Design of Composite Stairs in UTP Academic Blocks

By
Mohd Azuan bin Mohd Azlan

Submitted to the Mechanical Engineering Programme
in Partial Fulfillment of the requirement
for the Degree
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
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January 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

(Mohd Azuan Bin Mohd Azlan)

ACKNOWLEDGEMENT

Praise to Allah S.W.T for the opportunity to successfully completed the thesis, with the given time and blessings in the way that everything were made at ease. Special mention needs to be made for individuals that made this thesis possible.

First, I would like to thank to Mr. Muhamad Ridzuan bin Abd. Latif of Mechanical Engineering department as supervisor for the project. Much of the work on this thesis was accomplished by the help from him.

Next appreciation to all technical personnel from Mechanical Department especially Mr. Anuar, Mr. Suria Adam, Mr. Zamil, Mr. Faisal and others from Meteorology Laboratory and Geotechnical Laboratory for their kindness and assistances in operating the equipments, for every lab work to be done.

Special thanks to my colleagues who are doing the related study over the course of my thesis work. All of the helping hands, contributions and efforts are greatly appreciated.

Thank you.

ABSTRACT

This report basically discusses the research done on the proposed topic, which is **Design of Composite Stairs in UTP Academic Block.** The objective of the project is to design and analyze the proposed composite stairs structure using glass fiber reinforced plastic, specifically glass fiber reinforced epoxy, GRE. LAP software will be platform for the first phase to determine the suitable thickness of the components under the maximum tensile and compressive loading situation, by the use of core (sandwich laminate) and without core (pure laminate). Next, fabrication process of the stairs components using the state of the art Vacuum Infusion Process (VIP) will be designed that suits the design shape. Specific tooling and equipments for the purpose are identified where the process route would be different between the sandwich laminate and pure laminate. Few procedures are created and investigated for the least cost and material used to produce the whole stairs. In the end, a sample will be produced and will be tested for flexural strength. The sample's actual thickness and flexural strength then will be used again for re-analysis in LAP to get the new laminate thickness and number of layers. The components' design likely to be nine rectangular tubular shape of specific dimension, assembled as stairs which has three steps. Final thickness value for sandwich laminate is 8.12 mm and for without the use of core, the value is 5.72 mm. Designed fabrication route starts with VIP, cutting process using diamond cutter machine and assembly by the means of epoxy adhesive.

Keywords: **composite stairs, glass fiber reinforced epoxy, vacuum infusion process.**

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATION

ABD	Mechanical response components in laminate
ASTM	American Society of Testing and Material
BS	British Standards
CLT	Classical Lamination Theory
IRC	International Residential Codes
GRE	Glass Fiber Reinforced Epoxy
GRP	Glass Fiber Reinforced Plastics
LAP©	Laminate Analysis Program©
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PU	Polyurethane
UTP	Universiti Teknologi Petronas
UTM	Universal Testing Machine
VIP	Vacuum Infusion Process

LIST OF NOMENCLATURE

A_{ij}	Extensional response
B_{ij}	Flexural response
D	Deflection at maximum load in load-deflection curve
D_{ij}	Extension-bending coupled response
E	Modulus of elasticity
E_{11}	Longitudinal modulus of elasticity
E_{22}	Transverse modulus of elasticity
E_B	Flexural modulus
F	Maximum load in load-deflection curve
G_{12}	Shear modulus
L	Length of flexural test specimen
M_i	Flexural stress resultants
P_1	Atmosphere pressure
P_2	Vacuum pressure
S_{11}	Longitudinal tensile strength
S_{12}	In-plane shear stress
S_{22}	Transverse tensile strength
V_i	Shear stress
a_i	Individual box component multiplier
b	width/breadth of flexural test specimen
d	thickness/depth of flexural test specimen
m_f	mass of fiber
m_m	mass of matrix
n	number of fiber layer
o	core application multiplier
t	laminate thickness
t_f	fiber thickness

x	Cartesian coordinate system component
y	Cartesian coordinate system component
ε	Strain
κ	laminate deflection or twisting or curvature
ρ	GRE’s density
ρ_m	matrix density
σ	Stress
σ_f	Flexural Strength
σ_u	Tensile Strength
υ	Poisson’s ratio

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Stairs is one of the most ancient and universal structure used to connect or to give an access from a path to another which are disconnected by difference in level. It helps much in reducing work or energy used during walking up and down instead of just climbing up or down to overcome high steepness between those levels.

1.2 Problem Statement

Pedestrians (lecturers, students and staffs) walking along the grass path in UTP Academic Blocks 17-19 face difficulty in climbing up and down the raised corridors of the building. A ramp is already available in each block which permits safe and convenient passage. But one has to turn around (much further distance to be crossed between blocks) from a ramp to the other block's ramps. Those who are in hurry have no choice but to hardly climb down and up the corridors which the height reaches more than half a meter. In term of ergonomics, the height is dangerous and could pose fall, fatigue and muscles related complication. For safety reasons, a flight of stairs need to be installed to avoid accidents and facilitate students and staff movement. Composite stairs can fit this purpose.

The proposed material for stairs construction is GRE composite which is used in several structural applications. The thickness of the composite structure is the main interest in this study as well as designing the fabrication route for the stairs manufacturing.


Figure 1.1: Block 17's raised level

1.3 Objectives and Scope of Project

The main objectives of this project are:

- To design a composite stairs that conforms to the established stairs standard, as well as to minimize the geometrical complexity of the design for the fabrication purpose.
- To analyze the thickness of the stairs which meets the requirement of loading condition using Laminate Analysis Programming (LAP) software.
- To design suitable vacuum resin infusion process route for the fabrication and manufacture of the stairs components.

The scope of work for this project is to design stairs using glass fiber reinforced plastic epoxy, GRE and the method of fabricating the material for all of the stairs' components. The finalized design will be modeled by LAP to be analyzed for the determination of thickness corresponds to the strength and stressed condition of the stairs. Suitable resin vacuum infusion process (VIP) procedures is to be studied for the most practicable fabrication method to produce all of the components. Later, the sample produced will be tested by standard flexural testing method. The actual laminar thickness and strength of the sample will be applied for re-analysis for the final design thickness of laminate.

1.4 Significance of Study

The main significance of the project is exploring the possibilities of fabricating consumers' products in daily life, anything from stairs, dust bin, car body kit to boat building. Also in engineering aspects, improvements of the method to fabricate the components by the least costs (in term of equipment) may be fulfilled.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

There are many standards established for stairs construction. Each local town or district council shall have its own standards and regulation in designing stairs. The well known referred standards are British Standard (BS), American Standards, International Residential Codes (IRC) and National Building Standards, UK. According to a research done by group of health and medical experts, falls occurs mostly at outdoor rather than indoor (Wenjun, et al, 2006). Mostly those falls are associated with the poorly designed ramp or stairs and also uneven floor or ground surface in a pathway. In the grass pathway between the UTP academic blocks, the rise of the corridors from the ground are about 540 to 550 mm in height. Therefore there is a need to design a safety stairs so that they can climb up and down between corridors and ground easily by using it.

2.2 Stairs Construction

Stairs are built of multiple steps which are arranged accordingly by specific horizontal and vertical separation which are called going and rise respectively. The steepness of a stairs is denoted by the pitch angle or simply the tangent of its total height to the total horizontal distance. As in Appendix A, the minimum going is supposed to be 220 mm while for rise, it should be at less than 250 mm (See **Figure A-1**).

2.3 Glass Fiber Reinforced Plastic Epoxy

Glass fiber reinforced plastic epoxy (GRE) is a composite material which falls under glass fiber reinforced plastic, GRP. This composite material uses glass fiber reinforcement and epoxy resins as the matrices and is often used in high performance structural applications.

2.3.1 Glass Fiber

The type of glass fiber that is going to be used in this project would likely be the S-Glass and E-glass which is higher in modulus of elasticity as compared to steel. The 'S' represents structural or high-strength glass and this type of fiber is much stronger than the steel where the tensile strength, σ_u of S-glass fiber, is about 3.5 to 4.6 GPa while for steel has only about 0.34 to 2.1 GPa (Potter, 1997). However, some E-glass fiber (σ_u from 1.5 to 3.0 GPa), is still better than steel and may be considered as it costs less than S-glass.

2.3.2 Epoxy Matrix

The matrix used is epoxy resins and is applied along with a hardener which is amine or anhydride. Low temperature epoxy itself has wide composition of resin and hardener to give different cured properties and also broad of processing conditions. As compared to polyesters resins, "epoxies usually are better in mechanical properties and performance at elevated temperature and lower degree of shrinkage" (Campbell, 2004).

2.4 Laminate Level

The GRE will be constructed either by layers of multidirectional laminate or plain woven laminate that will build up the thickness of the stairs parts. The multidirectional laminate is actually a "stacked of unidirectional plies" that is defined by ordered sequence of angles such 0/90 or +45/-45 (Bank, 2006).

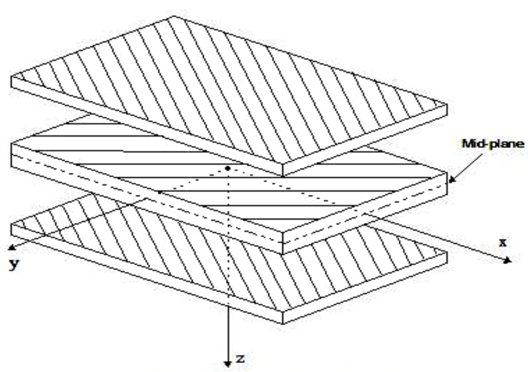


Fig 2.1: Exploded view of laminate (*courtesy of LAP©)*

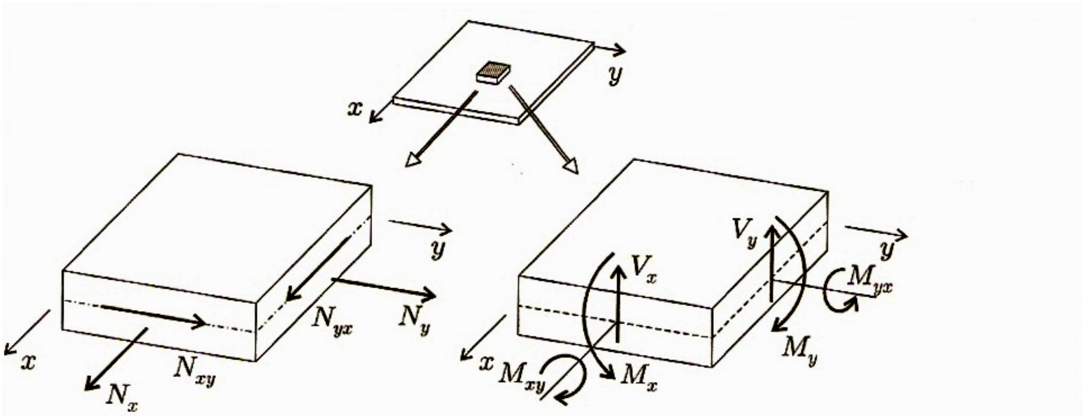


Fig 2.2: The in –plane forces and moments acting at the reference plane (*Courtesy of* he Barbera, 1998, *"Introduction to Composite Material Design",* Taylor and Francis)

Plain woven type of ply properties can be approximated by assuming it as multidirectional laminate and generally, Classical Lamination Theory, CLT will be used as analytical approximation to describe the constitutive relations of a thin laminate. The stiffness matrix ABD (Eq. 2.1) characterizes the thin laminates. Under this theory, the strains are approximately vary linearly across the laminate where as the shear deformations are negligible, and the normal stress, σ_z and shear stresses are small compared to the in-plane stresses.

$$\begin{Bmatrix} N_1 \\ N_2 \\ N_6 \\ M_1 \\ M_2 \\ M_6 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{61} & A_{62} & A_{66} & B_{61} & B_{62} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{21} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{61} & B_{62} & B_{66} & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1^0 \\ \varepsilon_2^0 \\ \varepsilon_6^0 \\ \kappa_1 \\ \kappa_2 \\ \kappa_6 \end{Bmatrix}$$

(Eq. 2.1)

Where; N_1, N_2, N_3 = stress resultants

M_1, M_2, M_3 = flexural stress resultants

A_{ij} = extensional response

B_{ij} = flexural response

D_{ij} = extension-bending coupled response

ε^o_i= in-plane strains, κ_i = twisting or curvatures

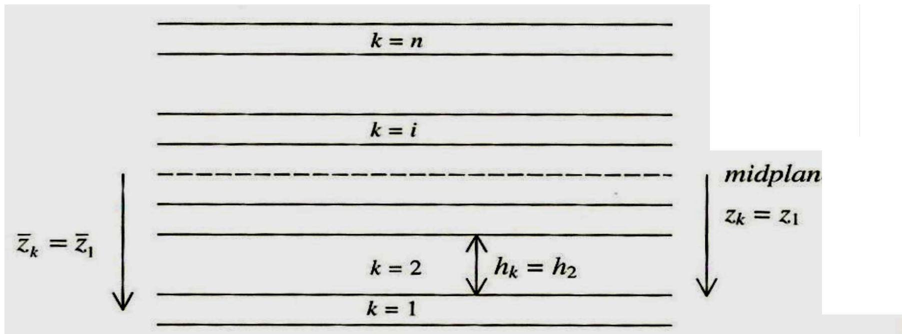


Figure 2.3: Laminate notation (*Courtesy of Barbera, 1998, "Introduction to Composite Material Design", Taylor and Francis)*

The type of laminate used is symmetrical with respect to the mid-plane as in figure above.

2.5 Core Application

Applying the core means that we will have the laminate as sandwich structures. Sandwich construction is used in the extreme engineering such as aerospace and commercial industries because of its super lightweight with high stiffness and strength-to-weight ratios. Basically, the principle of sandwich is not far from the I-beam concept, where the facesheets (equal of flange of I-beam) which is the laminate itself carries the bending load while the core carries the shear load (see **Fig. 2.4**). Commonly types of core used are metallic and non-metallic honeycomb, balsa wood and foams.

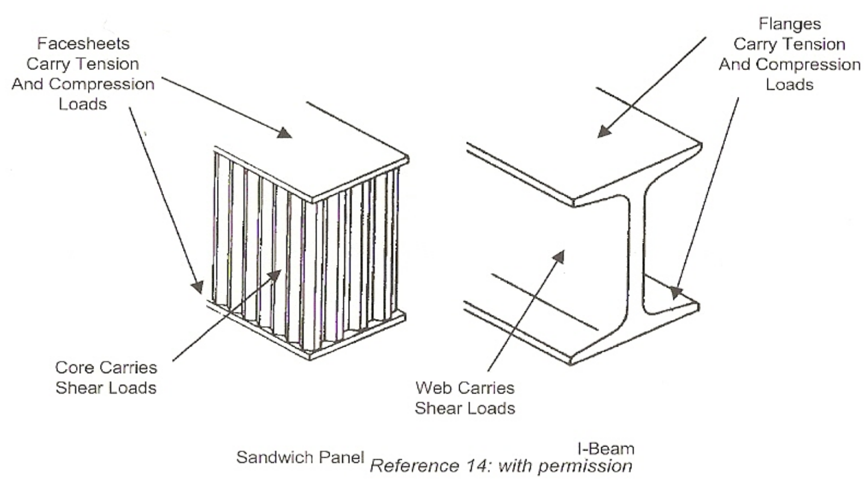


Figure 2.4: Sandwich Panel and I-Beam (*Courtesy of Campbell, 2004, Manufacturing Processes for Advanced Composites*)

2.6 Vacuum Infusion Process

The vacuum infusion process (VIP) is an alternative and way improved technique of applying resins into a laminate that uses vacuum as mean of the flow mechanism. Materials are placed in the mold and vacuum is applied by the use of a compressor. Right after the mold is totally vacuumed, resins will be sucked via a single or more inlet. One marvelous idea behind VIP is that the excess resins will be sucked out and only minimum of resins is introduced. The feature significantly produces one well-defined surface with no size limit, lowers weight, increases strength and optimizes the mechanical properties of fiber and resins [**5**].

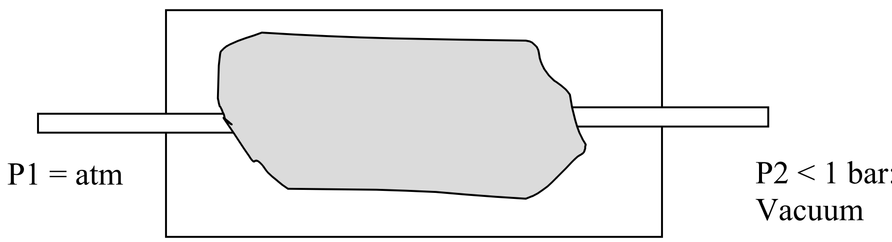


Figure 2.5: Principle of vacuum infusion, where the resin flows through mould cavity, impregnating dry reinforcement.

The process parameters are governed by Darcy's Law where it describes well the time needed to fill a product and shows its dependency on various process parameters (PIEP Composites).

$$\text{Fill time} = \frac{\text{Viscosity x Flowlength}^2}{\text{Permeability x Pressure difference}} \qquad \text{(Eq. 2.2)}$$

Few infusion strategies had been studied which shows that fill time of a same product can vary depending on the number and position of the resin feeding channels (see **Figure 2.6**).

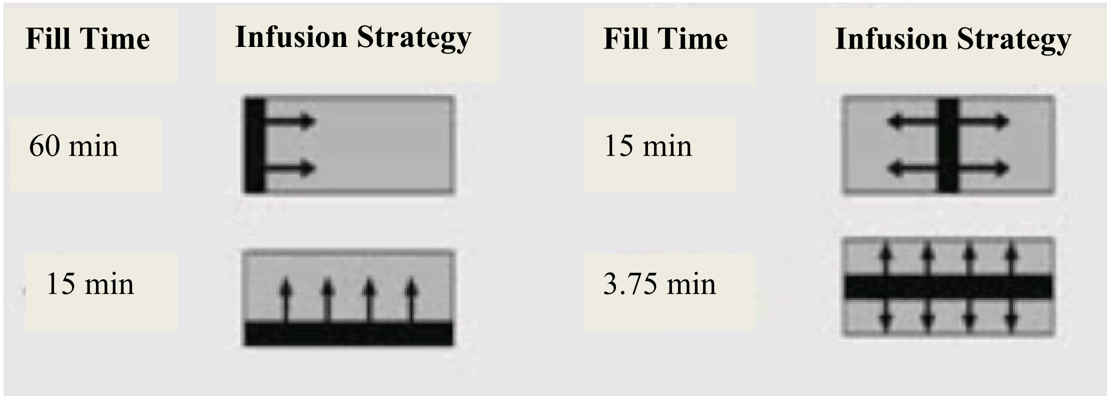


Figure 2.6: Infusion strategy (*Courtesy of PIEP Composites*)

However, this state-of-the-art technique has its drawbacks. Firstly, the set-up for infusing resin onto the glass fiber is very complicated and its degree of difficulty depends on the shape of the product. Secondly, it is very to ruin part of the product as one has started the infusion, less can be done to correct the errors without any defects. Lastly, based on the previous pitfalls, this technique can be considered as trial-and-error process.

CHAPTER 3
METHODOLOGY

3.1 Project Identification

This project is consists of activities which in the region of three major phase, namely stairs designing, analysis of the structure and designing the fabrication route by using resin infusion process.

3.1.1 Designing Stairs

The first phase would mostly deal with revision of established standards and codes, material selection based on its desired performance, designing few conceptual models and finalizing the design selection. Designs are generated simply by sketches or visualization through AutoCAD and then are compared. Also, the finalized design requires specific size and dimension for each component before proceeding to the next phase.

3.1.1.1 Design Specification

Below are the design specification and features that are desired from the safety stairs:-

1. The stairs design should comply with the local or any standards and regulation in terms of size and dimensions.
2. The structure should be able to hold maximum of distributed 150 kg load exerted at a time.
3. The steps surface should give enough grips to pedestrian's shoes steps and not slippery for any spill or watery condition.

4. The component of the stairs should be geometrically simple and avoids any complex shape for the ease of parts fabrication.
5. All of the components are totally made of the chosen composite material where no ‘alien’ joins are needed to the assembly.

3.1.1.2 Material Selection

There are wide ranges of GRE’s resins formulation which differs in its epoxy and hardener composition. The properties of the composite should be suitable to its service performance at outdoor environment where strength, stiffness and resistant to fatigue and corrosion will be accounted (Eckfold, 1994). The most less in cost is epoxy based resins that we are going to use in the project. Low temperature epoxy resins would be beneficial for the ease of curing. The same goes to the fiber glass where the chosen material would be the least cost which is plain woven E-glass fiber. By choosing plain woven which has two directions (transversal and longitudinal), the analysis in LAP will be simplify as the E_{11} and E_{22} will have the same value.

Below is the mechanical properties of balanced woven E-glass (Bunsell & Renard, 2005) where the data will be used in the LAP under assumptions that the material composite is non porous and the thickness of each laminar is consistent.

Furthermore, the core materials that are suitable are polyurethane (PU), polystyrene (PS) or wood which are readily available in stationery. These selections are relatively less in cost even if they are not as good as honeycomb core in term of strength. Despite all of that, those materials’ strength is considerable for the project (see **Table B-3**).

Table 3.1: Typical values of GRE for balanced woven E-glass

Fiber volume fraction (%)	45
Fiber Thickness, t_f (mm)	0.33
Fiber weight, m_f (g per mm^2)	3.754×10^{-4}
Density, ρ (kg/mm^3)	2.2×10^{-7}
Longitudinal modulus, E_1 (GPa)	33
Transverse Modulus, E_2 (GPa)	33
Shear Modulus, G_{12} (GPa)	5.9
Poisson's Ratio, υ_{12}	0.17
Longitudinal Tensile Strength, $S_{11}T$ (MPa)	360
Transverse Tensile Strength, $S_{22}T$ (MPa)	360
In-plane Shear Strength, S_{12}	92
Longitudinal Tensile Failure Strain (%)	2.78
Transverse Tensile Failure Strain (%)	0.25
Longitudinal Compressive Strength, (GPa)	0.55
Transverse Compressive Strength, (GPa)	0.55

The matrix that is going to be used is Prime™ 20 LV Epoxy Infusion System from Gurit. This type of epoxy has very low viscosity, variable infusion times, very low exoterm even in thick sections and suitable for very large structures.

Table 3.2: Properties of Matrix (Resin & Harderner used)

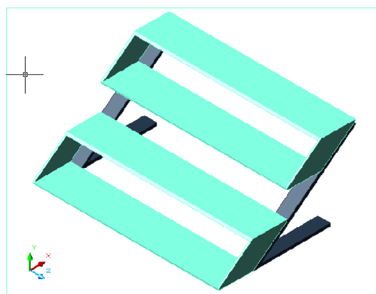
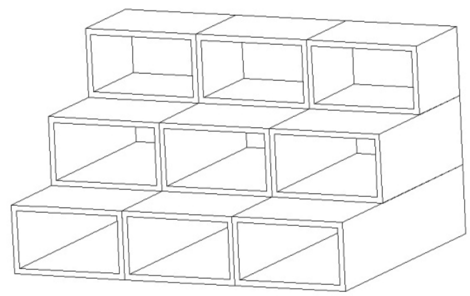
Matrix Volume fraction (%)	55
Density, ρ_m (g/cm^{-3})	1.084
Resin/Hardener Viscosity @ 30^o (cP)	1010-1070/12-14
Resin-to-hardener Mix Ratio (by Weight)	100 : 26
Hardener Type (Fast/Slow/Extra Slow)	Slow

3.1.1.3 Conceptual Design and Selection

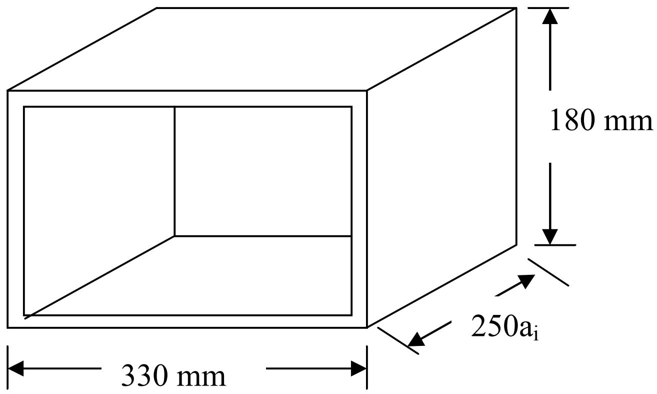
Conceptual designs were produced based on the design specifications and were generated using AutoCAD software. Only design that meets the most terms is chosen.

The designs, namely Design X and Z are compared as in below:-

Table 3.3: Comparison of Designs

	Design X		Design Z	
Diagram	 **Figure 3.1: Design X**		 **Figure 3.2: Design Z**	
No. of Components	4 (excluded of joints, etc)	5	9 (3 x 3 box) or 12 (4 x 3)	3
Components built-up	GRE – steps Steel - frame	3	GRE	5
Joining Method	Mechanical fastener (Screws, bolts and nuts)	2	Without or Composite adhesive	4
Fabrication method	VIP, steel machining, assembly	2	VIP, cutting, assembly	4

Design Z is the most suitable since all the box components can be fabricated through a single method and requires no major ‘alien’ structure material (no steel frames, etc).



Where;

i = 1,2,3

a_1 = 1 (upper level)

a_2 = 2 (middle)

a_3 = 3 (below)

Figure 3.3: Dimension of the proposed individual box components

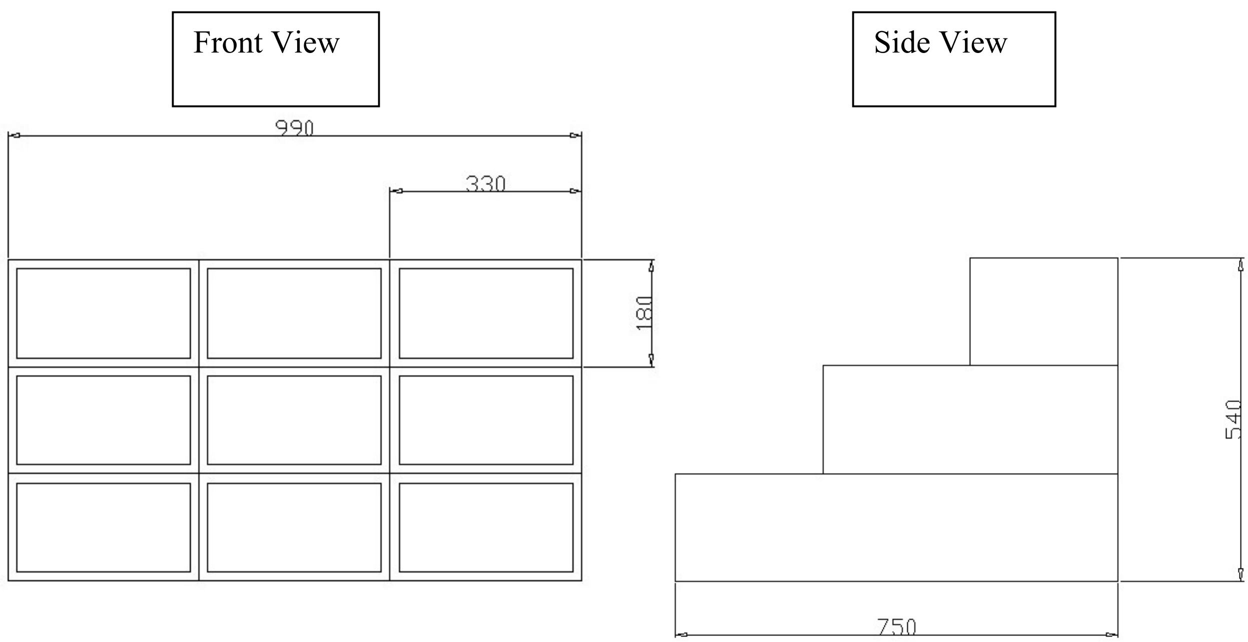


Figure 3.4: Stairs Dimension

3.1.2 Design and Structure Analysis

Next is to model and do virtual analysis on the selected design's performance under load for its strength, buckling, deformation, stress distribution and deflection correspond to the thickness of the stairs.

The previous phase is only producing basic dimensions of the components which are the going and rise. Thickness of the component, regardless the design selected, is to be determined and this is done by laminate analysis (see sect. 2.4). In the project, we are going to utilize the known mechanical properties of woven glass fiber as the reinforced material but its laminate properties are yet known. Hence, an approximation of CLT (see sect. 2.4) is applied to get the thickness of the parts as well as the mechanical properties (E, σ_u, v, etc).

Prior to the laminate analysis, the suitable symmetrical number of layers (see **Fig 2.1**) is to be investigated. This part is important to check whether the designed laminate sequence is free of extensional-bending coupling that can affect the response of thin laminates (Bank, 2006).

Laminate Analysis Program, LAP is used to simulate the multidirectional layers under loading. The number of layers is to be varied for different thickness of the components. Then minimum thickness that can withstand the maximum loading condition can be interpreted. From the safety factor, we can determine the design thickness for the structure.

3.1.2.1 Laminate Analysis

The analysis in LAP software will consider only 1) the loading on the center of individual box which cause deflection, and 2) loading on the vertical wall of the boxes where buckling takes place. These two points where people steps on them, are the most critical among other places. The other positions are not taken into account due since the loading related are distribution load and weight of upper level components.

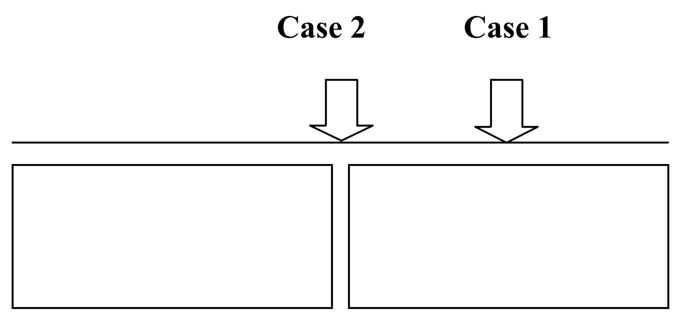


Figure 3.5: Loading position

3.1.3 Designing Fabrication Method

The last part should be studying and designing suitable and the most effective fabrication route using the VIP method and verify its practicability. The routes are depends on the decisions to use or not to use core for the structure.

3.1.3.1 VIP Tooling, Equipment and Procedure

This infusion process requires few tools, equipment and non-identical options and arrangement of those things. Below is the general configuration of the VIP set-up. However, the actual configuration depends on the project complexity.

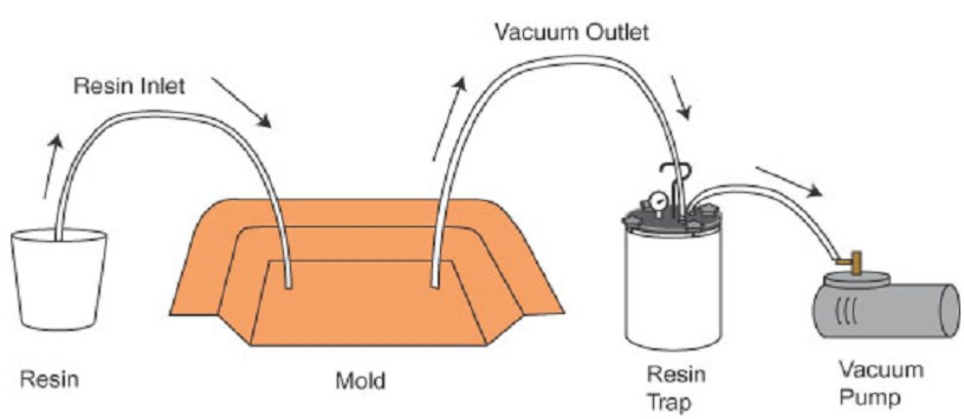


Figure 3.6: General VIP Set-up [5]

The mold is actually made of several parts and usually the resin is infused into a center point in the laminate (see **Fig. 3.7**).

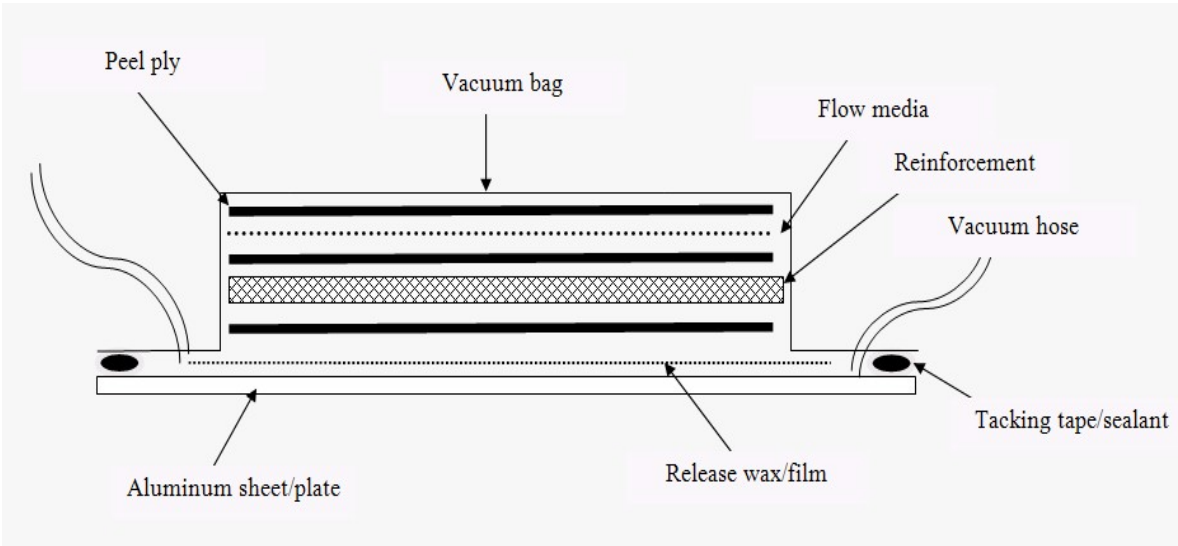


Figure 3.7: Mold Arrangement

Basically, general procedure of using this technique is as following:-

1. Preparing the mold, reinforcement, flow media and core, if any

   The mold should have an inlet and outlet for the resin infusion. It is made of (see **Figure 3.7**):-

   i) Aluminum plate.
   ii) Tacking tape as sealant.
   iii) Reinforcement/ glass fiber sheet, plus core if any, of desired dimension.
   iv) Flow media which allow the resin to flow through the whole reinforcement.
   v) PTFE coated peel ply to prevent flow media and vacuum bag from stick to end product.
   vi) Nylon vacuum bag.

2. Resin and vacuum lines selection

   In VIP, the resin will be sourced from a bucket through a nylon tubing/ hose to the mold. The vacuum line is spiral tubing inside the mold in which it will be the first place where the matrix touches the reinforcement.

3. Vacuum bag building (as in **Figure 3.7)**

4. Vacuum pumping

   Basically a higher capacity pump will gives better infusion time. One important thing is to have a resin trap that is connected between mold outlet and pump. It avoids the resin from getting through and damages the pump.

5. Infusion preparation, resin selection and resin bucket set-up

6. Infusing resin.

7. Oven curing after infuse.

8. Experimenting and testing for improvement.

These steps are acceptable for the two designed fabrication route, each for sandwich laminate and pure laminate. As stated previously, the VIP is unique to for every project. Even in our case, for the same end product author had come out with two different routes proposed.

3.1.3.2 VIP Route for Laminated Core

In this case the infusion is done as a long laminate with the desired thickness and width of the product. The long sheet then is cut into segments of specific lengths. Lastly the components are assembled all together by using adhesive to produce the box-like structure of the stairs. The idea is depicted in the figure below.

Note that the total length of the laminate should consider the cuter width of cut (2 mm). Also, there will be two laminate of 990 mm x 660 mm x t mm (refer Appendix **C-2**).

The use of core is basically to prevent or lessen the effect of moment or bending of the laminate thus the number of layers can be minimized. From this, the infusion process complexity can be improved where we have already a structured core to be layered without having to build a mould.

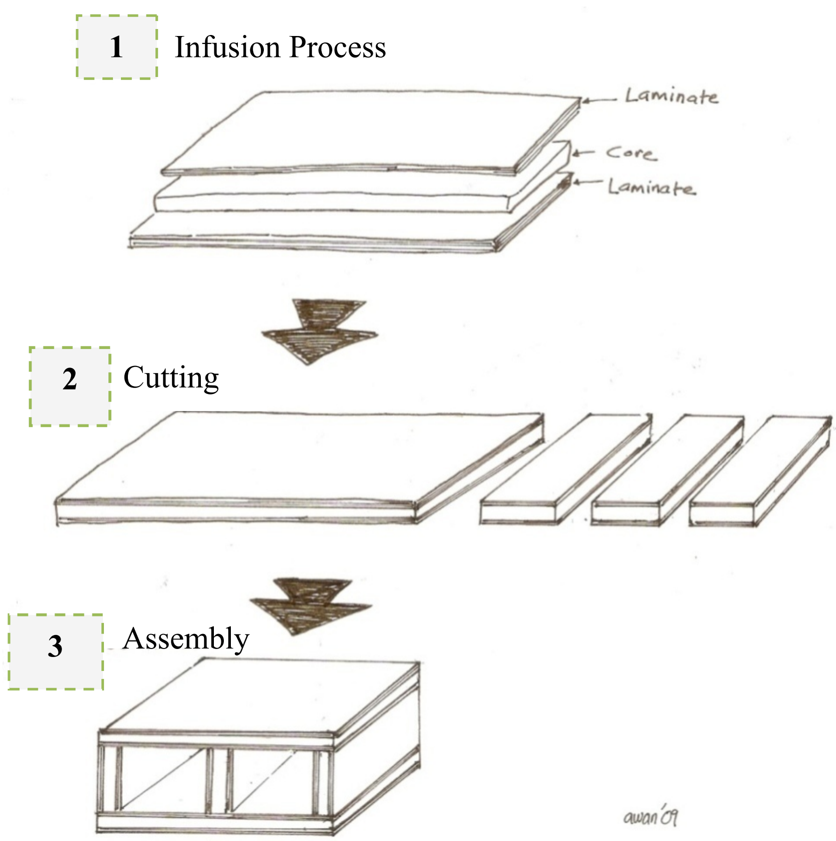


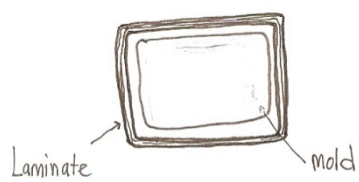
Figure 3.8: Proposed Fabrication Route for Sandwich Laminate (laminated core)

3.1.3.3 VIP Route without Core

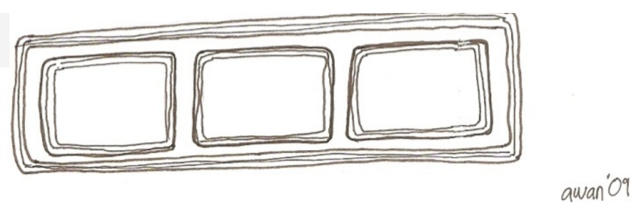
Infusing laminate without core (pure laminate) is much easier but one need to use internal mold so that the laminate can hold as a box shape. Individual boxes are infused by the use of the mold. Then the boxes are arranged and infused as a whole. This step is repeated for other two stairs level with different length. In the end, the levels are infused altogether to get the desired thickness as in figure below.

Also, the pure laminate can be produced using the same technique for laminated core.

1 Infusion Process



2 Infuse three components all together to produced one level



3 Infuse all three levels

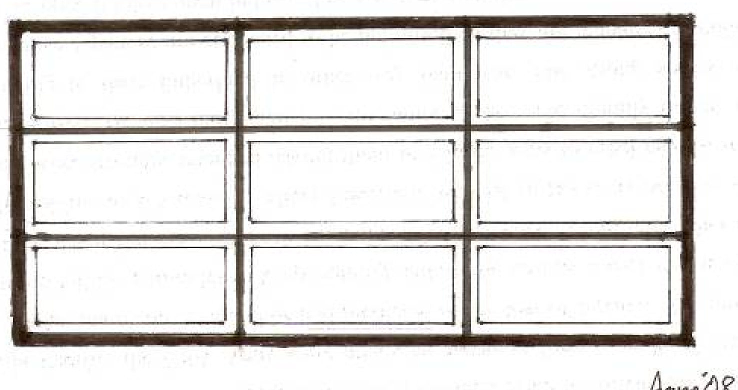


Figure 3.9: Proposed Fabrication Route without Core

3.1.4 Fabrication of Sample and Analysis Verification

After all the consumables and suitable equipments are gathered, the next phase is to fabricate a sample using the VIP. The sample then is to be tested by standard flexural testing (ASTM 790: Standard Test and Methods for Flexural Properties of Unreinforced and Reinforced Plastics).

The sample is cut by using diamond cutter machine into numbers of rectangular specimens with dimension of 80 mm x 10 mm (L x b).

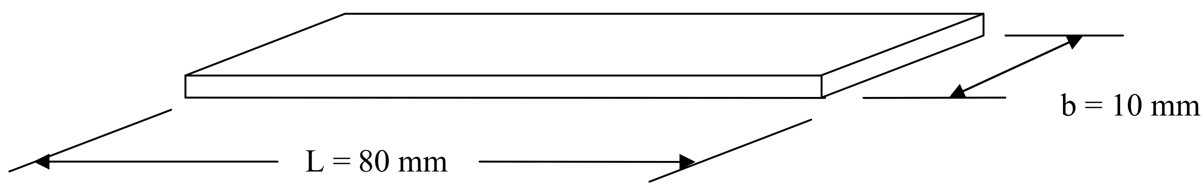


Figure 3.10: Specimen Dimension

The flexural test configuration of specimens is as below:-

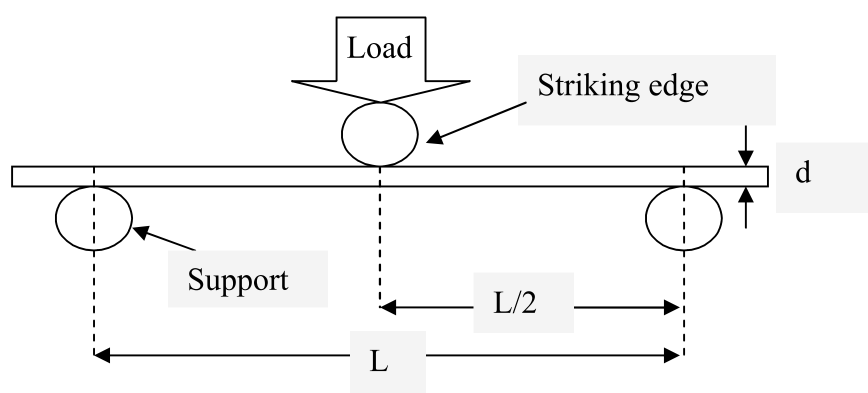


Figure 3.11: Flexural Testing Configuration

Length of span, L will be based on the 16: 1 span-to-depth (L: d) ratio. Thickness or depth, d is to be measured out of the sample produced. The maximum stress or flexural strength, σ_f for each specimen is calculated as:-

$$\sigma_f = 3 F L / (2 b d^2) \qquad [\text{MPa}] \qquad (\text{Eqn. } 3.1)$$

Where; F = maximum load at load-deflection curve (N)

And the flexural modulus is, E_B :-

$$E_B = F L^3 / (4 b d^3 D) \qquad [\text{GPa}] \qquad (\text{Eqn.} 3.2)$$

Where; D = Deflection at maximum load (mm)

The flexural modulus is usually the initial modulus from the stress–strain curves in tension. The test's results will be compared to the theoretical values of laminar thickness and the composite's mechanical properties such as flexural strength and elasticity modulus. Then the values are to be used again in the LAP for a new laminate design thickness.

3.2 Flow of Project

A project work flow is constructed based on the discussed methodology starting from the research study till the final thickness determination.

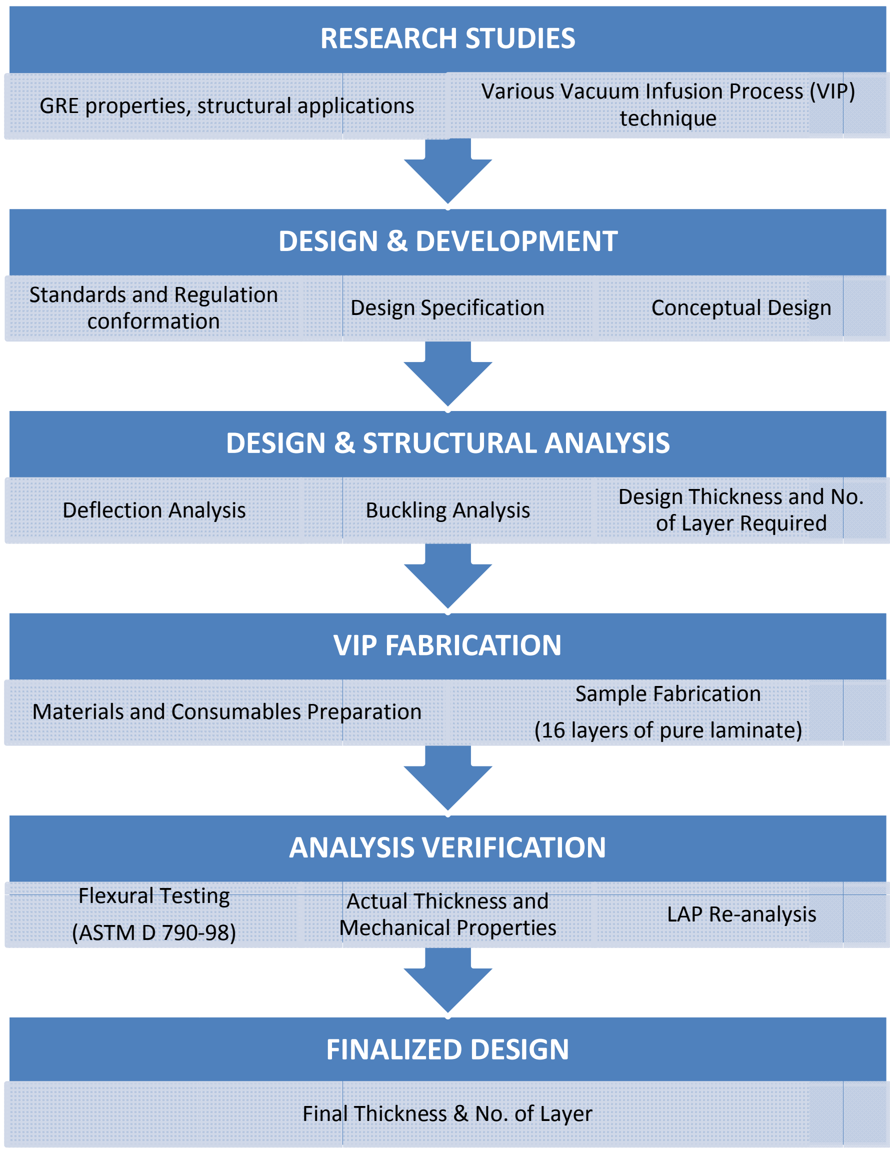


Figure 3.12: Process Flow of the Project

3.3 Project's Milestone

Detailed project progression and time allocation for each work is described in the Gantt chart below.

Table 3.4: Project Work Timeline/ Gantt Chart

MOHD AZUAN BIN MOHD AZLAN M8249 DESIGN OF COMPOSITE STAIRS IN UTP ACADEMIC BLOCKS SUGGESTED MILESTONE FOR THE SECOND SEMESTER (FYP II)																
No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Design of Fabrication Route • Core material's properties and features • Fabrication GRE using VIP															
3	Sampling • Equipment and Consumables Gathering • Material (fiber and resin) and Mold Preparation • Fabrication Process of Sample (Infuse and Curing) • Sampling cutting															
4	Verification of Analysis • Flexural Testing • Result Interpretation • Re-Analysis in LAP															

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Design Analysis

Up until now, the project has reached the design analysis to determine the suitable laminate thickness. The two under loading condition (**Sect. 3.1.2**) analyses will be taken with and without the use of core.

Another thing is the load is only assumed to be only in one direction which is only the weight of stairs users at a time, as stated by the design specifications. This comes with a deflection effect which is denoted by the moment, M_x and buckling effect on the vertical component of stairs. The mean value of each laminar is about 0.33 mm and the proposed core thickness is 10 mm. Safety factor of 3 is used for the analysis.

The thicknesses, t of the laminate for with and without the use of core are as below:

$$t = 0.33n + 5o \qquad \text{[mm]}$$

(Eq.4.1)

Where; n = number of layer

o = 1 for core, 0 if no core is used.

For deflection analysis, the horizontal surface of the stairs is modeled as thin plate with only moment per unit length in x-axis, M_x of 1500 N is acting on it. The deflection (κ_{xx} x 330 mm where width of the each individual box is 330 mm) should be never exceeding 1 mm. In case of compressive analysis, the vertical loading is modeled as in-plane compression stress acting on two ends the wall component as in Figure 3.6. The value of load exerted is 1500 N.

4.1.1 Laminated Core Analysis

As we can see, by the use of core, the number of layers can be reduced for the eased of infusion fabrication process. Laminate fails at thickness of 4.46 mm and below with 12 layers for deflection analysis. While for compressive analysis, the laminate fails for 8 layers and below.

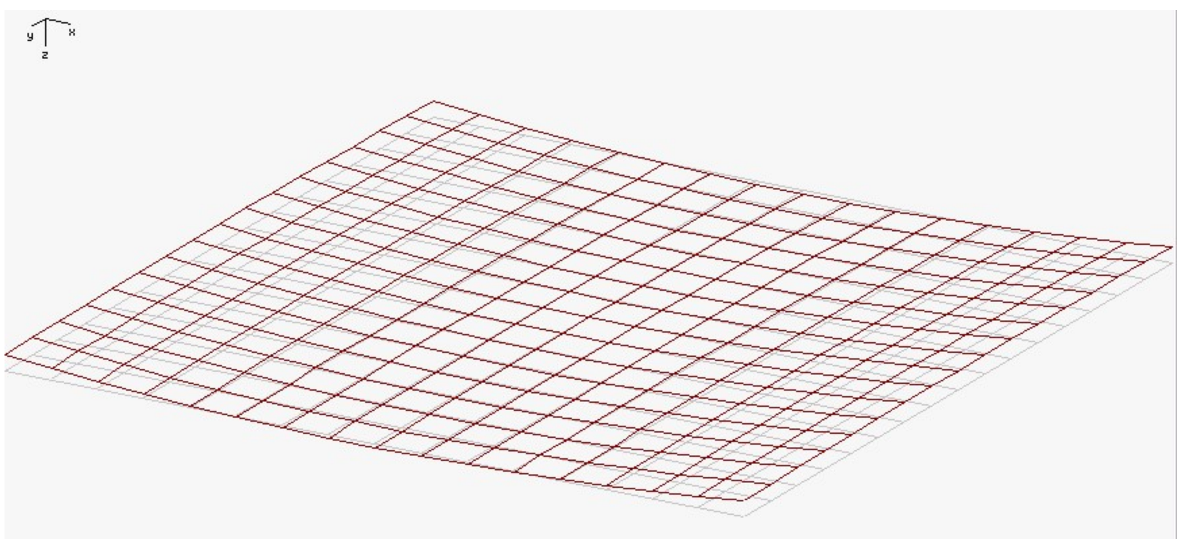


Figure 4.1: Graphical representation of deformed shape of laminate (Deflection)

Table 4.1: Results from LAP analysis for flexural deflection (laminated core)

No. of layer	2	4	6	8	10	12	14	16	18	20
Thickness, t (mm)	5.56	6.32	6.98	7.64	8.3	8.96	9.62	10.28	10.94	11.6
Deflection, κ_{xx} (1/mm)	0.00968	0.00428	0.00254	0.00170	0.000122	0.000918	0.000713	0.000567	0.000461	0.00038
Max Stress, S_{xx} (N/mm^2)	904.39	446.33	292.09	214.24	167.19	135.68	113.14	96.24	73.10	72.07
Max Strain, ε (%)	2.7410	1.3530	0.8850	0.6490	0.5070	0.4100	0.3430	0.2920	0.2520	0.2200
Remarks	FAIL	FAIL	OK	OK	OK	OK	OK	OK	OK	OK
k_{xx} x 330 mm	3.1957	1.4124	0.8369	0.5608	0.0403	0.3029	0.2352	0.1872	0.1520	0.1254

Table 4.2: Results from LAP analysis for buckling in vertical wall component (laminated core)

No. of Layer	2	4	6	8	10	12	14	16	18	20
Thickness, t (mm)	5.56	6.32	6.98	7.64	8.3	8.96	9.62	10.28	10.94	11.6
Maximum Compressive Stress, σ (N/mm^2)	2272.18	1136.23	757.51	568.15	454.52	378.77	324.66	284.52	252.52	227.27
Maximum Compressive Strain, ε (%)	1.171	3.443	2.296	1.722	1.377	1.148	0.984	0.861	0.765	0.689
Remarks	FAIL	FAIL	FAIL	FAIL	OK	OK	OK	OK	OK	OK

4.1.2 Pure Laminate Analysis

Below are the tabulated results of analysis on the pure laminate. The laminate fails at below than 16 layers. The system should have at least 18 layers of laminar with thickness of 5.94 mm with the allowable structure's deflection of 0.8587 mm which is below than maximum of 1 mm.

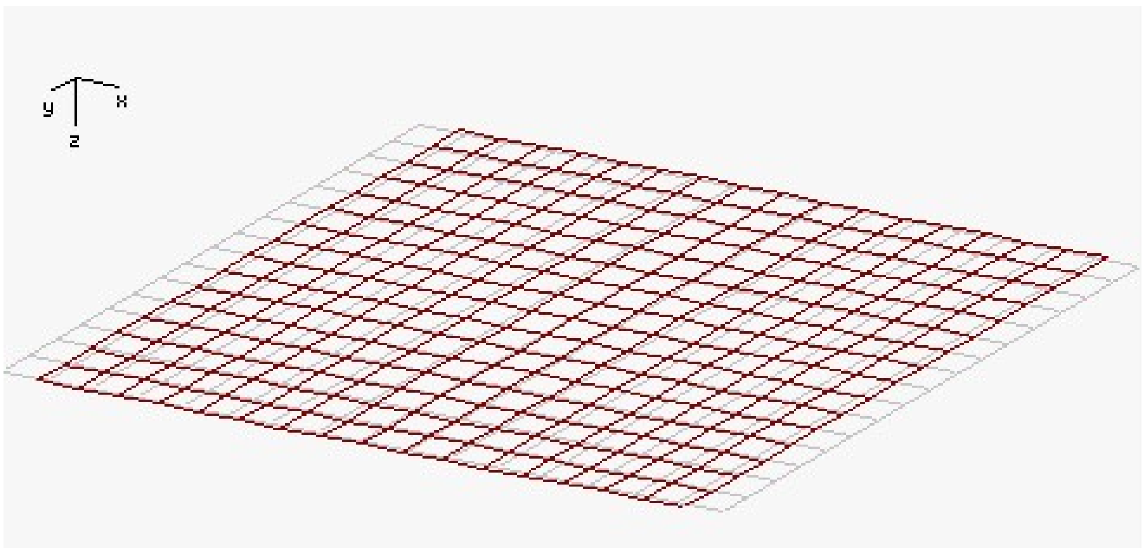


Figure 4.2: Graphical representation of deformed shape of laminate (Buckling)

Table 4.3: Results from LAP analysis for flexural deflection (pure laminate)

No. of Layer	2	4	6	8	10	12	14	16	18	20
Thickness, t (mm)	0.66	1.32	1.98	2.64	3.3	3.96	4.62	5.28	5.94	6.6
Deflection, κ_{xx} (1/mm)	1.8973	0.2372	0.07027	0.02964	0.0151	0.008784	0.005531	0.003706	0.002602	0.001897
Max Stress, S_{xx} (N/mm^2)	20661	5165.3	2295	1291.3	826.45	573.92	421.66	322.83	255.08	206.61
Max Strain, ε (%)	62.5	15.7143	1.182	0.6691	0.4286	1.7308	1.2778	1	0.7857	0.625
Remarks	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	OK	OK	OK
k_{xx} x 330mm	626.109	78.2628	23.1884	9.7829	5.0087	2.8986	1.8254	1.2228	0.8587	0.6261

Table 4.4: Results from LAP analysis for buckling in vertical wall component (pure laminate)

No. of Layer	2	4	6	8	10	12	14	16	18	20
Thickness, t (mm)	0.66	1.32	1.98	2.64	3.3	3.96	4.62	5.28	5.94	6.6
Max Compressive Stress, σ (N/mm^2)	2272.70	1136.40	757.58	568.18	454.55	378.79	324.79	284.09	252.53	227.27
Max Compressive Strain, ε (%)	6.8871	3.4435	7.2957	1.7218	1.3774	1.1478	0.9839	0.6088	0.7652	0.6887
Remarks	FAIL	FAIL	FAIL	FAIL	OK	OK	OK	OK	OK	OK

Table 4.4: Minimum No. of Layers and Minimum Thickness for Deflection and Buckling Analyses

Analysis	Deflection			Buckling		
Minimum	No. of Layers	Thickness, t (mm)	Deflection, κ_{xx} (mm)	No. of Layers	Thickness, t (mm)	Compressive Strain (%)
Laminated Core	6	6.98	0.8369	10	8.3	1.3770
Pure Laminate	18	5.94	0.8587	10	3.3	1.3774

Now we are to compare findings between the two analyses. From the table, for buckling analysis, both laminate with and without core give values that are not much difference and fail below 10 layers with thickness of 8.3 mm and 3.3 mm respectively.

For pure laminate, the flexure effect is much severe. Thus the minimum layer is 18 with thickness of 5.94 mm with deflection of 0.8587 mm (less than 1 mm). Minimum number of layers for laminated core is 10 which corresponds to laminar thickness of 8.3 mm with respected to 0.0403 mm deflection.

4.2 Fabrication Route Design

Since we have already the suitable thickness for both cases, next thing to do is to evaluate the proposed fabrication routes. Eliminating core would reduce the complexity of the fabricating the parts but increase the numbers of laminate layers which means more resin and glass fiber will be used and may costs more. The first technique might saves raw materials but to find or cut the core to be as the preferred thickness is another thing to ponder. Availability of a very accurate and precise cutting machine or tools is to be verified, so that the cutting process does not affects or causing any defects onto the laminate, at the cutting area especially.

It is decided to produce a sample of pure laminate using the first technique as in **Section 3.1.3.2**.

The activities done during the process, apart from Section 3.1.3.1, are mold and VIP equipment setup, resin preparation, infusion process, curing and cutting. The sample is produced as a 16 layers laminate and sized by 400 mm x 100 mm.

4.2.1 Mold and Equipment Setup

Figure 4.3: VIP Mold and Equipment Setup

4.2.2 Resin Preparation

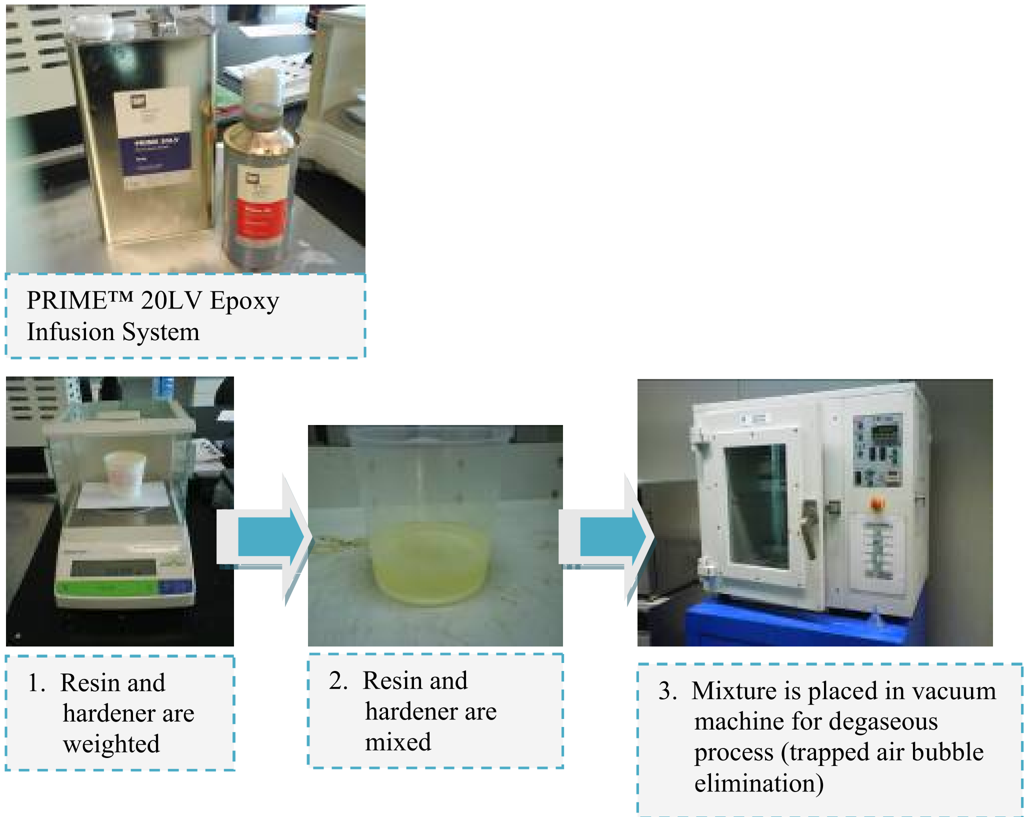


Figure 4.4: Matrix preparation

The degaseous procedure is done for 20 minutes. The vacuum chamber is supposed to reach vacuum (0 bar) along the degaseous procedure, but in this case the minimum it can reach is 115 bar. Micron scale of air bubbles might still be trapped in the mixture. These air bubbles are the main contributor for the laminate porous or void defects later on.

4.2.3 Infusion Process

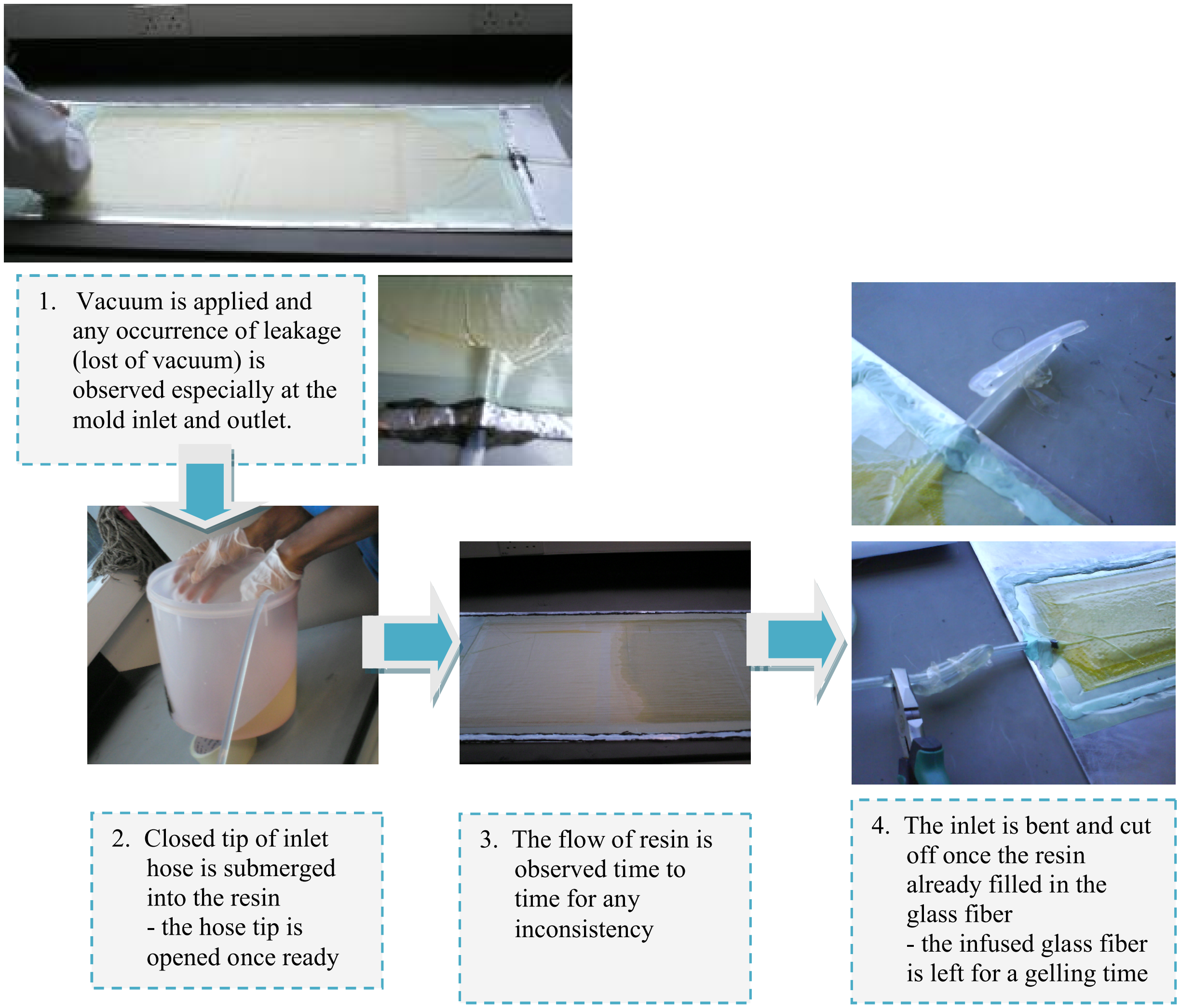


Figure 4.5: Infusion Process

Problems occurred during the process are loss of vacuum and air is sucked in accidentally. Vacuum loss is due leakage between the vacuum line and the equipment fittings, especially at the mold inlet and outlet where a whistling sound can be heard when they are not sealed well. The effect is the flow will not be smooth and in worst case, it will not directing towards the outlet vacuum line. Thus the resin would clog along the net and might affect the desired thickness of the laminate. Type of sealant tape chosen is crucial for making the perfect mold.

Air is introduced along the vacuum line by leakage, through the inlet hose tip and trapped air bubbles in the mixture. Improper bucket setup for positioning the inlet hose might cause it to be misplaced where the tip would be pointing above the resin surface and air will get in. One has to ensure the tip is always well submerged in the resin mixture. Trapped air is caused by inappropriate degaseous procedure or the degaseous mixture is not infused as soon as it is taken out of the vacuum chamber, probably due to the faraway location of the VIP setup.

4.2.4 Curing

After few hours of gel time, the composite (without the mold being tear-off) is cured in the oven for seven hours at 65^{o} C. Once cured, the composite plate is left for a while to cool down and its thickness is measured.

Prior to the composite to be cured, the oven is ensured to be already heated to the specific temperature prior to the curing of composite. This is because of the temperature will rise higher than the temperature set for a few minutes until it 'settled down'.

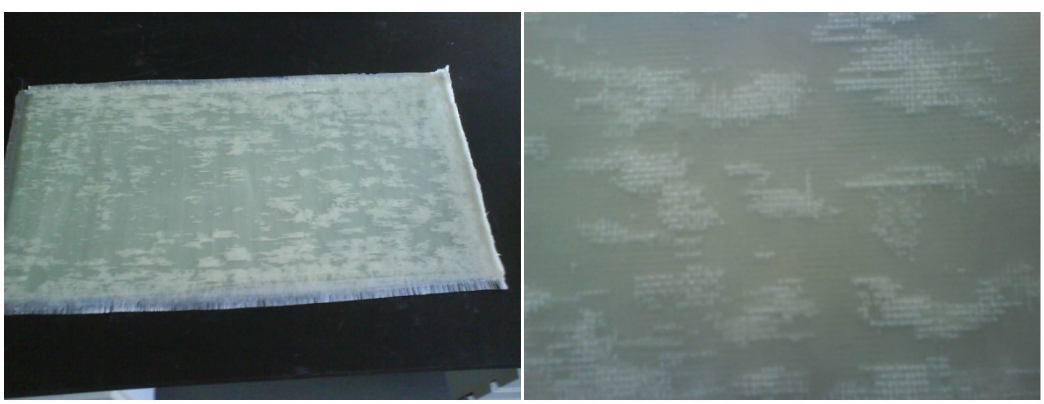


Figure 4.6: Laminate Sample Produced

The product has many voids especially towards the edge of the plate. Voids will affect the flexural testing results and the data might not be as accurate as possible.

4.2.5 Cutting Process

The 400 m x 100 mm sample is cut into few specimens by using Diamond Cutter Machine.

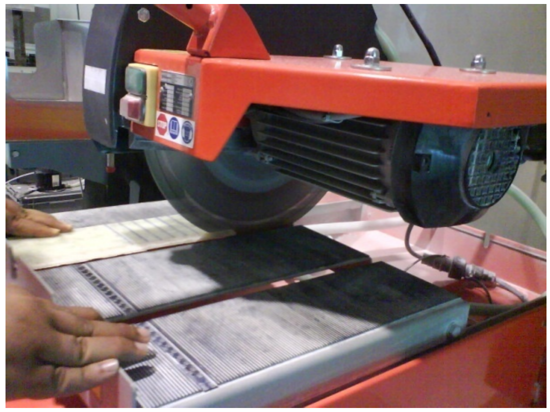


Figure 4.7: Diamond Cutter Machine

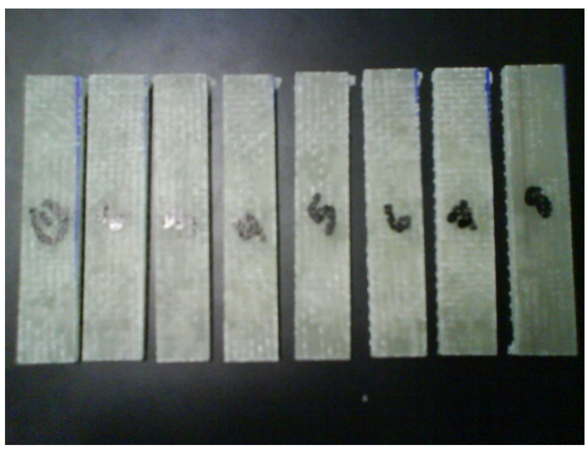


Figure 4.8: Specimen cut for testing.

The surface finish of the cut area is quite good in just one cut but the width of cut is not steady. This is shown by the variation of the entire seven specimen's width. Highly trained personnel should be appointed in executing the process.

Since the cut surface is smooth, no additional works needed to grind or smoothing it. Thus the epoxy based adhesive is applicable for the components joining method.

4.3 Analysis Verification

This phase is to verify the analysis value of laminar thickness and mechanical properties such as elasticity modulus and strength from the LAP.

4.3.1 Flexural Testing

Seven 80 mm x 9.42 mm laminated specimens are tested using Universal Testing Machine, UTM for flexural test to verify the analytical simulation results in term of thickness and strength. Since the mean thickness of the specimens is 3.84 mm, according to the 16: 1 span-to-depth ratio, the span length, L is round off to 60 mm. The summarized result for the whole test is in **Table 4.5**:-

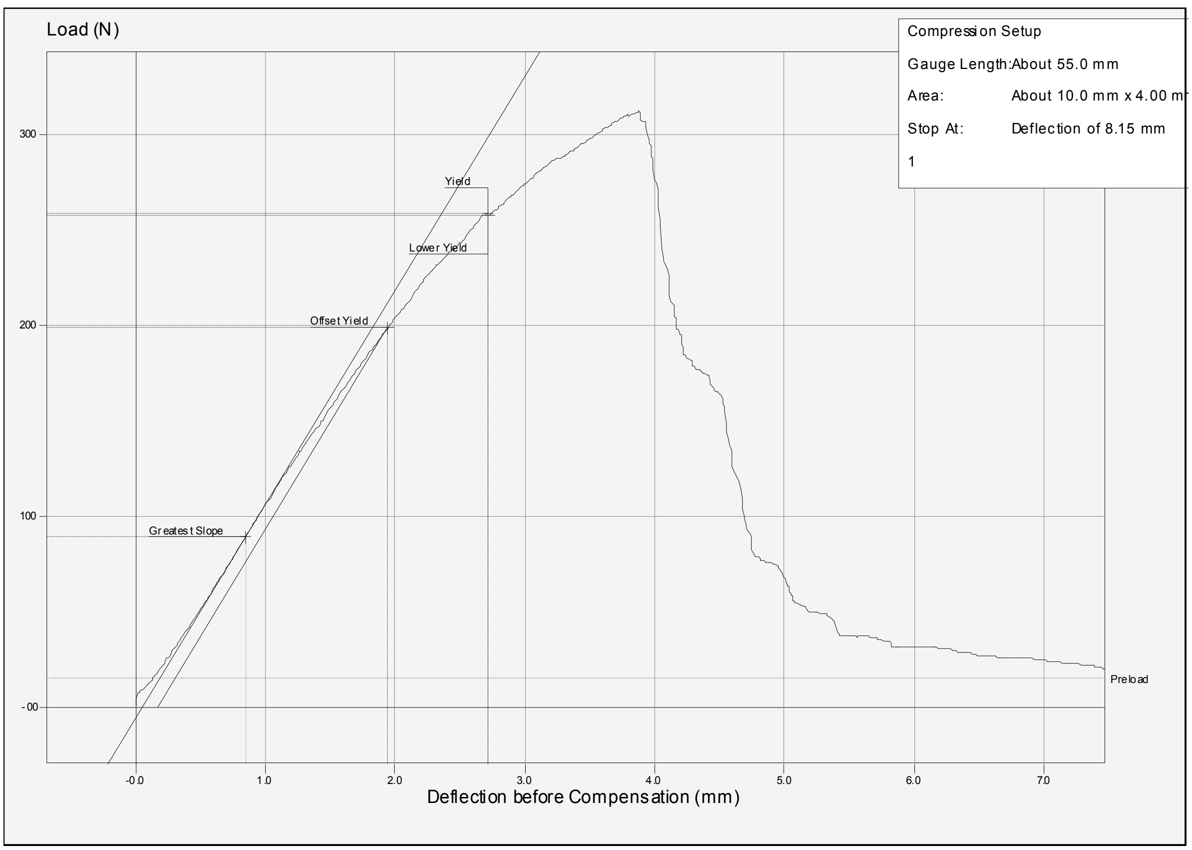


Figure 4.9: Load-deflection curve generated for Specimen 4

Table 4.6: Result of Flexural Test on 7 Specimens

Specimen	Depth (mm)	Breadth (mm)	Span (mm)	Maximum Load (N)	Deflection at Maximum Load (mm)	Flexural Strength (MPa)	Maximum Load at yield (N)	Deflection at Yield (mm)	Flexural Modulus (GPa)	Flexural Strain
1	3.78	9.92	60	295.3601	3.7123	187.54	294.2051	3.4208	8.6682	0.02339
2	3.88	9.96	60	339.4015	3.5454	203.72	220.0985	1.8556	11.0097	0.02293
3	3.89	9.68	60	311.9827	3.7451	191.69	258.3808	2.5864	9.4675	0.02428
4	3.74	10.04	60	271.1093	2.9243	173.74	257.8469	2.6313	10.0749	0.01823
5	3.90	9.42	60	326.1534	3.8198	204.87	326.1534	3.8198	8.2513	0.02483
6	3.94	9.46	60	281.5992	3.0365	172.58	281.5992	3.0365	8.6550	0.01994
7	3.76	9.82	60	336.6046	4.1702	218.21	287.8239	2.8287	10.5260	0.02613
Mean Value	**3.84**	**9.76**			**3.56**	**193.19**			**9.5218**	**0.02282**

4.3.2 Actual Results versus LAP Data

The inserted mechanical properties of GRE differ from the actual product's tested values. In the study, we are only considering for two values of elasticity modulus and strength. Also the actual laminate thickness is 3.84 mm for 16 layers which means for a layer the thickness is 0.24 mm. The value varies the common used value for LAP which is 0.33 mm, by 0.09 mm. All of these differences in value are summarized in **Table 4.6** below:-

Table 4.7: Comparison of LAP Properties Values and Experimental Values

	LAP Value	Flexural Value	Variation (%)
Total Thickness for 16 layers (mm)	5.28	3.84	27.27
Laminar Thickness (mm)	0.33	0.26	21.21
Longitudinal Modulus, E_1 (GPa)	33	9.52	71.15
Transverse Modulus, E_2 (GPa)	33	9.52	71.15
Longitudinal Tensile Strength, S_{11} (MPa)	360	193	46.39
Tranverse Tensile Strength, S_{22} (MPa)	360	9.52	46.39

Although the flexural properties do not represent exactly the composite's strength and modulus of elastic, the flexural results values should be around those properties. We can say that the flexural results as benchmarking on verifying the GRE prior to further testing such as tensile testing and compressive testing, which are not covered in this thesis.

The variations of the actual value for the fabricated laminate are likely because of the void defects. With this condition, only laminar or layer thickness is considered.

4.3.3 Reanalyze Results

Deflection and buckling analysis are redone in LAP with a new value of laminar thickness from previous section. Below is the summarized result:-

Table 4.8: Result of re-analysis in LAP

Analysis	Deflection			Buckling		
Minimum	**No. of Layers**	**Thickness, t (mm)**	**Deflection, κ_{xx} (mm)**	**No. of Layers**	**Thickness, t (mm)**	**Compressive Strain (%)**
Laminated Core	8	7.60	0.7830	12	8.12	1.457
Pure Laminate	22	5.72	0.9520	12	3.12	1.457

Since the thickness value is reduced from 0.33 mm to 0.26 mm, for sure the minimum number of layers would be increased. As for laminated core, number of layers needed hikes to 12, an increase of two layers from the previous analysis. Minimum 22 layers are required for pure laminate with thickness of 5.72 mm.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Conclusions

Box-like Design Z is chosen as the stairs structure since its geometrical shape is useful for the simplification on VIP fabrication technique**.** The specifications are possible can be achieved by the VIP. Its dimension complies with the design standards referred.

The preferred thickness of the components by the use of core is 8.12 mm with maximum 0.783 mm of deflection. For pure laminate, the minimum thickness is 5.72 mm with maximum deflection of 0.952 mm. The maximum bending stress is proportional to the thickness of the laminate up to certain value. After that point, increasing thickness or number of layers has no significant implication to reduce the maximum stress and considered as waste.

The proposed design in **Section 3.1.3.2** is suitable for the composite stairs, both laminated core and no core. It consists of three main processes which are VIP procedure, cutting of the laminate to specific components dimensions and joining method by the use of epoxy adhesive.

5.2 Recommendations and Suggestions of Future Works

The analysis in LAP should be simulated with accurate data like mechanical properties of the actual E-Glass fiber and resin used in the lab. This can be achieved by conduct several test to examine the actual mechanical properties prior to be used for the VIP.

The flexural testing should not be the only testing done. Other test such as tensile testing is more promising in determining the actual mechanical properties of the fabricated laminate. It is just that the specimen must be shaped into the dog bone plate which requires more sophisticated fabrication or cutting process.

This VIP process can be executed at higher successful rate by utilizing the best and the right tools and equipment. For example, a vacuum motor with much higher capacity is required to ensure the best resin impregnation quality. Furthermore, the problem of mold sealing can be eliminated by exploring new and better techniques of fittings between vacuum lines and mold or resin trap.

The consumables cost can be reduced by looking for suitable alternate items which are readily available in local market.

Extensive research can be done on infusing resin the more complex mold i.e. in this project, to infuse the whole stairs structure in one piece. The idea is to have numbers of directed vacuum lines inside the mold; in addition of the appropriate numbers and positions of the mold inlet and outlet.

More analysis could be carried out such as stress analysis at the adhesive joint area to investigate whether it is reliable to withstand the load applications since this study is assuming the structure as homogeneous (built as single structure).

Further information and data of epoxy adhesive properties should be gathered to get the finest and cheapest type that fit for our purpose.

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APPENDIX A

STAIRS CONSTRUCTION STANDARDS

Appendices A: Stairs Construction

A-1: The National Building Regulations for Protection from Falling, Collision and Impact, Approved Document K1, British Standards.

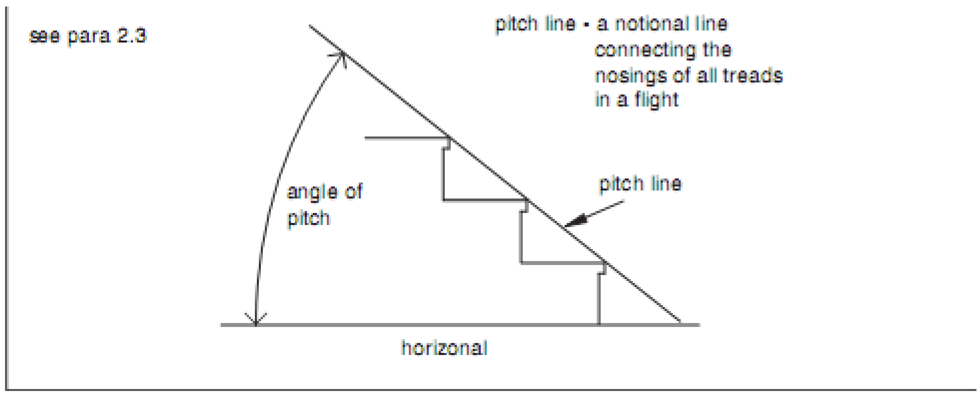


Figure A-1: Pitch line and pitch angle of stairs construction

Table A-1: Rise and going standards

Category	Rise		Going
	minimum (mm)	maximum (mm)	minimum (mm)
1 Private stair	75	220	220
2 A common stair in a block of dwellings	75	170	250
3 A stair in any building (other than a private stair or a common stair in a block of dwellings)	150	170	250
Note A stair within more than one category shall be constructed to the more onerous standard			

A-2: Designs and Calculation of Sizes and Dimensions of Stairs

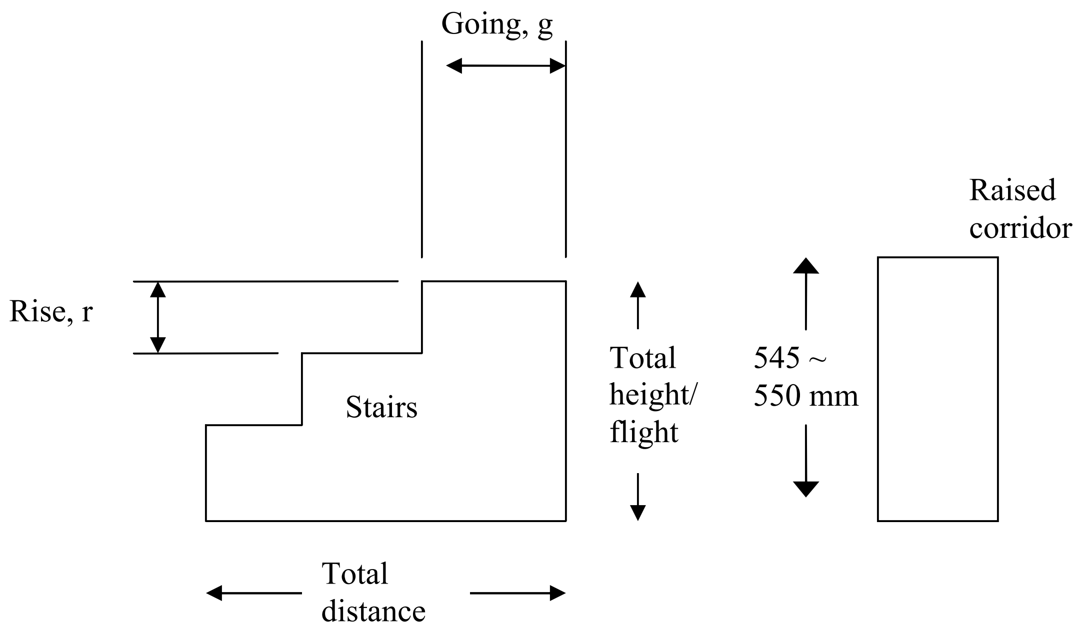


Figure A-2: Basic diagram of the designed stairs

The stairs going is set for the minimum of 250 mm. therefore, the total distance is 250 mm x 3 which is 750 mm. The rise and the angle pitch, α is related to going by:-

$$\alpha = \arctan (r / g) \qquad \text{Eq. A-1}$$

From this point, we can either calculate the rise by setting the angle or vice versa. Given the maximum pitch angle is 42°. For the ease of drawing and dimension calculation, we choose the rise 180 mm instead. So the flight will be 180 mm x 3 which is 540 mm (slightly lower than the corridors height).

Applying previous equation (1), the pitch angle is 35.75° which is below than the maximum. For the width of the steps (or in this design, the whole structure), it is set as 990 mm where as the minimum length is 800 mm.

APPENDIX B

GLASS FIBER REINFORCED EPOXY PROPERTIES

(Courtesy of Barbera, 1998, *"Introduction to Composite Material Design",* Taylor and Francis)

Table B-1: Typical properties of glass, carbon, organic, boron and ceramic fiber

Fiber	Modulus [Gpa]	Tensile Strength (*) [GPa]	Compres-sion Strength [GPa]	Elongation [%]	Density [gr/cc]	Longitudinal Thermal Expansion [10^{-6}/°C]	Transverse Thermal Expansion [10^{-6}/°C]	Poisson Ratio	Thermal Conduct [W/m/°C]	Maximum Operating Temperature [°C]	Resistivity [micro ohm-m]
E-Glass	72.345	3.45	–	4.4	2.5–2.59	5.04–5.4	–	0.22	1.05	550	–
S-Glass	85	4.8	–	5.3	2.46–2.49	1.6–2.9	–	0.22	1.05	650	–
C-Glass	69	3.31	–	4.8	2.56	6.3	–	–	1.05	600	–
D-Glass	55	2.5	–	4.7	2.14	3.06	–	–	–	477	–
Carbon											
T300	230	3.53	–	1.5	1.75	−0.6	7–12	0.2	3.06	–	18
M50	490	2.45	–	0.5	1.91	–	–	–	54.43	–	8
AS2	227	2.756	–	1.3	1.8	–	–	–	8.1–9.3	–	15–18
AS4-D	241	4.134	–	1.6	1.77	−0.9	–	–	8.1–9.3	–	15–18
IM6	275.6	5.133	–	1.73	1.74	–	–	–	8.1–9.3	–	15–18
HMS4	317	2.343	–	0.8	1.8	–	–	–	64–70	–	9–10
UHM	441	3.445	–	0.8	1.85	–	–	–	6.5	–	120
P55	379	1.9	–	0.5	2	−1.3	–	–	120	–	8.5
P100	758	2.41	–	0.32	2.16	−1.45	–	–	520	–	2.5
Kevlar 29	62	3.792	–	–	1.44	–	–	–	–	–	–
Kevlar 49	131	3.62	0.72	2.8	1.45	−2	59	0.35	0.04	160 (#)	–
Kevlar 149	179	3.62	0.69	1.9	1.47	–	–	–	–	–	–
Technora H	70	3	0.6	4.4	1.39	−6	59	0.35	–	160 (#)	–
Boron	400	2.7–3.7	6.9	0.79	2.57	4.5	0.2	0.2	38	315 (#)	–
SCS-6	427	2.4–4	–	0.6	3	4–4.8	–	0.2	10	–	–
Nextel 720	260	2.1	–	–	3.4	6	–	–	–	1200 (#)	–

Note: Typical data from product literature and other sources, some values estimated for broad class of materials. The designer is responsible for obtaining actual values. (*) See Table 2.2. (#) Long term temperature.

Table B-2: Typical properties of unidirectional composites

Property	E-Glass/ Epoxy	S-Glass/ Epoxy	E-Glass/ Isophtalic Polyester	Kevlar 49/ Epoxy	Carbon/ Epoxy AS4/3501-6	Carbon/ Epoxy T800/3900-2	Carbon/ Epoxy IM7/8551-7	Carbon/ PEEK AS4/APC2	Carbon/ Polyimide AS4/ AvimidK-III
Density [g/cc]	2.076	1.993	1.85	1.380	1.58	–	–	1.6	–
Longitudinal Modulus E_1 [GPa]	45	55	37.9	75.8	142	155.8	151	138	110
Transverse Modulus E_2 [GPa]	12	16	11.3	5.5	10.3	8.89	9.0	10.2	8.3
Inplane Shear Modulus G_{12} [GPa]	5.5	7.6	3.3	2.07	7.2	5.14	5.6	5.7	–
Poisson's Ratio ν_{12}	0.19	0.28	0.3	0.34	0.27	0.3	0.3	0.3	–
Longitudinal Tensile Strength F_{1t} [MPa]	1020	1620	903	1380.0	1830	2698	–	2070	–
Transverse Tensile Strength F_{2t} [MPa]	40	40	40	34.5	57	–	–	86	37
Inplane Shear Strength F_6 [MPa]	60	60	40	44.1	71	–	–	186	63
Longitudinal Compressive Strength F_{1c} [MPa]	620	690	357	586.0	1096	1691	–	1360	1000
Transverse Compressive Strength F_{2c} [MPa]	140	140	68	138.0	228	–	–	–	–
Intralaminar Shear Strength (F_4 or F_5) [MPa]	60	80	76	48.69	–	–	–	150	–
Longitudinal Tensile Strain ε_{1t} [%]	2.3	2.9	2.4	1.8	1.29	1.68	1.64	1.45	–
Longitudinal CTE α_1 [10^{-6}/°C]	3.7	3.5	6.5	−2.0	−0.9	–	–	0.5	–
Transverse CTE α_2 [10^{-6}/°C]	30	32	22	60	27	–	–	30	–
Longitudinal moisture expansion β_1	0	0	0	0.01	0	0.0095	–	–	–
Transverse moisture expansion β_2	0.2	0.2	0.2	0.2	0.2	0.321	–	–	–
Fiber Volume Fraction V_f [%]	60	60	50	60	60	–	57.3	61	–
Void Content V_v [%]	–	–	2.0	–	–	–	0.1	–	0.5
Fiber Misalignment Ω [deg]	–	–	3.53	–	–	–	–	–	–

APPENDIX C

MATERIALS QUANTITY ESTIMATION

C-1: Average Weight of Woven E-Glass Fiber

i) Average weight of fiber per area, $\mathbf{m_f}'$.

Eight samples of equal surface area of fiber are weighted.

Area of fiber, $A_f = 100 \times 100\ mm^2 = 0.01m^2$

Table C-2: Sampling of fiber weight

Sample	$\mathbf{m_f}$ (g)
1	3.707
2	3.669
3	3.799
4	3.748
5	3.754
6	3.714
7	3.819
8	3.783
Total	30.032
Average, $\mathbf{m_f}'$	30.032/8 = **3.754**g

Therefore, $\mathbf{m_f}' = 3.754\ g / (100 \times 100)\ mm^2$

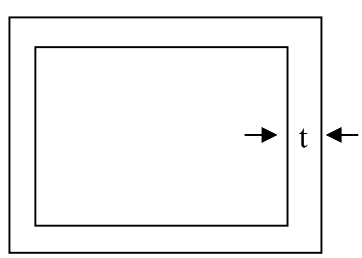
$= 3.754 \times 10^{-4}\ g/mm^2$

$= \underline{0.3754\ kg/m^2}$

C-2: Fiber Quantity Estimation

i) Volume of fiber used

a. Total volume of pure laminate stairs is given by;



Where;
Thickness, t = 5.72 mm
Height = 180 mm
Width = 330 mm

V_i = 3 x Frontal area of box component x depth of each component

$= 3 \times [(330)(180) - (330 - 2t)(180 - 2t)] \times 250\,(1 + 2 + 3)\ mm^3$

$= 8{,}555{,}289.6\ mm^3$

$= \underline{0.008555\ m^3}$

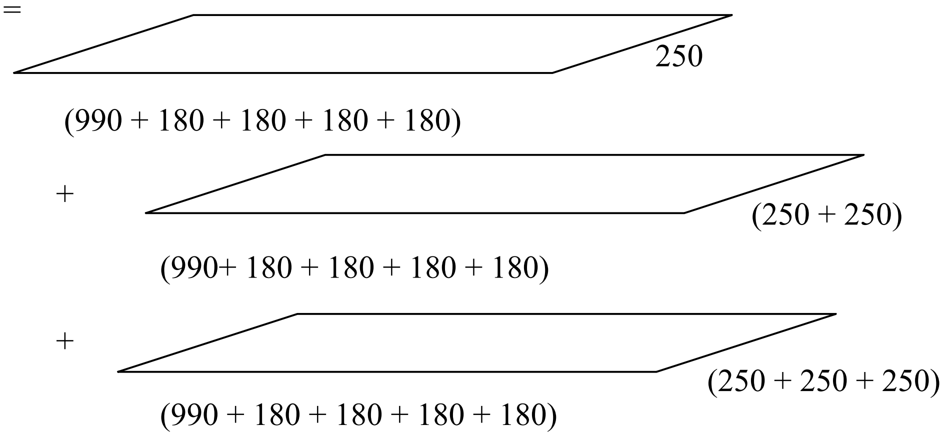
Since volume of fiber, $V_{f,i} = 0.45V_i$

$= 0.45(0.008555)$

$= \underline{0.00385\ m^3}$

b. Total volume of laminated core stairs, V_{ii};

Area, A_{ii} =



$A_{ii} = \underline{2.565\ m^2}$

Thus;

$V_{ii} = A_{ii} \times t$ (thickness of laminate, from section **4.1**)

$= 2.565 \times 0.00026$

$= 6.669 \times 10^{-4}\ m^3$

Volume of fiber needed, $V_{f\,ii} = 0.45V_{ii}$
$= 0.45(6.669 \times 10^{-4})$
$= 0.0003\ m^3$

C-3: Resin Weight Estimation

Matrix volume, V_m is 0.55 V_i. Thus, the matrix weight would be;

m_m = density of resin x volume of resin

i) For fully laminate

Volume of resin, $V_m = 0.55V_i = \underline{0.00471\ m^3}$

Plus of approximately 30% waste;

$V_m = 0.00471 + (0.3)(0.00471)$

$= \underline{0.006123\ m^3}$

So, $m_m = [1.084\ g/cm^3 \times 1000\ m^3/kg] \times 0.006123\ m^3$

$= \underline{\underline{6.6373\ kg}}$

For hardener, weight of hardener, m_h to resin ratio is 21:100. Thus;

$m_h = 0.21 \times 6.6373 = 1.3938\ kg$

ii) For laminated core

Volume of resin, $V_m = 0.55V_{ii} = 3.668 \times 10^{-4}\ m^3$

Plus of approximately 30% waste;

$V_m = 1.3 \times 3.668 \times 10^{-4}$

$= \underline{4.7684 \times 10^{-3}\ m^3}$

So, $m_m = [1.084\ g/cm^3 \times 1000\ m^3/kg] \times 4.7684 \times 10^{-3}\ m^3$

$= \underline{\underline{5.1689\ kg}}$

Weight of hardener, $m_h = 0.21 \times 5.1689 = \underline{1.0892\ kg}$