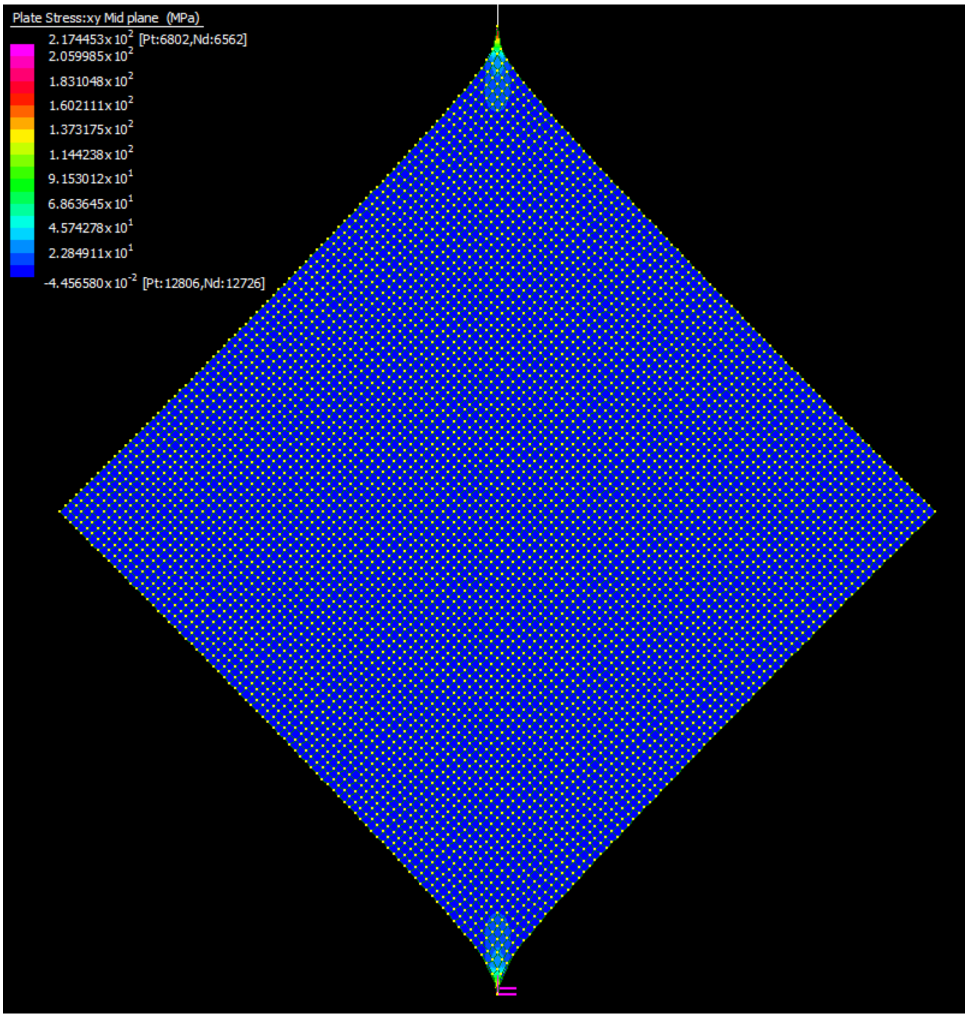

Figure D.8: Hemp panel plate shear stress

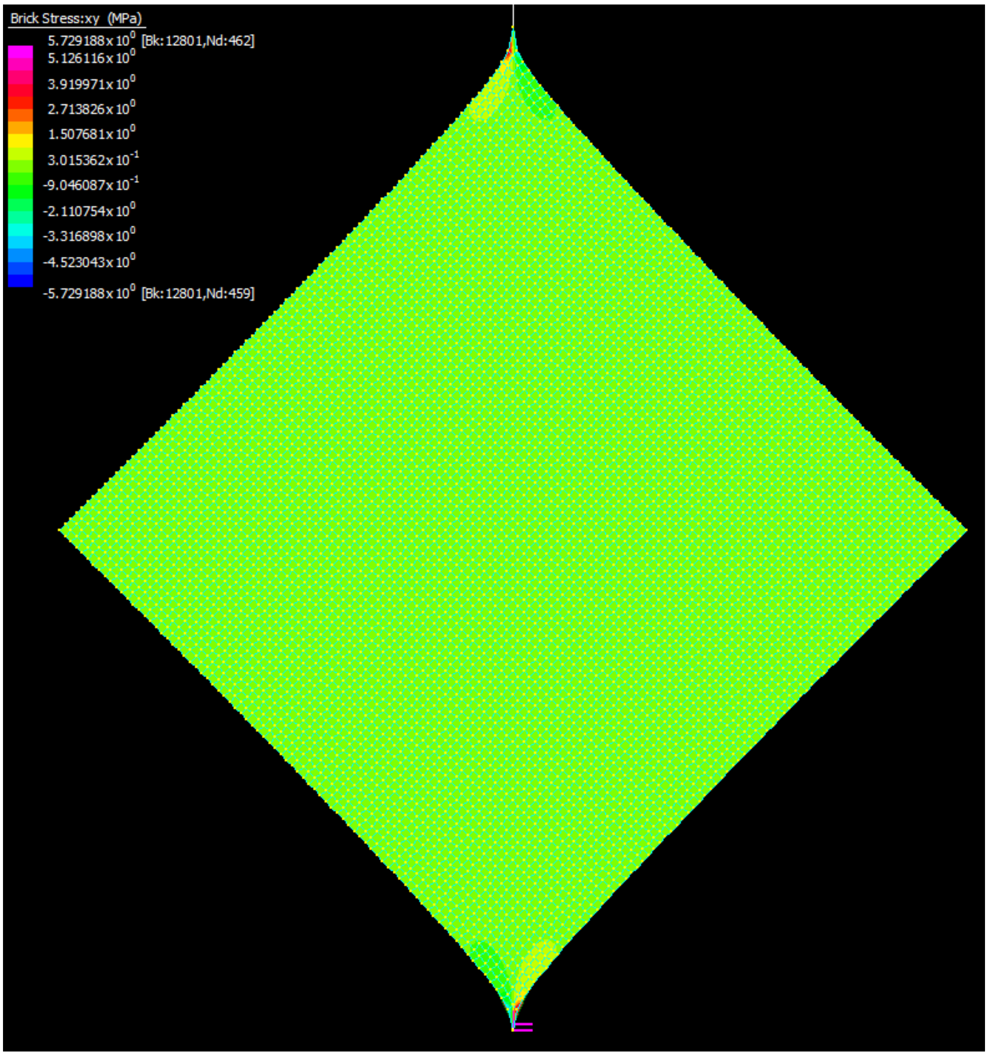

Figure D.9: Hemp panel intermediate layer shear stress

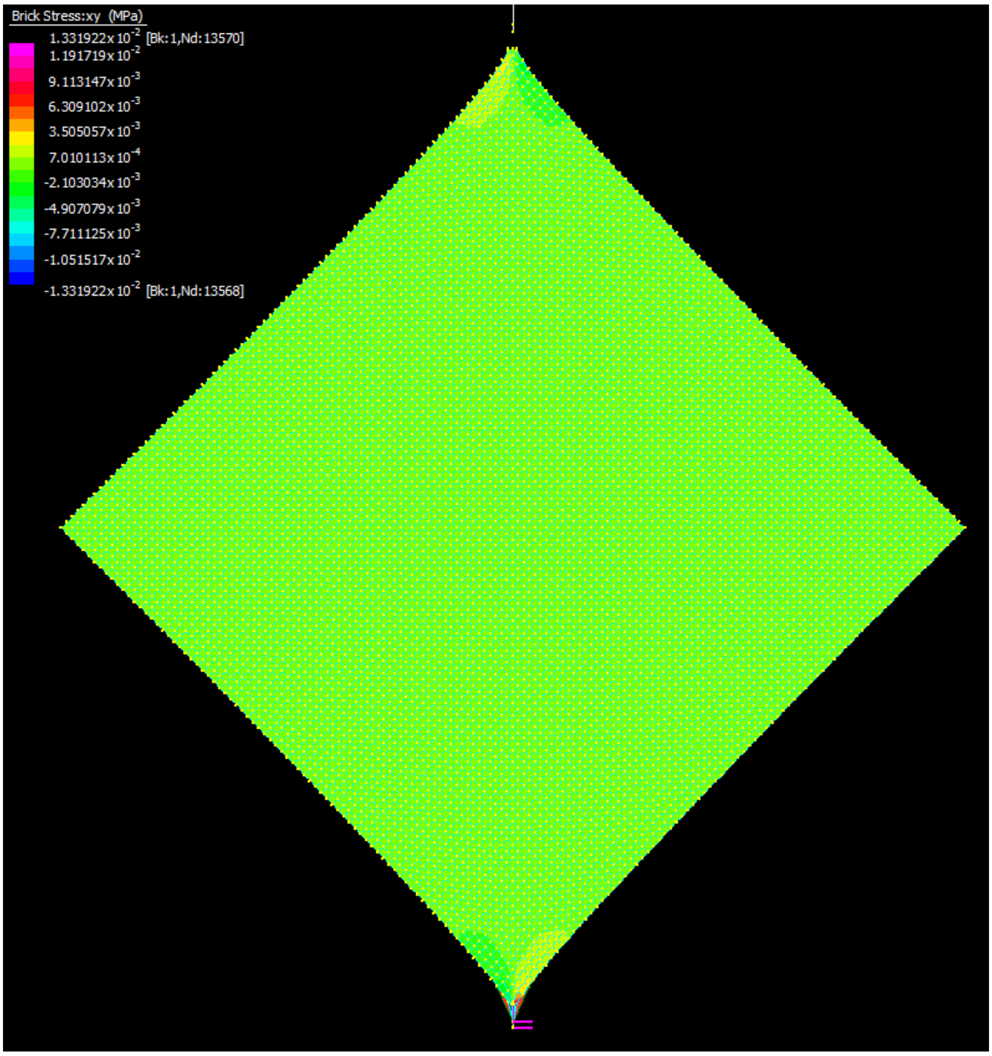

Figure D.10: Hemp panel core shear stress

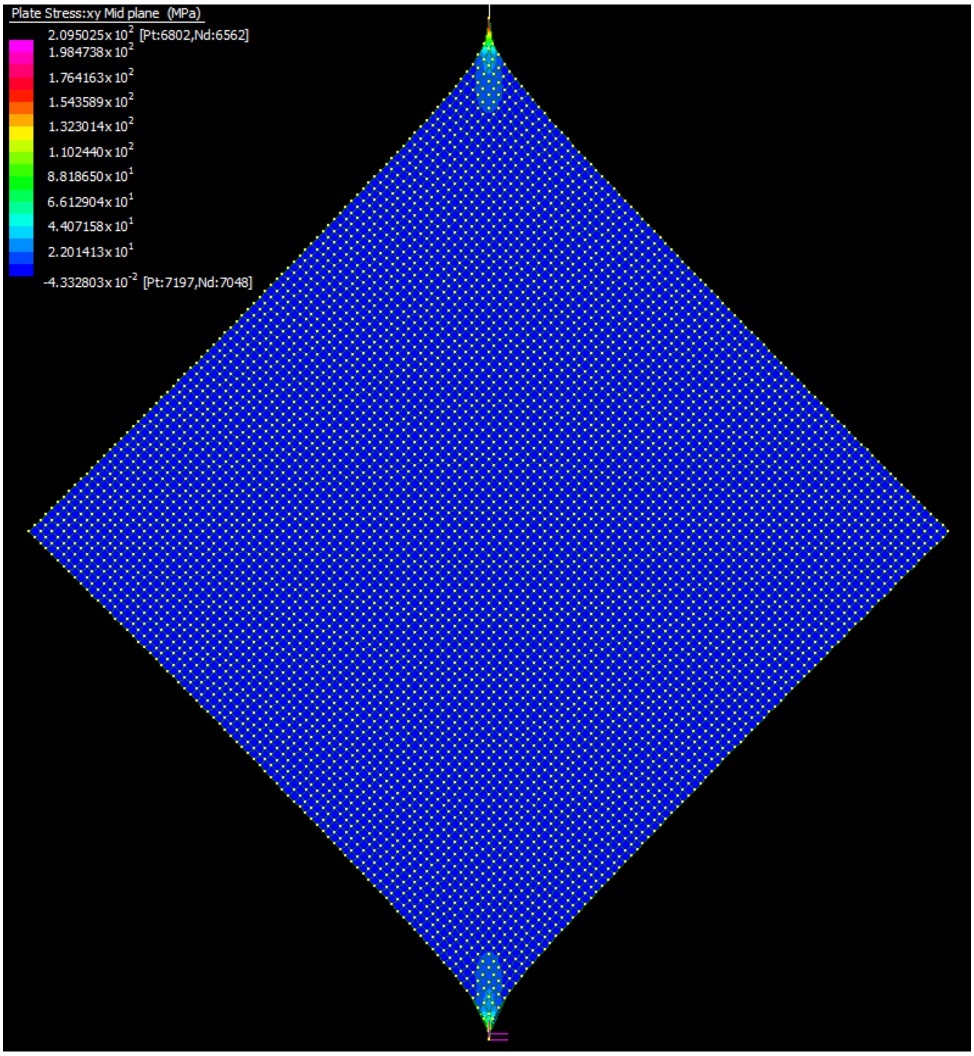

Figure D.11: Sisal panel plate shear stress

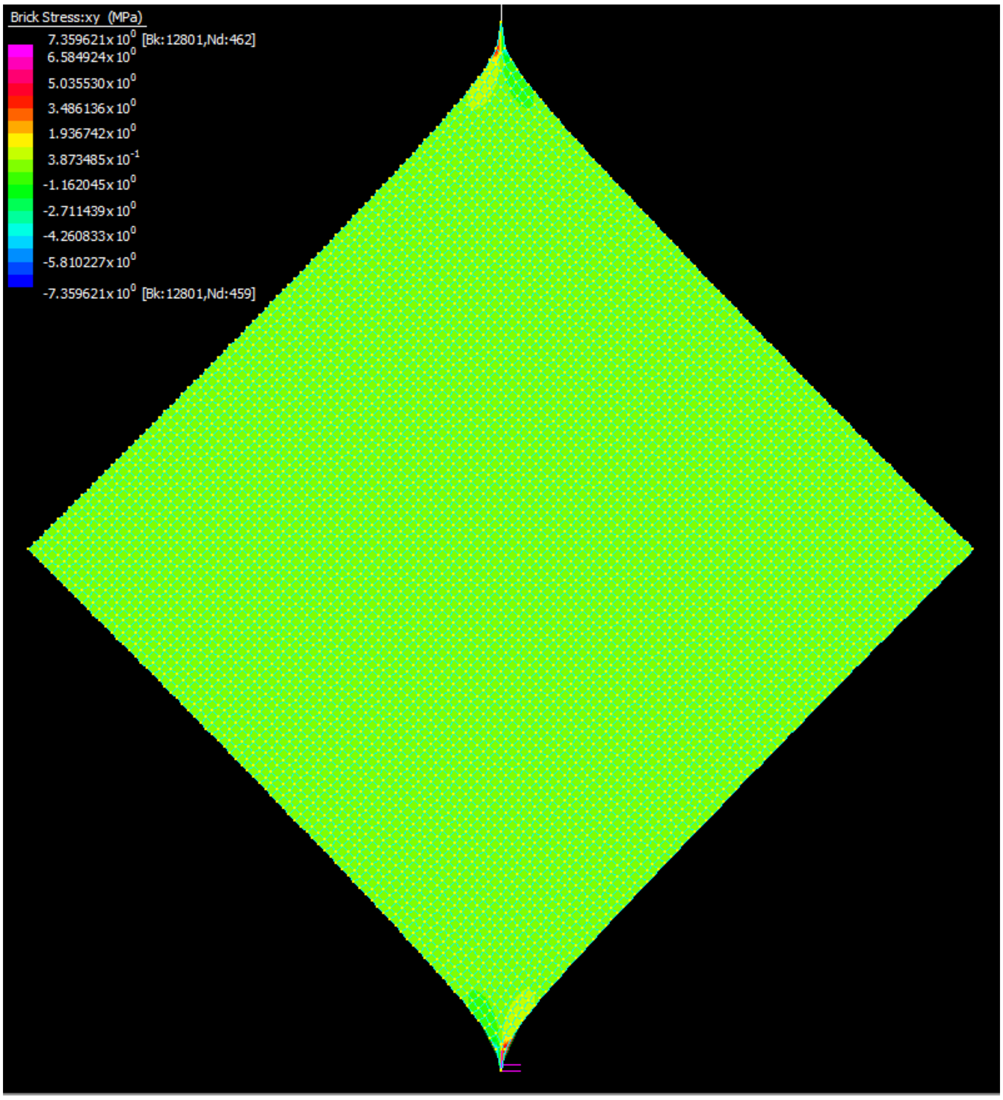

Figure D.12: Sisal panel intermediate layer shear stress

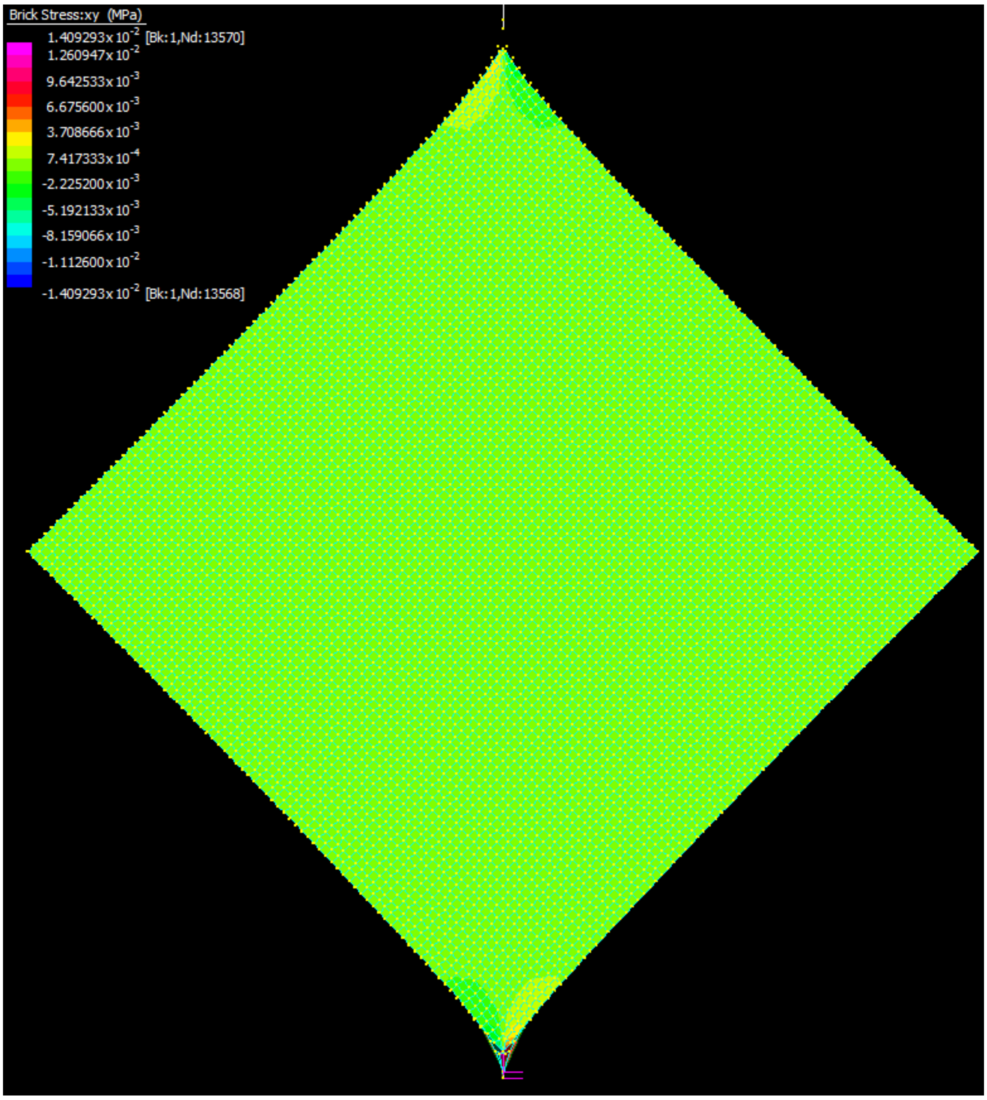

Figure D.13: Sisal panel core shear stress

Appendix E

This appendix lists the models in Strand7 used in this analysis.

- 1x1 2D
- 3D core LA base
- 3D CTR NLA model
- 3D_Model_1
- 3Dcore with 2Dplates
- 3Dcore2DskinsNLA
- 5x5 2D
- 10x10 2D
- 40x40 2D
- 80x80 2D
- 80x80 3D LA
- 100x100 2D
- 160x160
- BASE MODEL
- Basic2D3layer3
- Hemp 3D
- Hemp fibre 2D
- Hemp new 3D
- JFC 2D
- JFC 3D
- JFC new 3D
- MDF 2D
- MDF 3D
- MDF new 3D
- Mesh3
- new2Dmodel
- new3Dmodel
- NFC 3D LA base
- No NFC 3D
- Shand and Muni 2D
- Shand and Muni 2D NEW
- Shane and Muni 2D NEW
- Sisal 3D
- sisal fibre 2D
- Sisal new 3D
- Working2Dmodel-IR

Figure E.1: List of Strand7 models