University of Southern Queensland
FACULTY OF ENGINEERING AND SURVEYING

Behaviour of fibre composite walkways and grating

A dissertation submitted by

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Abstract

Throughout modern engineering, there has been a push to research, develop and implement new and innovative building materials as a substitution for the materials currently being used which have showed various forms of deterioration and faulting. This project specifically focuses on the field of construction of boardwalks and walkways.

The aim of this research project was to investigate how fibre reinforced polymer (FRP) grating behaves mechanically while being subject to various types of static loading. A numerical simulation using 3D modelling software was also undertaken to compare simulation results with results found during the physical testing. A series of full scale and sample sized tests were undertaken to help in determining the mechanical properties and behaviour of the FRP grating. The full scale testing included static line loading, and two different concentrated loadings; central to the panel as well as off centre loading. 3 different sample sized tests were also undertaken to help gain an understanding of the material properties. These sample sized tests included, flexural, compressive, as well as a burn out test.

The failure of the full scale line loading test was observed as major cracking and slight delamination of the grating directly underneath the loading bar. The two concentrated loading cases showed very similar failure modes to each other which consisted of the loading block sinking into the grid immediately surrounding the loading area while the rest of the panel remained intact. The line loading cases reached a maximum of approximately 56.16kN of force which resulted in 64.85mm of deflection. The centred concentrated load was tested to 33.37kN for a maximum deflection of 49.14mm, whereas the off centre loading reached 57.24mm for a maximum load of 34.93kN.

As part of the sample sized testing system, a burn out test was undertaken to estimate firstly the density of the provided FRP grating as well as the glass to resin ratio. The density of this material was calculated to be 1544kg/m^3 with a glass to resin ratio of 54% glass fibre to 46% resin. As part of the sample sized tests, other material properties were determined including a flexural modulus of 9.89GPa and a compressive strength of approximately 69.84GPa. These results aided in assigning a material property to a model as part of the FE analysis using the software PTC Creo for simulation. The results from the various FEA simulations gave very closely comparable results to those in the physical testing.

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111 Research Project Part 1 &

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Limitations of Use

Certification

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.

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Signature

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Nomenclature

AS –Australian Standard

C_{1x1} – Compressive loading for a 1 by 1 block

C_{2x2} – Compressive loading for a 2 by 2 block

C_{3x3} – Compressive loading for a 3 by 3 block

CEEFC – Centre of Excellence in Engineered Fibre Composites

CL – Centred concentrated loading

FEA – Finite Element Analysis

FL – Flexural loading

FRP – Fibre Reinforced Polymer

ISO – International Organization for Standardization

LL – Line loading

NZS – New Zealand Standard

OC – Off centred loading

PPE – Personal Protective Equipment

USQ – University of Southern Queensland

1. Introduction

This chapter will provide an outline of the general aims and objectives associated with the completion of the project. The overall purpose of this research dissertation is to analyse the behaviours of fibre composite grating under different loading cases to gain an understanding on how this particular type of grating performs structurally to help promote its use throughout the engineering and construction industries, primarily as a form of walkway.

1.1 Project topic

'Behaviour of fibre composite walkways and grating'

1.2 Project background

For a very long time within the engineering and construction industries, there has been a somewhat non varying selection of materials used in the construction of boardwalks and walkways. The industry standard materials most commonly used today include concrete, steel, and wood.

These traditional materials have posed various problems due to dilapidation and deterioration over time as well as an ever increasing influence due to costing within the materials selection process. Given the flaws of these modern engineering materials, there has been a call recently for a more sustainable product which will assist in increasing the longevity and lifespan of boardwalks throughout Australia and the world.

Fibre reinforced polymer (FRP) grating demonstrates numerous advantages over customary materials for a large range of scenarios, particularly within harsh and corrosive environments where traditional materials have proven to suffer.

Within the civil engineering industry today, the popularity of fibre composite walkways and boardwalks is slowly gaining momentum. However, there is not enough information or knowledge on the products available and their mechanical capabilities to be able to use it more commonly as an essential material.

Fibre reinforced polymer composites or advanced composite materials are very attractive for use in civil engineering applications due to their high strength-to-weight and stiffness-to-weight ratios, corrosion resistance, light weight and potentially high durability *(Lelli Van Den Einde et al. 2003).*

Figure 1 – Deteriorated concrete (A. Davies, 2003)

Figure 2 – Deteriorated steel (A. Davies, 2003)

Figure 3 – Deteriorated wood/timber (J. Hoath, 2006)

1.3 Project aim and objectives

To be able to reach the overall goal of analysing the mechanical behaviours of FRP grating under various loading cases, various objectives need to be worked towards and completed. A thorough investigation into fibre reinforced polymer grating needs to be conducted including the analysis of various load cases including full scale static loading as well as sample sized tests including flexural, compressive and burn out. Not only will FRP grid be physically tested and recorded, but a computerised finite element analysis will also be conducted to help verify and simulate results. Within this project, a great deal of research needs to be conducted in order to gain a greater understanding of not only fibre composites in general but also specific research into the developing knowledge surrounding FRP grating and walkways in particular.

The research objectives to aid in the analysis of FRP grating as a form of walkway material are itemized below:

- Complete an extensive literature review in regards to FRP grating as well as testing and analysing of materials
- Develop an in depth test schedule and programme for the testing procedures to fully establish the aims and objectives that are needing to be accomplished over the course of this research project.
- Perform static load testing on a number of equal sized decking panels under line and point loading.
- Perform sample sized testing including flexural, compressive, and burn out fibre tests.
- Analyse and compare results between testing to gain a better understanding of the different physical behaviours/properties of FRP grating.
- Perform a Finite Element Analysis on the grating to help map out the stresses and strains associated with the separate loading cases.
- Write and submit a final academic dissertation on the research and results from the entirety of this project.

1.4 Justification of project

The driving factor for conducting this research project is the need for a more sustainable material for walkways and boardwalks to act as a permanent substitute to the traditional materials used today. Fibre composites can possibly offer an efficient alternative while increasing the life span and minimising the deterioration due to varying corrosion circumstances.

The use of fibre composite grating within Australia is relatively insignificant with minimal knowledge regarding its physical and mechanical properties. There are some circumstances where this form of grating has become very popular for example the grating can most commonly be found as flooring in highly corrosive factories or plants such as desalination plants or pumping stations. This form of grating was developed when simply no other alternative would suffice for use over long period of time.

This project aims to help promote the use of FRP grating throughout engineering in Australia by exploring and reviewing previous studies as well as conducting a number of related tests to help increase the knowledge available for use of the product. The lack of specific Australian standards for this particular type of product is also an influence as to why this exact project was taken on.

1.5 Scope

The testing and analysis conducted for the entirety of this project is focused on the moulded FRP grating supplied by Nepean engineering and innovation with regards to the mechanical testing procedures: line load, centred/non centred concentrated load, sample compressive and flexural tests, and a burn out fibre analysis. A finite element analysis was also conducted to correlate physical results with an analytical sequence of simulations using the program Creo. “Creo is a scalable, interoperable suite of product design software that delivers fast time to value” *(P.T.C Creo).*

Since the samples tested were produced by external and unknown sources the raw materials, exact manufacturing process, and curing procedures are unidentified and certain factors either need to be assumed or investigated. The fibre burn out analysis aids in determining one unknown; which fibre was used for the structural makeup of the grid being tested.

Throughout the mechanical testing programme there are certain limitations which were accepted and noted to be considered in the analysis of results. One limitation was that the load cell available at the Centre of Excellence in Engineered Fibre Composites was limited to a serviceable 220kN force which needed to be considered if the question of what would happen at higher loading was asked. Impact testing was not considered for this project, however it would be a test which could provide you with a set of results to accompany the outcomes found in this particular project.

During the review of literature, due to the lack of research and comparative testing with regards to FRP grating specifically, similar products such as honeycomb cores and FRP flat panels have been used. It was deemed acceptable to use such products for research as there are numerous similarities between the materials used in production as well as their manufacturing processes and finally the similarities in the applications within the construction industry are comparable.

1.6 Resource requirements

Throughout this project, there are certain resources which are to be sourced and acquired to be used for the testing programme with an available budget determined. The test specimens themselves have been provided by Nepean engineering and innovation with a total of 14 panels supplied at the beginning of the project for testing purposes. These 14 test panels have been supplied in a range of lengths and widths which will need to be considered for the analysis of results. For analysis of stress and strain, strain gauges are attached to the test specimens, both full scale as well as sample. To help reduce costing, the sample sized test pieces were shaped from either undamaged sections of the test panels or the unused panels. The strain gauges and concentrated load block used for testing have been generously supplied by the second sponsor, Buchannan’s advanced composites. In regards to testing equipment, since this project is of interest to the Centre of Excellence in Engineered Fibre Composites at the University of Southern Queensland, all testing was conducted in the CEEFC’s test laboratories using their supplied equipment. Given the potential costing for all of these discussed materials and test equipment this project could have been very expensive, however with the generous sponsorships provided there will be minimal out of pocket costs.

2. Literature Review

2.1 Introduction

This literature review will focus on the analysis and discussion of previously conducted studies as well as currently published literature relevant to fibre composites and more specifically Fibre Reinforced Polymer (FRP) grating. Information on the topic of FRP grating has also been obtained from non-published sources in addition to the correspondence and guidance from people such as supervisors and colleagues who have relevant experience in the industry or familiarity with the subject matter. A brief historical background of the use of fibre composites within the engineering industry will be provided with detail in regards to polymers and fillers used as part of modern day fibre composites. The production process of FRP grating will be included and will cover the various procedures involved in the manufacturing of the different forms of FRP grid.

Gibson *et. al.* (2013) explain how composite gratings have been employed for lightweight, corrosion-resistant grid-flooring on offshore platforms, ships, floating production systems, drilling rigs and, elsewhere, for over 20 years. The selection of materials for use offshore is commonly ‘performance-based’, so the case for choosing composites is generally made by comparing key properties such as density and corrosion resistance to those of steel.

This leads to a suggestion that there is a substantial amount of recognized research with respects to both the investigation of FRP grating for off-shore platform use as well as the determination of density and corrosion resistance in comparison to traditional materials such as steel or concrete. The need in the past for research development into these areas was a necessity and has already been conducted, however as fibre composites are being looked at as a more suitable alternative material within a growing number of industries, the need for broader research and investigation is apparent. Particular attention needs to be paid to the use of FRP grid in on land applications rather than simply for offshore use. This leaves a gap in research which this project aims to help minimise by investigating numerous mechanical properties and behaviours for not only off-shore use but also the use on land in boardwalks and walkways.

2.2 Fibre composites

Lubin *(1969)* gave a common definition for a modern composite material as: A composite is a system that is created by the synthetic assembly of two or more materials; namely, a selected filler or reinforcing element and a compatible resin binder to obtain specific characteristics and properties. More specifically, Fibre Reinforced Polymer (FRP) suggests the use of a thermoset polymer matrix containing fibres, either synthetic such as glass or natural such as bamboo fibre strands. Cooperation and synergy of the combined constituents typically ensures a composite with enhanced material properties as the matrix and fibre work together to form a combination of properties which are superior in comparison to the materials in unaccompanied states.

While the composite industry is thought to be an emerging industry in modern engineering, the concept of composites has in fact been thought to date back as long ago as the ancient Egyptian and Mesopotamian settlers who used a mixture of straw and mud to construct housing which proved to be the most durable and strongest buildings at the time *(Moorey, 1994).* This combination of straw and mud fits perfectly into the description of what constitutes a composite material; mud, a natural matrix component being reinforced by the straw fibre to create a material with structural properties surpassing that of the materials when individually used.

Fibre Reinforced polymer as we know today was not developed until the 1930's where it was extensively researched with minimal commercial use and was not commercially used on a mass level until the late 1950's for use in the aerospace and motor vehicle industries. The production and application of FRP grating is a relatively new material within the engineering field, especially within Australia where very little is known about its property performance and mechanical abilities. It is gaining popularity throughout Australia and the world for its use in corrosive environments as well as the electrical industry for its non-conductive nature. In Many applications, fibre reinforced polymers provide superior performance to other materials of construction *(Stevens, 2012).*

The strength of FRP walkways is often dependent on the mechanical properties displayed in both the fibres themselves as well as the matrix, the concentrations relevant to one another, as well as the fibre length, orientation and direction set within the resin matrix.

2.3 Resin Matrices

Resin systems such as epoxies and polyesters have limited use for the manufacture of structures on their own, since their mechanical properties are not very high when compared to most metals *(Cripps, unknown date).* However, they are very desirable within engineering for their ability to be easily moulded into complex shapes and forms which other standard materials struggle to do. The functions of the polymer matrix are to transfer load, secure the fibre reinforcement and to prevent any mechanical or environmental damage to the fibres *(Manthey, 2009).* The polymers used as matrix materials can be divided into two primary families, the natures of which depend on their molecular structures. These are thermosetting and thermoplastic resins, for example, respectively, epoxy resin and polyamide (Nylon) *(Bunsell & Renard, 2005).* Resins commonly used in FRP grid systems are, Isophthalic polyester, vinyl ester, phenolic. The use of different types of resin can be influenced by the need for different mechanical abilities required in the use of the grid system, this can include increased fire resistance, different types of chemical resistance, as well as resins that can perform in a more brittle or flexible state. Bunsell & Renard display a comparison between various physical property performances of different resins as well as how resistant to chemical attack they are in table 1.

Table 1 - Typical characteristics of common unreinforced thermosetting resins used in composite materials. (Bunsell & Renard, 2005)

Resin	***Physical Properties***					***Chemical Resistance Properties***				
	Flexural Strength (MPa)	***Tensile Strength (MPa)***	***Tensile Modulus (GPa)***	***Failure Strain (%)***	***Heat Deflection Temperature (°C)***	***Normal Maximum Temperature Limit (°C)***	***Water***	***Solvent***	***Acid***	***Alkali***
Unsaturted polyester										
Ortho-phthalate	*100-135*	*50-75*	*3.2-4.0*	*1.2-4.0*	*55-100*	*80-100*	*fair*	*poor*	*fair*	*poor*
Iso-phthalate	*110-140*	*55-90*	*3.0-4.0*	*0.8-2.8*	*100-130*	*100-130*	*good*	*fair*	*good*	*poor/fair*
Modified bisphenol type	*125-135*	*65-75*	*3.2-3.8*	*0.9-2.6*	*130-180*	*130-180*	*very good*	*fair*	*good*	*fair/good*
Epoxy (bishpenol)										
Aliphtatic polyamde cure	*85-125*	*50-70*	*3.5*	*1.0-3.5*	*60-90*	*100*	*good*	*fair/good*	*fair/good*	*fair/good*
Boron trifluoride complex	*110*	*85*	*3.0-4.0*	*1.0-2.5*	*120-190*	*90-150*	*good*	*fair/good*	*good*	*good*
Aromatic amine cure	*80-130*	*60-75*	*3.0-3.5*	*1.5-3.5*	*85-170*	*120-180*	*excellent*	*good*	*fair/good*	*good*
Aromatic anhydride cure	*90-130*	*80-105*	*2.65-3.5*	*2.0-2.5*	*130-200*	*150-220*	*poor/fair*	*poor/fair*	*good*	*poor*
Vinyl ester										
Polyimide	*110-130*	*70-85*	*3.3*	*1.0-4.0*	*90-125*	*90-125*	*good*	*fair/good*	*good*	*good*
Friedel-Crafts	*75-130*	*50-120*	*3.1-4.7*	*2.0-3.5*	*250-360*	*250-360*	*low*	*-*	*-*	*low*
Phenolic furane	*110-120*	*95-110*	*4.1*	*1.5-3.0*	*160-240*	*150-300*	*excellent*	*good*	*good*	*fair/good*
Silicone	*100-120*	*60-75*	*2.5-3.5*	*0.5-1.0*	*180-220*	*250-300*	*good*	*excellent*	*good*	*poor*

2.4 Fibres

Composite materials owe their remarkable characteristics to the fibres which are used to reinforce the matrix *(Bunsell & Renard, 2005)*. The fibres used in composite technology serve the purpose of providing reinforcement and strength for a material when combined with a matrix, such as resin. The fibres act as the 'bone structure' in composites and are the source of the strength generated when cohesion between the fibres and matrix phase is achieved. The use of fibres also helps to reduce the overall cost of fibre composites as they are generally a much cheaper commodity than the polymer matrix. The use of different types of fibres has become very popular in modern composite development as different mechanical properties can be achieved by using different sources as a fibre content.

Fibres can be categorized into two different forms, both synthetic and natural. As the name would suggest, synthetic fibres are artificially developed materials which do not occur naturally and are the most commonly used fibre for FRP gratings and walkways. The synthetic fibre group being used within the composite industry have traditionally been petro-chemical based materials. Traditional synthetic fibre reinforcements that are commonly used in engineering applications can be categorised into three main groups; glass, carbon and aramid fibres *(Manthey, 2013)*. Natural fibres used in modern FRP design are most commonly derived from plant sources but can also be sourced from animal by-products and in some cases from minerals. Natural fibres are beginning to be further looked into for their use ahead of traditional petroleum based fibres for their ability to be extracted from renewable resources. With the diminishing supply of petroleum, a sustainable alternative is becoming increasingly more desirable. Natural fibres that are gaining increasing popularity within the engineered FRP industry include: hemp, flax, cotton, asbestos, and wool amongst others.

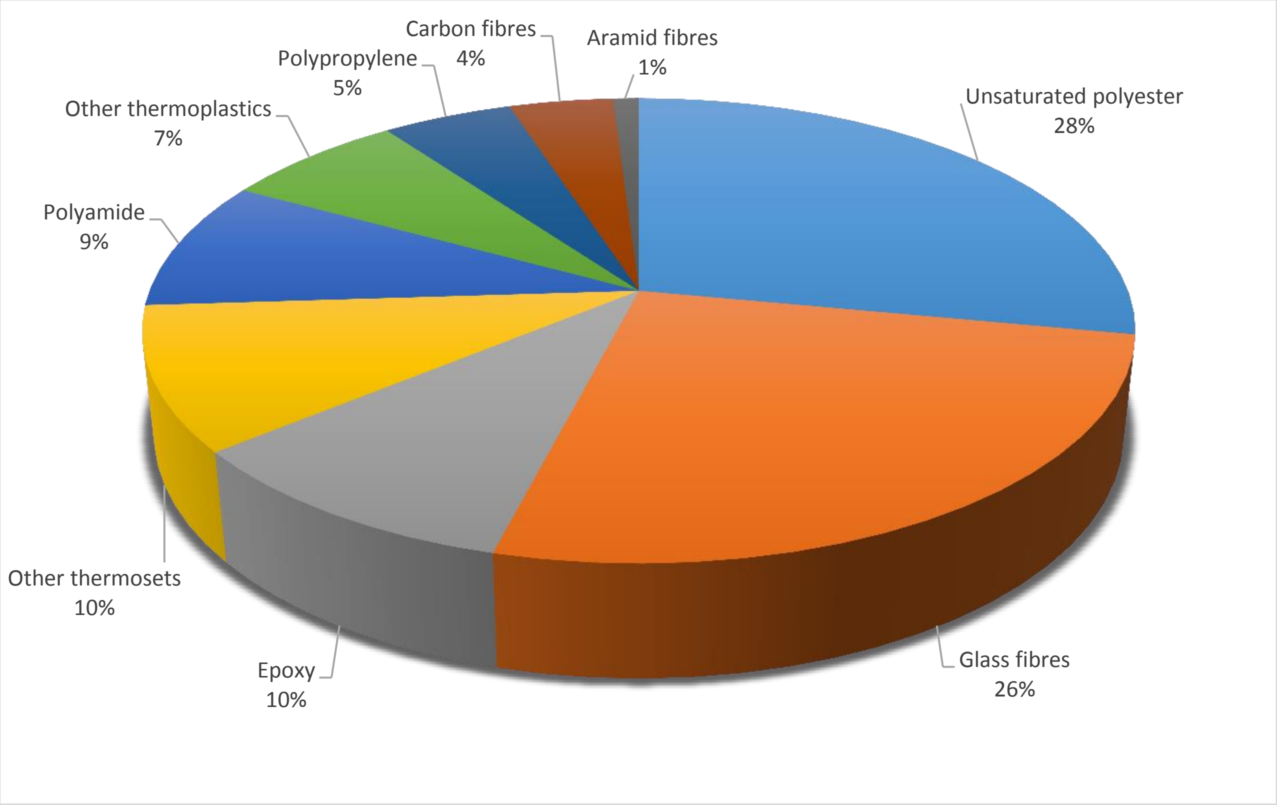


Figure 4 - Percentage value of materials in fibre reinforced composite market (Bunsell & Renard 2005)

Fibres are commercially available in various forms suitable for different applications *(Agarwal et. al., 2006)* including chopped strand mat, woven cloth, and woven roving. Woven cloth is similar to common fabric as it is woven tightly to create a cloth type texture with various weaving techniques used to provide different strength results. Chopped strand mat consists of randomly oriented short strands of fibre meshed together to form a mat of fibres. While chopped strand mat does not tend to hold as much strength as woven cloth, it is generally used for tight curves and corners as it is easier to conform than the woven cloths. Woven roving is the fibrous form used when producing FRP gratings given the impracticability of using cloth or mat for the specific grid shape. Fibres are bundled and yarns are orientated into two directions *(Fibreglass Warehouse, 2013).*

2.5 Manufacturing of FRP Grid

2.5.1 Introduction

In order to determine the requirement and need for fibre reinforced polymer grid it must first be understood why grids and gratings are used throughout various industries. Grid or grating structures are most commonly used for drainage systems and walkways frequently exposed to high volumes of water. In recent history, FRP grating has excelled in its application for corrosive, water prominent environments such as the marine industry, food preparation shops/factories, chemical plants, production factories, and most commonly in recent times throughout the mining industry of Australia which generally hosts a very corrosive environment. Grating can also be used for smaller scale applications other than walkways, including spillway covers, inspection hatches, and stairway treads. Not only is grid type flooring used for drainage, but it also assists in the significant reduction of cost by providing structural integrity over a substantial area while using minimal material to cover said area. In turn, this reduction in material can often result in a reduction in weight which can be very favourable in structures not designed to take very large loads, i.e. pedestrian walkways or platforms.

Traditionally steel has been the most common material used for the construction of grid walkways and decks and has served the construction industry well for a very long time. However, problems with the corrosion and degeneration of steel grids has gained the attention of many industrial leaders and governments for the possible replacement and solution to the issue regarding corrosive and wet environments. The engineering group at Kerr McGee Coal Company undertook an investigation into the fast deterioration of steel walkways titled ‘Alternative to Metal Walkways and Handrails’. Within this investigation it was found that in corrosive environments such as in the coal mine which was tested, steel undergoes significant deterioration within two years and stainless steel within six years *(Strongwell, 2013)*. The result of the investigation gave results leading to the need to use FRP grating in such a circumstance given its remarkable corrosion resistance. FRP grating poses a potential and very tangible substitute for the traditional use of metal grid with its record of being able to resist deterioration when challenged by corrosive environments and situations.

Glass Fibre Reinforced Polymer (GFRP) gratings are normally manufactured by moulding and pultrusion process. It may consist of various combinations of glass fibre and resin *(Habib & Akbar, 2014)*. Both manufacturing processes greatly differ from each other, however they can result in relatively similar products in terms of strength and possible uses. The different manufacturing processes will be explained in detail in the corresponding sections but as a general practice, moulded FRP grating is a process where fibres and the resin matrix is combined together by hand in a set mould and left to cure to form a grid structure, whereas pultruded grating has its fibres pulled through a machine where they are then infused with the resin matrix and cooled and cut to the required sizing.

2.5.2 Moulded FRP grating

Moulded grating is produced in a complex open mould and the entire sheet is monolithically moulded in one process (*Meng & Lo, 2000*). As the manufacturing process classification would imply, moulded FRP grating is manufactured using moulds which form the ‘base’ or profile of the grating to suit the desired dimensions. This moulded manufacturing process involves the systematic laying of a fibre series, or commonly a roll of continuous fibreglass roving into an open, heated mould in an alternating progression pattern. The moulding process is constrained to the bounds of only being able to create FRP panels to a set size limit, restricted by the mould parameters. Generally, the alternating layers are placed longitudinally over the whole mould and then transversely to create an alternate cross pattern which encourages enhanced strength and structural integrity over the lifespan of the grating.

The layered fibres are thoroughly wetted out with the desired resin matrix to resolutely bond the fibrous material in place as well as form the fundamental shape of the grid as desired. During curing, the mould is subjected to reducing heat to help restrict shrinking throughout the curing process. Upon curing, the grating is cast out from the mould where post curing applications can then be applied such as a grit coating for additional slip resistance. Since moulded gratings are cast as one piece panels, there is an optimum distribution of load over the whole span with no weak points caused by joints which can be found while analysing the pultruded manufacturing process.

Figure 5 - Moulded FRP grid manufacturing process (ZarnitsaTeam, 2011)

2.5.3 Pultruded FRP grating

Pultrusion is a process of FRP manufacturing whereby fibreglass roving is drawn through a resin wet bath to fully immerse the fibreglass in the resin bonding matrix and is then drawn through a series of dies which form the desired shape of the finished product and helps in forming the structural make-up of the pultrusion profile. Once the pulled roving/matrix combination forms the general profile required, it is then pulled through a final set of forming dies which are heated to cure the matrix and fibre combination. The process of pultrusion is constant and required lengths are cut as the final part in the manufacturing chain. This continuous pultrusion operation can be readily automated and allows for low labour involvement *(Compositebuild.com, 2014).*

Since a profile such as grating is not easily manufactured using pultrusion method, the most common practice is to manufacture a series of thin pultruded FRP bars and glue on joints (or commonly cross-rods) to create a large grid superstructure panel. These pultruded bars are most commonly manufactured as ‘T’ bars or ‘I’ bars to maximise the strength to weight ratio. Unlike the singularly formed moulded grating, pultrusion can often fail due to unsatisfactory cohesion between grid lengths and the glued joints. Pultruded FRP grids can most commonly be located with various industry plants which are subject to high moisture or are located in highly corrosive environments being used as cover for ‘flow away’ drains for any moisture which might be found on the factory floor. The grid itself allows liquid to fall beneath the floor level into the drains while still allowing workers to walk freely and safely on top of the grid as a safe walkway area.

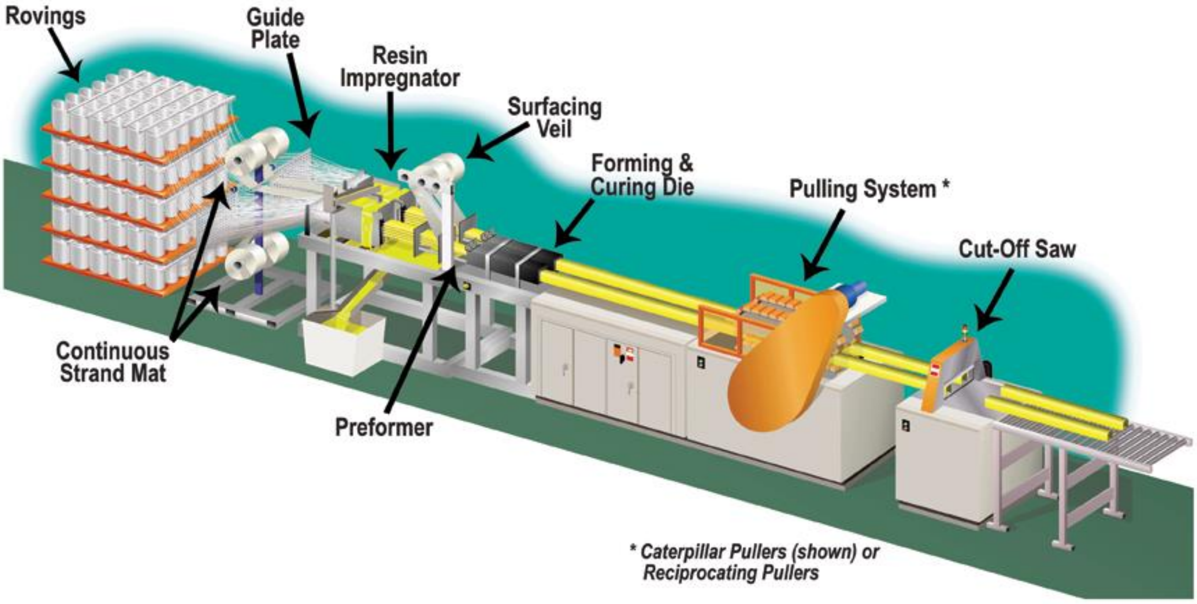


Figure 6 - Pultruuded FRP manufacturing process (Creative Pultrusions, 2014)

2.6 Current uses of moulded FRP grating

In 2006 the Queensland Government issued the “Fibre composites action plan – new technology taking shape” initiative which was aimed at promoting the use of fibre composites over a varied range of fields throughout Queensland. As part of this initiative, the Government issued informational handbooks which included the varied uses and benefits fibre composites could offer. In their handbook titled ‘Composites in industrial plants’, a large number of uses for FRP grating was suggested by the Government for use in large industrial plants or factories.

2.7 Testing

Testing is a vital element in analysing the properties of different types of fibre composite walkways in order to determine the optimum grating system for particular situations, requirements and environments. Since minimal testing has been recorded or reported on publically with respects to moulded FRP grating specifically, the literature used for this particular section was often related but not confined to the testing performed on what is known as honeycomb sandwich panels. These sandwich panels are fairly similar to FRP grating in their uses and can be formed to be of similar profiles and shapes to the panels which are tested as part of this project. The literature that is available discusses various testing techniques to gain results to help determine the tensile, compressive, impact, and flexural properties of a particular material.

2.7.1 Mechanical testing

While mechanical testing often covers tensile, compressive, shear, impact, and flexural tests, shear and impact testing will be neglected from the testing programme as they lie outside of the scope of this project. The mechanical testing which will in fact be conducted will include the full scale static loading tests which form the line load test, centred concentrated load test, and the off centre concentrated load test. Sample sized analysis will also be conducted and the sample sized testing procedures which will be completed during this project include flexural, burn out, and several compressive tests.

2.7.1.1 Full scale static loading tests

Line load test

Line load testing of FRP grating can be closely comparable to the three point bending tests of sandwich panels conducted by Ugale et al. *(2013).* In Ugale *et.al* 's paper, a three point bending test setup is described on a relatively small scale compared to our full scale panel tests, however the basic principles can be applied on a larger scale as required. Further guidance for test setups was found in the Australian standard AS 4155 – 1993 '*Test methods for general access floors'* with correct test setup, test procedure/methodology, and recording procedures listed and discussed with respect to line loading.

Another test paper which was used as guidance for the line loading test was undertaken by A.I.Habib and I.Akbar in their investigation into the ‘effect of accelerated ageing process on the strength of moulded and pultruded GFRP gratings’ in 2014. The aim of Habib and Akbar’s research was to try and determine the effect ageing of grating had on its mechanical properties. The concept of the testing procedure and methodology of Habib and Akbar’s three point full scale bend test was closely followed for the line loading tests.

The line load was chosen not only for the importance of the results which can be determined but also the simplicity and ease of preparation and set up of the tests. The line loading test system can provide results which are of great importance to the mechanical analysis of a panel. Most notably the modulus of elasticity is determined by load-deflection measurements at stresses below the proportional limit *(E. Shapiro, 2000).*

The modulus of elasticity in bending is used to define the stiffness of a material and aids to determine the behaviour of said material while subject to loading by using the ration of stress to strain in flexural deformation. This modulus is calculated by using the gradient of the load vs deflection increments when load is applied to the midspan of the test piece following the formula:

Modulus of Elasticity:

$$E = \frac{L^3}{4bd^3} * \frac{\Delta P}{\Delta \delta} \tag{1}$$

Where:

L = Length of supported span (mm)
b = Width of test specimen (mm)
d = Thickness of test specimen (mm)
ΔP = Load increment (N)
$\Delta \delta$ = Deflection increment at midspan (mm)

The elastic modulus is calculated in the form Pascals (Pa) or more commonly for ease of representation can be presented as Gigapascals (GPa).

Concentrated Load Tests

Awad, Aravinthan & Zhuge *(2011)* conducted an experimental analysis of a newly developed GFRP sandwich panel, where a fibre composite sandwich panel system was subject to a number of testing methods and analytical simulations. One of the testing processes used for analysis was the concentrated (or point) loading tests which displayed an important set of results for the analysis of mechanical properties. Similar to the line loading cases, an Australian standard was used as a guide for the testing setup and procedure as well as the proper recording techniques employed for a successful testing programme. While AS 4155.8 – 1993 '*Test methods for general access floors – test for 25mm x 25mm concentrated load'* is not a standard generally associated with the testing for this particular project in reference to FRP grating, in the absence of a more relevant standard, this was used as a general guide for employing general procedures for this form of testing.

2.7.1.2 Sample sized tests

Flexural load test

A four point bend test was chosen for the flexural testing and helps to determine the peak flexural stress (σ_f) of the grating material in a singular grid strip. As well as the peak flexural strain, the flexural testing will also help to determine the peak flexural strain (ε_f) and the flexural modulus (E_f).

Flexural Stress equation:

$$\sigma_f = \frac{3P(L_1 - L_2)}{2bd} \tag{2}$$

Where:

L_1 = Length of supported span (mm)
L_2 = Length between load bars (mm)
b = Width of test specimen (mm)
d = Thickness of test specimen (mm)
P = Maximum applied load (N)

Flexural stress (flexural strength) is calculated/measured in Pascals (N/m^2) but is more commonly reported in megapascals (N/mm^2) for ease of recording. The peak flexural stress is originally derived from the bending moment equation which relates to the load at failure.

Flexural Strain equation:

$$\varepsilon_f = \frac{6Dd}{L^2} \tag{3}$$

Where:

L = Length of supported span (mm)
d = Thickness of test specimen (mm)
D = Maximum deflection

The flexural strain as indicated by equation 3 is an indication of the deformation occurring at the point of failure of the test specimen in relation to the applied load. Flexural strain is directly related to the displacement change between pre and post loading. Strain will always give a dimensionless result as it gives the ratio of change rather than a dimension of the change itself.

Flexural Modulus equation:

$$E_f = \frac{L^3 m}{4bd^3} \tag{4}$$

Where:

L = Length of supported span (mm)
b = Width of test specimen (mm)
d = Thickness of test specimen (mm)
m = Gradient of load/deflection curve

Flexural modulus is the ratio of stress to strain in flexural deformation (i.e. the tendency for the specimen to bend). It is primarily a factor of the gradient produced by the load deflection curve produced during a flexural load test.

Since a 4 point bend test records the deflection at the point of applied loading instead of in the centre, it is necessary to calculate the deflection in the centre to be able to compare results from the FE analysis as well as gain an understanding of the maximum deflection for the flexure test. Equation 5 uses the recorded deflection at the points of loading to calculate what the approximate deflection at the centre of the specimen would be.

$$D = \frac{PL_2}{24EI}(3{L_1}^2 - 4{L_2}^2) \qquad (5)$$

Where:

P = *Maximum applied load (N)*
L_1 = *Length of supported span (mm)*
L_2 = *Length between load bars (mm)*
E = *Modulus of elasticity (GPa)*
I = *Moment of inertia* (mm^4)

Compressive load test

Compressive Stress formula:

$$\sigma_c = \frac{P}{A} \tag{6}$$

Where:

P = *Maximum applied load (N)*
A = *Total loaded area (mm^2)*

The compressive stress equation (equation 6) is a direct relation to its compressive strength for the load at failure. The units used for compressive strength are N/m^2 or more commonly N/mm^2 (megapascals (MPa)). Compressive stress is the stress of the test specimen in the uniaxial direction i.e. the force is applied by 'compressing'.

Burn out test

Glass Content formula:

$$M_{glass} = \frac{m_3 - m_1}{m_2 - m_1} * 100 \tag{7}$$

Where:

m_1 = *Initial mass of crucible (g)*
m_2 = *Initial mass of crucible plus specimen (g)*
m_3 = *Final mass after calcination (g)*

ISO 1172:1996 - '*Textile-glass-reinforced plastics'* provides a guide on the proper procedures of how to successfully conduct a fibre burn out test. Within this standard there is a proper operating procedure, recording procedure, as well as the formula to determine the fibre content of a particular specimen. This formula is stated here in equation 7 above. The equation for M_{glass} gives a percentage of weight that the glass contributes to the overall weight of the specimen. From this glass percentage, and indication of the glass to resin ratio can be calculated. Since the result for M_{glass} does not have any formal units, only a percentage, the percentage value can be used to determine the physical weight of glass by applying the ratio of glass to the overall weight of a piece of grating.

Another material property which could be obtained during the burn out test is the density of the FRP grid being tested. It is always important to be able to compare densities of products and would be essential for final recommendations and analysis. Density (ρ) is simply calculated by dividing the weight of a sample by its volume as shown below in equation 8.

Density Formula:

$$\rho = \frac{m_s}{V} \qquad (8)$$

Where:

m_s = *Sample mass (g)*
V = *Volume of sample* (mm^3)

The results of this density calculation will give g/mm^3 but for easy comparison between other materials it will be converted to kg/m^3.

2.7.2 Testing not included in this project

Due to the restraints on this project such as time, number of personnel and, resources, some testing procedures have been excluded from the scope of this project but are essential in the full determination of all grid properties and are very important in the recommendation of the use of fibre composite grating as a viable alternative material for use in walkways. Other tests which could be conducted as part of further analysis could include but not limited to; corrosion resistance testing, impact tests, and fire resistance testing.

A cost analysis may also be an essential factor in determining the best possible material to replace traditional materials with a more corrosion resistant alternative. In today's market, costing tends to be the driving factor ahead of any other property and needs to be considered to fully determine the best alternative material in construction of walkways and boardwalks.

2.8 Risk Management

2.8.1 Introduction

Throughout this project there is a degree of risk which needs to be noted and control methods need to be enforced to ensure no accidents or incidents occur during the course of this project which could have been prevented. The aim of this risk management and assessment is to determine, analyse, and document any risks which may be related to the works done throughout this project. Risk management is generally a case of if the risks are not thought about with a solution known to the operator then they will usually occur. However, if all risks and hazards are properly analysed and the correct working procedures are followed then the possibility of an incident occurring is significantly reduced.

2.8.2 Risk Identification

The major risks associated with this project are primarily found throughout the entirety of the testing programme. The project risks can be characterised as sample sizing, housekeeping, test setup, sample testing, and workplace restoration. The risks associated with sample sizing are quite hazardous as the operator is subject to running electric saw blades, airborne dust particles, the possibility of flying fragments, and high noise exposure. The injuries associated with these risks can range from as little as skin irritation to a major incident such as loss of limbs.

While the risks found through improper housekeeping are easy to avoid, they could possibly create quite a hazardous environment if the risks are not avoided. Such risks can include tripping hazards, slippery or wet surfaces, and unmaintained equipment.

There is a degree of high risk associated with the testing setup process which includes working at elevated heights, working with heavy tools above head height, weights which can cause pinching or crushing, as well as more general risks which may cause hand and feet injuries.

The testing process creates risks which can be associated with not only sample destruction in the form of airborne fragments, but also operator error. Due to the risks involved with the test processes, injuries may occur if the operator is either not confident, not trained, or a combination of the two. These injuries have the potential to be quite major such as the crushing of body parts if they were caught under the test piece while loading was occurring.

Workplace restoration is simply the risks which may be produced during the entirety of my project which may create a hazardous work environment for people in the future either using the same test equipment or sharing the same workspace. Such risks may include any debris left after testing, the proper disposal of any waste or finished test pieces, and reduction of any particles which may become airborne during sample sizing.

2.8.3 Risk Evaluation

Risks associated with this project can be identified into separate categories to analyse the immediate risk importance and consequence outcome. The consequences due to the stated risk are labelled from levels one to five and are as follows:

1. Insignificant
2. Minor
3. Moderate
4. Major
5. Catastrophic

The risk consequences are scaled from insignificant where there are no formal injuries and only minor delays, to catastrophic which could include death as well as possible destruction to the external environment. The risks are also rated on their probability of occurring and ranging from rare which is very unlikely to happen and would only generally occur when hazard management is avidly avoided, to almost certain where day to day risks occur and can generally be avoided.

The highest probability for a serious injury which the operator may come upon in the sample sizing stage. This process also includes the largest array of possible hazards which can range from insignificant to even a major risk. The minor hazard consequences include skin irritation which is a minor inconvenience but can still be avoided during sample sizing. The consequences then continue to increase upwards until possible appendage loss due to improper use of the electric saw; the other associated risks and consequences can include, minor cuts and scratches, flying fragments caused by sample pieces breaking apart during cutting are a risk to the operator’s eyes and exposed skin, as well as long term and short term breathing problems associated with airborne particles.

The risk is regards to housekeeping are relatively minimal as the CEEFC follow a strict maintenance regime where the workspaces and environment remain clean and tidy to reduce any risk on a day to day basis. These housekeeping risks can be classified as almost certain to occur but are easily fixed providing all users of the CEEFC's facilities accepts the possibility of risk and acts to avoid any potential hazards.

Test setup also has the potential to generate fairly substantial consequences if the risk management is not properly followed as there are a number of heavy works at elevated heights. Within the process of adjusting the load frame for this particular test, there is a degree of risk associated with using a ladder to undo the bolts which hold the frame in place. There is potential for the ladder to be unstable and cause the operator to fall to what could become a possible injury. There is also work with undoing bolts above head height which could cause serious head injury if a bolt or tool was to fall. An unlikely but still quite dangerous risk could be the crushing weight of the load frame if the chain block were to give way while adjusting the height if somebody was caught underneath. The loading frame has a total mass of 1000kg which would cause very serious injury if it were to crush somebody.

With a fully confident and trained operator, the testing procedure offers fairly low risks providing the proper procedures are followed. The only non-human risk which may pose as a potential hazard is during sample destruction where fragments and debris may become airborne and potentially impale people within the immediate surrounding area. If the operator is not confident or properly trained there is a large risk of potential crushing or pinching by the load cell during loading.

The risks which are caused by lack of workplace restoration can include debris being left on the ground, test equipment not properly secured and/or packed up, or improper disposal of waste and test pieces.

2.8.4 Risk Control

Risk control is a straight forward process and firstly involves the identification and classification of all risks into the appropriate consequence and probability categories. Onc the risks are assessed based on possible consequence and likelihood of occurring, the necessary steps in helping prevent such an incident from occurring can be put in place to either reduce the risk of an accident arising or to ensure the operator of each particular task is fully trained and confident with the particular safe work method relevant to the task at hand.

If the operator is deemed to be fully trained in a particular task, it becomes their responsibility to provide the knowledge and direction as to what safe working in a specific task consists of. Some examples of the questions a fully trained operator need to ask themselves before beginning could include;

- What hazards are associated with performing the task at hand?
- What is the necessary personal protective equipment (PPE)?
- What steps can be taken to avoid an incident or accident?
- Am I confident with completing this task safely?

What could potentially be the most important step in a successful risk management plan, the effectiveness monitoring of the risk control methods is as simple as following some questions to be able to review and determine if the methods put into action are deemed successful.

- Have the chosen control measures been implemented as planned?
- Are the chosen control measures in place?
- Are the measures being used?
- Are the measures being used correctly?
- Are the chosen control measures working?
- Have any of the changes made to manage exposure to the assessed risks given a successful result?
- Are there any new risks?
- Have the implemented introduced any new problems?
- Have the implemented control measures resulted in the worsening on any existing problems?

3. Methodology

3.1 Introduction

This chapter details the specimens used as well as the testing methods and processes used in both full scale and sample sized mechanical testing of FRP grating. Included is the preparation of the testing specimens, including the shaping and sizing as well as the sizes of testing samples associated with each form of testing procedure. Also covered in this chapter is a guideline into the finite element analysis methods and procedures used to computationally investigate/correlate the grating properties and data.

3.2 Preparation of test specimens

3.2.1 Full Scale Tests

The Full scale load tests consisted of three (3) specimens for each type of test, resulting in a total of nine (9) test specimens being used for the line load, as well as the centred and off centred concentrated load tests. To accurately compare each specimen the profile (thickness) and grid alignment needed to remain consistent over all tests. One investigation as part of the burn out test involved comparing materials between the different colours of grating to determine whether or not the colour symbolised different materials or if it was purely for cosmetic purposes. The two colour types of grating supplied were green and yellow, as much as possible, the colours were divided evenly between each test to ensure a minimum of at least one (1) of each colour was tested across all three testing procedures.

The specimens used in the full scale line load and concentrated load tests were provided by Nepean Building & Infrastructure as part of their Weldlok Fibreglass Grating & Handrail collection. The grating was supplied in pre-cut sizes with a collection of both green and yellow colours. The associated sizing and colour indication as well as their respective test is found in table 2. Since these test pieces were supplied by Nepean, the moulding and curing processes had already been completed prior to this research project, the test pieces were ready for use immediately. One problem associated with the provision of test materials is the lack of information supplied with regards to the materials and chemical combinations used in the manufacturing process. The glass to resin ratio as well as the fibre/resin materials are unknown. The methodology behind testing for consistency of materials is explained in 3.2.2 Burn Out Test.

Table 2 - Full scale load testing specs.

Specimen number	Length (mm)	Width (mm)	Thickness (mm)	Colour
Line Load				
LL-1	830	920	40	Yellow
LL-2	835	920	40	Yellow
LL-3	1020	920	40	Green
Centre Concentrated Load				
CL-1	1020	920	40	Yellow
CL-2	1220	1040	40	Green
CL-3	830	920	40	Yellow
Off Centre Concentrated Load				
OC-1	970	920	40	Green
OC-2	1200	920	40	Green
OC-3	1220	790	40	Yellow

3.2.2 Sample Sized Tests

Since only full scale testing pieces were provided, the smaller sample sized testing pieces needed to be individually shaped and prepared from the extra grating sections not used as part of the full scale tests. The three sample tests included flexural, compressive, and burn out; for each of these tests, a different type of sample portion of the larger panels was produced.

During the shaping of all sample sized test pieces, appropriate PPE in the form of safety glasses, work boots, gloves, dust mask, and earmuffs was worn to ensure maximum safety. The samples were shaped using dangerous power tools and all proper procedures and instructions of use were acknowledged and followed. In regards to dust, the stationary machines used such as an electric saw have in built dust extractors which were used, if extractors were not a part of the tool used, all means of trying to alleviate the risk of the fibre dust becoming airborne in the workshop was taken.

Flexural Test

The flexural testing specimens consisted of five (5) thin lengths of grating approximately 500mm in length. The width of the samples was determined by cutting webs of the larger panel directly through the centre. The final specimens needed to contain one (1) fully in tact row of grating and half webs on either side. It is estimated that the two lengthwise strips took all of the flexural loading and the smaller perpendicular webs were only counted as 'connectors' to hold the lengthwise strips in place while the load was applied. The specimens can be viewed in the corresponding figure 7 below.

The flexural test pieces were cut using a diamond tipped electric saw at Buchanan's Advanced Composite Technologies (BAC). The accuracy of measuring and cutting of these samples was paramount as to ensure the accuracy of results was not hindered by the simple task of sample shaping. A selection of five (5) test pieces was decided to ensure an appropriate amount of results could be compared for the flexural loading.

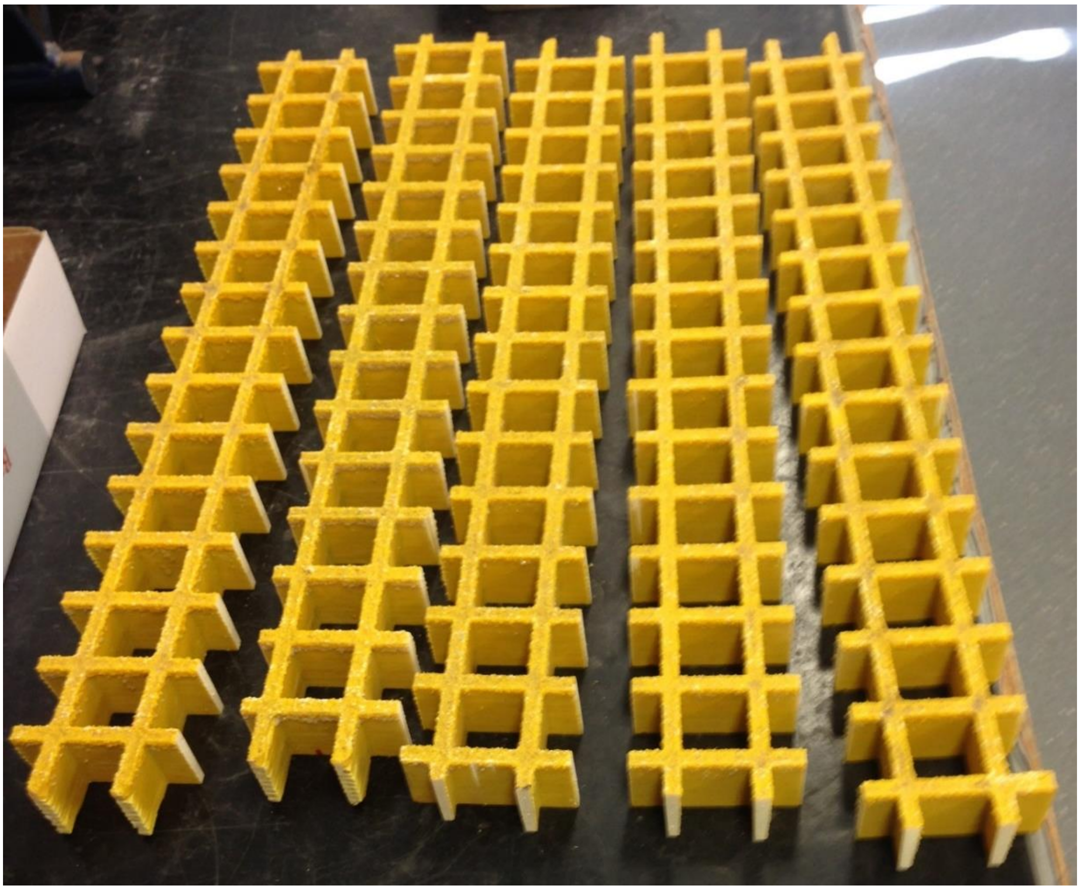


Figure 7 - Flexural test specimens (Nicol, Lachlan. 2014)

Compressive Test

The compressive load test samples consisted of creating a range of square blocks containing a ranging number of full grid pieces. The samples created comprised of three (3) specimens for 1x1, 2x2, and 3x3 grid blocks giving a total of 9 compressive samples. The arrangement of the final test specimens for the compressive tests are displayed in figure 8. Similar to the flexural test specimens, the compressive samples were cut to size using a diamond tipped electric saw with proper PPE being worn whilst shaping.

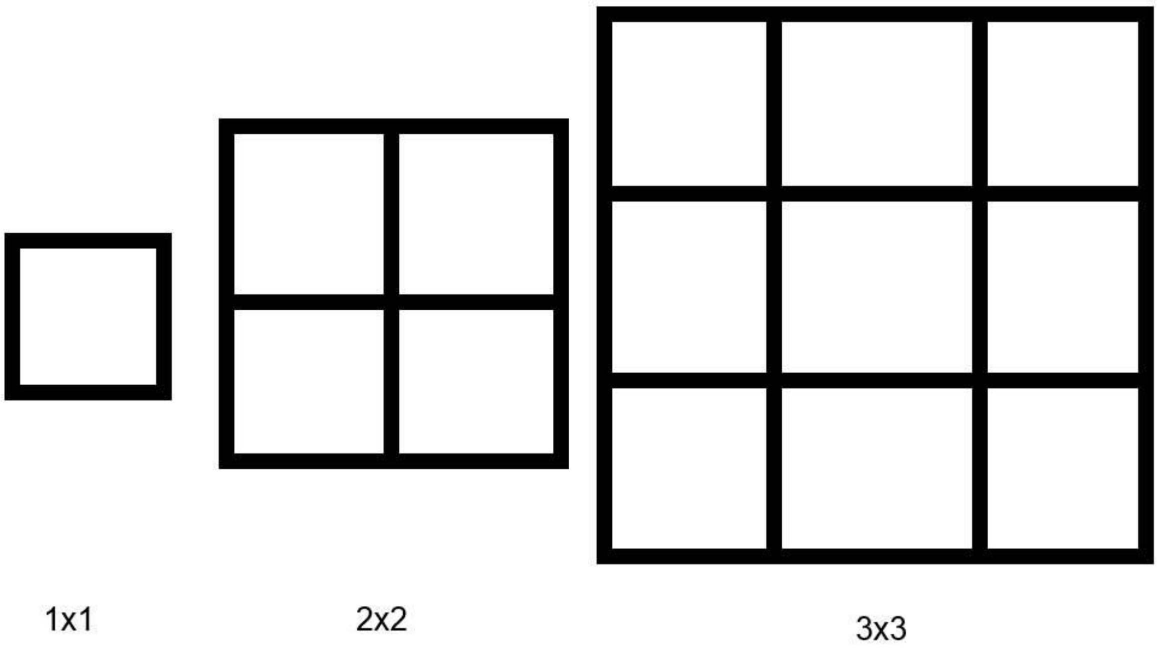


Figure 8 - Compressive test specimens (Nicol, Lachlan. 2014)

Burn Out Test

For the burn out test, the requirement for very small samples was important to be able to fit the test pieces in the appropriate crucibles to be placed in the oven. It was determined that singe webs of the grating would suffice for such a test. The investigation of materials used after the burn out test was completed involved determining whether or not the colour difference was a result of different materials between the green and yellow panels. It was important to ensure that a minimum of one (1) sample for each colour was tested to be able to investigate any differences between the colours.

Since the sample sizes were so small, it was determined to be too dangerous to use the same cutting procedure as the flexure and compressive test samples. With this in mind, a diamond tipped drop saw with a thin blade was used with the samples being cut fully secured using clamps so that they did not flick out of the saw and become airborne with the possibility to injure someone.

Figure 9 - Burn out test specimens (Nicol, Lachlan. 2014)

3.3 Testing Procedures

3.3.1 Full Scale Tests

All three forms of full scale load testing, line load and the two concentrated loading cases were all conducted using the same test setup. This setup included the use of two large metal round bars spaced at 830mm centres acting as the supports of the testing panels. These round support bars were in turn connected to large, heavy ‘I’ beams which ensured no movement of the support width during testing. The accuracy of the test results is paramount and movement in the support width would give incomparable and unusable data, with this in mind, the support bars and large ‘I’ beams provided a solid support for test panels to ensure maximum accuracy of results. The test pieces were then placed evenly onto the support bars with a distance laser placed underneath all specimens directly in the centre of the applied loading. Specific loading procedures and tool set ups are clarified in the following sections: Line Loading, and Concentrated Loading (Centred & Off Centre). Figure 11 shows the testing frame and set up for the line loading test, the frame setup is identical for all three testing types with the exception of the load application specifics.

In order to record the data for stress and strain, strain gauges were attached to a number of test panels to in turn be connected to a computer for recording of the stresses and strains observed during each loading case. These strain gauges were positioned on the centre webs in either a vertical or horizontal manner, across the longitudinal or transverse webs. The longitudinal and transverse orientation is determined by the positioning of the loading, longitudinal being parallel with the load and transverse being perpendicular to the load. Below in figure 10 is a depiction of how the strain gauges were attached to the testing samples.

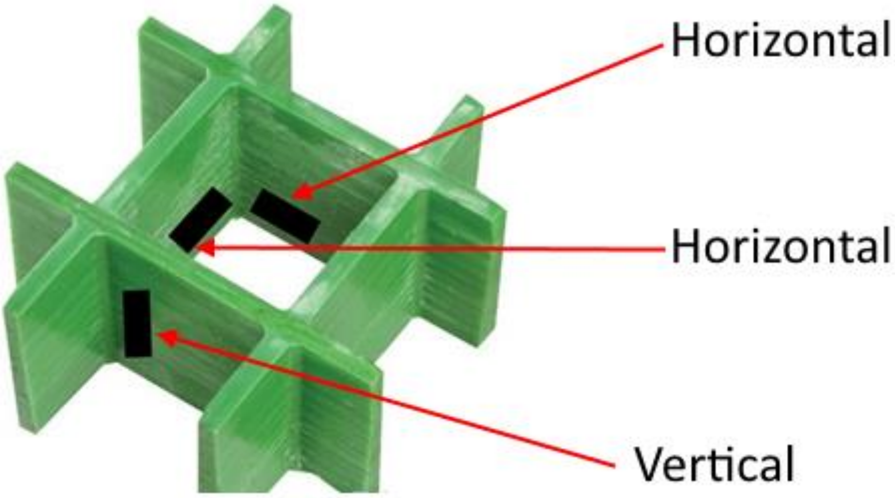


Figure 10 - Arrangement of strain gauges (Nicol, Lachlan. 2014)

Line Loading

The line loading setup involved attaching a 200kN hydraulic load cell to the large scale testing frame and adjusting the frame height to ensure the load applicator was as close to the test panel as possible. There was a restriction on the distance the load cell could be moved towards the test panel and was a constraint governed by the amount of bolt holes in the testing frame, the frame itself could not be safely lowered any further which resulted in a very large gap between the load cell and the testing panel. The load cell was then connected to a large 'I' beam which reduced the gap between the load cell and the test panel significantly and meant the loading bar could be positioned within a few millimetres of the load cell (i.e. 'I' beam plus the load cell). Between the 'I' beam and the test panel, a rectangular hollow metal bar was positioned directly in the centre of the testing width. This rectangular bar would essentially become the applied loading area for the line loading tests.

Once set up was completed, the force was slowly applied to the load cell with the data for applied force, deflection, stress & strain being recorded by the computer for investigation and analysis. The load was steadily applied until the FRP panels reached final failure or the load cell reached its maximum load limit, i.e. the load plateaued and would not significantly increase. The load was then released and the data recorded and stored.

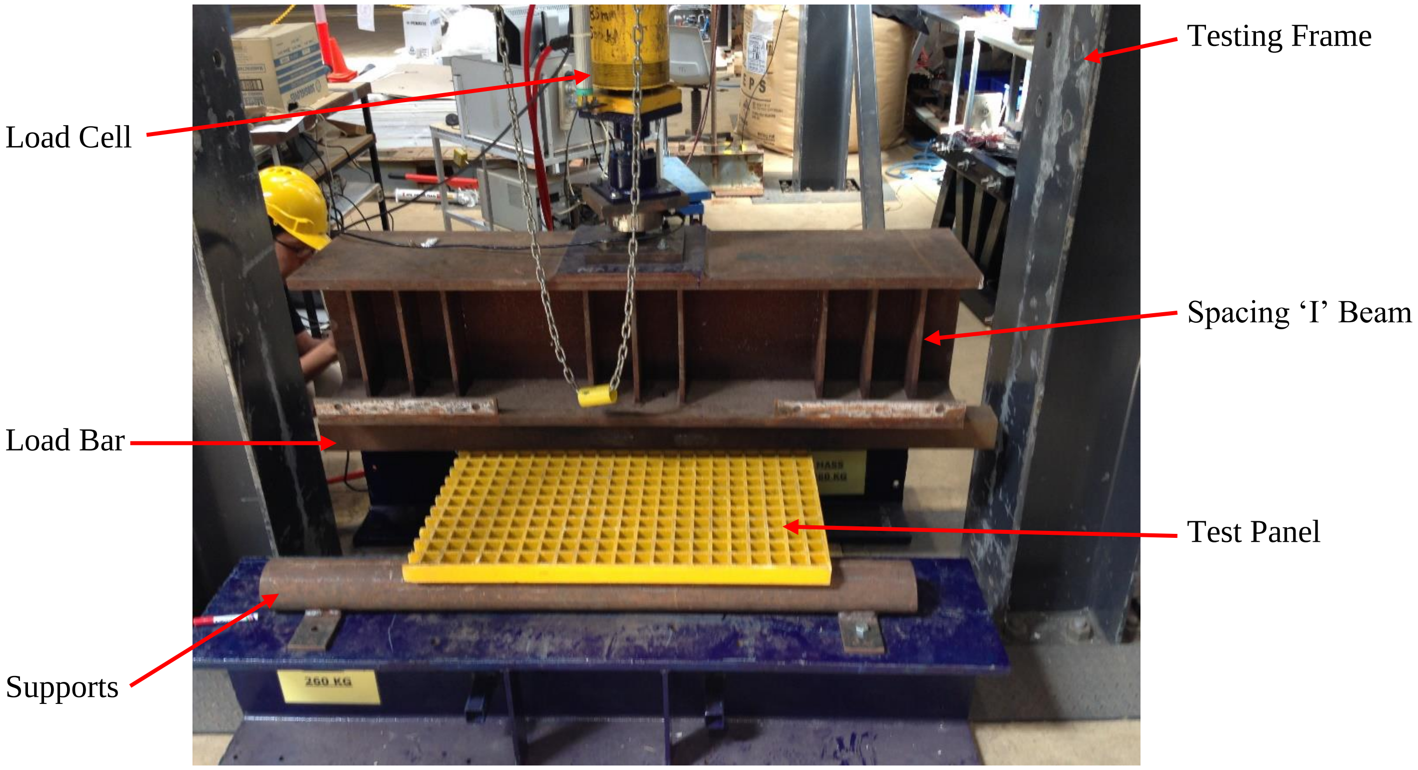


Figure 11 - Line load testing setup (Nicol, Lachlan. 2014)

Concentrated Loading (Centred & Off Centre)

The concentrated loading cases both involved the use of the 500kN load cell and a concentrated load block 60mm square by 50mm depth. This load block would simulate the effect a concentrated load has while being applied to molded FRP grating panels. The load block consisted of solid steel welded to a base plate which would in turn be bolted to the loading cell and positioned ready for testing.

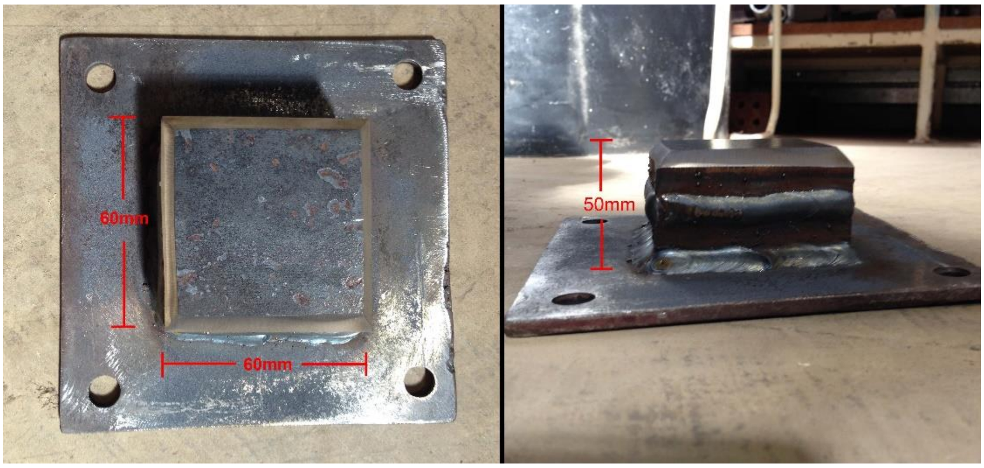


Figure 12 - Concentrated load block dimensions (Nicol, Lachlan. 2014)

For the centred loading case, the load block was positioned directly in the centre of the test panel, both longitudinally and transversely. However, the off centre load was positioned at a distance of 230mm from the support. This distance was determined to ensure the concentrated load was far enough away from the centre of the panel to provide a difference in results to be compared to the centred loading, as well as being sufficiently far enough away from the end support so that the deflection recording would not be hindered by being too close to the support itself.

The distance recording laser was positioned so that it was directed exactly in the centre of the applied load, this would ensure the maximum deflection during loading was recorded, it also guaranteed accuracy between the different samples so that the set up was equivalent for each case. Similar to the line loading, once the setup for the test panels was complete, load was applied steadily to the specimen until either full failure was observed or the load cell reached its maximum operative limit.

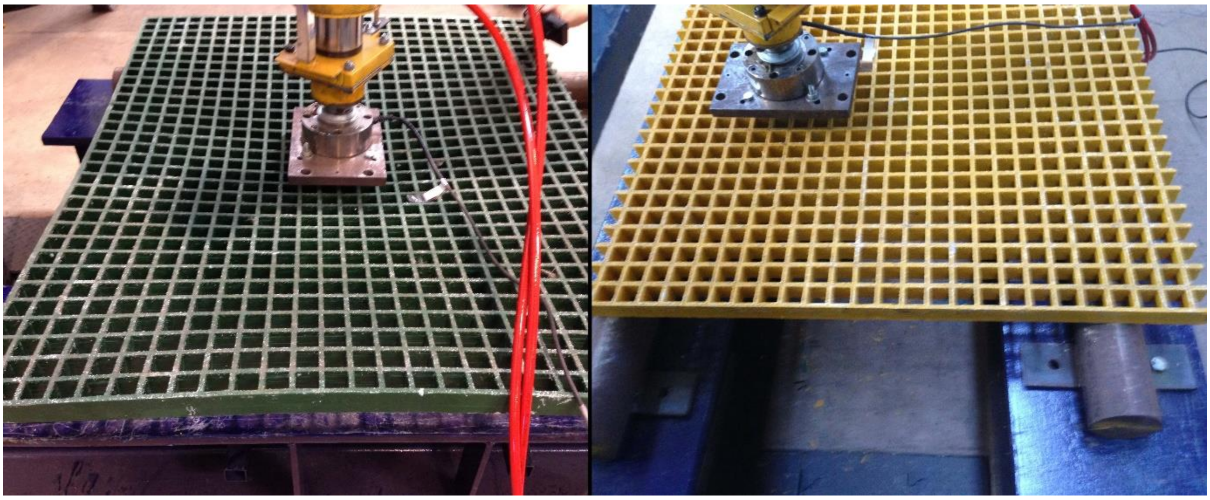


Figure 13 - Centred & off centred loading (respectively) (Nicol, Lachlan. 2014)

3.3.2 Sample Sized Tests

Flexural Test

The flexural sample testing of the five test pieces previously outlined in 3.2.2 *Preparation of Test Specimens* entailed the use of the MTS Insight Electromechanical 100kN load testing machine in a four point bend test. Two fixed supports were spaced 450mm apart which would comfortably support the 500mm flexural samples prepared earlier. Since this particular form of testing is a four point bend test, the load is applied using a set of two round bars spaced at 150mm centres, is attached to the loading crosshead to create the four points (2 supports, and 2 load bars). Once the specimen is in place, the crosshead was lowered to approximately 1mm from the panel surface. Once the test setup is complete and the specimen is ready, the load is applied automatically with data such as crosshead distance and applied load being recorded on to the computer for interpretation and analysis at a later date. An example of one of the flexural test specimens in the process of being loaded is shown below in Figure 14.

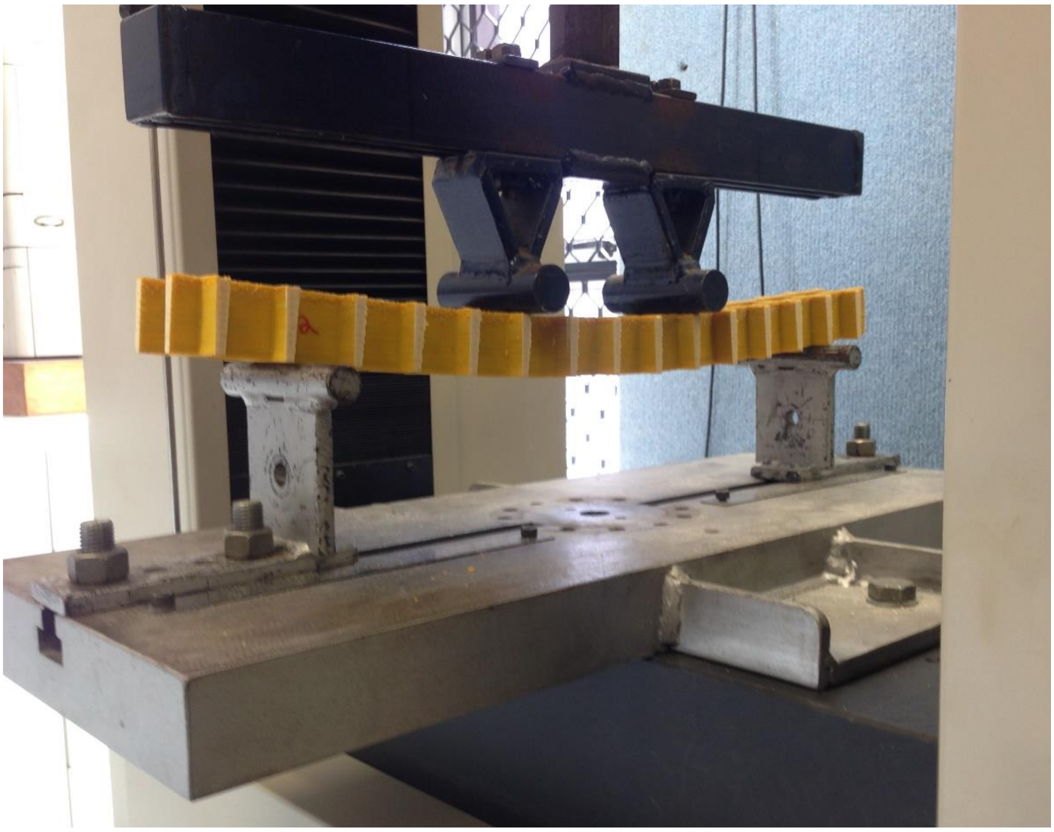


Figure 14 - Flexural sample during loading (Nicol, Lachlan. 2014)

Compressive Test

The SANS Hydraulic Compression Testing Machine – 2,000kN was used as the compressive force application machine in the series of sample compressive tests. The series of compressive tests consisted of 1x1, 2x2, and 3x3 grid blocks to compare the difference of results between singular grid blocks and the possible strength increase of blocks kept in larger combinations. A quick brush down of the test bearing pad was required to clean away any remnants from previous tests which could potentially hinder the accuracy of the results during testing. The test samples were place directly in the centre of the bearing pad with the crosshead manually adjusted to move no more than 1-2mm away from the test specimens.

Once these setup procedures were competed, an input of load rate for the test was entered into the computer to determine how fast (in seconds) the load would be applied, this would be a factor of both accuracy and time available for testing, the load rate of 3mm/min was selected as it would give relatively accurate results for this testing while not taking too long. If extremely accurate results were needed, the load rate could have been slowed down to ensure higher accuracy was achieved, however for this particular set of tests, increased accuracy was not necessary as the results will only be examined to a certain tolerance and the difference in accuracy of test results would not have been worth the extra time the tests would have taken.

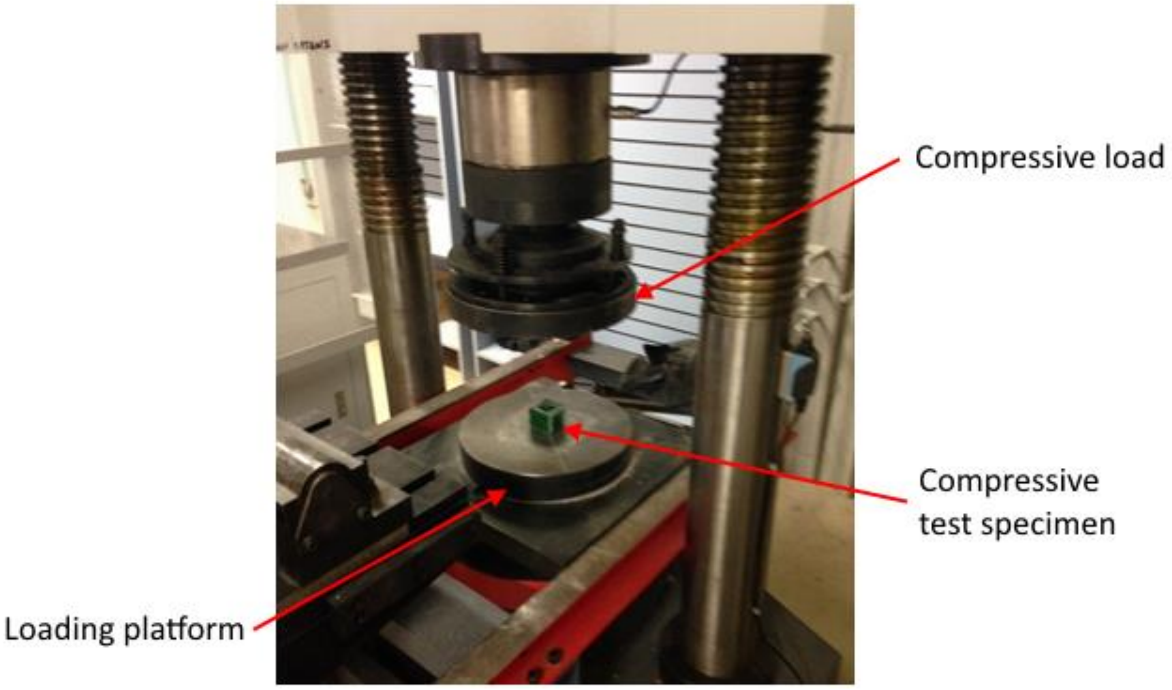


Figure 15 - Compression testing for a 1x1 grid sample (Nicol, Lachlan. 2014)

The output data which is used to analyse the test samples compressive strength include the play time and the applied load. The compressive strength is determined by dividing the peak load before failure by the cross sectional area of the samples.

Figure 16 - Computer used to record compressive testing data (Nicol, Lachlan. 2014)

Burn Out Test

The burn out test is an examination of the fibre content within a FRP product and involves the burning away of the resin matrix which surrounds the fibres. In this particular case, the material content of the FRP grating is unknown as the grating was supplied by a third party (Nepean Engineering) so the results of the burn out test give a good indication of exactly what type and amount of fibre that was used in production of the grating. Not only is the burn out test a comparison between both transverse and longitudinal contents but also a comparison between the colours of the grating. It is unknown if the fibre contents between the green and yellow samples is consistent or if the colour itself could be an indication of the fibre percentage it contains.

The test itself is very easy to set up and conduct as it is a matter of weighing all specimens prior to heating and in turn re-weighing the samples post heating. The specimens used in the burn out test are a collection of webs from both green and yellow panelling in both transverse and longitudinal directions for each. The testing procedure is in accordance with ISO 1172:1996 '*Textile-glass-reinforced plastics*' with particular attention directed towards chapter 7. The method involves firstly weighing of the crucibles fully dried and entirely empty. The small FRP webs are then placed in the crucibles and re-weighed to give a value for the weight of the crucible plus the weight of the sample piece itself.

Figure 17 - Weighing of the crucible and the grid sample (Nicol, Lachlan. 2014)

The burn out specimens were placed in a Thermolyne industrial benchtop furnace and heated to 600°C for a total of 4 hours to allow the resin matrix to be fully burnt away thus leaving solely the fibres.

From the remaining fibres left in the crucibles, an analysis is conducted to compare any differences of fibre content between the longitudinal and transverse webs as well as a comparison between the yellow and green samples to determine if there is in fact a difference with respects to the colour of the grating.

Figure 18 - Thermolyne industrial benchtop furnace (Nicol, Lachlan. 2014)

3.3.3 Finite Element Analysis

A finite element analysis (FEA) simulation was developed to aid in the prediction of the flexural behaviour of full scale FRP grip panels by using the results obtained from the sample sized testing. The concept of the FEA was to use values such as flexural modulus and density taken from the sample sized tests to be used for material properties as part of a model simulation in predicting deflection and the stress and strain which a full scale panel may be subject to in the different loading cases.

To be able to justify the use of the FEA as a prediction method of full scale panel mechanical properties, the results found using the program Creo need to match closely to the results found in the various tests conducted throughout this research paper. Models of both the flexural specimens and full scale panels were developed using the 3D modelling software SolidWorks, these models were then imported into Creo ready for analysis. The first model developed was the flexure sample. The reasoning behind the analysis of the flexure sample first is that if the results of the FEA simulation using the flexural mechanical properties corresponds closely to the actual results from testing then it can be said the properties used are indeed correct and successfully simulate the physical testing.

During the physical tests for flexure, dimensions of the grating were taken of all 5 sample pieces, the average dimensions of these tests were used in creating the model ready for FEA. Figure 19 shows the model created in SolidWorks with a few critical dimensions labelled. Since the support span of the flexural test was 450mm, the model in the FEA was used as a total 450mm with the fixtures acting at either end of the model. It was found that the average web thickness of samples was 7.87mm with an internal spacing of 30mm.

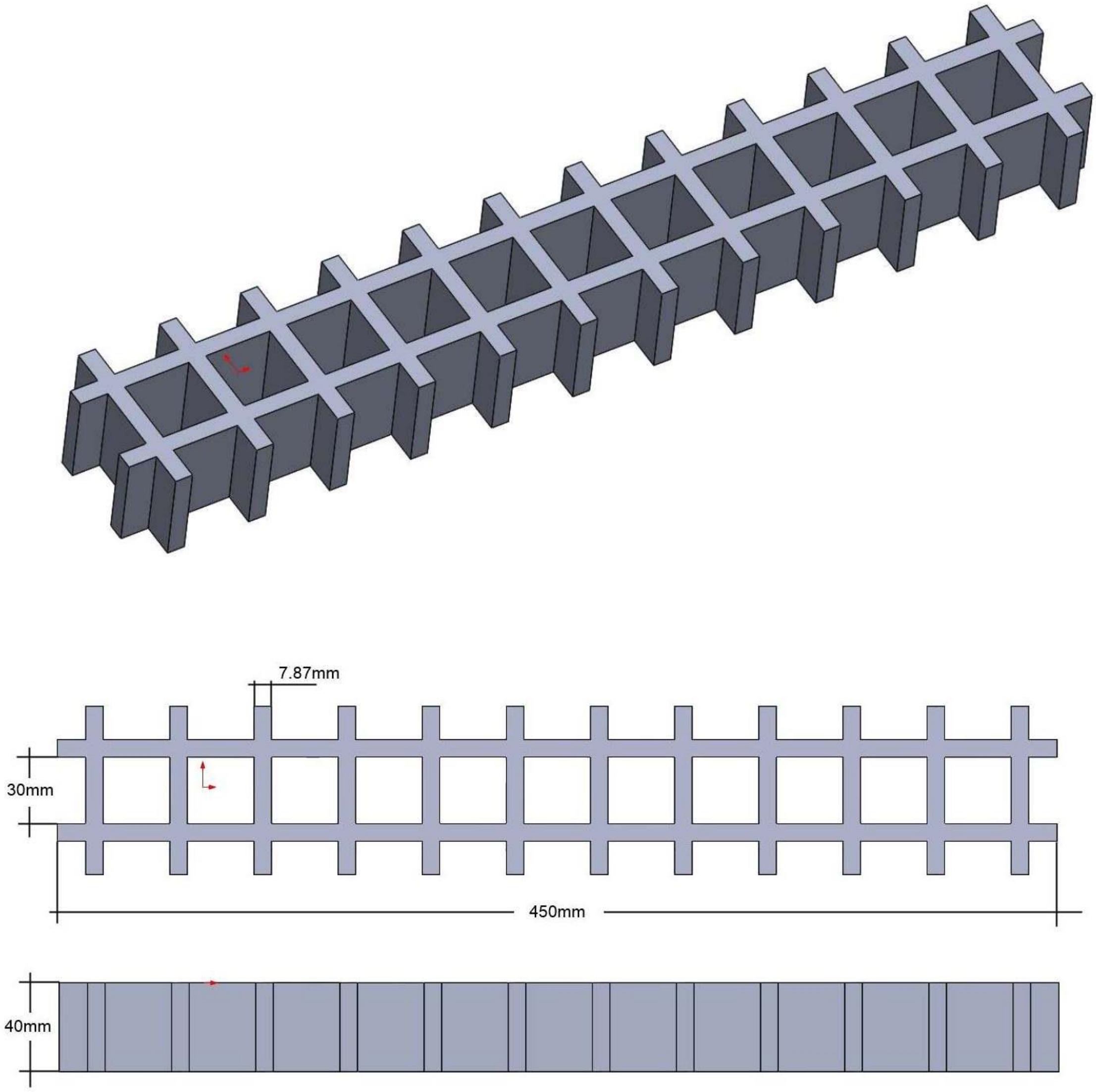


Figure 19 - Flexure test 3D model (Nicol, Lachlan. 2014)

In order to successfully simulate the tests via Creo, certain material properties need to be obtained and are assigned to the 3D model. Some of these properties include but are not limited to: flexural modulus (E_f), density of the material (ρ), and compressive strength. The values for these different material properties are established via the sample sized testing procedures discussed above in the methodology with the values taken from the results obtained during the physical testing. Figure 20 shows the flexure model ready for analysis in Creo, this figure shows all of the features needed for simulation including material assignment, fixed constraints, and the applied load spaced at 150mm to simulate the load from the physical flexure test. While the flexure test included two bars for the applied loads, Creo required the load to be fully applied to a surface on the model, hence why figure 20 shows 4 loads being applied. These four load points essentially represent the two loading bars being applied across the flexure samples.

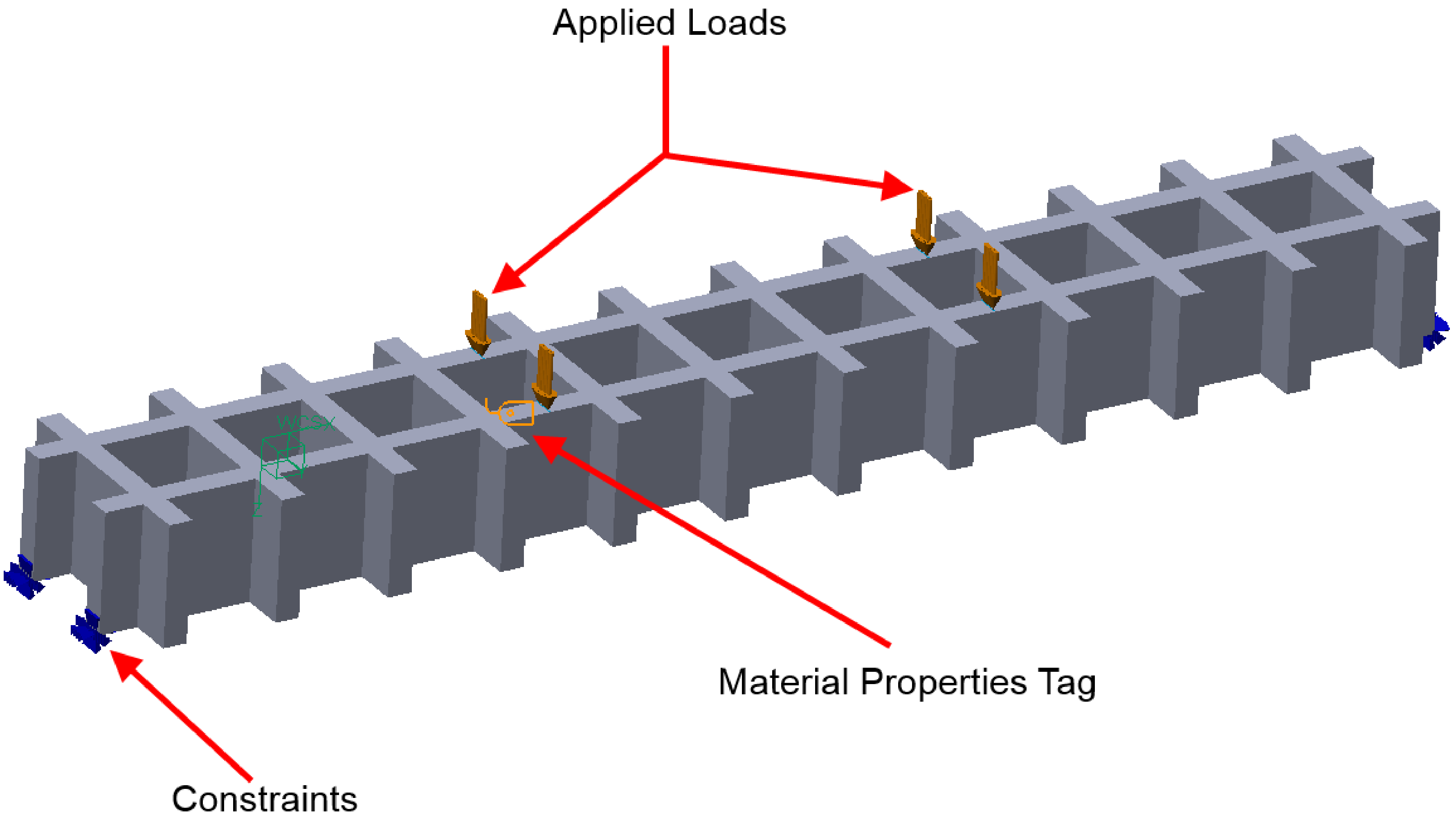


Figure 20 - Flexure 3D model ready for analysis (Nicol, Lachlan. 2014)

Once the flexure model was verified and the results of both the FEA and the physical testing were closely comparative, a full scale analysis was undertaken. Similar to the flexure analysis the 3D model of the full scale panel was developed in SolidWorks and imported into PTC Creo with all required features being added. For the line load analysis, the load was applied directly in the centre of the panel and covered the entire span, this closely simulates the setup which was used for the full scale line load testings.

A mesh is applied to the 3D model to help define the geometry which is to be analysed. The finer the mesh is, the more accurate Creo can interpret the geometry of the FRP grid panel and therefore provide a more accurate analysis with a more precise set of results. A mesh size of 3mm was used and applied for the flexure simulation alone, this mesh size was deemed unusable for the full scale simulation due to the amount of computing time needed to obtain a solution. Therefore, a mesh sizing of 7mm was used for the full scale analysis which was determined to give an accurate result while still being computed within a practical timeframe. The material properties used for the full scale simulation remain the same to that used in the sample sized simulations.

The analysis setup for the two concentrated loadings was identical to that of the line loading case, however the applied loads were positioned differently, in the centre as well as 230mm from the edge of the supports. Instead of the load following a line across the span of the panel, the two concentrated load analyses had an applied load which simulated the loading block of 60x60mm square. From all loading cases, a coloured model was produced for the displacement, stress, as well as the strain observed during simulation and analysis.

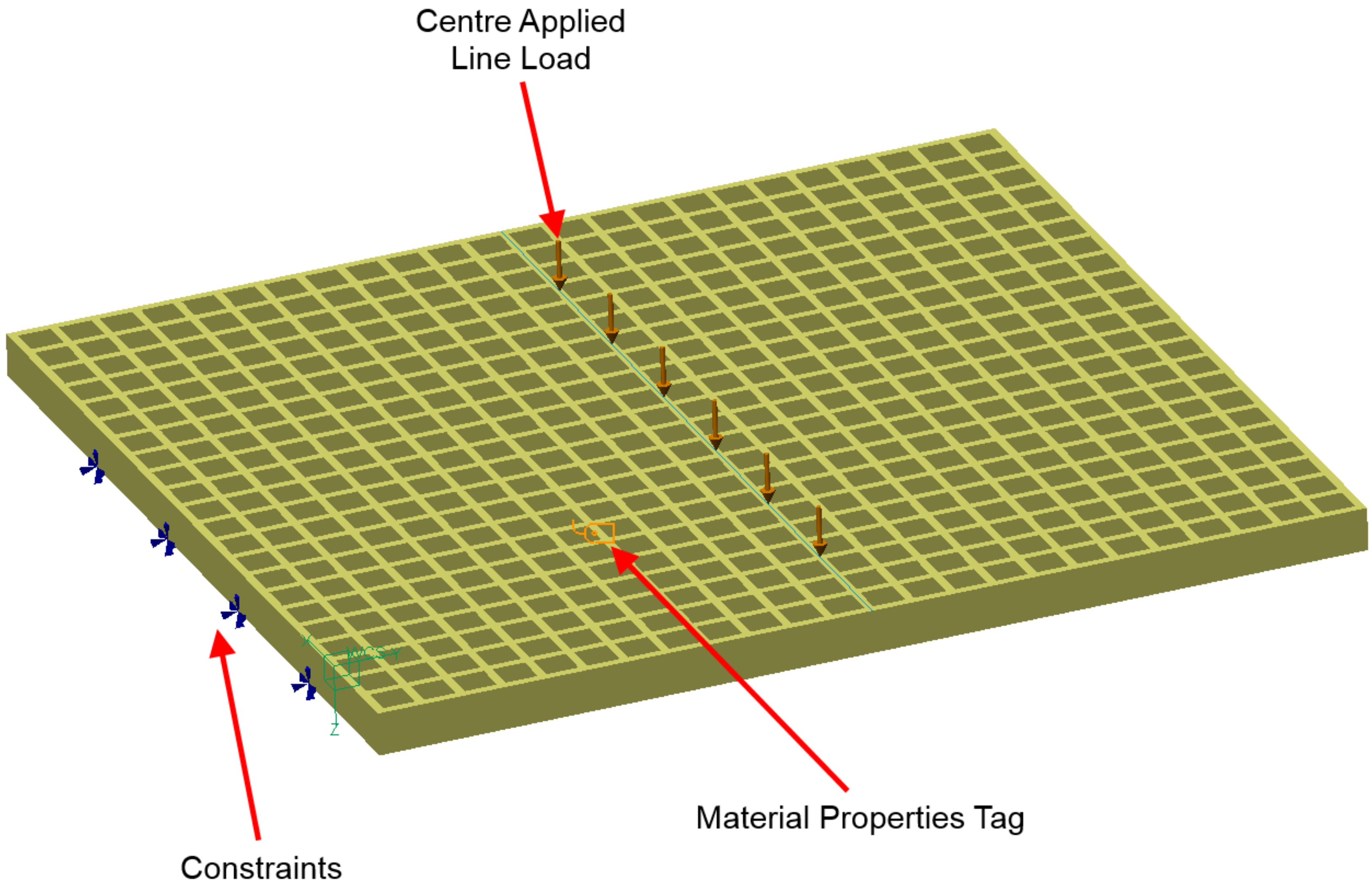


Figure 21 - Full scale line load ready for analysis (Nicol, Lachlan. 2014)

4. Results and Analysis

4.1 Introduction

This chapter contains an in depth analysis and discussion on the results found from all forms of testing performed in this research project. The testing analysed includes the full scale testing (line load and concentrated loading), sample sized testing (flexural, compressive, and burn out testing) as well as a finite element analysis which compares the results obtained from physical testing with a set of simulation results obtained from 3D modelling analysis.

4.2 Full Scale Testing Analysis

4.2.1 Line Loading

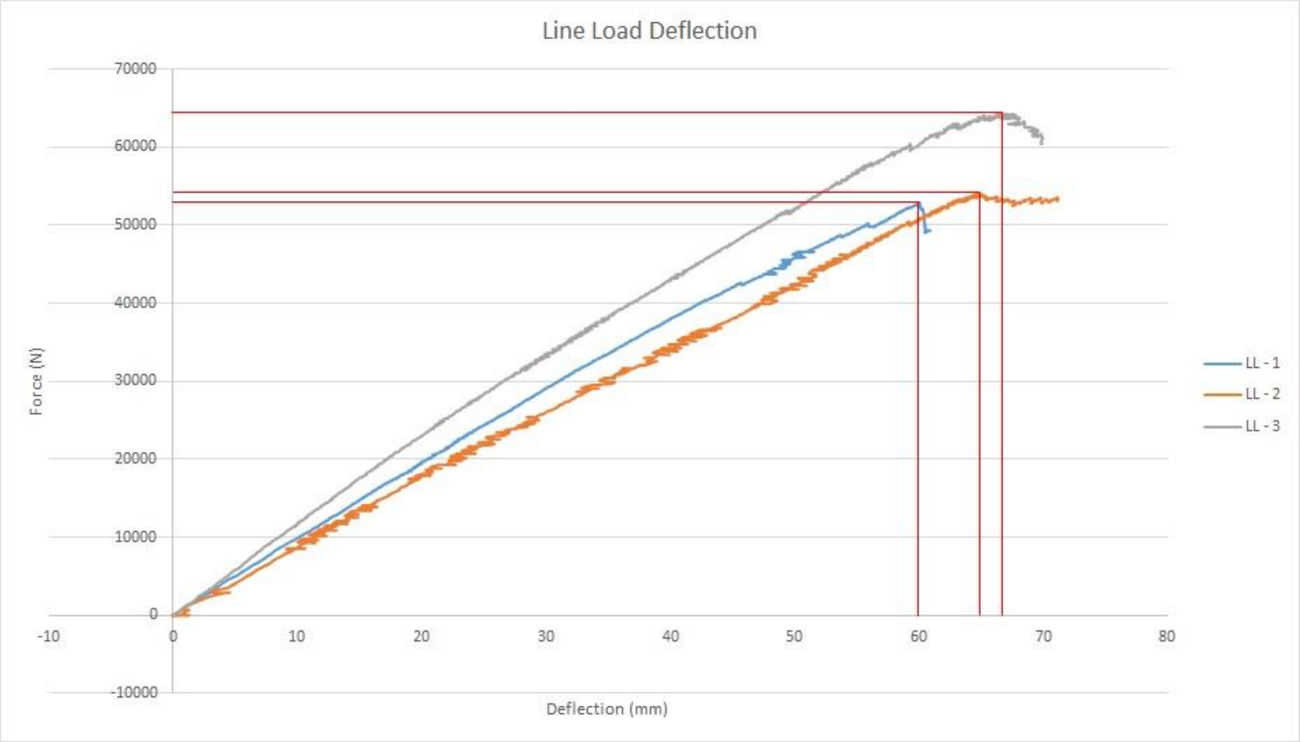


Figure 22 - Deflection results for line loading

Figure 22 displays the deflections until physical failure for the line loading cases of the three separate test specimens. The figure displays a peak deflection range prior to failure between approximately 60-68mm. The deflection due to increasing loading displays an almost linear relationship from commencement of loading up until failure of the test specimens.

The load applied to both LL-1 and LL-2 when failure occurs is within the region of 53kN whereas LL-3 displays a much higher peak load of approximately 64kN. The determination of failure associated with the physical results ascertained from the recording equipment can be explained by the rapid decline in applied load i.e. the breaking of the linear pattern. As an inspection observation taken during the testing procedure, the physical failure is described as major cracking and delamination on the bottom face and side of the grating.

Figure 23 - Failure of line loading test panel (Nicol, Lachlan. 2014)

Table 3 - Line load test results

Test ID	Deflection Max (mm)	Load Max (kN)	Support Length (mm)	Width (mm)
LL-1	60.00	52.90	830	920
LL-2	64.67	53.90	830	920
LL-3	69.88	61.68	830	920
Average:	**64.85**	**56.16**		

4.2.2 Centred Concentrated Load

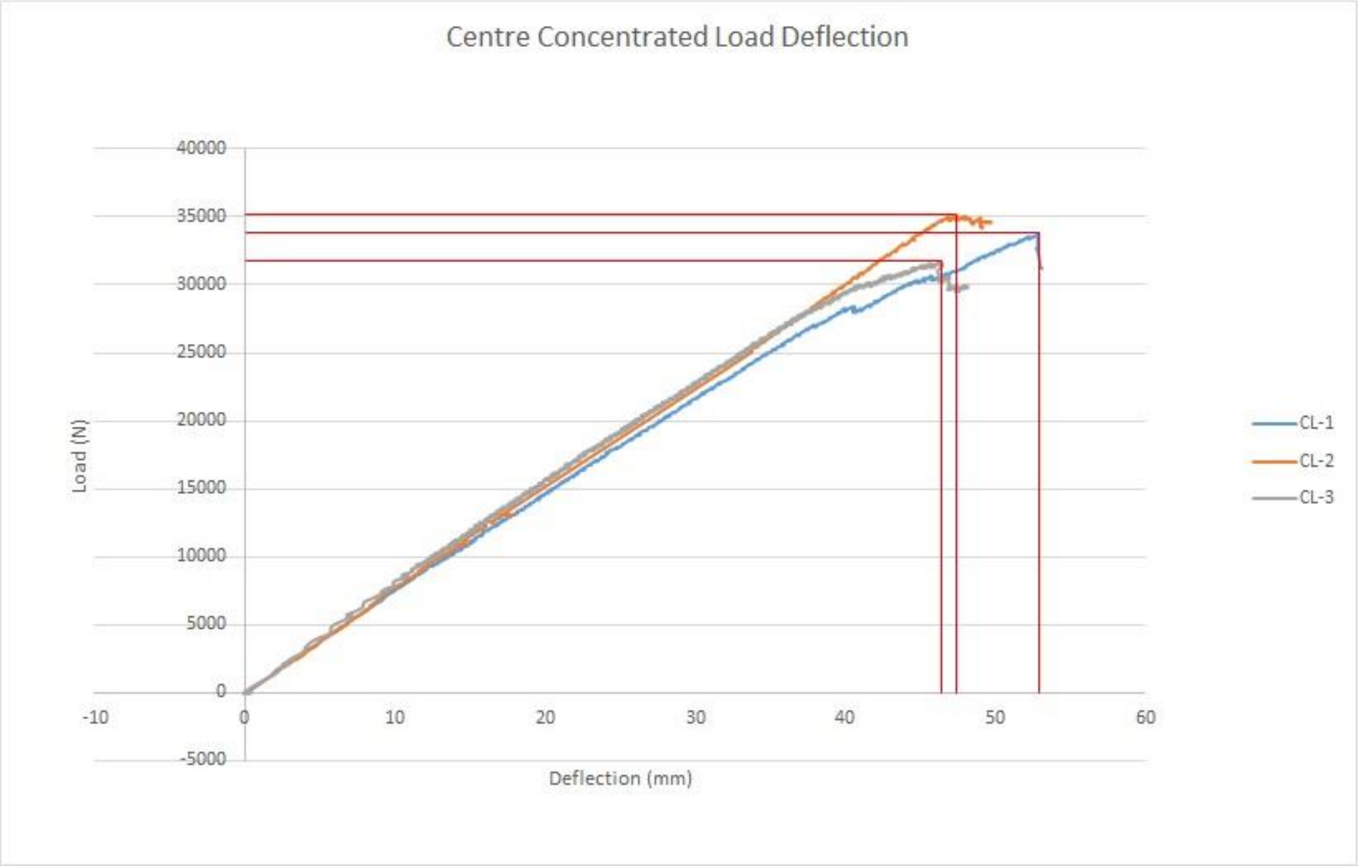
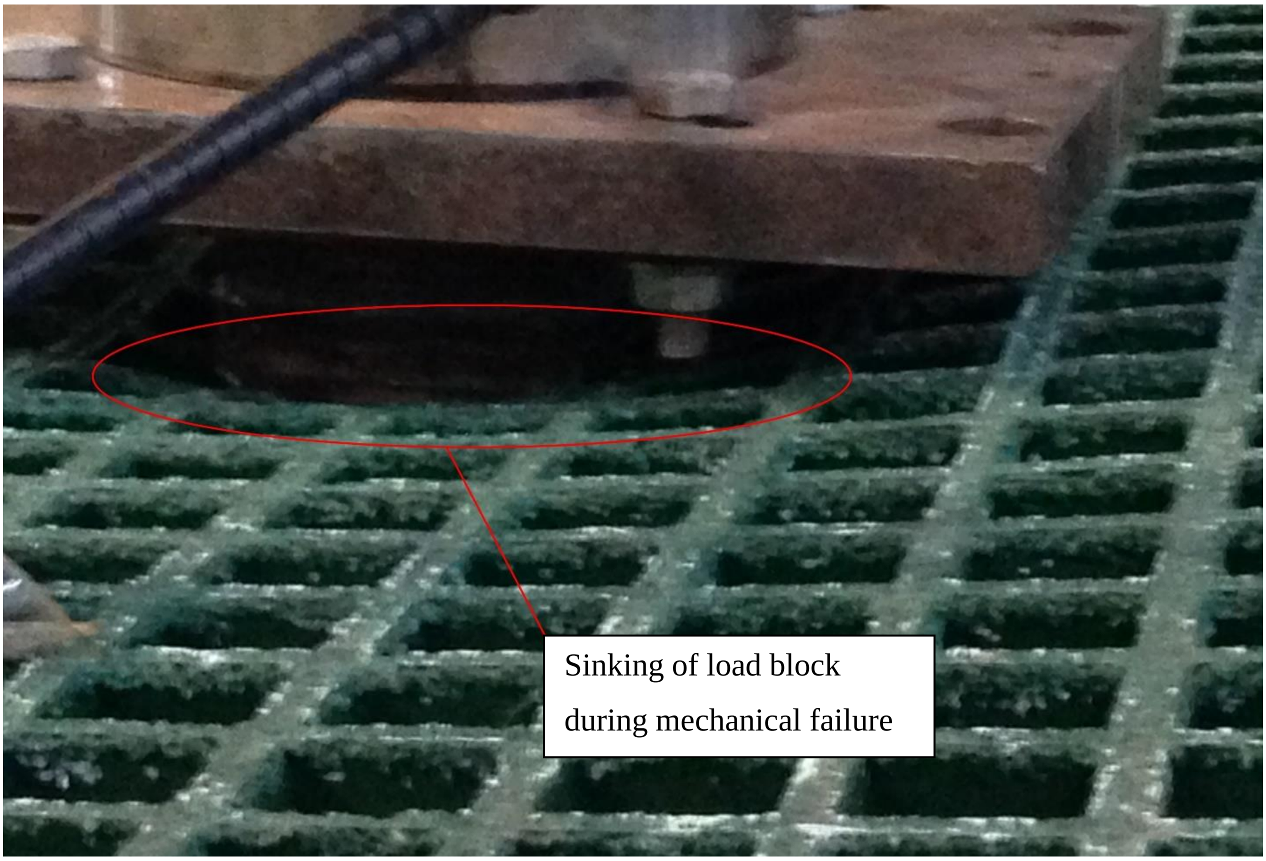


Figure 24 - Deflection results for centred concentrated loading

Similar to the deflection found for the line loading, the load to deflection ratio is relatively linear for the centred concentration load tests. The exception is the slight changes close to the failure point, the change associated with CL-1 is observed as a slight drop of applied load at approximately 28kN, the change is CL-3 is not a drop as such but more of a slight change in direction of the linear load/deflection pattern. These minor differences could be due to a number of factors including the strength loss as a result of the development of minor cracking of the polymer resin matrix or a slight pressure error caused by the load application. CL-2 remained relatively linear throughout the test until it reached physical failure status.

The peak applied loads for all three test specimens fall within a range of 31.5-35kN before reaching their respective failure limits. The maximum deflection for centred concentrated loading appears substantially lower than the line load tests with a maximum out of the three tests (CL-1) only reaching 53mm with CL-2 and CL-3 deflecting to approximately 47.3mm and 46.5mm respectively. The failure determined by observation for concentrated loading in the centre was the cracking of laminates within the immediate surrounds of the loading block with the block appearing to 'sink' into the test panels. Once the load was released, the area which the load block sunk into the grating in fact rebounded back to near its original profile with only approximately 2-3mm of permanent depression of the grating webs.



Sinking of load block during mechanical failure

Figure 25 - Failure of centred concentrated load test panel (Nicol, Lachlan. 2014)

Table 4 – Centred concentrated load test results

Test ID	Deflection Max (mm)	Load Max (kN)	Support Length (mm)	Width (mm)
CL-1	52.26	33.52	830	920
CL-2	49.00	34.94	830	1040
CL-3	46.15	31.64	830	920
Average:	**49.14**	**33.37**		

4.2.3 Off Centre Concentrated Load

Figure 26 - Deflection results for off centre concentrated load

As observed in figure 26, the off centre concentrated load deflection did not remain linear after about 30kN for OC-1 & OC-3, and the variation away from a linear pattern was observed after approximately 25kN for the OC-2 test sample. The load to deflection ratio begins to deviate fairly dramatically until the complete failure of the specimens is detected at 55-60mm of deflection. One interesting point to take note of from the failure limits of this particular test is that the deflection slightly rebounded when the mechanical failure limit was hit whereas the failure in the centred load tests did not rebound but in fact slightly increased the deflection of the samples.

The physical failure itself was observed to be the same as the centred concentrated load in that the loading block sunk into the grating and in turn recovered to near original profile once the applied load had been released.

Table 5 - Off centre concentrated load test results

Test ID	Deflection Max (mm)	Load Max (kN)	Support Length (mm)	Width (mm)
OC-1	59.02	32.61	830	920
OC-2	55.78	36.41	830	920
OC-3	56.92	35.77	830	790
Average:	**57.24**	**34.93**		

4.3 Sample Sized Testing Analysis

4.3.1 Flexural Loading

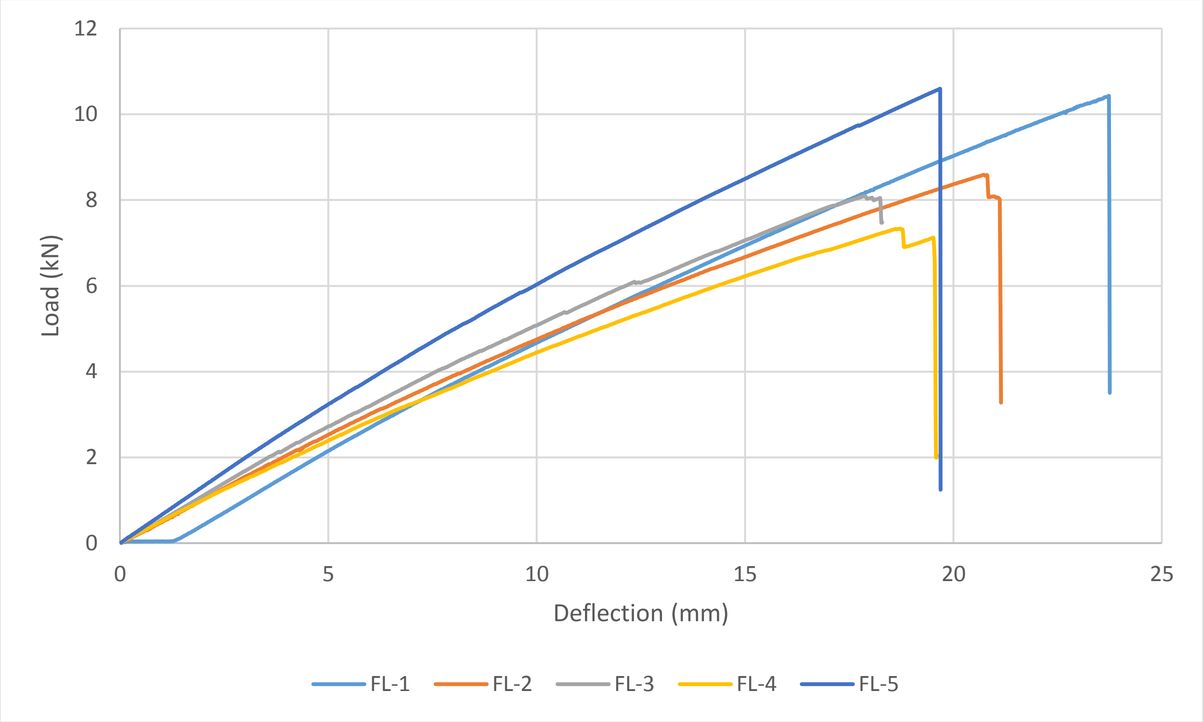


Figure 27 - Flexural deflection results at load points

The load deflection relationship for the five flexural loading samples is shown in figure 27. The figure shows that the load capacity retains a relatively linear relationship with deflection for the entirety of the loading until the observed failure limits. The failures observed are clear on the graph as the sudden decline in loading on the test specimens. The maximum applied loads for the flexural tests lie within a range between approximately 7.3 and 10.6kN with deflections between 17-24mm at the load points. The collection summary of the flexural loading results is shown in table 6.

It is interesting to note that flexural test 3 (FL-3) displays slight drops of applied loading at approximately 5.5 and 6kN, whereas the other four tests remain constant over the entirety of the test until failure. This could possibly be deduced as slight cracking or delamination of the specimen which immediately reduces the load capacity of the flexural test piece. Another interesting point is that FL-3 was also witnessed to be the smallest deflection until failure, therefore giving a smaller applied load as well as the smallest deflection before complete failure (17.87mm & 8.09kN).

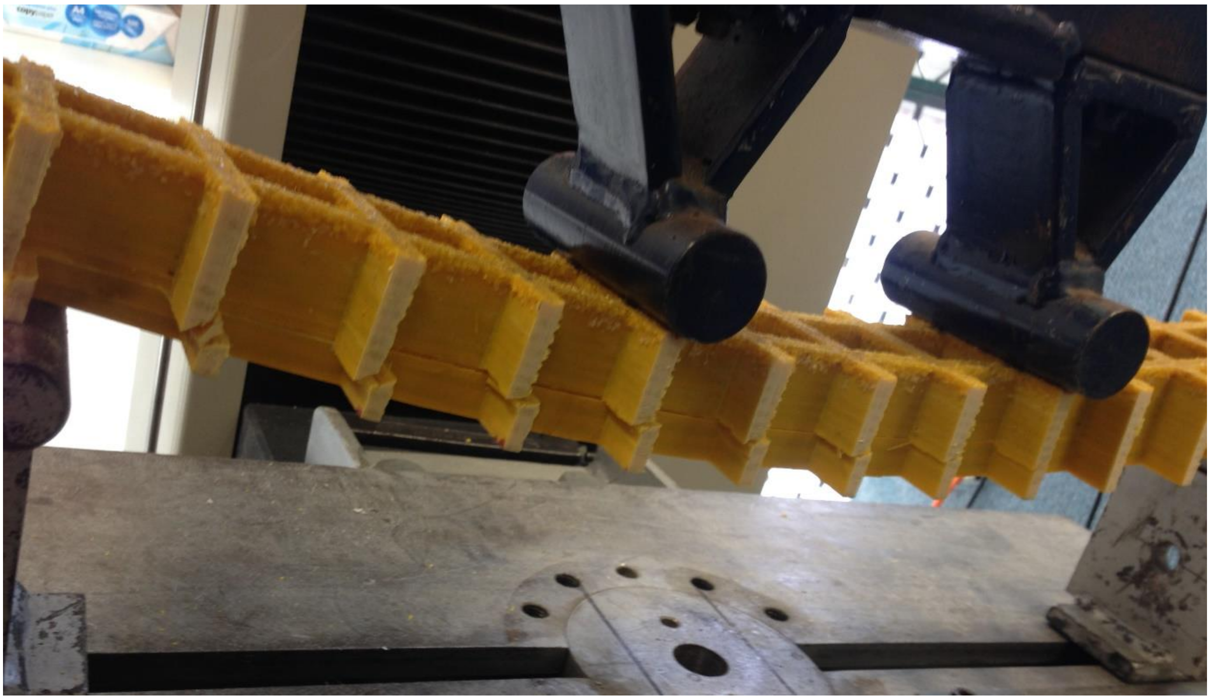


Figure 28 - Example of shear failure for flexural loading (Nicol, Lachlan. 2014)

The failure modes of the flexural tests were observed as shear failures, where longitudinal cracking of the specimens lead to complete delamination of entire fibre layers creating separation. Figure 28 shows this particular delamination where it can be said that cracking occurred between two fibre layers which broke the bond of the resin matrix. This would suggest that the thin flexural samples are weaker in the lengthwise directions (i.e. weaker over the 450mm span).

As discussed in section 2.7.1.2 in regards to the calculation of deflection at the centre of the flexure specimens, the deflection at mid span i.e. maximum deflection needs to be calculated to create a comparable set of results. Equation 5 was used to develop an approximation of the deflection at mid span for all 5 specimens. The average maximum deflection equated to be approximately 31.84mm

Table 6 - Flexure test results summary

Test ID	Deflection Max (mm)	Load Max (kN)	m	Flexural Stress (MPa)	Deflection at Centre (mm)	Flexural Strain	Flexural Modulus (Gpa)
FL-1	23.73	10.425	0.46	186.28	34.96	0.04143	10.40281032
FL-2	20.73	8.587	0.375	153.44	35.32	0.04186	8.480551888
FL-3	17.87	8.09	0.446	144.56	27.98	0.03316	10.08620305
FL-4	18.72	7.33	0.376	130.98	30.07	0.03564	8.503166693
FL-5	19.68	10.59	0.529	189.23	30.88	0.03660	11.96323186
Average:	**20.15**	**9.00**	**0.4372**	**160.90**	**31.84**	**0.03774**	**9.89**

Table 6 as viewed above, shows the results of the 5 separate flexural loading cases with worked calculations for equations 2 – 5. Also included in table 6 is the calculation for deflection at the mid-point since the recorded data only displays deflection at the applied loading points. Over the 5 different tests, an average value for flexural modulus was obtained of 9.89GPa. This modulus was added to the material properties used in Creo for the FE analysis simulation process. The calculation of the flexural modulus required a value of m which was the gradient of the load deflection curve and was taken directly from the graph displayed in figure 28.

The calculation of deflection at mid span rather than at the load points now gave a range between 27 and 36mm and an average centre deflection of 31.84mm. The average flexural stress of all test specimens was calculated to be 160.9MPa, ranging between 130-190MPa. This range of stress is rather large with a 37.5% of variation which is relatively substantial considering the products are all manufactured out of the same material.

4.3.2 Compressive Loading

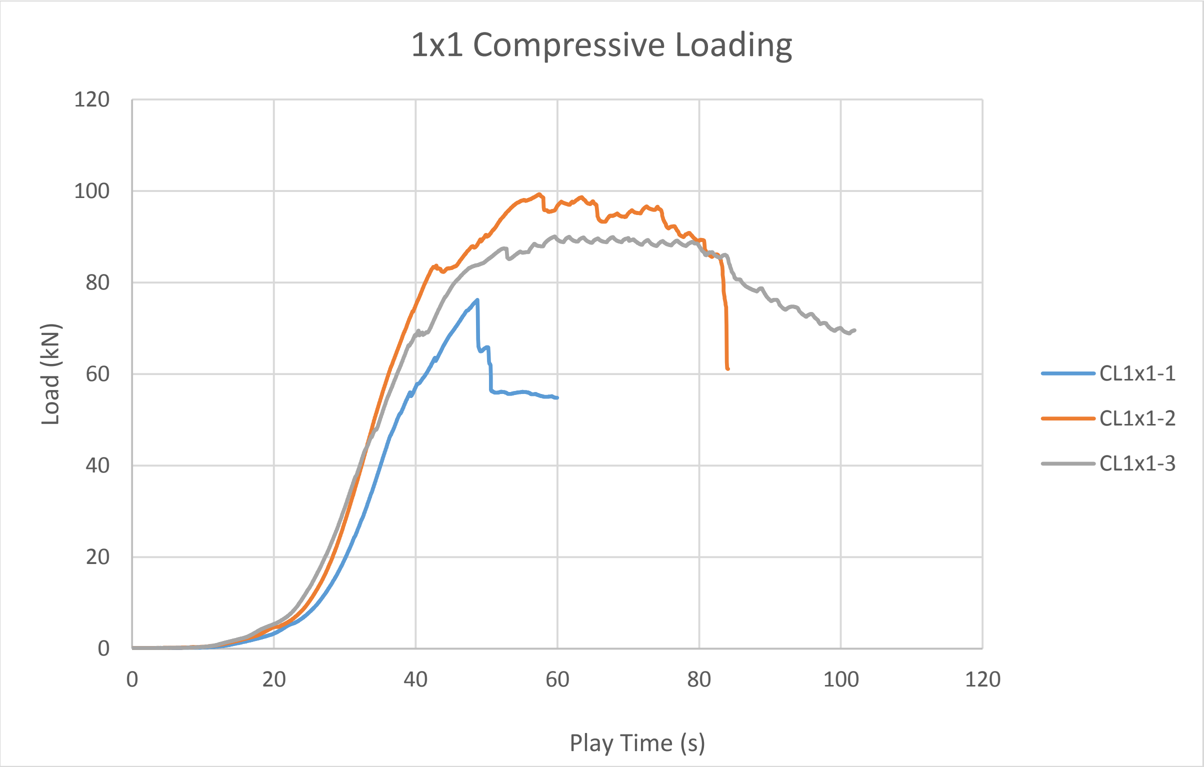


Figure 29 - 1x1 compressive loading results

Figure 29 illustrates the combined compressive load test results for all three 1x1 blocks. The behaviour of the three specimens appears relatively consistent and comparable for the majority of the loading over the observed time, i.e. the load to play time curves are all very similar and follow a consistent trend. It's not until after approximately the 60kN mark do the three samples vary from one another. As observed, CL_{1x1}-1 rises to a maximum of 76.24kN before rapidly dropping in applied load. CL_{1x1}-3 on the other hand maintains its complete compressive strength up to an applied load of 70kN where a slight drop in load is detected before the compressive strength picks back up again and continues to rise constantly to 79-82kN. At this point, the applied load over time starts to taper off and begins to plateau while displaying small load drops which indicates slight compressive failure of the block and is a direct contribution from the internal cracking of the resin matrix while the fibres still manage to hold the grid structure together. This 'plateau' of loading occurs over about 35 seconds before the eventual decline of the loading which indicates full compressive failure of the singular block.

Similar to CL_{1x1}-3, the second test block (CL_{1x1}-2) rises consistently for 42 seconds before displaying a small load drop. The applied load rises again, noted as a rise not quite as steep, until approximately 100kN where the results then show a decline of load including a number of compressive strength load drops until a play time of 80 seconds (or approximately 90kN). At this time, the load suddenly drops which again is an indication of complete compressive failure of the 1x1 sized block.

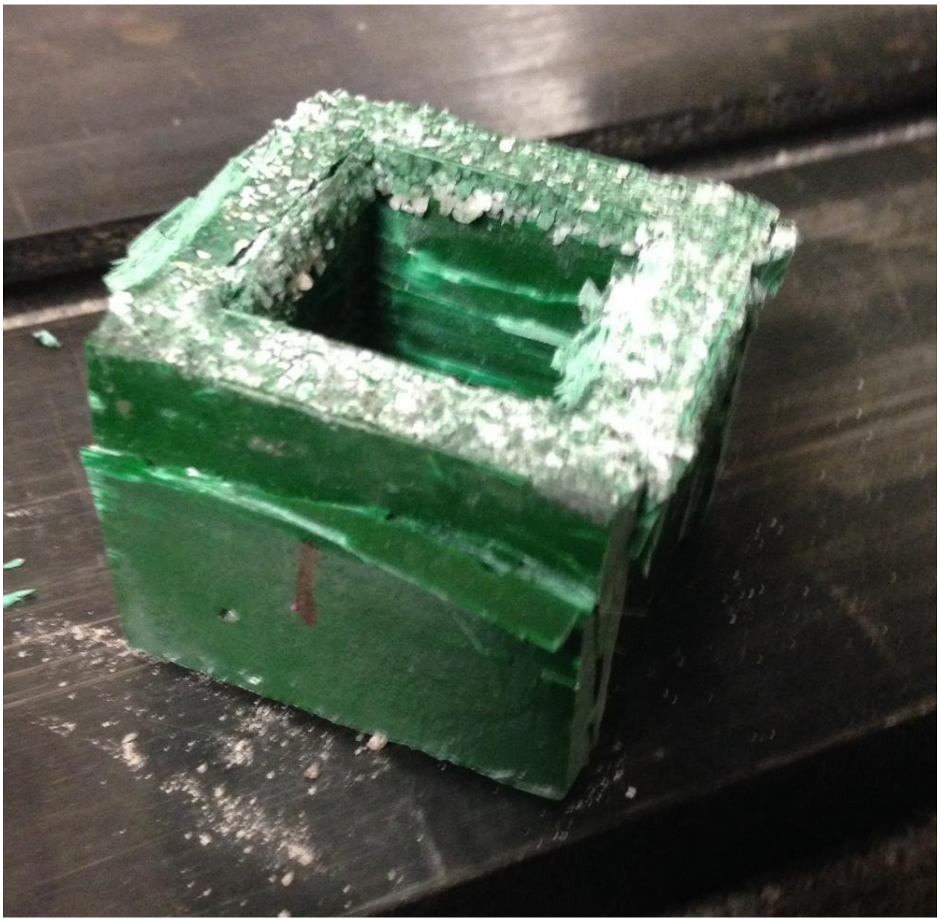


Figure 30 - Example of 'crushing' compressive failure for 1x1 block (Nicol, Lachlan. 2014)

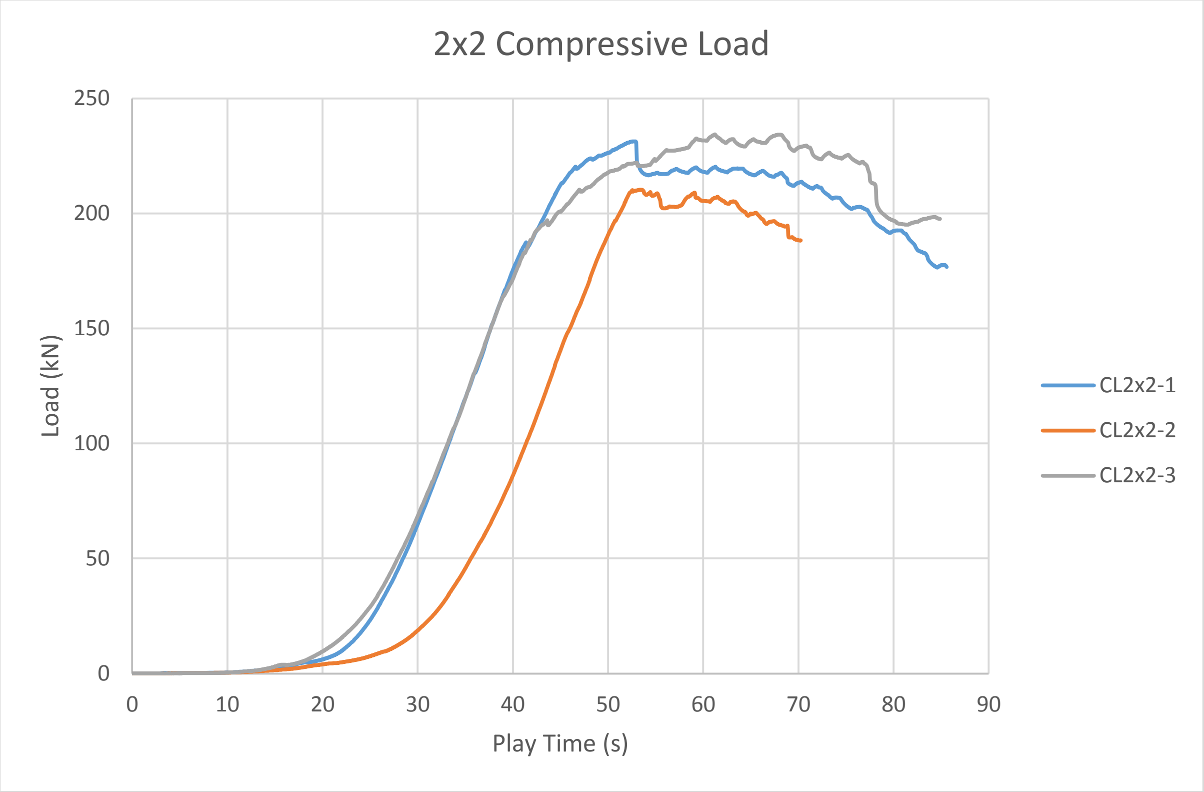


Figure 31 - 2x2 compressive loading results

The results displayed in figure 31 of the 2x2 grid block tests show very similar trends to that observed in the CL_{1x1}-2 & CL_{1x1}-3 results, where there is a comparable rise of loading over time with a point in time reaching failure stage and showing a plateau of loading with small load drops before an eventual decline of load. CL_{2x2}-3 was the only test out of the three which showed an initial drop of load at around the 43 second mark. The other two tests (CL_{2x2}-1 & CL_{2x2}-2) rose constantly until the compressive strength began to decline. CL_{2x2}-1 displays a rather large and sudden drop of approximately 15kN before reaching the compressive plateau and displaying the constant load drops as expected.

In the figure of given results, CL_{2x2}-2 can be descried as an outlier as the results show a fairly large variation of the load to play time ratio. CL_{2x2}-1 & CL_{2x2}-3 follow an almost identical loading trend up until initial compressive failure and both show a maximum loading of 230-230kN whereas the outlier (CL_{2x2}-2) only ever reaches a maximum loading of 210kN. It is an observation that both CL_{2x2}-1 & CL_{2x2}-3 have a larger total compressive strength compared to CL_{2x2}-2.

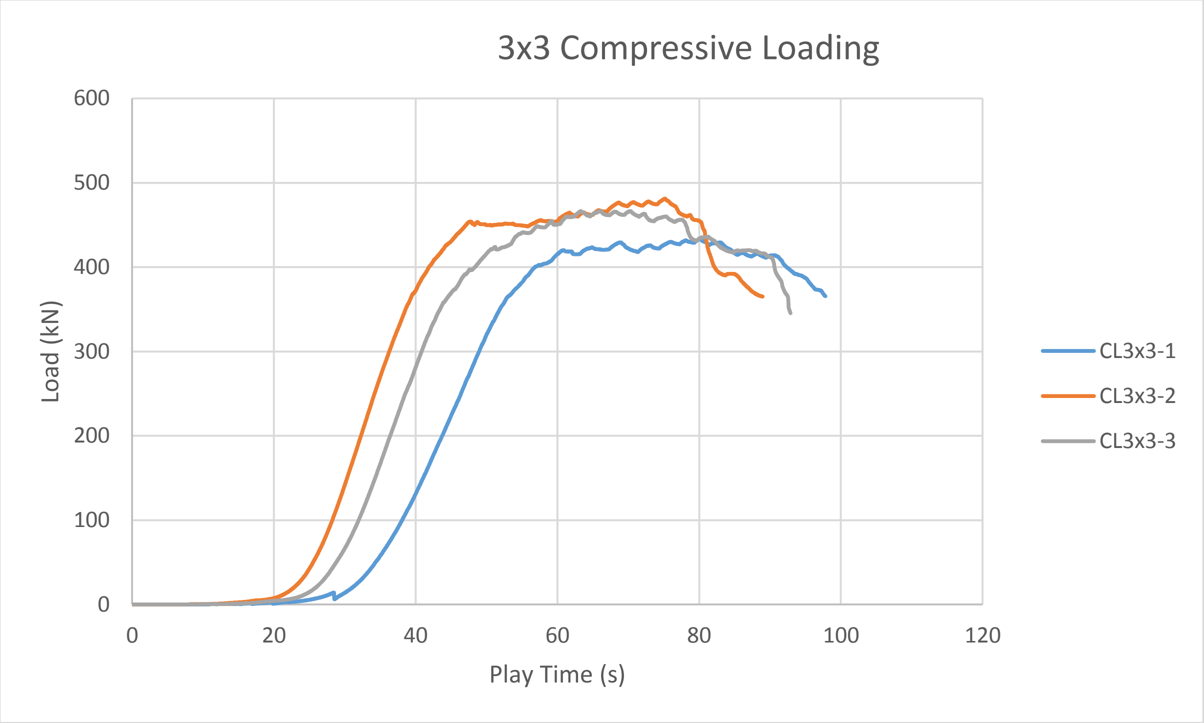


Figure 32 - 3x3 compressive loading results

The results of the 3x3 grid block tests show and array of very consistent load/play time trends. All three specimens slowly increase in load over time until they eventually begin to display the small load drops which has come to be expected for these particular types of tests. Different to the previous tests (1x1 & 2x2) however, the transition into compressive failure is relatively smooth with no obvious point in time where failure begins. One slight exception in the otherwise smooth set of results is the slight decrease in load early on in the CL_{3x3}-1 test. Since this is observed so early into the loading, it can be assumed that it is simply the failure of the non-slip coating on the top of the test piece. Since all grid specimens are coated on top with a non-slip sand and resin coating, it is assumed that at this load drop the sand 'settled' and the entire surface of the loading block began to be loaded. The range of maximum loads applied to all three of the 3x3 grid tests was observed as 433-482kN including an average load of 460kN.

Table 7 - Compressive loading test results

Test ID	Length (mm)	Width (mm)	Web Thickness (mm)	Total Area Under Loading (mm²)	Max Load (kN)	Compressive Strength (GPa)
C1x1 -1	45.94	45.86	7.98	1210.41	76.24	62.987
C1x1 -2	46.24	45.69	7.75	1184.67	99.31	83.833
C1x1 -3	45.26	46.02	7.78	1178.20	90.05	76.430
C2x2 -1	83.36	83.74	7.96	3420.09	231.37	67.649
C2x2 -2	83.78	83.92	7.90	3412.80	210.40	61.650
C2x2 -3	83.26	83.8	7.91	3401.22	234.35	68.902
C3x3 -1	122.22	122.44	7.84	6689.09	433.36	64.786
C3x3 -2	121.73	122.1	7.76	6605.00	481.41	72.886
C3x3 -3	122.2	121.85	7.91	6720.65	466.58	69.424
					Average:	**69.838**

4.3.3 Burn Out Test

Table 8 - Burn out test results

Colour	Green	Green	Yellow	Yellow	Average
Orientation	**T**	**L**	**L**	**T**	
m1	20.6133	21.3045	20.1489	23.3442	
m2	43.6617	41.3639	44.1289	45.2253	
m3	32.9777	32.5350	33.0859	34.8854	
Sample Mass (g)	23.0484	20.0594	23.9800	21.8811	**22.24**
mglass (%)	53.6454	55.9862	53.9491	52.7451	**54.08**
mglass (g)	12.3644	11.2305	12.9370	11.5412	**12.02**
Volume (m^3)	1.4399E-05	1.44E-05	1.44E-05	1.44E-05	
Density(kg/m^3)	1600.69983	1393.115	1665.399	1519.631	**1544.71**

The results displayed in table 8 show the formulation of equation 7 from the literature review section 2.7.1.2 *'Burn Out Test'*. This formula is made up of the difference factor between the initial mass of a test specimen and the final mass of the remaining fibrous content. The results of the burn out test and applying equation 7 give a fibre content ranging between 52-56%. As an average over the four (4) separate tests, it can be said that as an average, the FRP grating has a glass content percentage of approximately 54%. This means that in total, the combination of glass and resin is at a 54% to 46% respectively. This ratio can be applied to much larger panels to still gain a good understanding of the fibre ratio.

For full sized panels, the total weight of glass which is included in the total weight can be calculated by finding 54% of the total weight of panel. The reverse can be done if the weight of resin is required. The reasoning behind having different sample types (i.e. both green and yellow as well as both transverse and longitudinal webs) was to compare and determine any differences there may be between both the colour of the panels and direction of fibres. Since the resulting standard deviation is approximately only 2, there is minimal difference between all of the specimens as they all display a similar amount of fibres. A larger investigation into the fibre to resin ratio would have needed to be undertaken if results were not so closely comparable. However, since the results of the burn out test do indeed display very similar results between specimens, it is safe to assume that the percentage of fibre remains relatively consistent over all panels.

A small amount of what can be described as filler material was found once the resin had been burnt away. Since the amount of filler was relatively minimal its weight was neglected in the analyis and calculation of the glass to resin ratio. The filler merely retained the grating web structure once the resin matrix was burnt away and did not contribute to the weight or strength enough to conduct a different separation test.

Figure 33 - Burnt out FRP web containing 'filler material' and glass fibres (Nicol, Lachlan. 2014)

As well as calculating the fibre ratio within the FRP grating, it was important to calculate the density of the product to aid in the finite element analysis. Given the average volumes and weights of the 4 specimens analysed, the average density was calculated to be 1544.71kg/m^3. As a theoretical comparison, the common density for glass fibres is 2580kg/m^3 and resin density is commonly 1200kg/m^3. Using the fibre-resin ratio evaluated earlier, a combined density should equate to approximately 1947kg/m^3. This value is however purely theoretical using common densities for both glass fibres and resin matrices and is only used to ensure the calculated density is somewhere within the expected range, which is in fact the case.

4.3.4 Finite Element Analysis

Flexure Analysis

From the collection of results obtained from the sample sized testing results previously discussed, mechanical properties and loads for use as part of the finite element anaysis were added to the flexural model in Creo ready for analysis. The values used include:

$\rho = 1544.71$	(kg/m^3)
$E_f = 9.89$	(GPa)
$\sigma_c = 69.84$	(GPa)
$P = 9$	(kN)

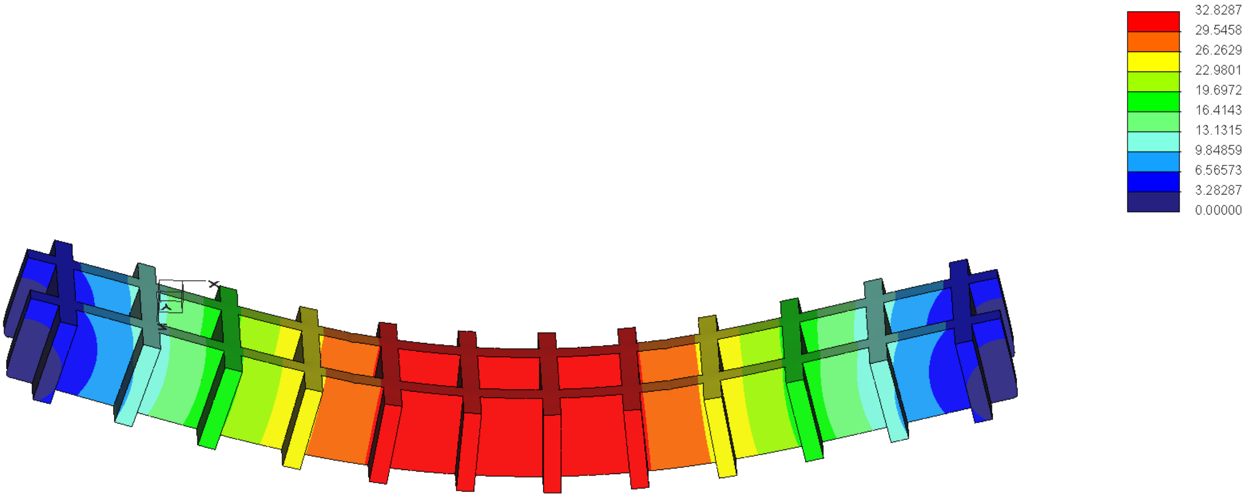


Figure 34 - Load-deflection simulation at 10% deformation of flexural model (Nicol, Lachlan. 2014)

The load-deflection behaviour of the flexural analysis is displayed in figure 34 with a deflection magnification of 10%. The deflection predicted using Creo's simulation processes was estimated to be approximately 32.83mm using a load of 9kN applied in a 4 point bending pattern spaced evenly at 150mm (i.e. 75mm from the centre).

To successfully proceed to full scale analysis, the FEA on the flexure specimen needs to correspond closely with the results obtained from the physical flexure tests undertaken. Since the testing undertaken gave a set of 5 separate results, and the FEA gave only one set of results, and average of all 5 physical tests was used in the comparison between theoretical and physical results. As an average, the physical testing specimens deflected approximately 31.84mm at mid span and the FEA gave a resulting deflection estimation as 32.83mm. This is a variation if only 1mm (or a 3% difference) which is extremely similar and therefore comparable.

Given the similarity in results between the physical testing and the finite element analysis, it can be assumed that the material values used are correct and can be used in the accurate simulation of the full scale tests. Figure 35 & 36 show the stress and strain distribution relationships for the flexure analysis. The results found using PTC Creo simulation process gave rather extreme results of both the stress and strain maximum and minimums, this can be described as stress/strain rises at the points of loading and at the fixtures. For applicable analysis, these values were neglected and the legend range modified to display the stress and strain distributions closer to the actual results i.e. for the stress distribution shown in figure 35, 4062.87MPa was neglected and the maximum stress of 160MPa was used in its stead, thus providing a new range between 10 and 160MPa.

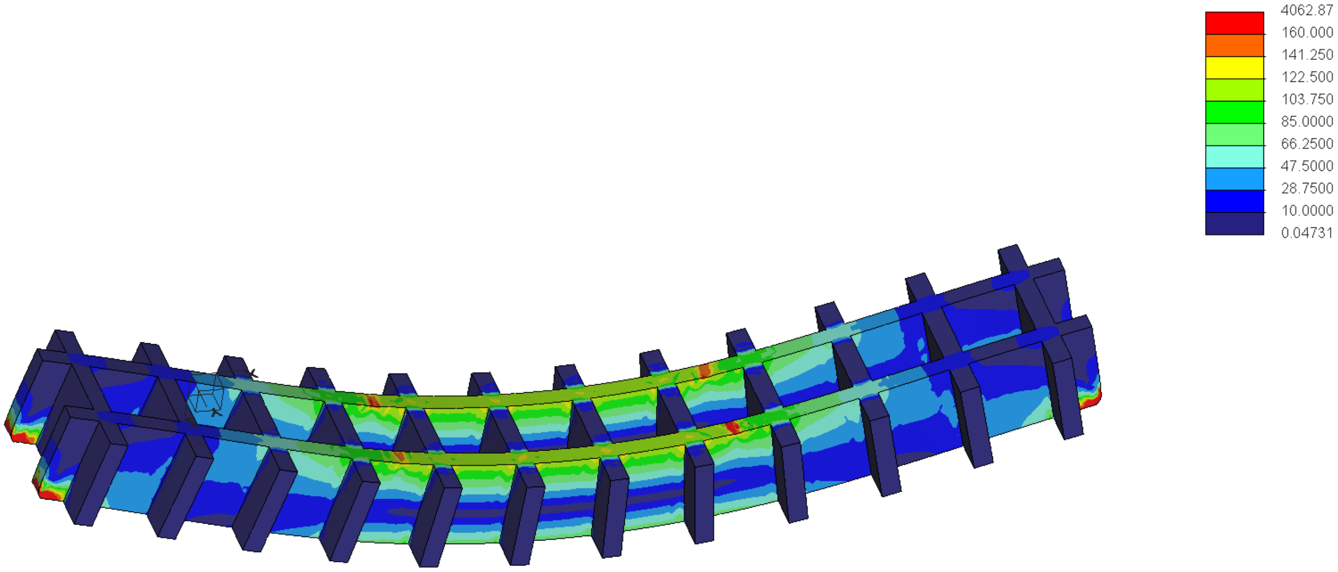


Figure 35 - Stress distribution for flexure analysis (Nicol, Lachlan. 2014)

With the legend range adjusted for accurate analysis, figure 35 shows the maximum stress at the centre of the specimen to be of yellow colouring, this corresponds to a flexural stress on the legend to be approximately 141.25MPa. As discussed in section 4.3.1 for the results of the physical flexural testing, an average flexural stress was calculated to be 160.9MPa over the 5 separate samples. This equates to a difference between the theortical and physical results of approximately 13% which is deemed to be an acceptable percentage of difference.

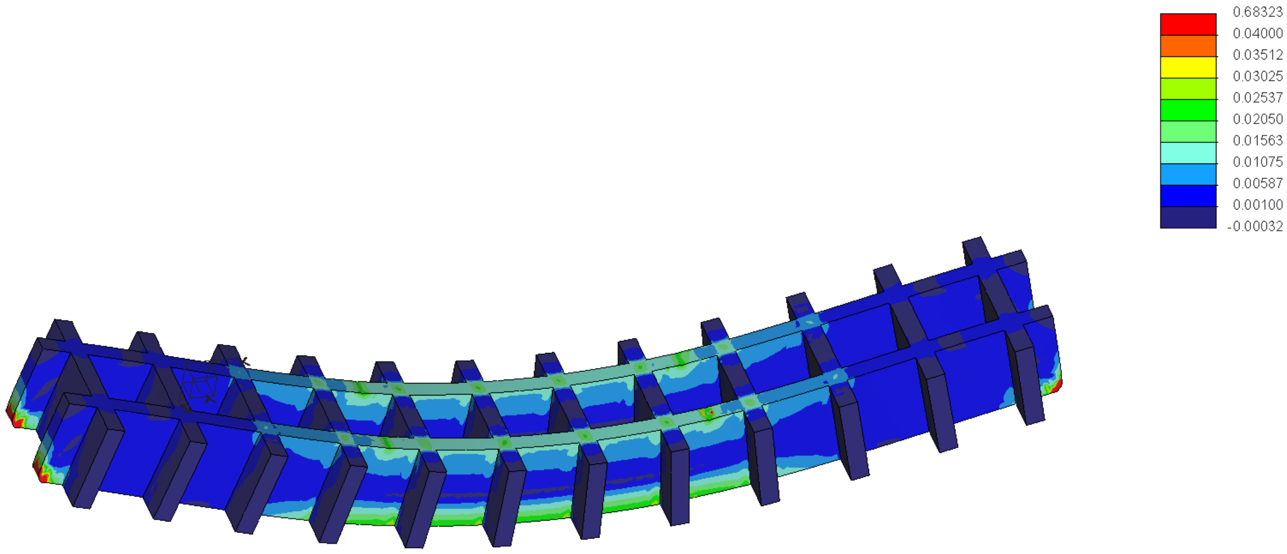


Figure 36 - Strain distribution for flexure analysis (Nicol, Lachlan. 2014)

Similar to the flexural stress FEA results, the legend in figure 36 needed to be adjusted to display the strain distribution which could be compared to the physical test results. The colour which displays the largest strain reading (excluding the values disregarded due to strain rises at loads and fixtures) is the green colour drectly below the yellow which corresponds to a strain value of 0.03025. This reuslts in a percentage difference of approximately 22% between the FEA and the physical testing results of 0.03774.

Full Scale Analysis

Since the flexural finite element analysis results were closely comparable with the physical test results, the full scale test panels used the same material properties listed in the flexural analysis section with the only variation being the maximum applied load and the loading location/type.

As discussed in section 4.2.1 the average maximum deflection which was observed for the line loading test panels was at approximately 64.85mm. The resulting maximum deflection at the centre for the FEA simulation gave a relatively similar resulting deflection of 73.0277mm. The percentage difference between these two values was calculated to be 11.8%, which can be considered relatively accurate for a FEA result comparison. As can be viewed in figure 37, the largest deflection occurs in the centre of the test panel and slowly decreases as it nears the supports, which correlated directly to what would be expected and what was observed in the physical testing.

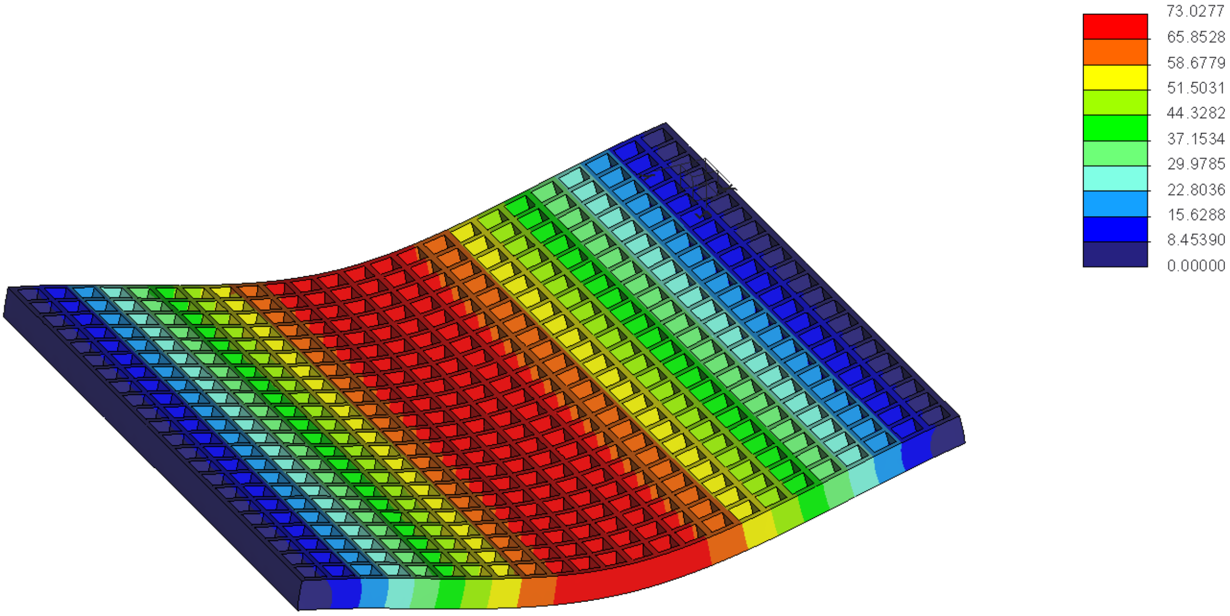


Figure 37 – Load-deflection simulation at 10% deformation for full scale line load (Nicol, Lachlan. 2014)

Figure 38 displays the deflection generated due to a point load of 33.37kN taken from the average maximum load found in the centred physical tests and is applied directly in the centre of the analysis model. The results from the FEA give a maximum deflection at the centre of the model as 47.63mm which corresponds relatively closely with the deflection found in the physical testing of 49.14mm. A difference percentage of only 3% between the two values was found which can be classed as extremely accurate for an FEA comparison. As expected, the deflection is greatest in the centre of the test panel and progressively decreases towards the supports and edges of the panel.

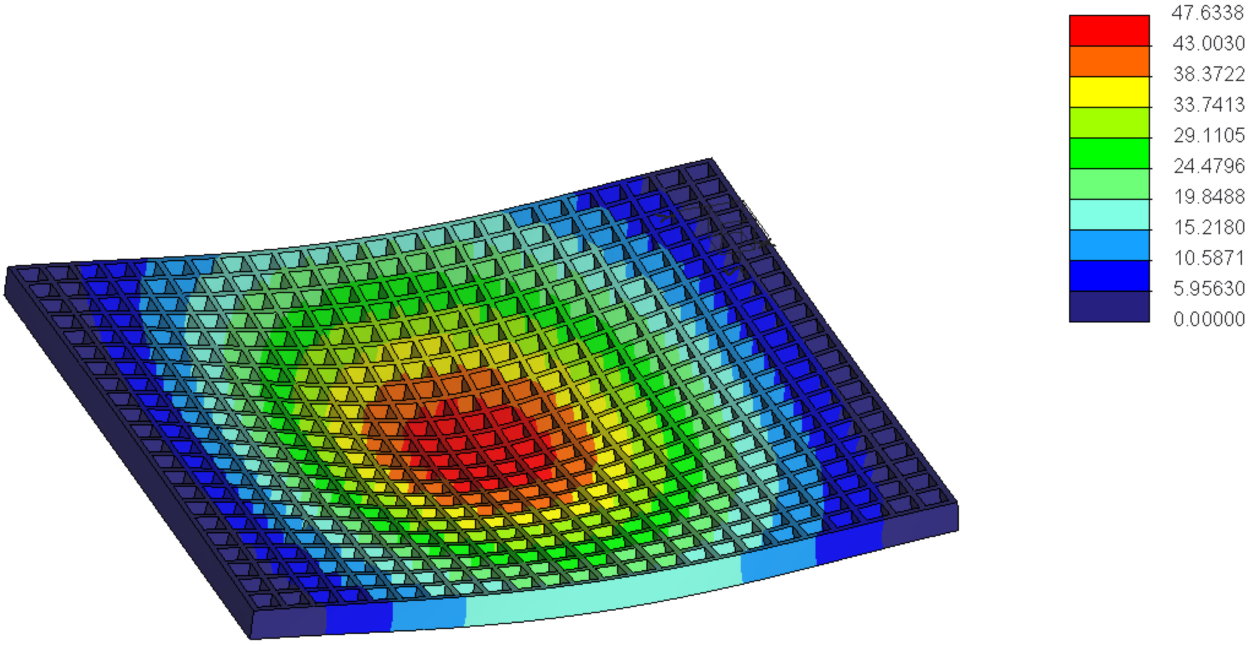


Figure 38 - Load-deflection simulation at 10% deformation for full scale centred concentrated load (Nicol, Lachlan. 2014)

Consistent with the centred loading case, the off centre loading in figure 39 shows a deflection which is greatest directly underneatht the applied load which gradually reduces closer to the edges and the fixtures. The reduction of deflection is spread over a greater distance on the side furthest away from the support i.e. the longer distance to the support. Whereas, the transition from maximum to minimum deflection on the shorter distance to the support is relatively rapid. The average maximum deflection taken from the physical tests for off centre concentrated loading was calculated to be 57.24mm. The deflection calcualated as part of the FE analysis was approximately 53.82mm.

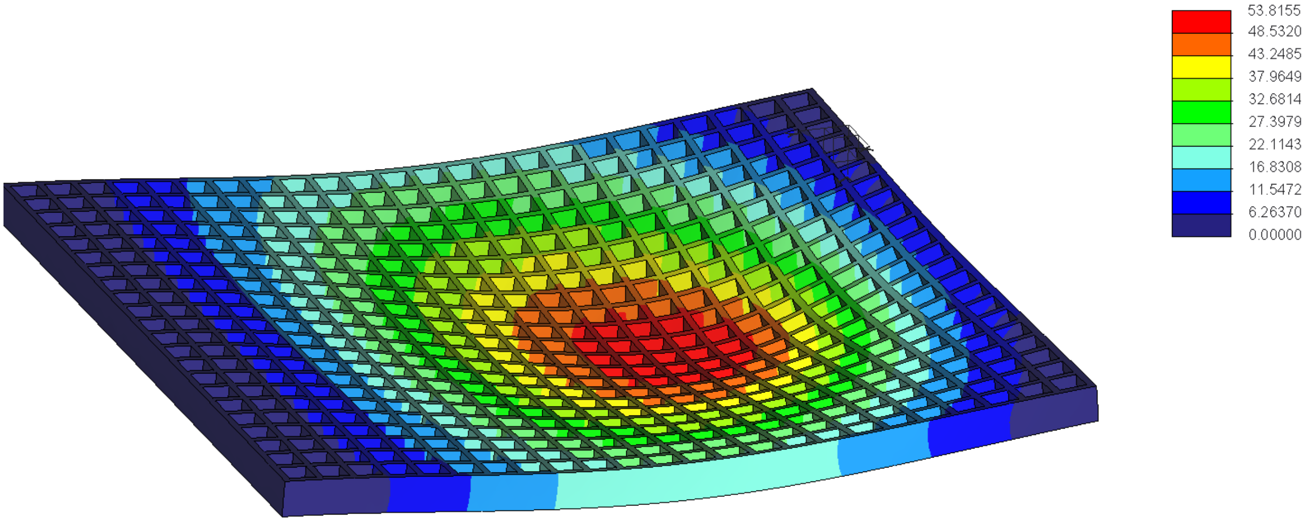


Figure 39 - Load-deflection simulation at 10% deformation for full off centre concentrated load (Nicol, Lachlan. 2014)

5. Conclusions & Future Work

5.1 Introduction

This project has investigated the mechanical behaviours of fibre reinforced polymer grating for use in walkways and boardwalks. The investigation has included the physical testing of both full scale and sample sized specimens as well as the theoretical simulation using the FE analysis function in PTC Creo. The physical testing included three full scale tests, line load, centred concentrated load, and an off centre concentrated load, in addition to the full scale tests, sample sized tests were also undertaken which included tests for flexure, compressive strength, and fibre content as part of a burn out test. The panels used for the testing were manufactured and supplied for investigation by Nepean Engineering. Buchanan’s Advanced Composites provided strain gauges to be attached to the full scale panels to aid in the investigation of mechanical properties.

The various properties which have been calculated using the results of the physical testing and the use of the equations listed in section 2.7 of the literature review aided in the development of material properties for use in the finite element analysis comparison. The use of FEA in Creo as a way to simulate results was verified by comparing the results of the sample sized tests and what was predicted using Creo’s simulation function.

5.2 Failure Modes in Testing

The failure modes observed in the physical testing varied depending on the different loading cases. The full scale line loading showed major cracking of the grating on the bottom side of the panel which could be described as failure due to excessive tension. While the major cracking and breaking occurred on the tension plane of the FRP grid, minor cracking was also observed on the compression side, i.e. directly below the applied line load. The failure of the two different concentrated loading cases, centred and off centred, was observed as the loading block sinking into the grid structure. This sinking is predicted to be caused by the failure of the grid structure immediately surrounding the load block, while the rest of the panel remained undamaged.

The failure mode for the five separate flexural tests was observed as major cracking along the longitudinal direction which led to full separation and delamination along the length of the specimen. This type of failure can be classified as a form of shear failure, where the weakest layer of glass & resin completely failed causing the specimen to break into two separate pieces. The compressive loading cases displayed failure similar between the three different sizes, 1x1, 2x2, and 3x3. This compressive failure was observed as the crushing of the specimens and collapse of the resin matrix, this failure corresponds to the decline of applied load using the computer recording software for compressive loading. While the burn out test essentially did not have a failure mode, the experiment was directly aimed at the investigation of the internal glass content of the FRP grating as well as calculation of the density of the product.

5.3 Loading Case Comparison

The principle aim of testing three different loading cases for full scale panels was to distinguish any differences as well determine which load case could be considered the most critical. The three line loading tests gave an average maximum load of 56.16kN for a maximum deflection of 64.85mm, whereas the concentrated loading cases both gave maximum applied loads of approximately 34kN. The centred concentrated loading was recorded to reach a maximum deflection of 49.14mm whereas the off centre loading reached 57.24mm for a similar applied load.

5.4 Use of FEA

The theoretical model simulation and prediction which has been undertaken using Creo’s simulation function provides a very good approximation for the flexural behaviour of the results found in the physical testing. The results obtained from the flexural specimen analysis was closely relatable with the deflection and stress/strain relationship results observed as an average of the 5 physical flexure tests undertaken. The confidence gained by closely comparing the flexural physical and theoretical results justified the use of the FEA software and material properties for full scale analysis and prediction. The confidence in the outcomes of the FEA was furthered with deflection results of all three full scale load cases being very closely relatable. Over the three load types, a percentage of difference between theoretical and physical ranged from 3-11% which is classed to be extremely accurate and deemed useable for any further predictions/analysis.

5.5 Summary

As a summary of the important results of this research and investigation into the mechanical propertied of FRP grating, a list of mechanical properties is supplied as well as a summary table which displays the maximum deflections and loads for the three different full scale loading cases. The summary table can be used as a quick reference to show the maximum loads as well as expected deflections for individual loading cases.

Mechanical properties found for FRP grating supplied by Nepean Engineering:

Table 9 - FRP grating mechanical properties

Property	Value	Units
Density	1544	kg/m³
Glass Content	54	%
Resin Content	46	%
Flexural Strength	160.9	Mpa
Flexural Strain	0.03774	-
Flexural Modulus	9.89	GPa
Compressive Strength	69.8	GPa

Table 10 - Full scale summary

Test ID	Deflection Max (mm)	Load Max (kN)	Support Length (mm)	Panel Width (mm)	Thickness (mm)	Panel Weigth (kg)
LL	64.85	56.16	830	920	40	18.29
CL	49.14	33.37	830	920	40	18.29
OC	57.24	34.93	830	920	40	18.29

Where:

LL – Line load

CL – Centred concentrated load

OC – Off centre concentrated load

5.6 Recommendations & Future Work

The results of this research and investigation project show great possibilities for the further use of FRP grating as a common material in the construction of walkways and boardwalks throughout not only Australia, but the world. The results show that this particular type of grating is best suited when a line load (or more commonly a uniformly distributed load) is applied compared to the application of a point load, either in the centre or closer to the supports. The added strength found closer to the supports allows a point load to be more resistant to flexural failure than if it was applied directly in the centre of the panel.

This research is primarily a starting platform for the full investigation of FRP grating for its suitability for use within the construction industry. Further investigation will need to be undertaken to fully conclude the viability the product has within the industry. Further investigation and research may be focused on a number of other testing procedures and methods such as the effect of impact testing or how resistant to damage the grating is under the influence of fire, UV, weather, and so forth. An economic investigation is also a necessity to be able to fully evaluate if the use of FRP is not only mechanically viable but also feasible on a cost based comparison, concentrating on the comparison between FRP grating and traditional materials such as concrete, steel, timber etc.

Other testing which will be useful for the full understanding of FRP grating may be the changing of certain parameters such as the thickness, fixings, or geometry of FRP grating panels. Given that the FE analysis provided accurate results, a FEA simulation program may be used within the industry for quick and accurate estimations for the behaviour of panels of varying sizes without the need to test the individual sizes. The use of Creo as a modelling software may not be the ideal software available globally however provided very accurate results for what was required in this project. An alternate simulation software may be used for higher accuracy or possibly even the development of a stand-alone program which predicts the behaviour of FRP grating.

Once the additional testing is completed, table 10 can successfully be expanded to show the predicted loads and deflections for a range of varying sized panels as well as the effects of other testing methods such as impact or fire resistance. The completed table could then be used as a quick reference for engineers to estimate the behaviour they may well expect when using FRP grating as a form of walkway.

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Standards:

AS 4155 – 1993 - *'Test methods for general access floors'*

AS 4155.8 – 1993 - *'Test methods for general access floors – test for 25mm x 25mm concentrated load'*

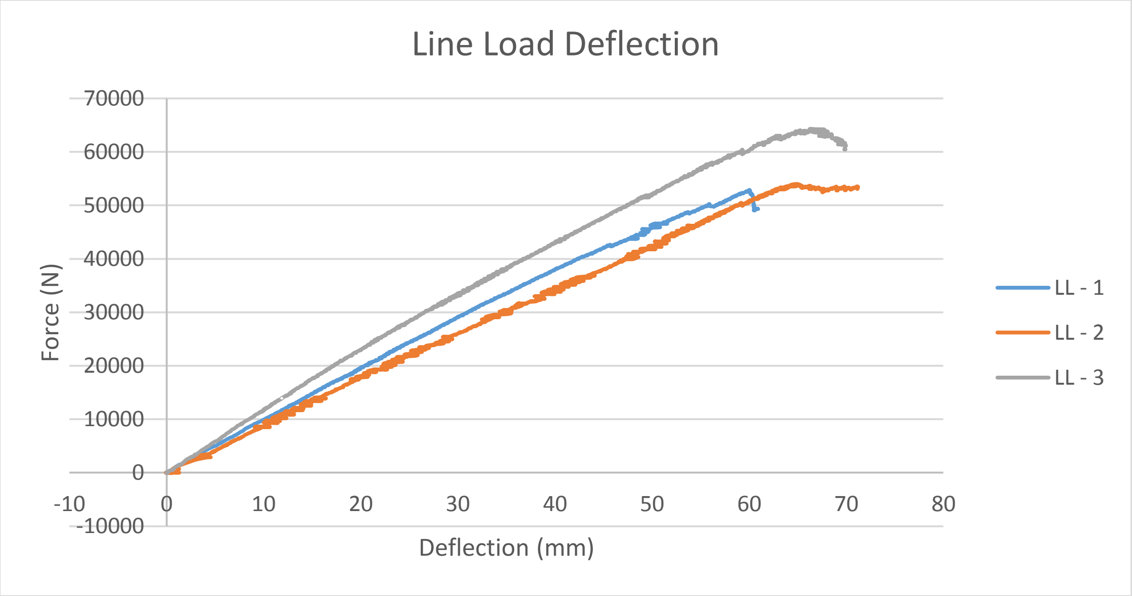
ISO 1172:1996 - '*Textile-glass-reinforced plastics'*

AS/NZS 1170 – 2002 – *'Structural design actions'*

Appendices

Appendix A – Test Results

Line Load

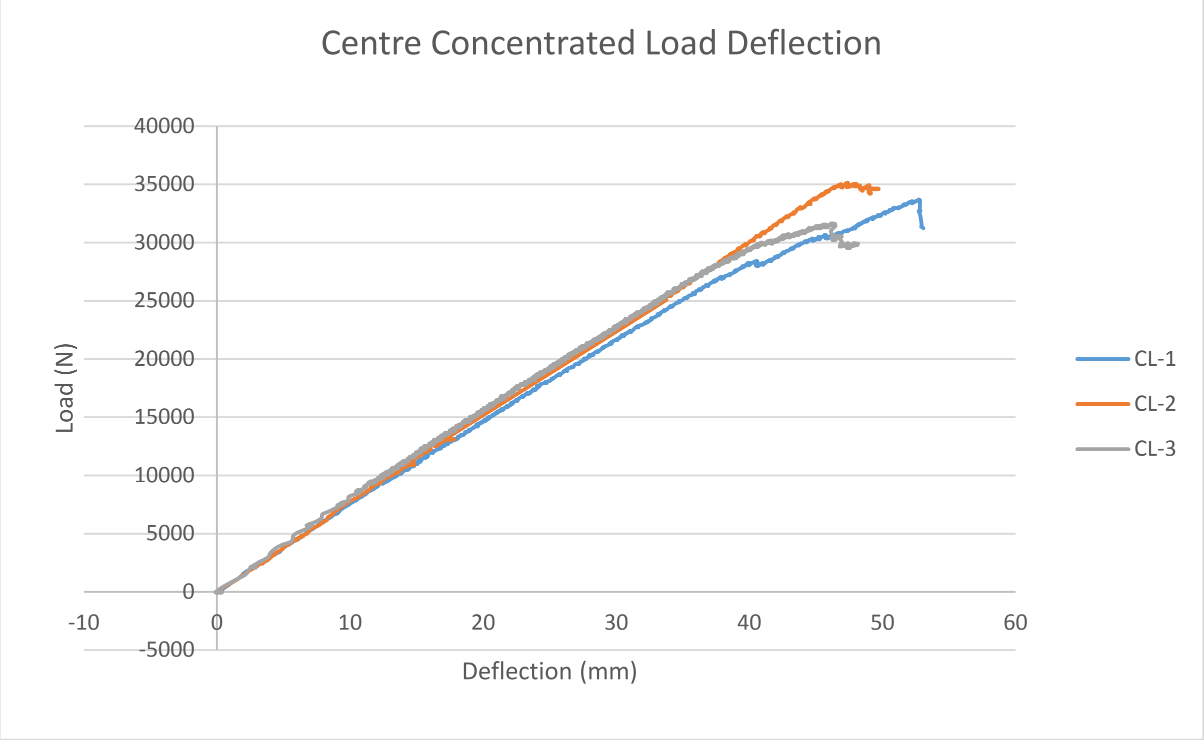


Line Load deflection results (3 records)

Test ID	Deflection Max (mm)	Load Max (kN)	Support Length (mm)	Width (mm)
LL-1	60.00	52.90	830	920
LL-2	64.67	53.90	830	920
LL-3	69.88	61.68	830	920
Average:	**64.85**	**56.16**		

Summary of Line Load test result

Centred Concentrated



Centred concentrated load deflection results (3 records)

Test ID	Deflection Max (mm)	Load Max (kN)	Support Length (mm)	Width (mm)
CL-1	52.26	33.52	830	920
CL-2	49.00	34.94	830	1040
CL-3	46.15	31.64	830	920
Average:	**49.14**	**33.37**		

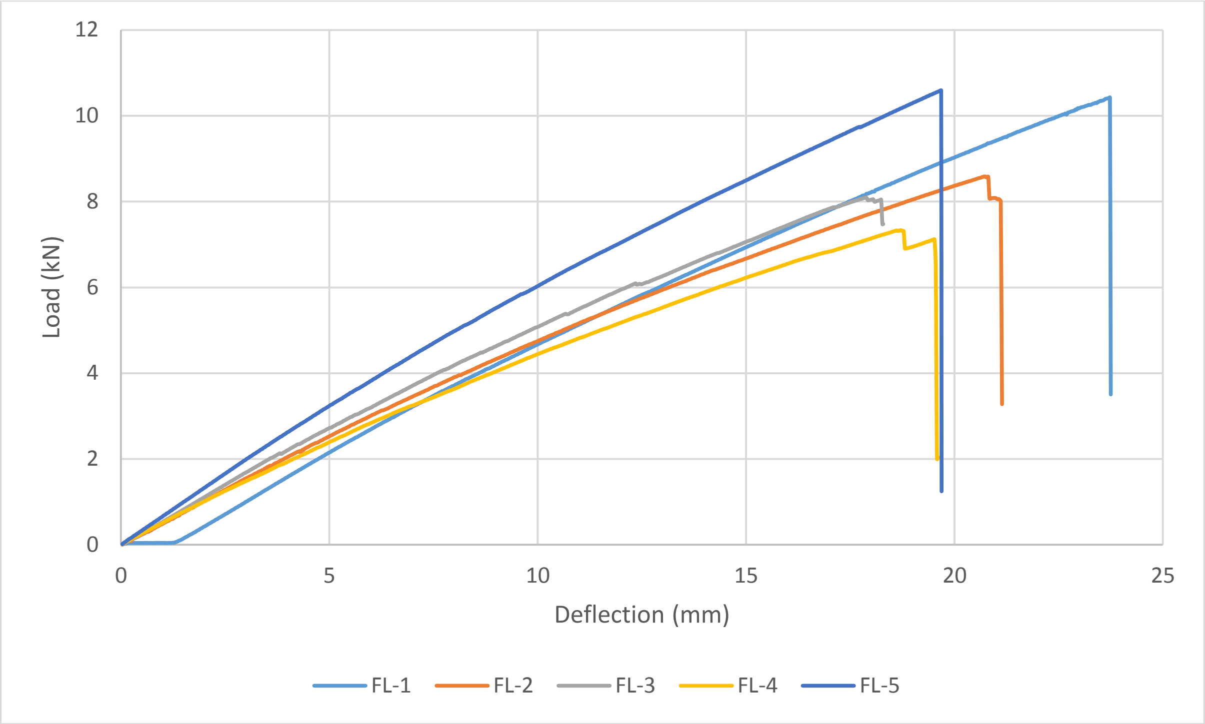
Centred Concentrated load summary of test results

Off Centre Concentrated

Off centre concentrated load deflection results (3 records)

Test ID	Deflection Max (mm)	Load Max (kN)	Support Length (mm)	Width (mm)
OC-1	59.02	32.61	830	920
OC-2	55.78	36.41	830	920
OC-3	56.92	35.77	830	790
Average:	**57.24**	**34.93**		

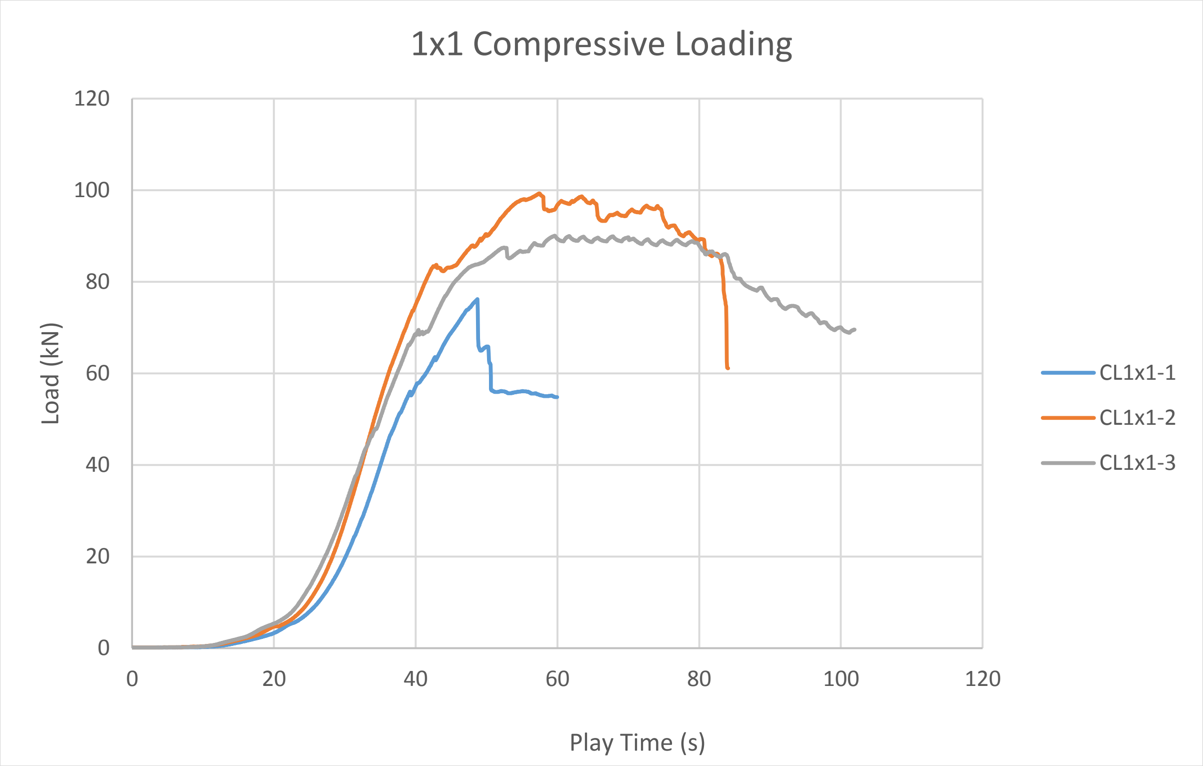
Flexure Test



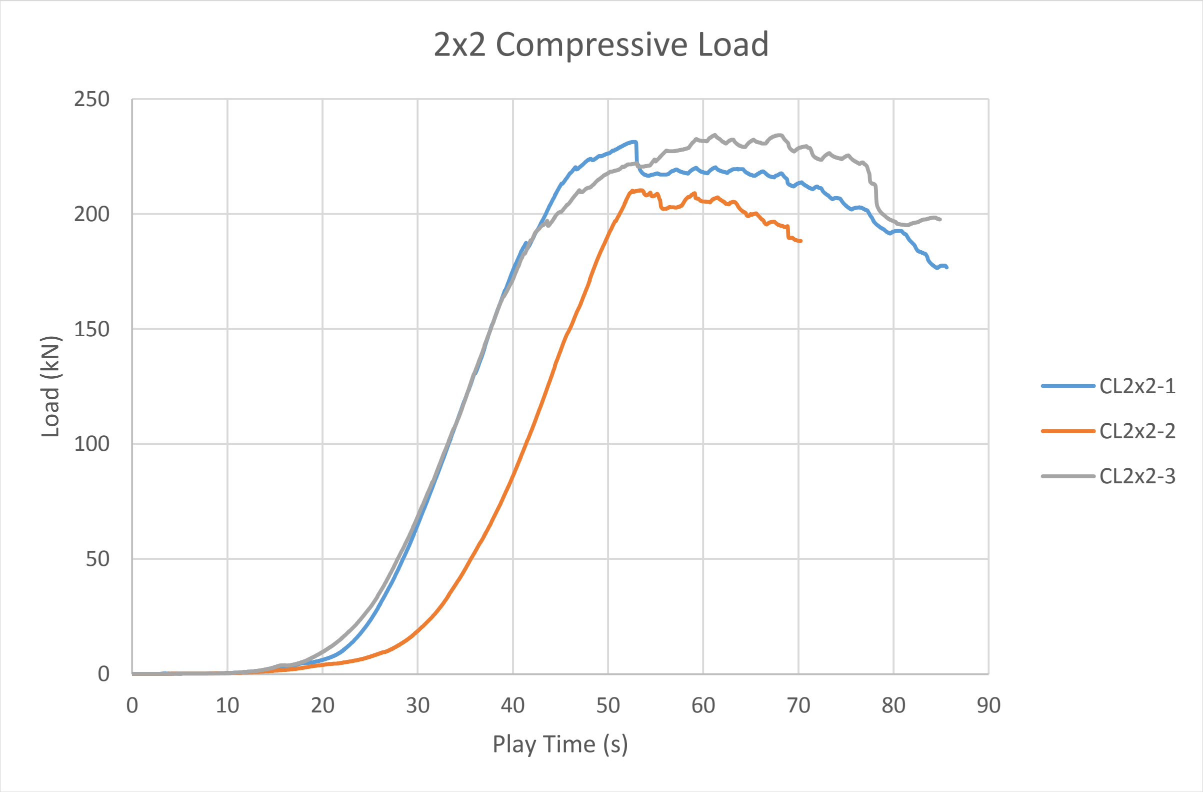
Flexure test deflection results (5 records)

Test ID	Deflection Max (mm)	Load Max (kN)	m	Flexural Stress (MPa)	Flexural Modulus (Gpa)	Deflection at Centre (mm)	Flexural Strain
FL-1	23.73	10.425	0.46	186.28	3.08	34.96	0.04143
FL-2	20.73	8.587	0.375	153.44	2.51	35.32	0.04186
FL-3	17.87	8.09	0.446	144.56	2.99	27.98	0.03316
FL-4	18.72	7.33	0.376	130.98	2.52	30.07	0.03564
FL-5	19.68	10.59	0.529	189.23	3.54	30.88	0.03660
Average:	**20.146**	**9.0044**	**0.4372**	**160.90**	**2.93**	**31.84**	**0.03774**

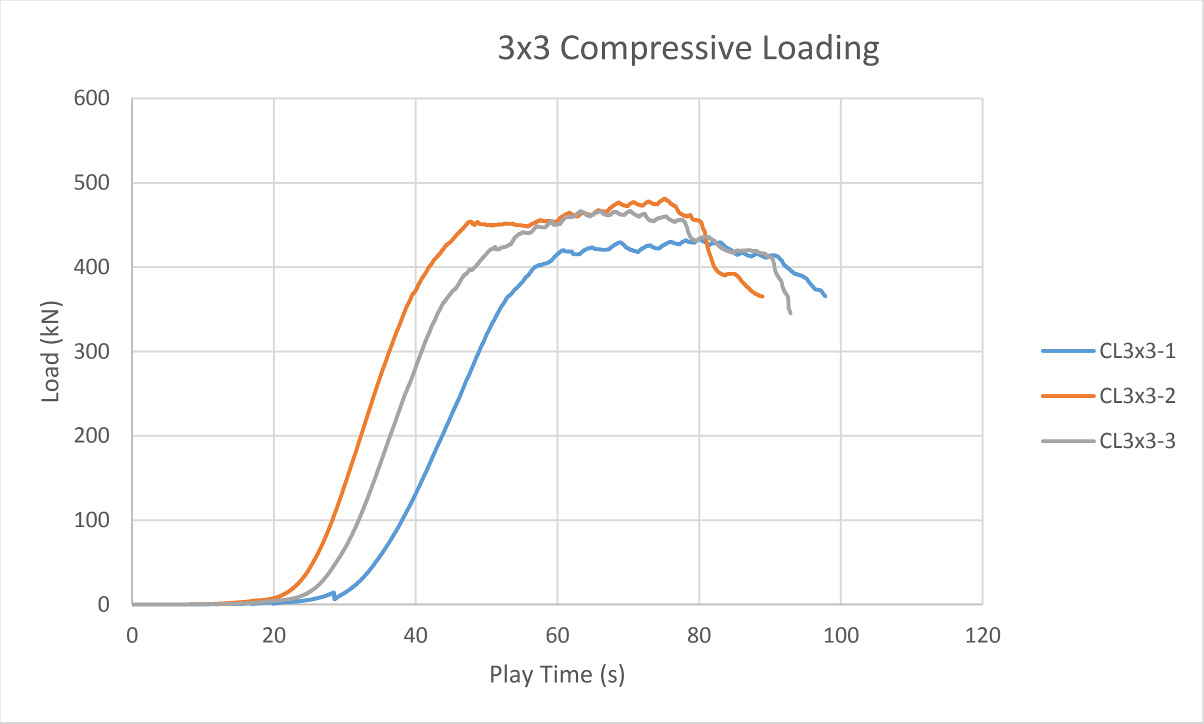
Compressive load



1x1 compressive load results (3 records)



2x2 compressive load results (3 records)



3x3 compressive load results (3 records)

Test ID	Length (mm)	Width (mm)	Web Thickness (mm)	Total Area Under Loading (mm²)	Max Load (kN)	Compressive Strength (GPa)
C1x1 -1	45.94	45.86	7.98	1210.41	76.24	62.987
C1x1 -2	46.24	45.69	7.75	1184.67	99.31	83.833
C1x1 -3	45.26	46.02	7.78	1178.20	90.05	76.430
C2x2 -1	83.36	83.74	7.96	3420.09	231.37	67.649
C2x2 -2	83.78	83.92	7.90	3412.80	210.40	61.650
C2x2 -3	83.26	83.8	7.91	3401.22	234.35	68.902
C3x3 -1	122.22	122.44	7.84	6689.09	433.36	64.786
C3x3 -2	121.73	122.1	7.76	6605.00	481.41	72.886
C3x3 -3	122.2	121.85	7.91	6720.65	466.58	69.424
					Average:	**69.838**

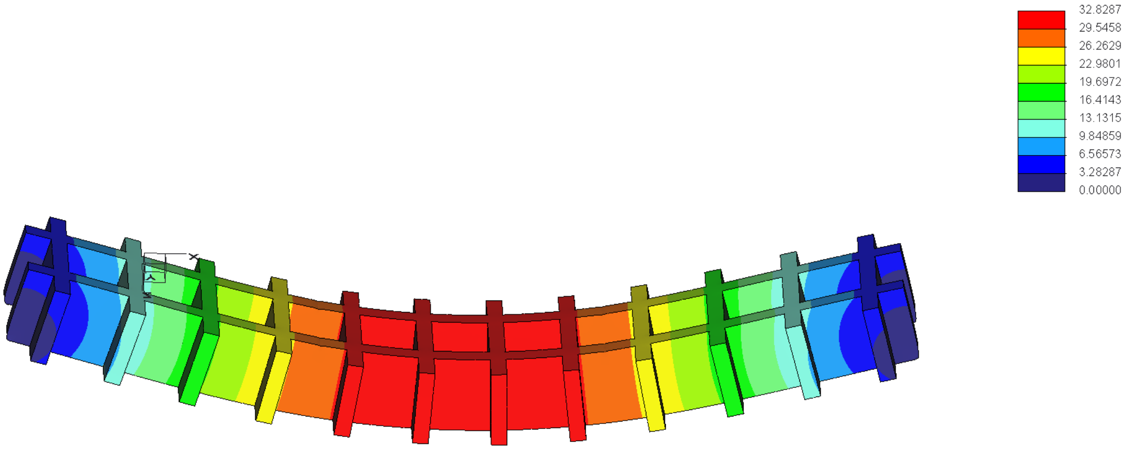
Compressive results summary

Burn Out Test

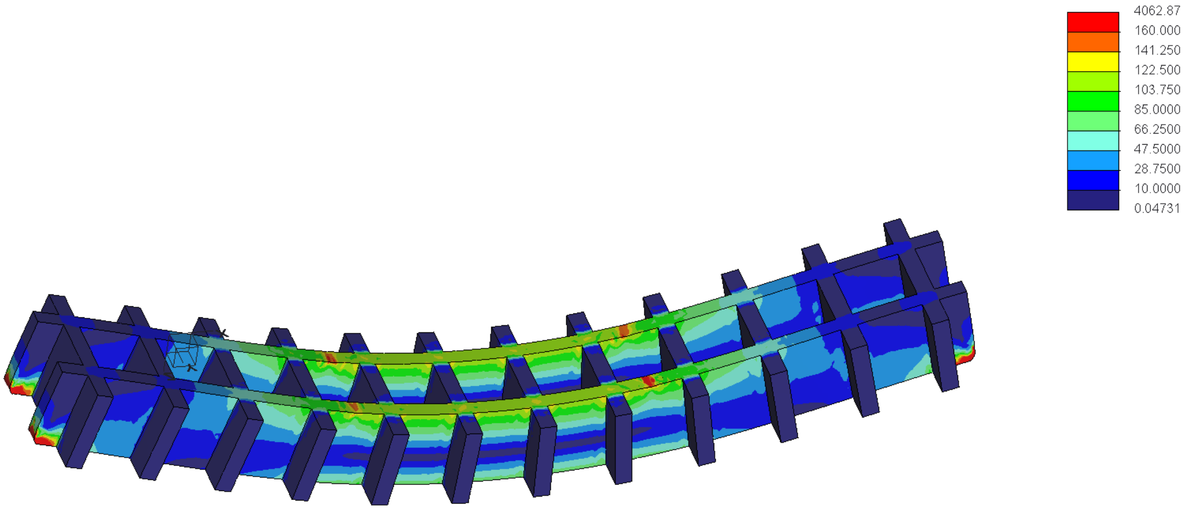
Colour	**Green**	**Green**	**Yellow**	**Yellow**	**Average**
Orientation	**T**	**L**	**L**	**T**	
m1	20.6133	21.3045	20.1489	23.3442	
m2	43.6617	41.3639	44.1289	45.2253	
m3	32.9777	32.5350	33.0859	34.8854	
Sample Mass (g)	23.0484	20.0594	23.9800	21.8811	**22.24**
mglass (%)	53.6454	55.9862	53.9491	52.7451	**54.08**
mglass (g)	12.3644	11.2305	12.9370	11.5412	**12.02**
Volume (m^3)	1.4399E-05	1.44E-05	1.44E-05	1.44E-05	
Density(kg/m^3)	1600.69983	1393.115	1665.399	1519.631	**1544.71**

Burn out test summary (4 records)

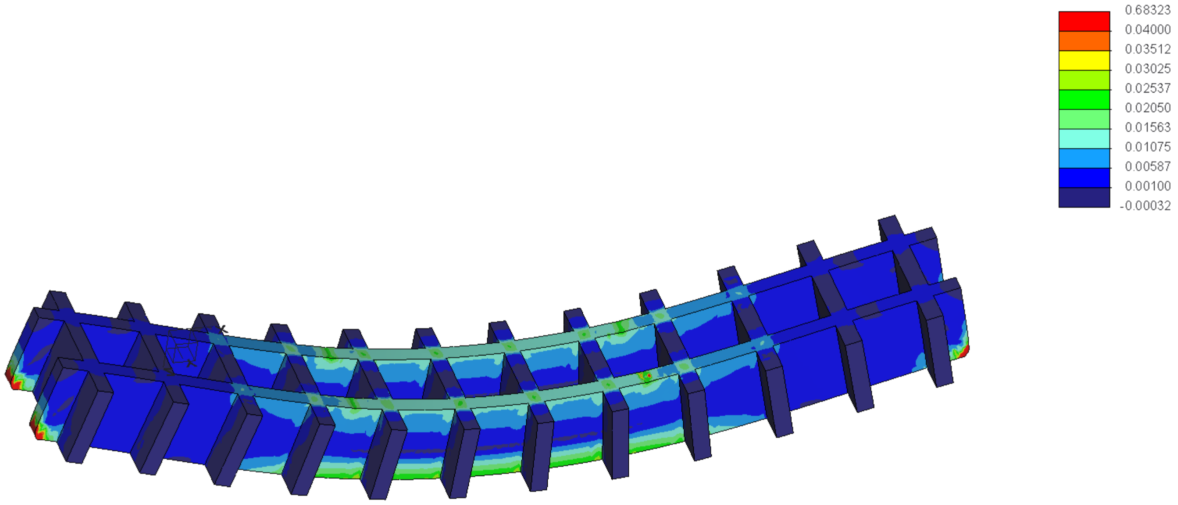
FEA Analysis



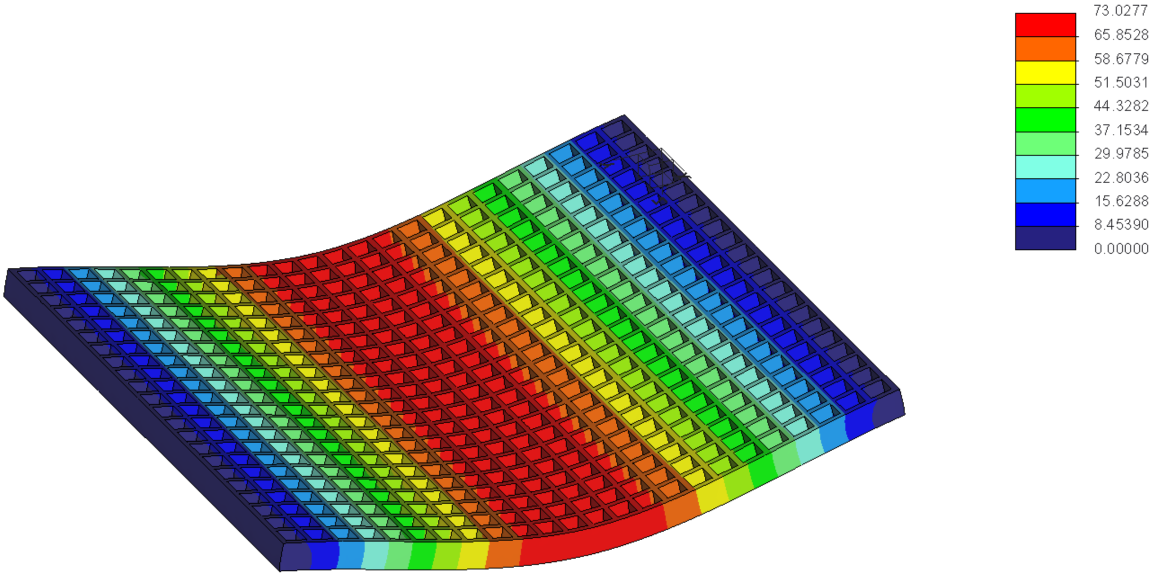
Flexure FEA deflection



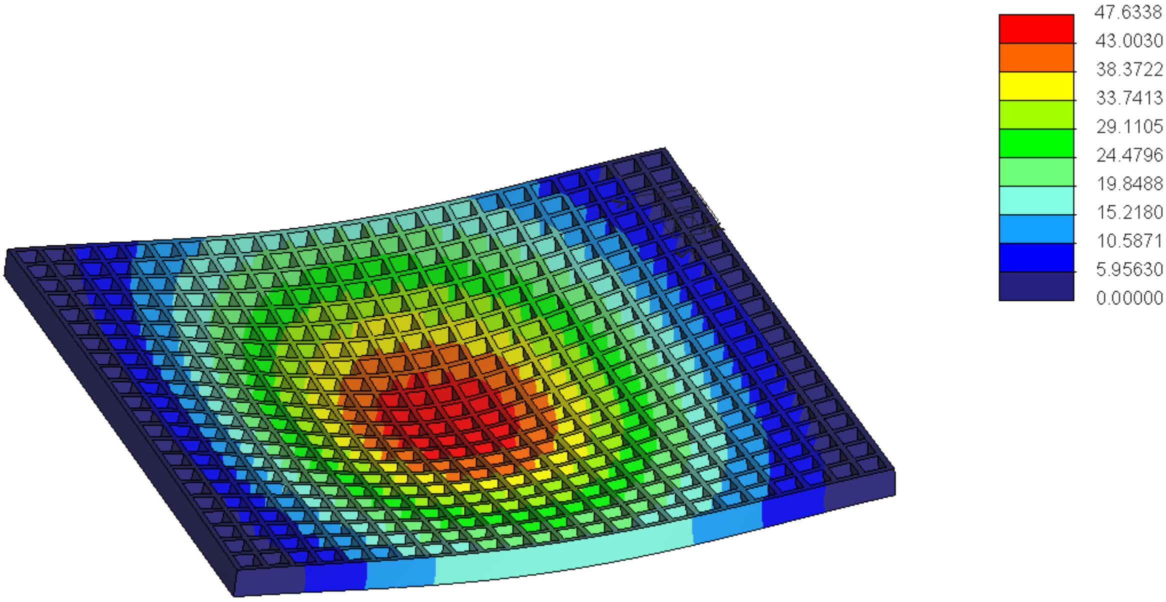
Flexure FEA stress



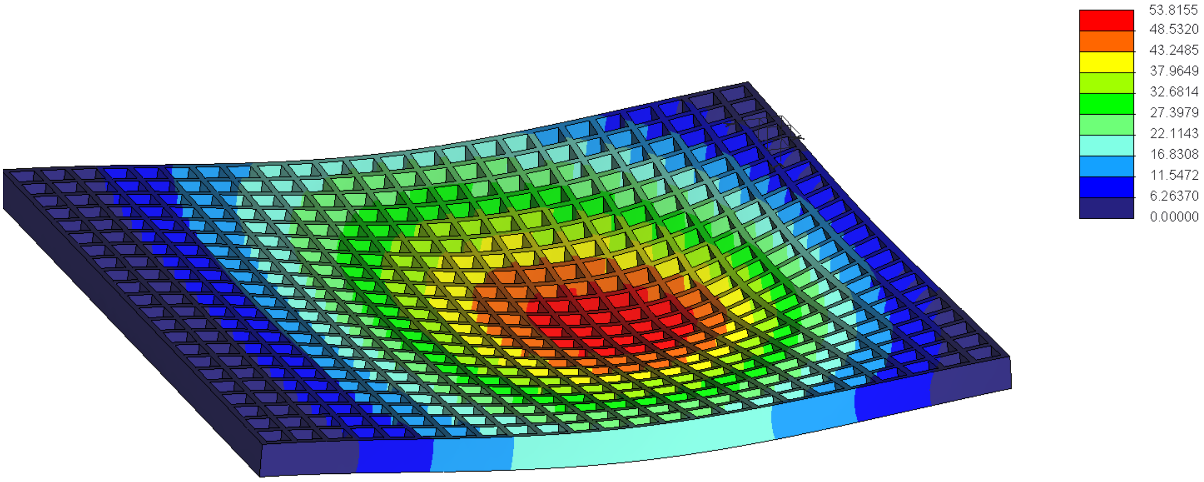
Flexure FEA strain



Line Load FEA deflection



Centred concentrated load FEA deflection



Off centre concentrated load FEA deflection

Appendix B – Project Offer (Allan Manalo)

PROJECT: Behaviour of fibre composite walkways and gratings

AUTHOR: Allan Manalo

KEYWORDS: Civil engineering, fibre composites, walkways

ABSTRACT:

The Queensland Government has long been promoting the use of fibre composites in various industry sectors. In the introductory guide they released in 2009 entitled “Composites in Industrial Plants” (http://www.industry.qld.gov.au/documents/FibreComposites/Composites-in-Industrial-Plants-Introductory-Guide.pdf), they identified walkways and drainage grating as some of the many applications of fibre reinforced polymer (FRP) materials in the mining and minerals and chemical processing plants due to its highly corrosion resistance. Furthermore, this type of FRP structures also found many applications in marine and other highly corrosive environments. Similar to other FRP materials used in many engineering applications, the limited understanding on the overall behaviour and the lack of designers' experience place FRP materials at a disadvantage when considered against traditional construction materials. Thus, it is important to investigate the behaviour of these FRP systems in order to gain a detailed understanding of their structural performance. When this is achieved, essential technical information can be provided to Standards Australia to establish design standards for this type of construction and could expedite the implementation of FRP in civil, marine and mining infrastructure through a more functional and economical design.

In this study, the behaviour of FRP walkways and grating will be investigated. The test procedures for this type of structures are documented in AS1657-1992 but the performance requirements for a fibre composite walkway gratings are not available. In addition, the effect of different restraint/fasteners on the structural behaviour of the FRP walkway under point load test (corner and midspan) will be investigated.

Suitability: For On-Campus (and for External who are able to travel to CEEFC on a regular basis) students.

Appendix C – Project Specification

University Of Southern Queensland

ENG4111/4112 Research Project

Project Specification

For: Lachlan Keith Nicol

Topic: Behaviour of fibre composite walkways and grating

Supervisor: Allan Manalo

Sponsorship: - Buchanan's Advanced Composites

- Nepean Engineering & Innovation

Project Aim: The aim of this project is to analyse the behaviour of fibre composite grating under static loading in order to gain an understanding on how this type of grating performs structurally to help promote its use throughout the construction industry, primarily as a form of walkway.

Programme:

1. Complete an extensive literature review in regards to FRP grating as well as testing and analysis of materials.
2. Develop an in depth test schedule and programme for the testing procedures to fully establish the aims and objectives that are needing to be accomplished over the course of this research project.
3. Perform static load testing on a number of equal sized decking panels under line and point loading.
4. Analyse and compare results between testing to gain a better understanding of the different physical behaviours/properties of FRP grating.
5. Perform a Finite Element Analysis on the grating to help map out the stresses and strains associated with the separate loading cases.
6. Analyse the behaviour of different sized FRP grating to evaluate the possible changes in behaviours due to sizing variations.

7. Submit a final academic dissertation on the research and results from the entirety of this project.

If time permits:

8. Analyse the effect on the overall behaviour of the deck system due to changes of geometry i.e. change of thickness, depth, mesh sizing, or support conditions.