SYNOPSIS

of the Ph. D. Thesis

Entitled

INVESTIGATIONS OF PROCESS PARAMETERS IN VACUUM ASSISTED RESIN TRANSFER MOLDING FOR THE DEVELOPMENT OF FIBER REINFORCED COMPOSITES

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ALPA GAUTAMBHAI MEHTA

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Under the supervision of

Dr. PIYUSH P. GOHIL

Associate Professor,
Department of Mechanical Engineering,
Faculty of Technology & Engineering
The Maharaja Sayajiroa University of Baroda, Vadodara

Faculty of Technology and Engineering, (Kalabhavan),
The Maharaja Sayajiroa University of Baroda,
Vadodara (Gujarat).

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Abbreviations and Nomenclatures

Parameter	Description
1D	One Directional
2D	Two Directional
XGYRZV	X GSM, Y RPM and Z in Hg Vacuum
3D	Three Directional
APBLCV	A number of ply Ply, B° inclination angle, C in Hg vacuum
NTEC	N number of layers, resin supply from Top and vacuum from Edge to Centre
XLWID	X number of Layers With degassing
XLWOD	X number of Layers With Out degassing
ASTM	American Society for Testing and Materials
A-VARTM	Advanced VARTMP
BD	Bi Directional
CFRP	Carbon Fiber Reinforced Plastic
DAQ	Data Acquisition
DMA	Direct Memory Access
DOE	Design of Experiments ,
FRC	Fiber Reinforced Composite
FVf	Fiber Volume fraction
GFRP	Glass Fiber Reinforced Plastic
GSM	Gram per Square Meter
HFVf	High Fiber Volume fraction
HL	Hand Layup
HPM	High Permeable Media
ILSS	Inter Laminate Shear Stress
KFRP	Kenaf Fiber Reinforced Plastic
LOI	Loss Of Ignition
LVDT	Linear Variable Differential Transformer
MACM	Magnetic Assisted Resin Transfer Molding
MPa	Mega Pascal
PMC	Polymer Matrix Composite

RIFT	Resin Infusion Flexible Tooling
RPM	Revolution Per Minute
RTM	Resin Transfer Molding
SCRIMP	Seeman Composite Resin Infusion Molding Process
SEM	Scanning Electron Microscope
THF	Tetra Hydro Furan
UD	Uni Directional
VAP	Vacuum Assisted Process
VARI	Vacuum Assisted Resin Infusion
VARTM	Vacuum Assisted Resin Transfer Molding
VERITy	Vacuum Resin Infusion
VI	Vacuum Infusion

1. Introduction

Composites are made from two or more constituents. One is called as reinforcement and the other is called as matrix. Reinforcement is load bearing member and matrix is a load transferring member in composite parts. Composite made with reinforcements in form of fiber are called as fiber reinforced composite (FRC).

Advantages of FRC composites are high strength to low weight ratio, high stiffness, corrosion resistance, tailoring of strength/ stiffness properties, possibility of molding complicated shapes, ease to repair, high dimensional stability, concept of bonded structure, smooth outer surface etc.

Limitations of composites are poor erosion resistance, poor electrical resistance, degradation of characteristics in moisture, high cost of material, special efforts for tooling, limited workshop facilities, new inspection techniques, requirement of skilled manpower, lack of standardization, part to part variation due to non-uniform fiber volume fraction and properties, biodegradability and people awareness about this process.

Applications of FRP composite includes transportation, construction, automobile, toys, aerospace, defence, furniture, medical, sports, electric engineering etc.

Composites are classified in many ways. Based on manufacturing techniques the composites are classified in Figure 1. One of the techniques of composite making process is liquid compression molding. There are many variants of liquid compression molding. One of them is Vacuum Assisted Resin Transfer Molding (VARTM). In this work, VARTM process has been studied in detail.

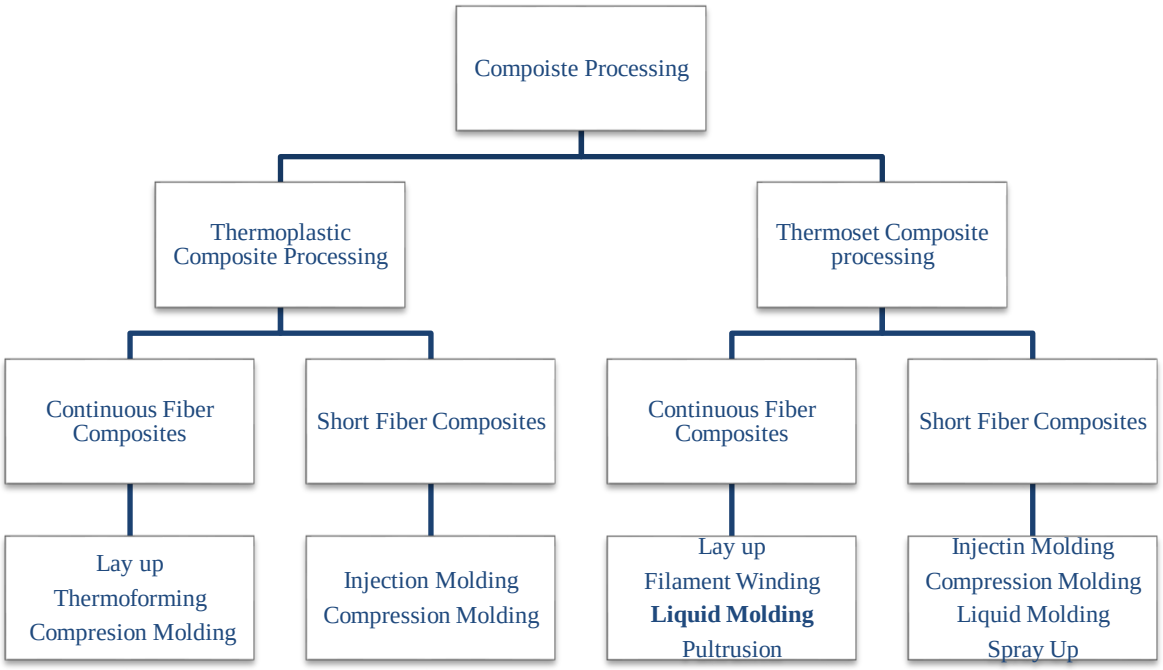

Figure 1 Classification of composite manufacturing processes

Understanding of VARTM is increasing day by day. This process was established in around 1950s (Williams, Summerscales and Grove 1996). As it faced manufacturing challenges, other methods were used to make FRC composite laminates. There are plenty applications of VARTM process especially for the large structures, like manufacturing automobile parts, boat hull, wind blade and aircraft parts. This process has many advantages like outsized structure can be made in single piece with less cost as only one side of the mold is required. The process is fast and clean. This process is eco-friendly and less human intervention is required. No autoclave is required and large complex structure can be manufactured.

The major limitation of this includes part thickness variation, amount of void content and multi trial approach. (Summerscales and Searle 2005, Glancey 2010) However, lots of work has been taken place to advance this process. The process has many variants like VARI, SCIMENS, RIFT, VI, VAP etc. (Schledjewski and Grössing 2016,Oosterom et al. 2019,Hindersmann 2019)

The VARTM process has been explain with schematic diagram in Figure 2.

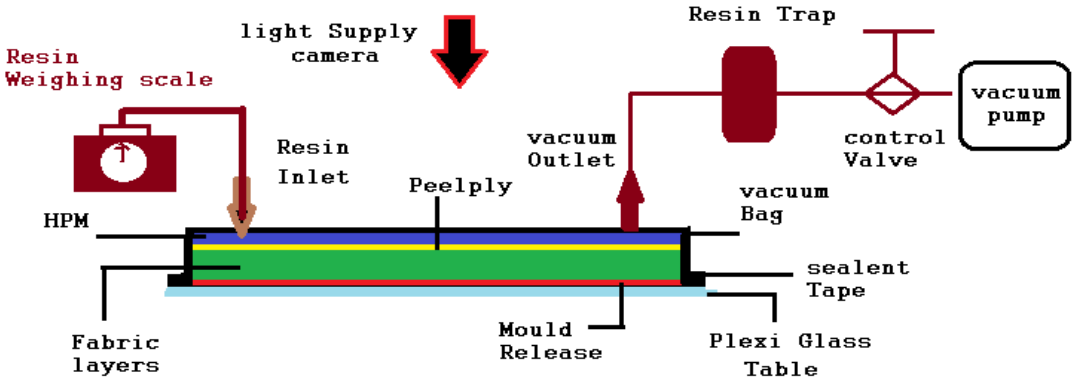

Figure 2 Schematic diagram of VARTM process

As shown in Figure 2 the set up consists of a glass table on which fabric layers are laid after application of three coats of mold release spray. On top of last fabric layer, one layer of peel ply is applied to ensure easy removal of part from high permeable distribution media (HPM) and vacuum bag after curing. On top of peel ply HPM is laid. This full assembly is covered with vacuum bag and sealed with sealant tape. Vacuum is applied from one side by vacuum pump and resin is applied from the other.

2. Research Review

Consolidated research review has been performed on various parameters, materials, experimental setup, degassing and testing required on VARTM process. Table 1 highlights partial review on material, various parameters affecting VARTM process, testing/ measurement performed, whether experimental setup was developed or not and kind of instrument used.

Table 1 Research review

Research	Material	Processing Method	Control Parameter	Testing and measurement	Experimental setup	Instruments Used
(Gama et al. 2001)	Plane weave glass and epoxy	VARTM	Debulking cycle, Flow rate control by open-open, close-open, close micro open	Thickness variation, FVF, Flexural stress	Yes	Laser displacement meter, Lab view s/w
(Sharma and Siginer 2009)	UD glass, BD glass, UD carbon	SCRIMP	Types of fabric (E glass UD, BD and Carbon BD, hybrid), Resin pressure (0, 10 , 20 psi), Vacuum pressure (27,28,29 in Hg) Debulking (applying pressure after closing inlet)	FVF, Void content, Tensile strength and tensile modulus, thickness gradient	Yes	-
(Grimsley et al. 2001)	Carbon Fabric + Epoxy resin	VARTM	Flow front	Resin Pressure, FVF, panel thickness	Yes	Camera, pressure sensors, LVDT, Lab view S/w
(Li et al 2004)	E glass + Epoxy resin	VAP and SCRIMP	Membrane	Thickness variation, Void content, FVF, Short beam shear test	Yes	SMART Weave sensors, CCD camera, glass tool.

(Naik, Sirisha, and Inani 2014)	-	RTM / VARTM	Architecture (weave style, surface condition, porosity), mold design, part geometry, human factor, resin properties (viscosity, surface tension, contact angle), processing condition (injection pressure, flow rate, temperature)	Flow velocity, 1D, 2D, 3D permeability	Yes	Camera, Flow Sensors
(Bender, Schuster, and Heider 2006)	Corn syrup and water	VARTM	Flow rate	-	Yes	Fuzzy logic controller, lab view, Precision Weighting Balances, Pressure controller, Viscometer
(Yoon et al. 2005)	Two different fabric + Corn syrup with water mixture with density approx. epoxy	VARTM	Gravity effect (horizontal, upward, down ward), Tube diameter and tube length	Flow, Resin fill time	Yes	Time-domain reflectometry (TDR) sensor, Pressure, Five pressure transducers, viscometer
(Govignon et al. 2008)	E-glass fabric with different GSM + Mobil DTE AA resin and Mobil DTE Heavy	Resin Infusion (RI)	GSM of fabric(480 g/m2 CFM, 800 g/m2 Biaxial stitched matrix), With and without HPM, Fluid viscosity	Thickness variation during filling and post filling, Resin flow rate, Flow velocity, Filling time, Resin pressure, FVF, Permeability	Yes	Thermocouple, Pressure transducer, Two high resolution camera for stereo photography, Weighing scale, 20 cm wide strip

(Yenilmez, Senan, and Sozer 2009)	Fabric (Fibroteks) Resin (Poliya PolipolTM 336-RTM)	Vacuum infusion (VI)	Dry compaction Cycle	Thickness and pressure variation during flow,	Yes	Digital dial gauge, Pressure transduces
(Francucci, Rodríguez, and Vázquez 2010)	Jute fabric Glass fabric, 22% V/V water/glycerin solution	VARTM	Viscosity of resin, Porosity, Type of fabric	Saturated and unsaturated permeability, Swelling of fiber	Yes	Viscometer Vacumometer, Optical microscopy
(Rigas et al. 2001)	Glass fabric and epoxy resin	VARTM	HPM, Height of resin supply to find effect of gravity, Single and double vacuum bagging	Resin flow, variation in part thickness, FVF, ILLS, Flexural test, Tensile, ILSS, Infusion time	Yes	SARTM Weave sensors
(Ghabezi, Golzar, and Jalall 2010)		VARTM	Tube diameter, Length of tube	Filling time, Pressure drop	Yes	-
(Kedari, Farah, and Hsiao 2011)	Chopped Glassed mat + Polyester resin	Heated dual Pressure control VARTM	Inlet pressure, Outlet pressure, Mold temperature,	Composite density, FVF, Hardness, Effect of Degassing, Viscosity of resin	Yes	Digital heater, resin trap to control vacuum and resin pressure they used pressure reservoir
(Arulappan et al. 2014)	Carbon fabric + Epoxy resin	VARTM	Fiber orientation, Configuration gravity, HPM	Pressure, Thickness variation, Filling time	Yes	Pressure sensors, LVDT

(Nasir et al. 2015)	GFRP + KFRP	VARTM	Laminate with different material	Tensile strength, Tensile modulus, Opening displacement curve	Yes	Fixture was made to make tensile coupon
(Chokka, Ben, and Srinadh 2019)	Carbon + Epoxy	Vacuum infusion (VI) + Hand lay up (HL)	Viscosity (SA + NSA), Vacuum pressure (50,250,350,500 mm of Hg)	Tensile , Wear properties, FVF	Yes	-
(Chang and Chen 2016)		VARTM – progressive compression	Vacuum pressure (100, 80 KPa) Number of compression segment (2, 3) Compression timing of the next segment (5. 10 sec) Temperature of the heated air (20, 40 ℃) Initiating segment of the heated air ($1^{st,}$ 3^{rd}) Initial cavity height (7, 10 mm) volume of infused resin (100, 130 ml)	Filling time	Yes	Taguchi method

(Das et al. 2016)	Plain weave jute + Polyester Resin	Hand layup and compression at 90° C for 10 min	Staking sequence	Tensile strength (TS), Tensile modulus (TM), Bending strength (BS), Bending modulus (BM), and Impact strength (IS)	-	-
(Wang et al. 2016)	Carbon fabric + Epoxy resin + Edible oil (COFCO group)	VARTM	Compaction pressure, Number of layers, Liquid viscosity, Post filling time	In plane permeability, Preform thickness	Yes	Vacuum pressure control, Eddy current sensors
(Pishvar, Amirkhosravi, and Altan 2018)	Random mat + E glass epoxy	Magnet Assisted Composite Manufacturing (MACM) Wet lay-up/vacuum bag WLVB) VARTM	Magnetic compaction	FVF by LOI, Density, Flexural properties, SEM, Thickness variation	Yes	-
(Yalcinkaya, Sozer, and Altan 2017)	E – glass fabric + Epoxy resin	Pressurised and heated VARTM	External pressure at given time for compaction, Mold temperature, Degassing	FVF, Flexural strength, Void content	Yes	Heat sheet insulated with silica fabric, electrical scale, solenoid valve and pressure regulator, Lab view +DAQ

(Yalcinkaya, Sozer, and Altan 2019)	Glass + Epoxy	VARTM	External pressure (0, 34.5, 69, 138 KPa), resin flushing, number of ply (6,12,18)	Void content, FVF, Flexural properties, Short bean shear strength	Yes	Gas pycnometer, Micrometre to measure thickness, Digital image analysis for void content
(Nauheimer et al. 2017)	Glass fiber Fabric + Epoxy resin	VARTM	Pressure drop	Flow front	Yes	Pressure sensors
(Sunilpete and Cadambi 2020)	Glass fabric + Epoxy resin	Vacuum infusion	Double bag, Resin trap, Silicon bag	Density test, FVF, void content, DMA, Tensile, Flexural, and ILSS.	Yes	-

2.1 Research review findings

Though, use of VARTM process has been started after 1940s for structural application, the demand for more sophisticated VARTM had arisen after 1990s, when it was envisaged to apply this technology to meet stringent requirement of airframe and defense applications.

Basic theory of VARTM starts with Darcy's law. Initially it was used to find permeability in incompressible porous media with RTM process. The further analytical formulation has been developed to find permeability in compressible porous media for VARTM process. Various softwares have been developed to simulate flow behaviors and filling time for VARTM process.

The feasibility of using natural fiber as a reinforcing material in composites is well recognize in literature review due to its biodegradability and less weight.

Analysis has been performed by various researchers to understand the complex phenomenon occurring inside the fabric - before, during and after impregnation for VARTM process. Which includes study of effect of dry and wet compaction, effect of de-bulking cycles, forces acting during the flow which includes viscosity, capillary, vacuum, pressure and gravity, in plane and through thickness permeability, unsaturated and saturated permeability, flow between and within tow and effect of post filling cycle also known as steady state condition.

Significant study of research review have been done till date to find out the effect of different parameters affecting VARTM process. The findings are tabulated in the form of parameters which can be controlled or measured during various stages of experiments (Refer Table 2).

Table 2 Parameters affecting VARTM process

Control Parameters		Measured Parameters	
Pre-process	**In-process**	**In-process**	**Post-process**
1. Architecture of fabric (Stacking Sequence, weave style, Number of layers, Fiber orientation, GSM, porosity) 2. Different materials (GFRP, CFRP, KFRP) 3. Dry compaction cycle 4. Compaction pressure 5. Effect of gravity 6. Effect of HPM 7. Membrane usage 8. Effect of inlet tube diameter and length 9. Height of resin supply 10. Single and double vacuum bag 11. Mold design 12. Part geometry 13. Human factor 14. Resin properties (Viscosity, Surface tension, Contact angle) 15. Degassing 16. Flushing/bleeding 17. Number of inlet ports & vents	1. Flow Front 2. Flow rate 3. Post filling time 4. Viscosity of resin 5. Mold temperature 6. Inlet/Injection pressure 7. Outlet pressure/Vacuum 8. External temperature 9. Applying pressure after closing inlet (debunking after impregnation 10.Pressure drop 11. Magnetic compaction 12. Co-efficient of thermal expansion.	1. Resin pressure 2. In plane permeability 3. Preform thickness during the flow 4. Filling/ infusion time 5. Viscosity of resin 6. Saturated and unsaturated permeability 7. Flow velocity 8. Flow rate 9. 1D, 2D, 3D permeability 10.Thickness variation post filling	1. Tensile strength/modulus 2. Bending strength/modulus 3. Impact strength 4. Flexural strength 5. Hardness strength 6. ILSS 7. Density of fiber 8. Weight fraction 9. Fiber volume fraction 10.Panel thickness 11.Void content 12.Short beam shear test 13.SEM- swelling of fiber 14.Opening displacement curve 15. Wear properties 16. Surface defect 17.Shrinkage

2.2 Identification of research gap

Based on research review and findings following research gaps have been identified.

Most studies were available for conventional high strength fiber based PMCs. Looking to this, there is a scope to develop - high strength, high fiber volume fraction (HFVf), natural fiber based FRCs using VARTM process by examining the various parameters as mentioned in Table 2.

In VARTM, during infusion process, natural fiber behaves differently than synthetic fiber. There is scope to understand the phenomena occurring during resin infusion in fabric made up of natural fibers.

Few studies were available for VARTM technique to get HFVf -PMC. However, among major issues were to optimize the process parameters for increasing fiber volume fraction.

Not much investigation was performed to study the effect of gravity in quality of laminate. There is scope of improvement after including effect of gravity by inclined impregnation.

Challenge faced while manufacturing parts by VARTM process includes control of part thickness variation; minimization void content, maximization of fiber volume fraction and optimization of mechanical properties.

Very few researchers have adopted the concept of design of experiments to study the effect of parameters on above challenges. Almost none has explained practical difficulties while manufacturing VARTM process which leads to make it a trial and error process.

Thus, the proposed research work is focused on developing indigenous experimental set up to manufacture composite made up from natural fibers. This will help to investigate effect of various parameters on controlling void content, part thickness, and fiber volume fraction, physical and mechanical properties for VARTM process.

3. Problem Definition and Research Methodology

Based on identified research gaps the research objectives decided are as follows:

3.1 Research objectives

1. To explore various application of FRP and its manufacturing process and to carry out in-depth study of VARTM process for the manufacturing FRP composite.
2. To initiate learning various experimental setup through exhaustive literature review on VARTM process.
3. To identify various challenges for conducting experiments on VARTM process.
4. To identify process parameters for VARTM process by extensive research review.
5. To implement design of experiment approach (DOE) for conducting experiments to minimize experimental run.
6. To develop methodology/process to perform VARTM process.
7. To design and develop indigenous VARTM experimental setup to investigate effect of various parameters affecting VARTM process.
8. To prepare natural fiber reinforced composite using VARTM process.
9. To investigate effect of degassing in laminate quality for VARTM process.
10. To carryout various testing involved in developing FRP composites for VARTM process.
11. To investigate effect of selected process parameters on fiber volume fraction, physical and mechanical properties and to perform morphological study.

Based on above objectives following problem definition has been identified.

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“Investigations of Process Parameters in Vacuum Assisted Resin Transfer Molding for the Development of Fiber Reinforced Composites”

3.2 Research methodology

Based on given set of objectives and problem statements, research methodology is mentioned in Figure 3. It demonstrates steps of performed research carried out during execution of the work.

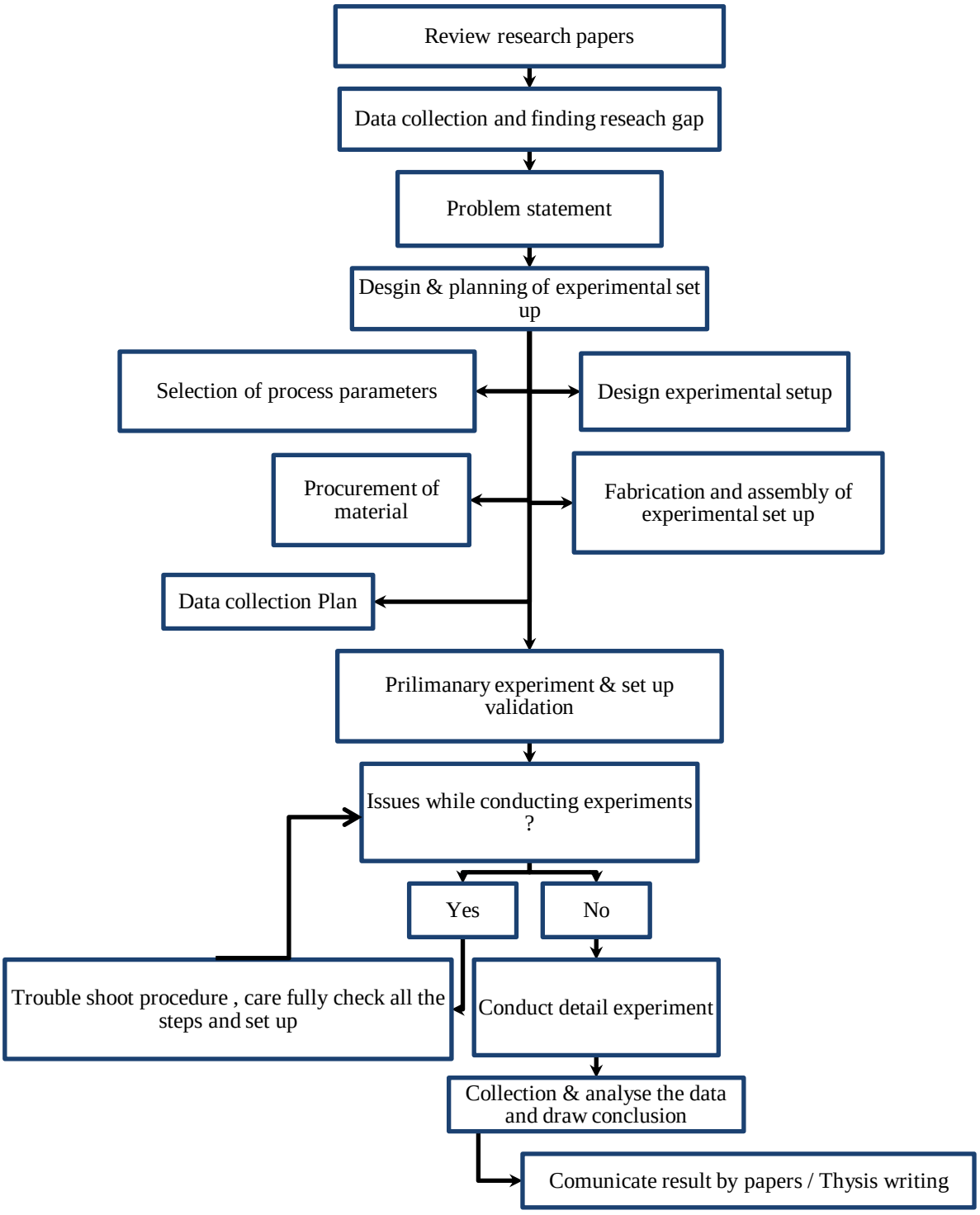


Figure 3 Research methodology

4. Materials and Methods

Experiments according to the order they are performed have been explained below. Each experiment demonstrates material used and methodology followed during the experimentation. The experiments are performed either with hollow grass fabric (211 GSM), jute fabric (plane weave) or glass fabric (plane weave) as reinforcement and polyester resin (resin + hardener (MEKP) + accelerator (cobalt) in ratio of 100:1.5:0.5) as matrix.

4.1 Preliminary experiment

Preliminary set up was developed to prepare laminate by VARTM process from hollow glass fabric (211 GSM) and polyester resin (Resin + Hardener (MEKP) + Accelerator (Cobalt)) in ratio 100:1.5:0.5). The consumables and accessories required for developing VARTM setup includes masking tape, mold release spray, peel ply, High permeable distribution media (HPM), vacuum bag, sealant tape, hose pipe, supply pipe and resin container, the accessories used is vacuum pump to supply vacuum, weighing machine to weigh the resin and scissor to cut material.

As shown in Figure 4, layers of fabric were laid on glass table after application of three coats of mold release spray. Peel ply was kept on layers of fabric and HPM was kept on peel ply. Inlet and outlet tubes were kept on HPM. The full assembly was covered with vacuum bag and sealed with sealant tape. After set up, the vacuum supply was started and vacuum leak was checked. Resin was impregnated inside fabric from inlet after weighing and mixing with hardener and accelerator. Resin supply was closed, once resin reached to vacuum line. Vacuum pump was kept on until resin was cured.

Preliminary experiment was developed to understand how VARTM system works. There were many learning after execution of this process. Some of the basic learning were, arrangement and placing of layers one after another, use of vacuum pump, use of sealant tape to seal the vacuum bag and to ensure system without vacuum leakage, learning of gelation time required for resin with given mixing ratio. It was observed that the hose pipe and tube

selections should be proper so that it does not compress during vacuum supply. Quantity of resin is required before impregnation should be enough as resin required is summation of amount of resin absorb inside fabric plus amount of resin required in HPM, supply and vacuum tubes. Cutting the fabric in fiber direction, weighing of fabric before actual impregnation to decide amount of resin require were some important learning.

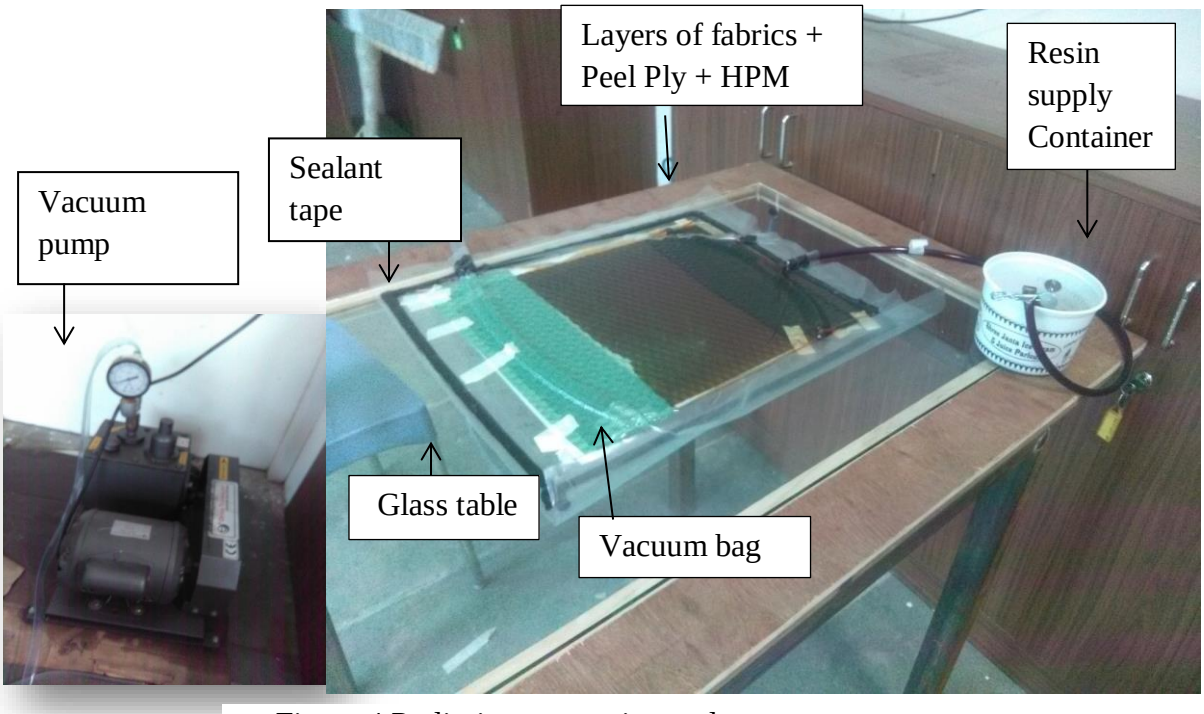


Figure 4 Preliminary experimental setup

4.2 Investigations on effect of number of layers, location of resin supply and position of vacuum supply for VARTM Process

Nine experiments were performed using experimental design, by Taguchi L(9) orthogonal array, for first set of experiments. The parameters selected were number of layers (4, 5 and 6), position of resin supply (top, middle and bottom) and location of vacuum supply (edge to centre, centre to edge and left to right). These parameters were chosen to understand effect of number of layers, pressure head during impregnation and flow direction on laminate quality.

Material used for this set of experiments was jute fabric (untreated, 290 GSM, 15X14 TPI) and polyester resin.. The experimental set up is shown in Figure 5. The set up was modified with frame, to keep top camera and light. Special frame was developed to put resin 500 mm top and 500 mm bottom, from table surface. Vacuum pump was directly connected to

experiment. Braded pipe were used to perform experiment, so vacuum could be sucked properly from the vacuum bag. The impregnation process was same as before.

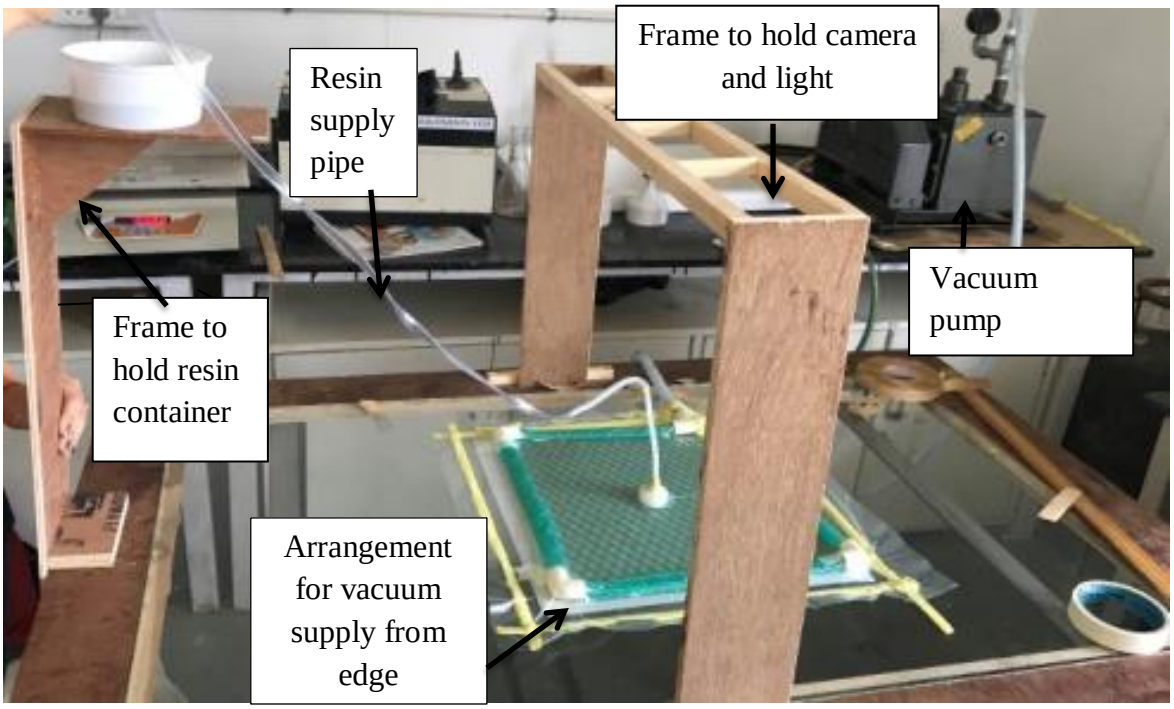


Figure 5 Experimental setup

During performing these experiments, the concept for design of experiments was learnt. Selections of tube were studied. Arrangement of vacuum line were studied and implemented. Fittings were used to connect the vacuum lines. Incomplete penetration and gelation before impregnation was observed initially in few laminates. Race tracking was also observed.

Selection of testing method, ASTM code identification, test coupons marking and cutting method, to perform testing, consolidation of results and data analysis was part of learning.
For this experiment tensile, flexural, volume fraction and thickness variation was performed. It was understood that there is no standard method for finding volume fraction for natural fiber and solvent method was developed. THF (Tetra Hydro Furan) was selected as solvent for weight fraction measurement.

4.3 Preliminary experiment on developed indigenous experimental setup

After conducting experiments and research review, a new indigenous experimental setup was developed to study effect of various parameters on VARTM process. The experimental setup is shown in Figure 6.

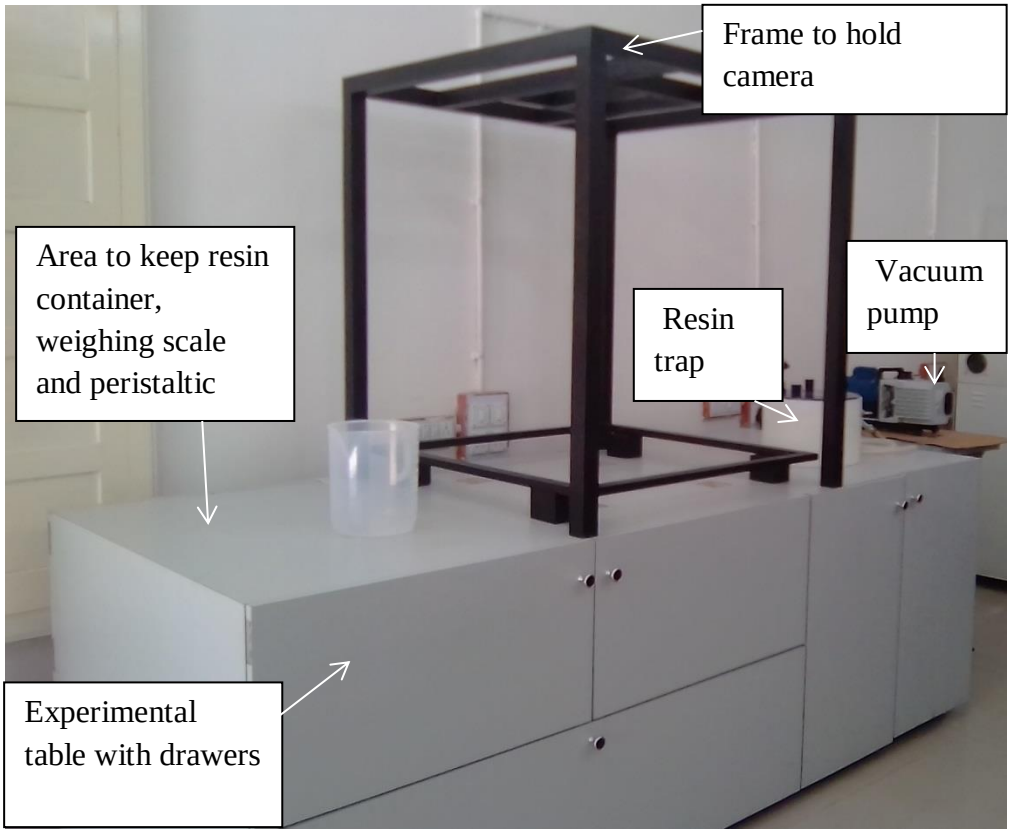


Figure 6 Indigenously developed experimental set up

As shown in Figure 6, experiment setup consists of a table with glass and a frame to hold camera and light at top side. The left side space was kept for resin container and right side was used for resin trap and vacuum pump. The drawers were provided to keep required material and consumables. Inclination arrangement was provided below the glass frame to adjust required inclination angle. Levelling of glass frame was possible by adjusting four screws provided down side the glass frame. Four light sources were provided below the glass table to ensure enough illumination to visualise the flow.

Preliminary experiment was performed with hollow glass fabric (211 GSM) and polyester resin to understand proper working and to determine short coming of the system. The preliminary experiment conducted on this indigenous set up is shown in Figure 7. The learning from the preliminary experiment has been incorporated in the next set of experiments.

The resin trap should have container inside to collect the resin. The clamps to lock vacuum pipe and resin supply should be readily available. The supply of resin should be on the left side and vacuum supply should be on the right side. The length of vacuum pipe should be such that vacuum supply can be easily managed with the open-close valve. Proper care should be taken while sealing the vacuum bag. Camera and stopwatch should be readily available during performance of the experiments.

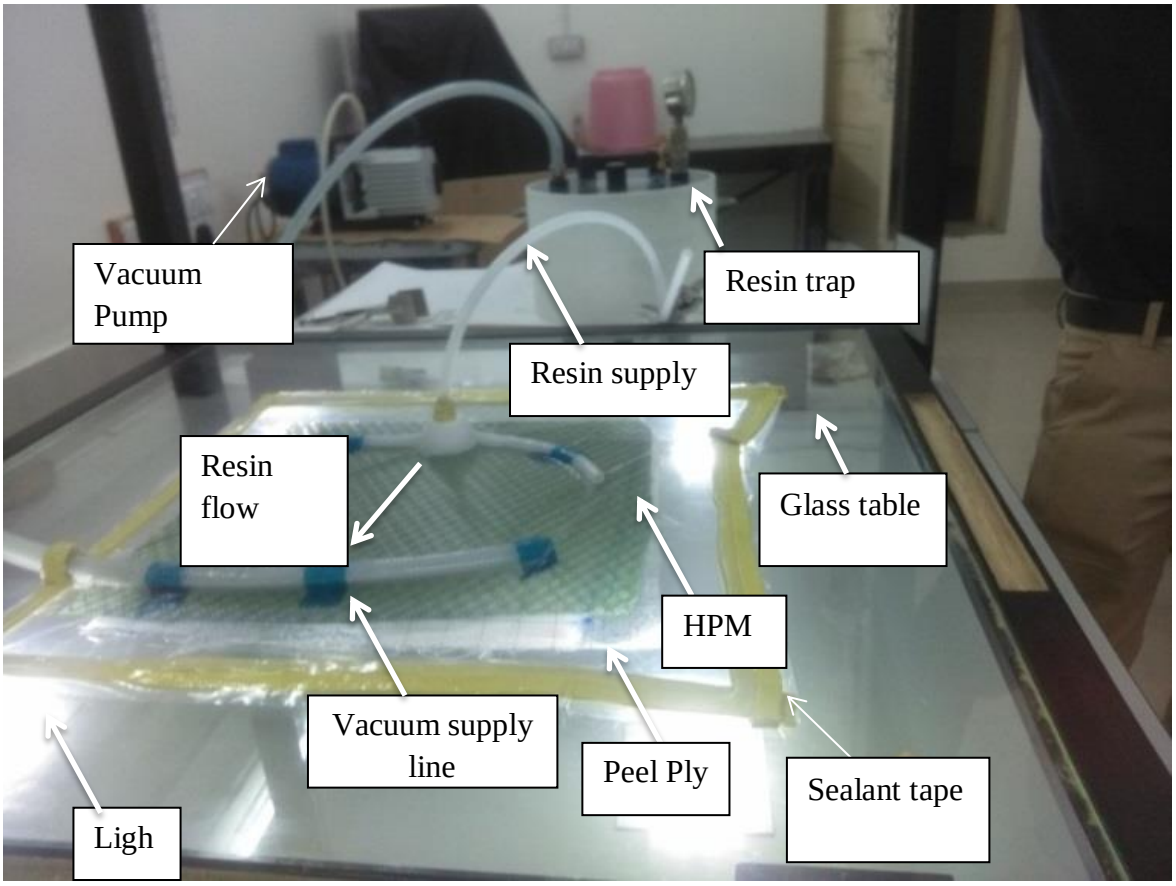


Figure 7 Preliminary Experiment on indigenously developed experimental setup

4.4 Investigations on effect of number of layers and degassing for VARTM Process

The laminates were prepared with jute fabric (untreated, 290 GSM, 15X14 TPI) and polyester resin. Six set of experiments were performed three with degassing and three without degassing by changing number of layers from 5, 10 and 15. The resin was degassed for 3 minutes after mixing with hardener and accelerator. Degassing time was decided based on amount of bubbles coming out from the resin. Degassing was done in resin trap at full vacuum. Tensile, flexural, 180x microscopic examination was performed on laminate;

thickness variation was measured for cured laminate. Figure 8 depicts experimental setup for degassing. The impregnation process was same as before.

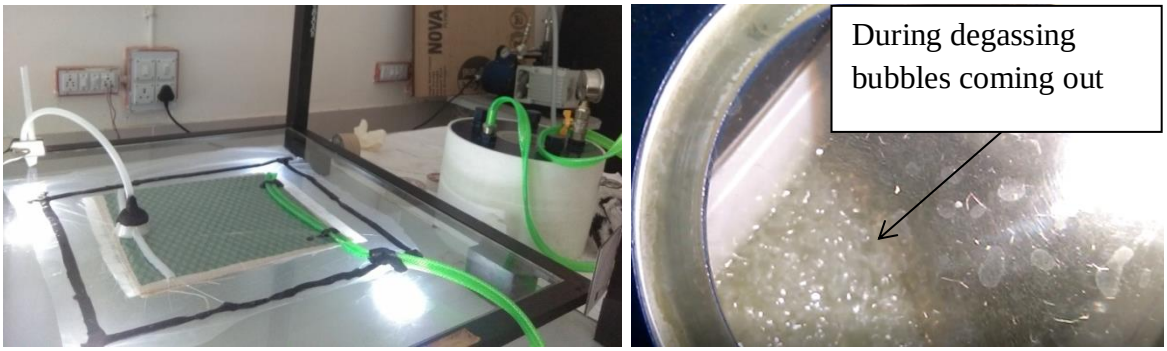


Figure 8 Experimental setup with degassing

4.5 Investigations on effect of number of layers, inclination of table and amount of vacuum supply for VARTM process

These experiments were performed with jute fabric (untreated, 290 GSM, 15X14 TPI) and polyester resin. Selected parameters and their levels were, number of layers (4, 8 and 12), amount of vacuum supply (29, 22 and 15 in Hg) and inclination of table (0°, 20° and 40°). As shown in Figure 9 many modifications were included in the experiments. Special fixture was developed to observe thickness variation during flow which includes three dial gauges and specially designed stand to hold the dial gauge, on inclined plane. A fixture was developed to hold the glass frame at required angle (20° and 40°) along with bevel protractor. Two cameras were used to observe resin flow from top and from front. A control valve was introduced to control supply of vacuum during and after impregnation of resin. The scale was kept along the length of laminate to study the flow velocity from top and side camera. The impregnation process was same as before.

Tensile test, flexural test, thickness variation during flow, cured laminate thickness measurement, fiber weight fraction and flow velocity measurement was performed to study the effects of input parameters.

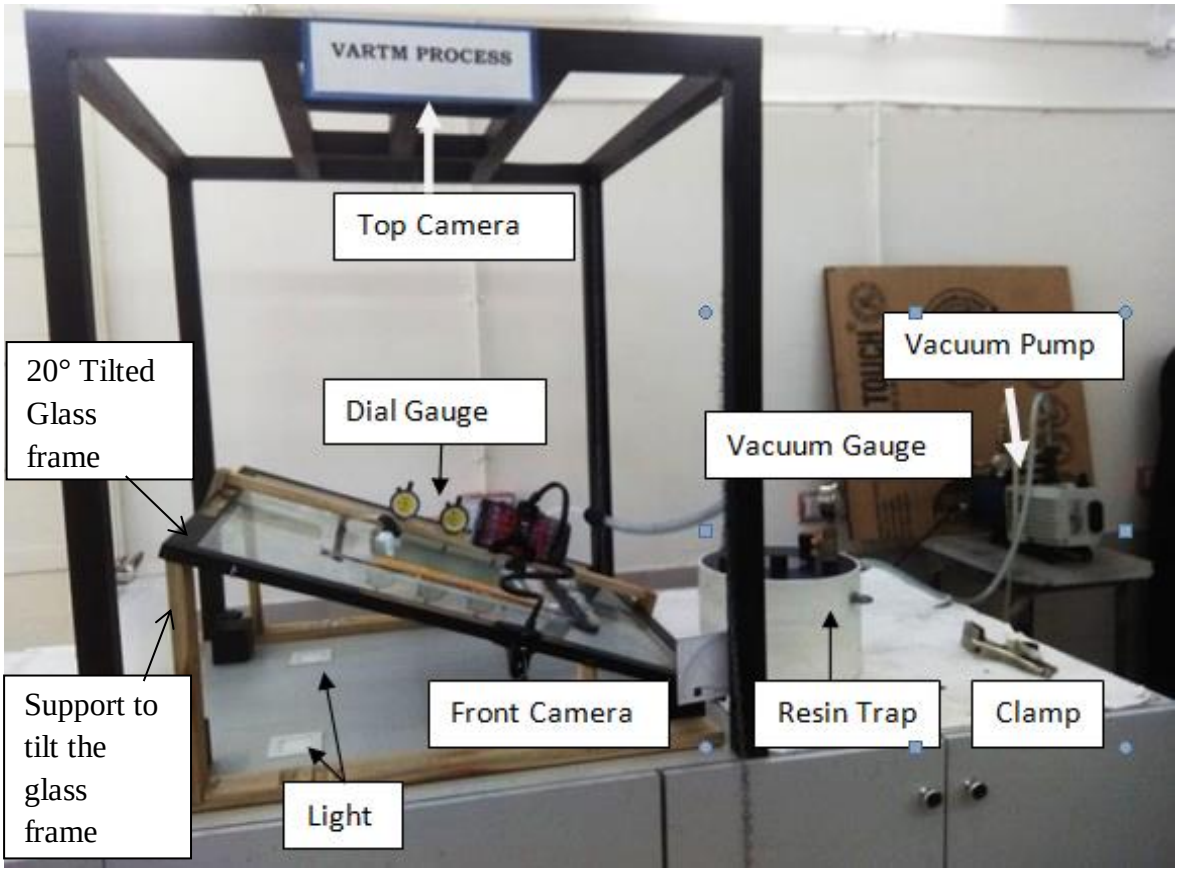


Figure 9 Experimental setup with variation in number of layers, inclination of table and amount of vacuum supply

4.6 Investigations on effect of GSM of glass fabric, RPM of peristaltic pump and amount of vacuum supply on VARTM process

These sets of experiments were done with the use of glass fabric (plane weave) and polyester resin. Full factorial approach was used to design experiments. Total 27 experiments were performed. The parameters selected were GSM of glass fabric (200, 400, and 600), RPM of peristaltic pump (70, 90 and 110) and amount of vacuum supply (15, 22 and 29 in Hg). Major modifications in these experiments were, use of peristaltic pump and glass fabric in place of jute fabric. Display check list was used to ensure nothing is missed during experiments. Scale and side camera were used to measure flow velocity during flow and dial gauge was used to measure thickness variation during flow. Weighing scale was used to measure flow rate during impregnation. Display of parameter near the layup was kept for record keeping. Spirit level was used to check the flatness of table. Resin was degassed before impregnation. 15

minutes pre-compaction of fabric was performed. Control valve was used between resin supply tube and hose pipe which was connected to resin trap.

Tensile, flexural and fiber volume fraction measurement with LOI method were performed. The tensile test coupons were provided with tabs before performing tensile test. Flow rate, flow velocity and thickness variation during and after curing of laminate was also performed. Figure 10 explains the experimental setup arrangement. The impregnation process was same as before.

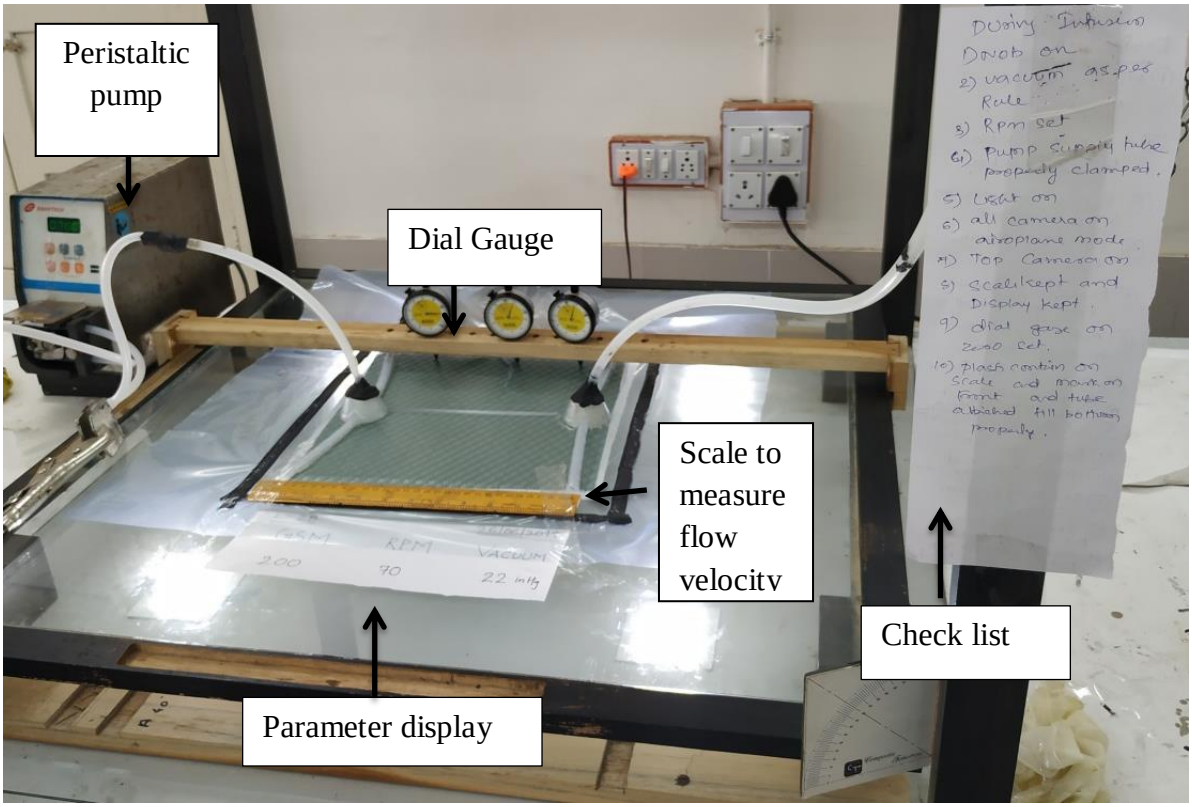


Figure 10 Experiment set up with variation in GSM, RPM of peristaltic pump and amount of vacuum supply

5. Measurements and Testing

Measurement and testing were performed in two stages. The measurements performed during experiments were considered as **in-process measurement**, whereas after conducting experiments, they were considered as **post-process measurement and testing.**

Thickness measurement during flow, flow velocity and flow rate measurements were part of in-process measurement. Tensile test, flexural test, cured laminate thickness measurement,

microscopic examination, weight measurement, density measurement and measurement of fiber volume fraction (FVF) were part of post-process measurement and testing. Specific tests were only performed for specific sets of experiments. In this section, details of all the measurements and testing methods have been explained.

5.1 In-process measurement

5.1.1 Measurement of thickness variation during flow

Variation in laminate thickness during flow was measured with dial gauge and front camera as shown in Figure 12. The dial was set to zero before actual impregnation and the camera was used to observe the variation in dial during the actual flow. There were three dial gauges placed with special fixture to measure the variation in part thickness at inlet, middle and outlet during flow. The special fixture was developed shown in Figure 11, which was held by glass frame and inclined at any angle.

Figure 11 Fixture to measuring thickness variations during the flow

5.1.2 Resin flow velocity measurement

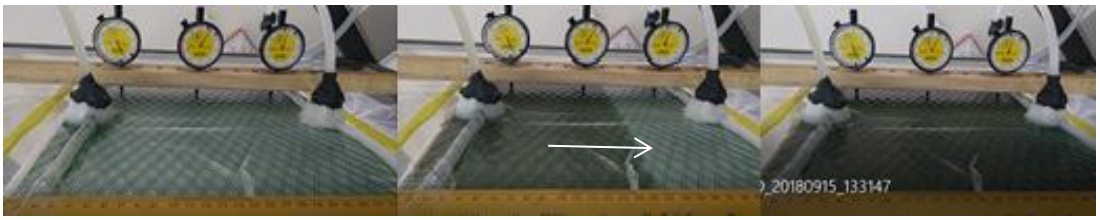


Figure 12 Flow velocity and thickness variation during the flow

Flow velocity was measured during the unsaturated/transient flow by front camera. Figure 12 shows photographs of before, during and after impregnation. The velocity was measured as time required by resin to reach from supply to vacuum line. The scale was kept along the length of laminate. Front and top camera were used to record distance travel by resin in given period of time. The velocity was considered as an average velocity.

5.1.3 Flow rate

Flow rate measurement was performed to measure the amount of flow moving during unsaturated condition. Flow rate was measured using weighing scale and resin container with volume marked inside the container with graduations. Peristaltic pump was set for particular RPM to control flow rate. Figure 13 depicts the method of measurements.

Figure 13 Flow rate measurement

5.2 Post-process measurement and testing

5.2.1 Tensile test

Tensile test was performed as per ASTM D 3039 (for thickness of laminate below 2.5 mm) and ASTM D 638 Type I for the laminate thickness below 7 mm and Type II for the laminate thickness above 7 mm) to measure ultimate tensile strength. It was performed in universal testing machine (TINIUS OLSEN/L-Series H50KL) at speed of 5 mm/minute. Five test coupons were cut from each laminate precisely with vertical blade cutting machine. Laminates were cut and held in universal testing machine as show in Figure 14. The tabs were applied for glass tesile test coupons for better gripping.

Figure 14 Tensile testing specimen & fixture details

5.2.2 Flexural test

Flexural test was performed on laminate as per ASTM D790. Five test coupons were cut from each laminate to get average flexural strength. As per para 7.5 of ASTM D790 span to depth ratio has been selected as 16:1. The three point bending test was performed with keeping minimum overhanging of 10%. Universal tensile testing (TINIUS OLSEN/L-Series H50KL) was used to perform flexural testing with speed of 5 mm/min as shown in the Figure 15.

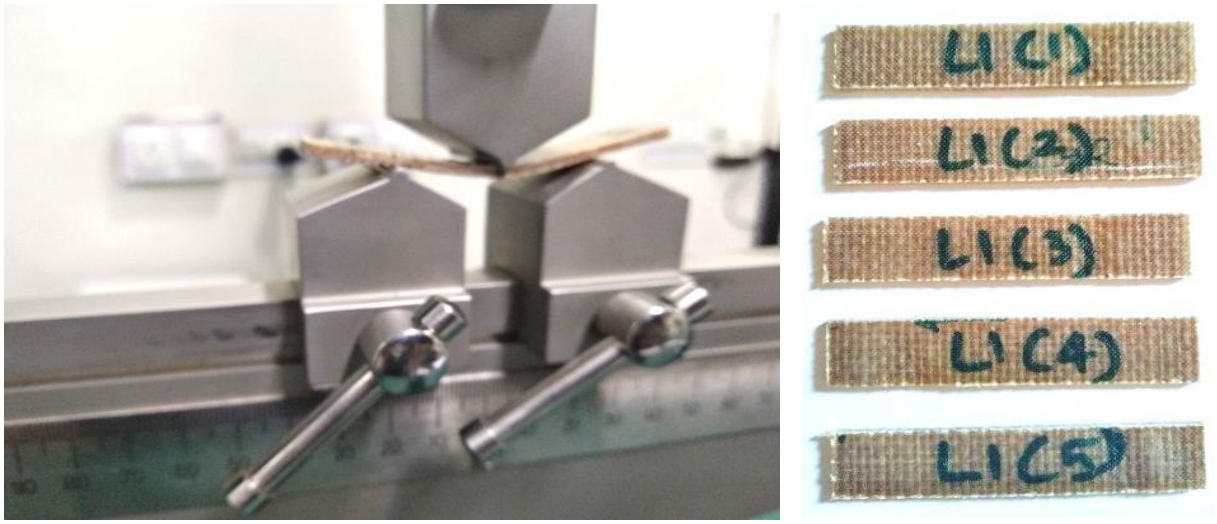


Figure 15 Flexural testing specimen and fixture details

5.2.3 Measurement of thickness variation of cured laminate

As shown in Figure 16, at 25 locations, part thickness was measured with mechanical comparator and variation in part thickness was studied for a laminate. Dial gauge with 0.01 mm least count was used to measure the laminate thickness on flat surface.

Figure 16 Measuring laminate with mechanical comparator

5.2.4 Microscopic examination

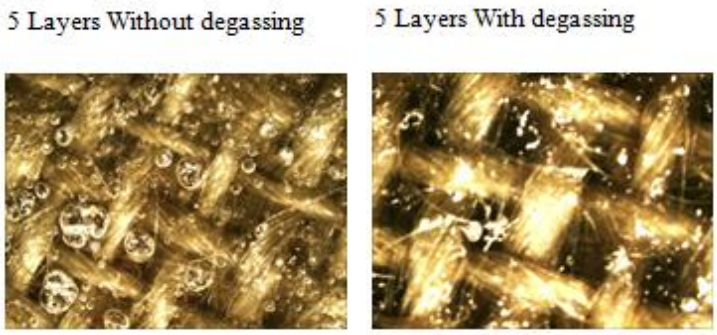


Figure 17 Microscopic examination

Degassing of resin mixture was performed to remove possible air bubbles, which would have generated during the mixture of resin with hardener or due to exothermic reaction. Degassing was performed for polyester resin for full vacuum for 3 minutes at room temperature after mixing resin with hardener and accelerator. Six micrographs of six laminates, made up of different numbers of layers with 180X magnification were captured with Nikon SMZ1000 microscope. First three laminates were impregnated before degassing and last three laminates were impregnated after degassing. Figure 17 shows micrographs with and without degassing for laminate made up of 5 layers.

5.2.5 Weight fraction

Weight fraction was performed in two different ways. For synthetic fibers laminate, loss of ignition method was used, whereas for natural fibers laminate, solvent method was used to measure weight fraction.

5.2.5.1 Weight fraction by Loss of Ignition method

The test was performed as per ASTM D 2584 – 94. Three test coupons of size 25 mm X 25 mm were used to perform the test. The test coupons were measured in weighing scale with crucible and weight (w_1) was been noted. After this the test coupons were kept at 565 ± 28°C for two hours in muffle furnace. The resin evaporated and the weight of fabric (w_2) was noted after two hours from removing them from furnace. Figure 18 shows weight fraction determination by loss of ignition method.

Figure 18 Weight fraction by LOI method for glass fabric. a) Weighing of glass laminate b) putting in muffle furnace 3) weighing fabric after keep in furnace for 2 hours at 565 +/- 28° C

5.2.2.2 Weight fraction by solvent method

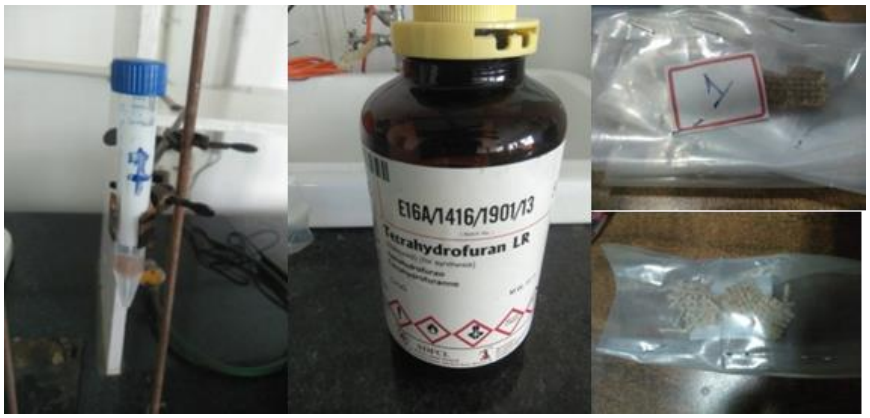


Figure 19 Weight fraction by solvent method for jute-polyester laminate

For the laminate prepared by natural fiber, weight fraction cannot be measured using loss of ignition method. There is no standard code available to perform fiber weight fraction for natural fibers. To calculate fiber weight fraction fibers were dipped inside the THF (Tetra Hydro Furan) solution for 48 hours. The weight of laminate before dipping (w_1) and weight fabric after removing from solvent (w_2) was measured. It was not very accurate method as some part of resin was stuck on the fabric. Figure 19 shows weight fraction by solvent method.

5.2.6 Density measurement

Figure 20 Composite density measurements

The density of composite laminate can be determined by dry & wet weight method as per ASTM D792. To measure the density of composite a density measuring kit was used. As shown in Figure 20, 25 mm X 25 mm test coupon was cut and weighting of test coupon was done in air and in demineralize water. The density of demineralize water was considered as 0.997 g/cc. The least count of weighing scale was 0.0001 g. The equation used to measure the density of composite laminate was

$\rho = [A/A-B] * \rho_L$

ρ = Density of the sample ρ_L = Density of auxiliary Liquid

A = Weight of the sample in air B = Weight of the sample in the auxiliary liquid

5.2.7 Fiber volume fraction

Volume fraction can be calculated by rule of mixture method. Let,

Vc = Volume of Composite, Vf = Volume of fiber, Vv = Volume of void

ρc = density of composite (mass/volume), ρf = density of fiber, ρm = density of matrix,

Mf = Mass of fiber, Mc = mass of composite, Mr = Mass of resin

vf = volume fraction of fiber, vm = volume fraction of matrix, vv = volume fraction of void

$$Vc = Vf + Vm + Vv \quad \text{(1)}$$

$$1 = \frac{Vf}{Vc} + \frac{Vm}{Vc} + \frac{Vv}{Vc} \quad \text{(2)}$$

$$1 = vf + vm + vv \quad \text{(3)}$$

so, volume fraction for fiber can be calculated as

$$Vf = \frac{Mf\ X\ \rho c}{\rho f\ X\ Mc} \quad \text{(4)}$$

6. Results and Discussion

Experimental results of in-process measurements and post-process measurement and testing for all sets of experiments have been discussed in this section. The effect of input parameters, on output parameters has also been discussed.

6.1 Investigations on number of layers, location of resin supply and position of vacuum supply for VARTM Process

Investigation was carried out on number of layers, location of resin supply and position of vacuum supply. The response parameters were 1) tensile test 2) flow velocity 3) weight fraction and 4) thickness variation of cured laminate. Jute fabric and polyester resin were used to perform experiments.

Table 3 displays details of experiments, designed based on Taguchi L(9) orthogonal array, parameters, their levels, tensile strength and flow velocity details.

Table 3 Effect of number of layers, position of resin supply and location of vacuum supply

Laminate Identification	Number of Layers	Position of Resin Supply	Vacuum Supply Location	Tensile Strength MPa	Flow Velocity (max) mm/s
4TEC	4	Top	Edge Centre	63.12	6.25
4BCE	4	Bottom	Centre Edge	48.63	5.55
4MLR	4	Middle	Left – Right	47.61	8.33
5TCE	5	Top	Centre Edge	52.56	4.32
5BLR	5	Bottom	Left – Right	59.23	7.16
5MEC	5	Middle	Edge Centre	63.41	3.33
6TLR	6	Top	Left – Right	29.53	8.13
6BEC	6	Bottom	Edge Centre	50.04	6.16
6MCE	6	Middle	Centre Edge	54.20	5.83

The main effect plots for tensile strength and flow velocity are shown in Figures 21 and Figure 22 respectively. Effect of thickness variation is shown by bar graph in Figure 23.

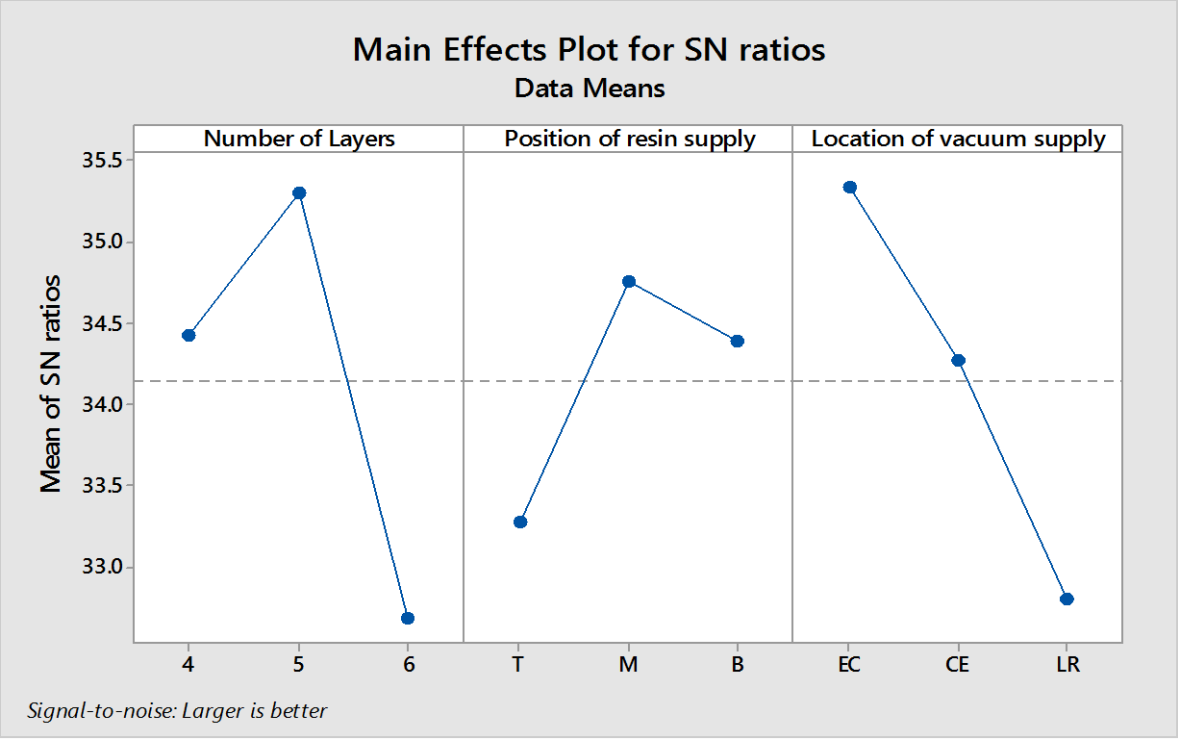


Figure 21 Effect of parameters on tensile strength (MPa)

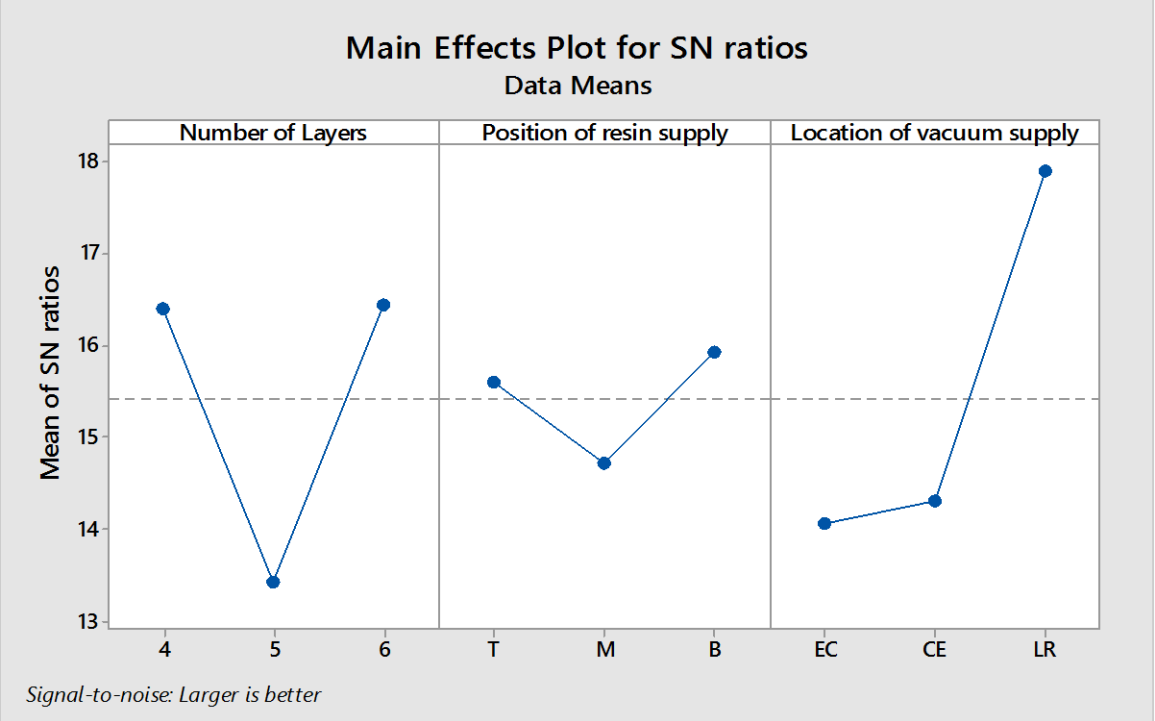


Figure 22 Effect of parameters in flow velocity (MPa)

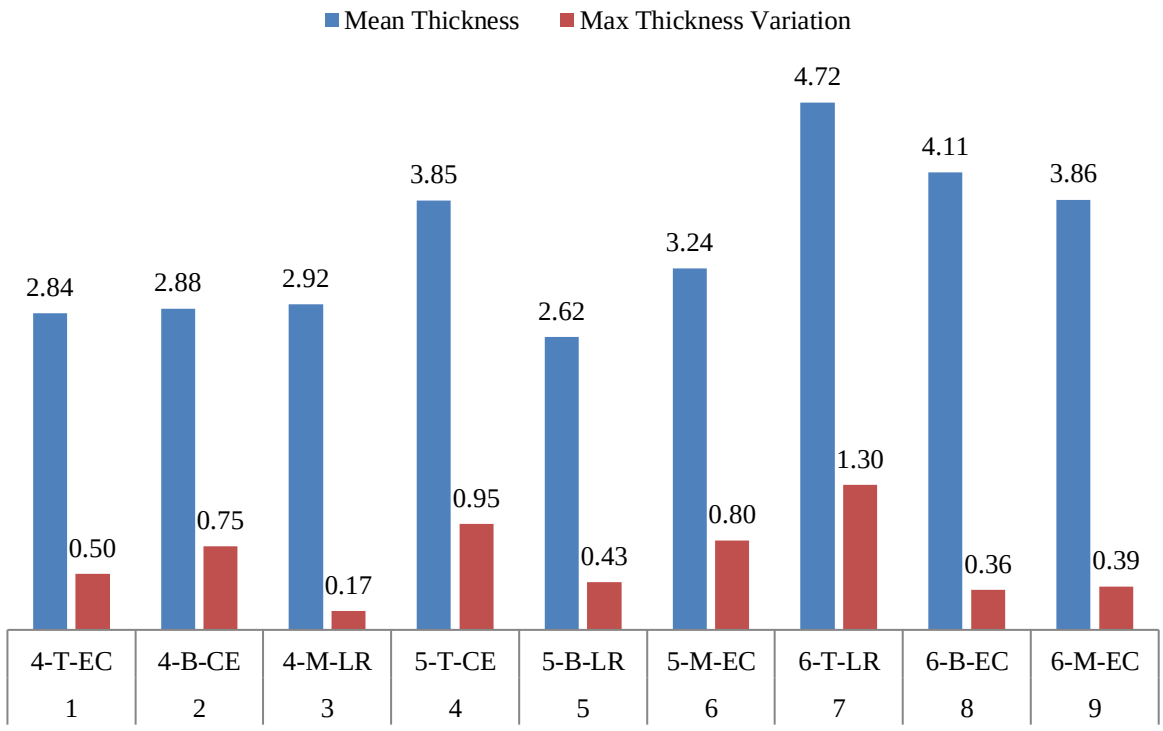


Figure 23 Laminate average thickness and thickness variation

Minitab 17 software was used to perform calculation based on design of experiments with Taguchi L(9) approach. Tensile tests were performed as per ASTM D 3039. As shown in Figure 21, tensile strength was more when numbers of layers were 5, position of resin supply

was at middle and vacuum supply location was from edge. As per Figure 22, maximum flow velocity was observed when number of layers was 4, resin supply was from top and vacuum supply was from centre. The resin supply location is an important parameter to increase the flow velocity. This was in agreement with experiments performed by Rigas et al. (Rigas et al. 2001) who concluded that elevation of resin feed source relative to part has significat effect on infusion time. However, maximum flow velocity does not ensure high strength in laminate. The quality of laminates depends on how well the resin is equally distributed between and within tows.

From thickness variation study it was observed that as number of layers increased thickness variation increased. The fiber weight fraction upto 70% was achieved by THF solution method. From this set of experiments it is observed that, position of resin supply should be in middle and vacuum supply should be from edge to centre. However for the next set of experiment it was practically difficult to perform experiment from edge to centre and hence left to right approach was chosen. The numbers of layers chosen for next set of experiments were 5, 10 and 15.

6.2 Investigations on degassing and number of layers for VARTM process

Effect of degassing was studied performing six experiments as mentioned in Table 4. For each laminate 1) flow velocity 2) tensile strength 3) flexural strength 4) weight fraction 5) thickness variation in laminate 6) microscopic examination was performed. Jute fabric with polyester resin was used to perform experiments.

Table 4 Vacuum degassing experiments with changing number of layers

Laminate Identification	Laminate Detail	Fabric Weight fraction (%)	Flow velocity (mm/s) Average	Tensile Strength (MPa)	Flexural Strength (MPa)
5LWOD	5 Layers, without degassing	36.5	30	47.7	104.4
10LWOD	10 Layers, without degassing	34.2	45	47.93	95.67
15LWOD	15 Layers, without degassing	31.6	165	60.92	85.18
5LWID	5 Layers, with degassing	39.3	40	50.60	115.12
10WID	10 Layers, with degassing	37.2	45	59.10	99.83
15LWID	15 Layers, with degassing	39.8	122	61.53	91.06

Weight fraction of fabric was improved after degassing. Flow velocity was reduced after degassing. Flow velocity was higher at resin supply location and gradually reduced at vacuum supply side. Flow velocity gradient was observed during impregnation for 15 layered laminate between top and bottom layers. Top layer side velocity was higher than bottom layer side. This observation was in line with observations found by Rigas et al. 2001. (Rigas et al. 2001)

Figure 24 shows effect of input parameters, number of layers and degassing on tensile strength. It has been observed that the tensile strength has increased by 6%, 23% and 1% for 5, 10 and 15 layers with degassing. This is in line with observations made by Li, W. et al.(Li W. et al 2004).

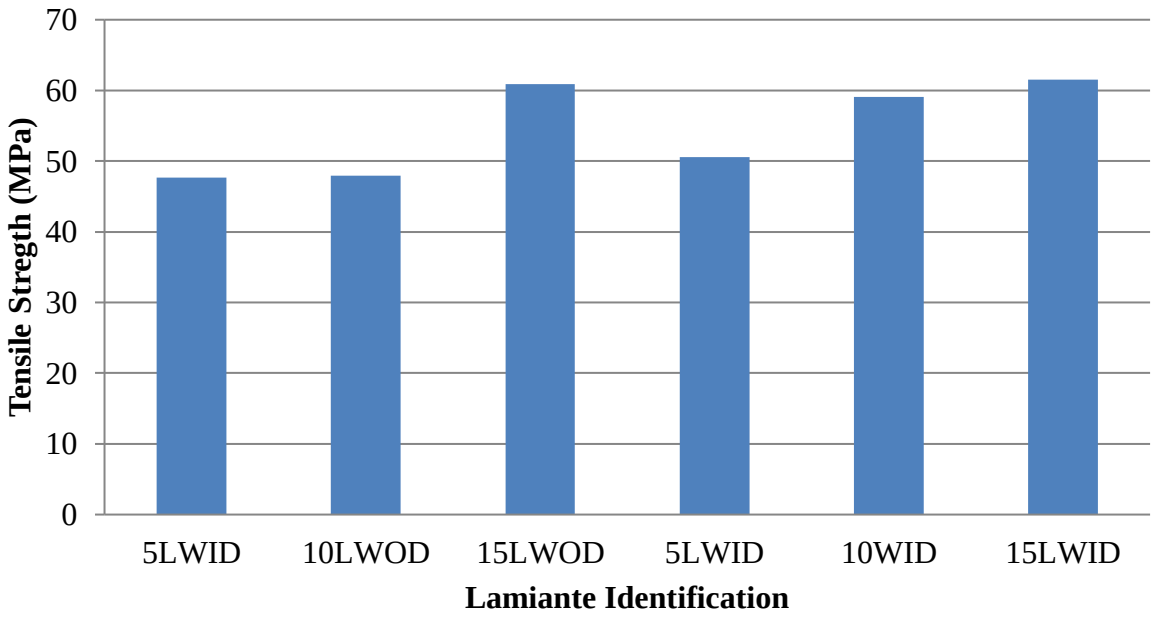


Figure 24 Tensile strength with and without degassing

Figure 25 shows effect of degassing and number of layers on flexural strength. Flexural strength increased by 10%, 4% and 7% for 5, 10 and 15 layers respectively with degassing.

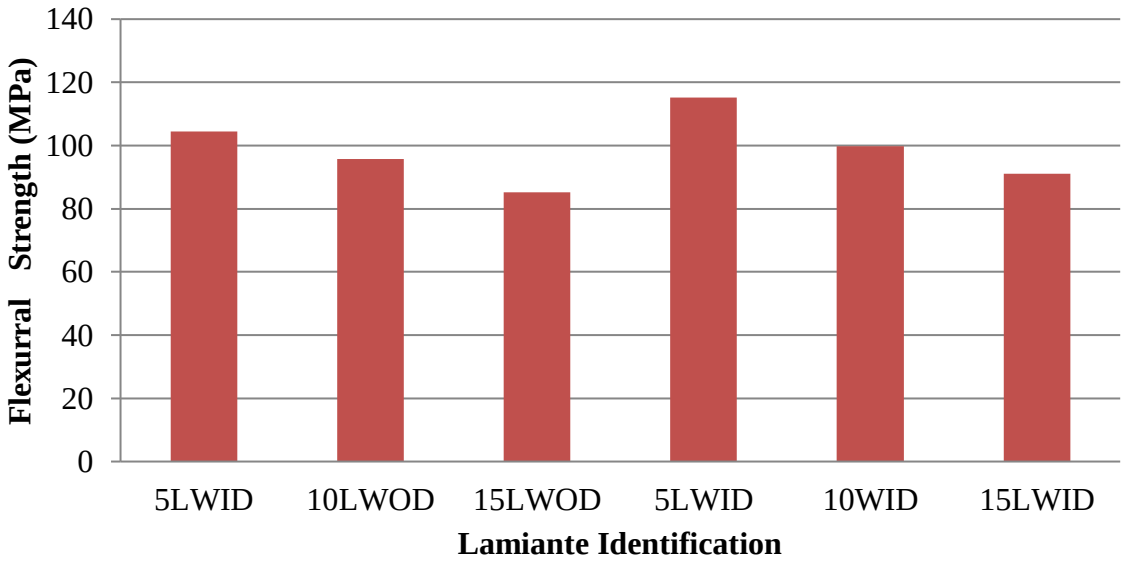


Figure 25 Flexural strength with and without degassing

Thickness variation in laminate during resin flow was observed in higher number of layers. Thickness variation in cured laminate increased, as number of fabric layers increased, which is shown in Figure 26. Effect of degassing was not observed on thickness variation.

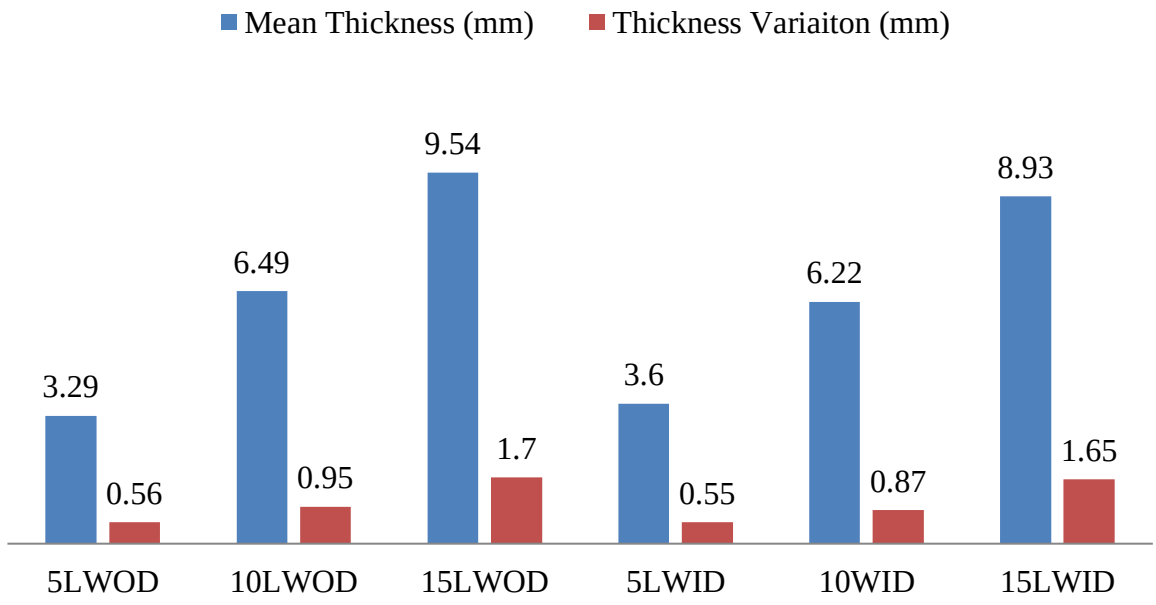
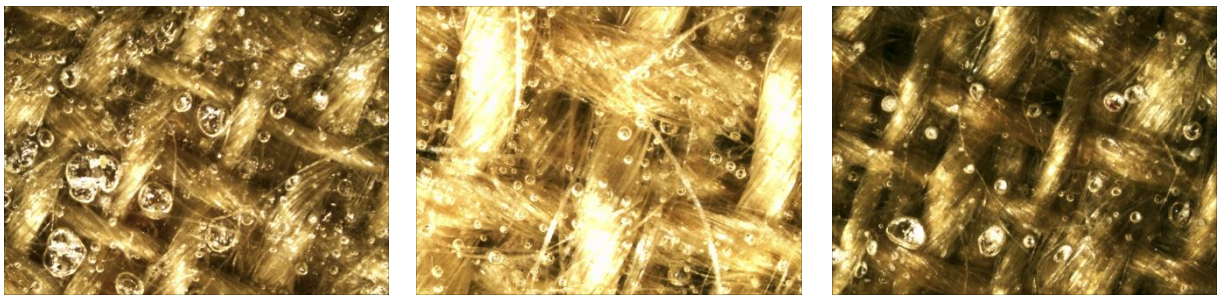


Figure 26 Average laminate thickness variations (mm) with and without degassing

Void inside the laminate was reduced significantly after degassing, which was observed by 180X microscope. Figure 27 depicts the picture showing void content for various laminates. It is evident from Figure 27 that void content reduced considerable after degassing which was

in line with observations fond by Yalcinkaya et al.(Yalcinkaya, Sozer, and Altan 2017). As shown in Figure 28, there was change in color of laminate before and after degassing.

Laminate 1, 5LWOD Laminate 2, 10LWOD Laminate 3,15LWOD



Laminate 4, 5LWID Laminate 5, 10LWID Laminate 6, 15LWID

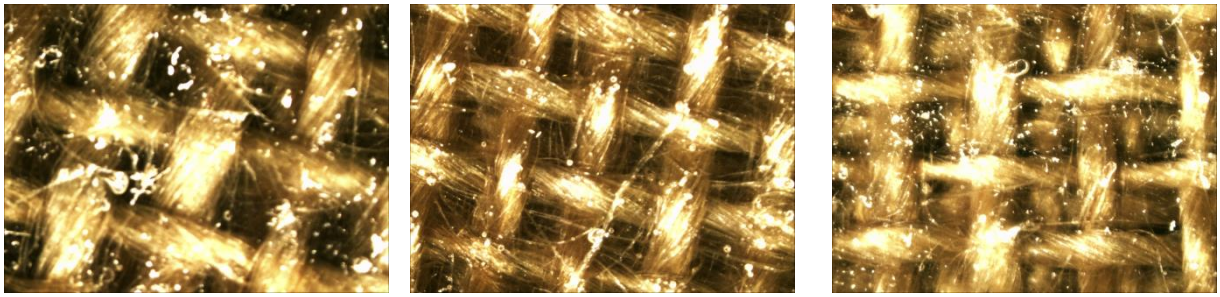


Figure 27 Air entrapments before and after degassing in laminates

Figure 28 Color of laminate with and without degassing

6.3 Investigations on number of layers, inclination of table and amount of vacuum supply for VARTM process

This set of experiments was performed with Jute fabric and polyester resin. Experiments were performed to study the effect of gravity with changing inclination of table and varying amount of vacuum supply. Parameter taken common from previous experiment was variation in number of layers. Taguchi L(9) orthogonal array was used to design experiments. 1) Tensile test 2) flexural test 3) thickness variation 4) fiber weight fraction and 5) flow velocity study was performed to find effect of input parameters as shown in Table 5.

Table 5 Taguchi L(9) approach with varying number of layers, inclination of table and vacuum

Laminate Identification	Parameters (Number of layers, inclination of table, amount of vacuum supply)	Average Tensile strength (MPa)	Average Flexural Strength (MPa)	Average Thickness (mm)	Thickness Variation (mm)	Fiber Weight fraction (%)	Flow velocity Average (mm/s)
4P0I29V	4-0-29	50.30	81.92	2.39	0.1	0.35	10.00
4P20I22V	4-20-22	52.04	87.40	2.65	0.1	0.35	2.50
4P40I15V	4-40-15	48.14	74.84	2.83	0.2	0.34	4.30
8P0I22V	8-0-22	59.70	80.28	5.06	0.3	0.38	5.70
8P20I15V	8-20-15	56.34	79.34	5.31	0.2	0.37	2.70
8P40I29V	8-40-29	58.90	80.64	5.01	0.1	0.38	7.50
12POI15V	12-0-15	60.28	92.50	8.38	0.2	0.35	2.50
12P20I29V	12-20-29	58.54	60.00	7.31	0.2	0.44	10.70
12P40I22V	12-40-22	42.36	47.73	9.00	0.5	0.41	5.00

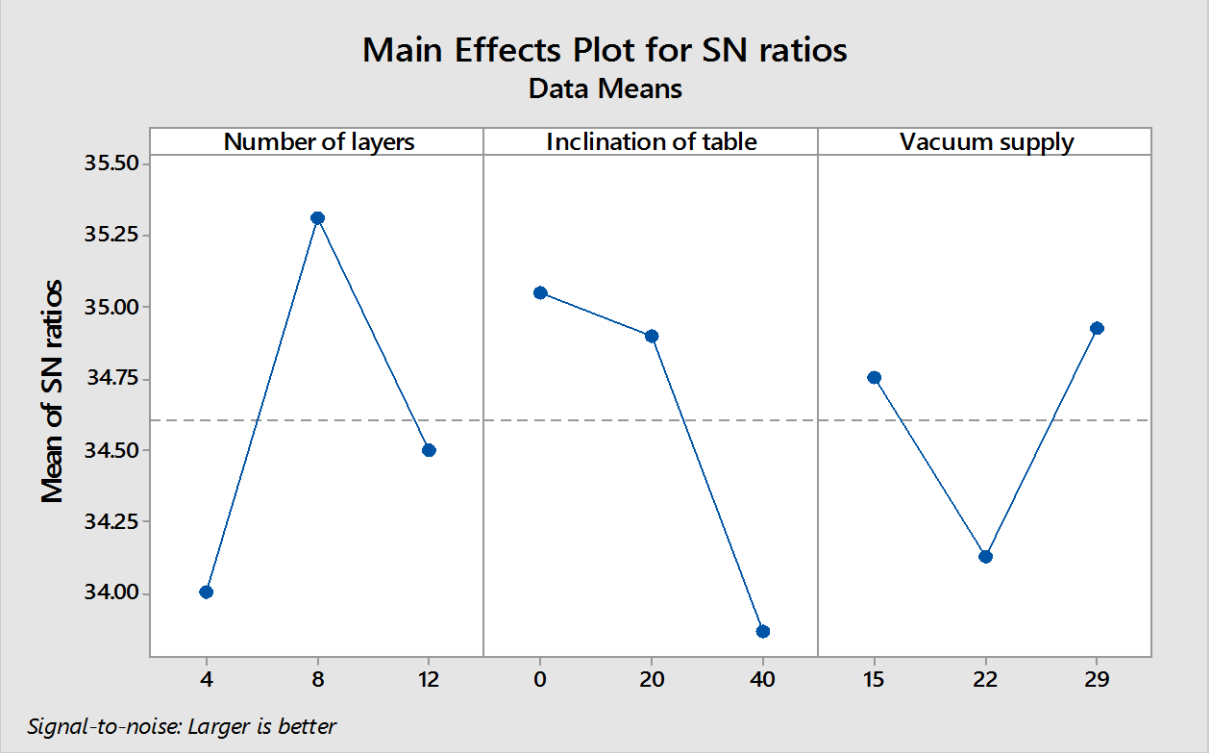


Figure 29 Main plots for tensile strength (MPa)

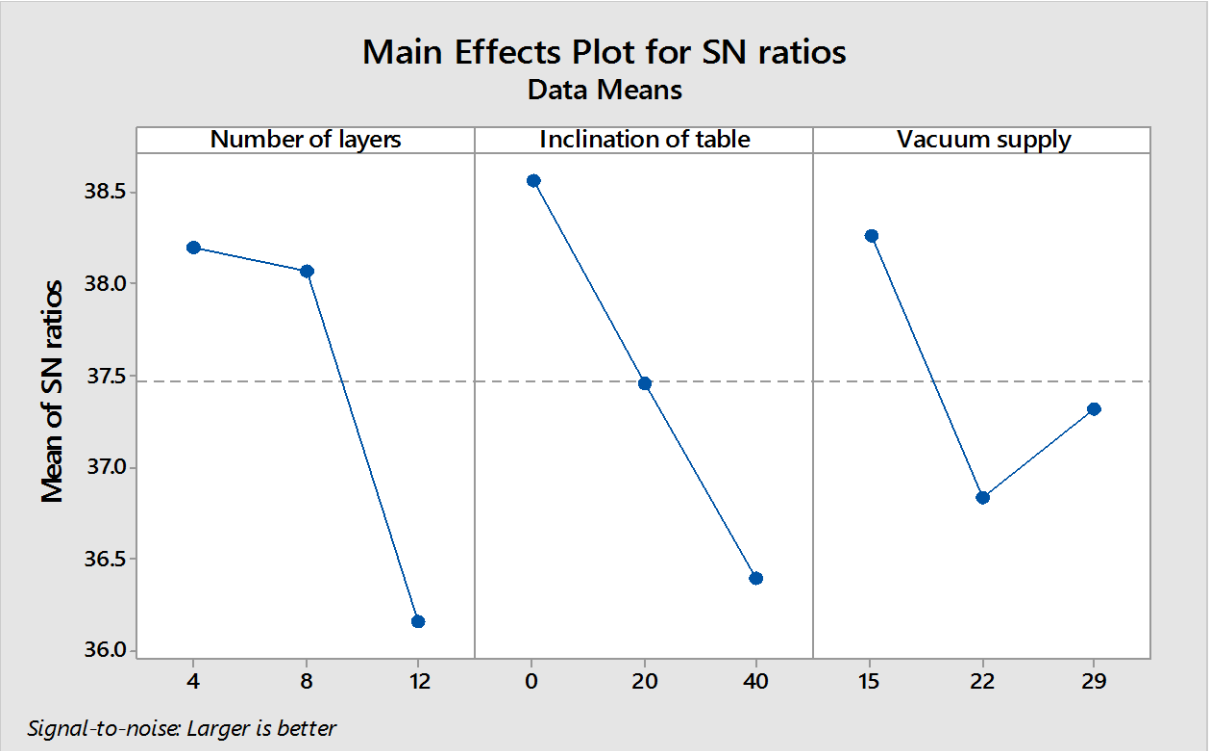


Figure 30 Main plots for flexural strength (MPa)

It was observed from Figure 29, that tensile strength was high for 8 numbers of fabric layers, 0° inclination of table and at full vacuum. High tensile strength at high vacuum was also observed by Chokka et al. (Chokka, Ben, and Srinadh 2019). As shown in Figure 30, flexural strength was high at 4 numbers of fabric layers, at 0 ° inclination of table and at 15 in Hg vacuum. The flexural strength was inversely proportional to thickness, as for four layers, it showed maximum value.

For 4 layers and 8 layers, there was no change in the thickness, during resin flow. However, for 12 layers, there was variation in part thickness during the flow of about 0.12 mm, 0.08 mm and 0.08mm in three dials respectively at 0° inclination of glass table.

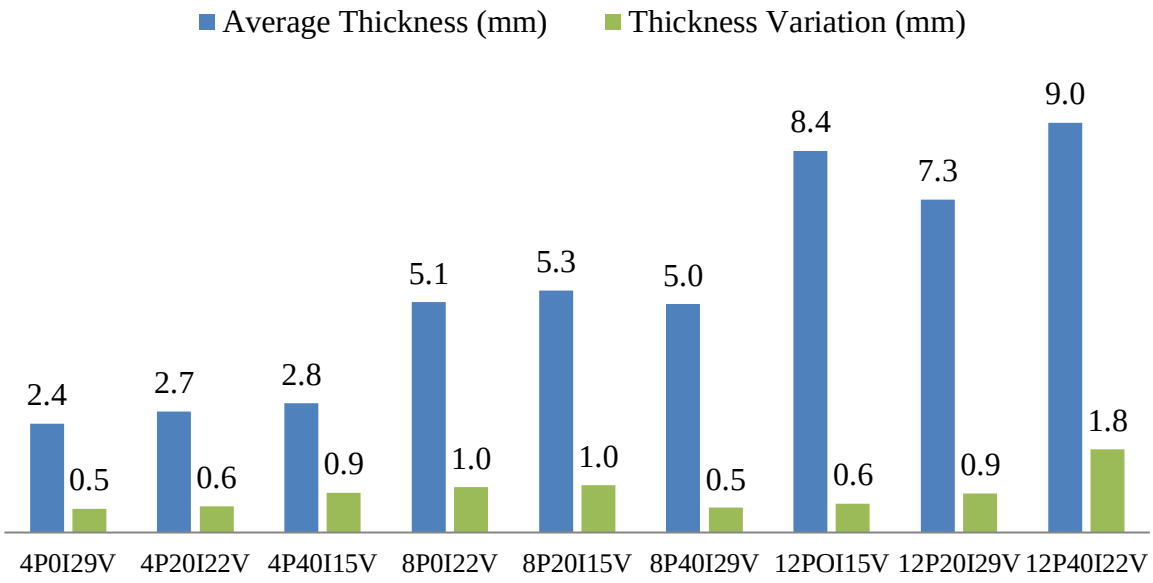


Figure 31 Thickness variations in cured laminate

The thickness variation in laminate increased as number of layers increased. The worst case found was for 12P40I22V. This might be due to more layers and high inclination; proper compaction would not have been achieved. It should be noted that, as number of layers and inclination of table increased, to manufacture the components by VARTM became difficult. Leak rate increased significantly from sealant tape and to hold the required vacuum may become challenging. Amount of vacuum played a major role in flow during impregnation. Fiber weight fraction increased as number of layers increased.

6.4 Investigations on variation in GSM of glass fabric, RPM of peristaltic pump and amount of vacuum supply for VARTM process

Experiments were performed to study effect of areal weight of fabric, RPM of peristaltic pump and amount of vacuum supply. Glass fabric along with polyester resin was chosen as material for conducting experiments. Full factorial design approach was considered while designing the experiments. Total 27 experiments were performed with three variables and three levels. Result of 1) flow velocity 2) tensile strength 3) flexural strength 4) thickness variation 5) volume fraction is depicted in Table 6.

Table 6 Results of full factorial design with varying GSM, RPM and vacuum

Laminate Id.	GSM	RPM	Vacuum (in mg)	Flow Velocity (mm/sec)	Tensile strength (MPa)	Flexural Strength (MPa)	Average thickness (mm)	Range (mm)	Volume Fraction (%)
2G7R15V	200	70	15	3.6	305	163	1.0	0.28	0.43
2G7R22V	200	70	22	8.1	309	180	1.0	0.37	0.44
2G7R29V	200	70	29	4.9	276	130	1.0	0.36	0.52
2G9R15V	200	90	15	2.1	253	148	1.0	0.5	0.41
2G9R22V	200	90	22	6.7	285	168	1.0	0.33	0.44
2G9R29V	200	90	29	6.8	276	141	1.0	0.41	0.46
2G11R15V	200	110	15	5.9	273	138	1.0	0.16	0.44
2G11R22V	200	110	22	3.1	274	165	1.0	0.37	0.45
2G11R29V	200	110	29	5.7	266	157	0.9	0.32	0.45
4G7R15V	400	70	15	4.1	357	222	1.6	0.42	0.50
4G7R22V	400	70	22	2.8	313	189	1.6	0.46	0.34
4G7R29V	400	70	29	7.2	449	172	1.6	0.46	0.53
4G9R15V	400	90	15	5.4	359	189	1.5	0.27	0.53
4G9R22V	400	90	22	3.6	363	200	1.6	0.42	0.51
4G9R29V	400	90	29	3.8	362	209	1.5	0.34	0.50
4G11R15V	400	110	15	5.6	344	154	1.6	0.45	0.52
4G11R22V	400	110	22	6.4	375	160	1.5	0.27	0.52
4G11R29V	400	110	29	2.6	352	190	1.5	0.46	0.54
6G7R15V	600	70	15	3.6	419	149	2.3	0.77	0.57
6G7R22V	600	70	22	4.8	327	132	2.3	0.65	0.57
6G7R29V	600	70	29	5	415	111	2.7	0.87	0.45
6G9R15V	600	90	15	5.5	349	110	2.8	0.86	0.44
6G9R22V	600	90	22	5.9	328	126	2.2	1.03	0.56
6G9R29V	600	90	29	6.5	409	148	2.2	0.45	0.55
6G11R15V	600	110	15	6.1	367	125	2.2	0.52	0.57
6G11R22V	600	110	22	7.4	375	173	2.4	0.71	0.54
6G11R29V	600	110	29	4.6	381	123	2.2	0.55	0.44

Flow velocity was varied from 8.1 to 2.1 mm/sec. There may be multiple reasons why flow velocity was having such variation. One of the prominent reasons might be resin viscosity, after mixing and before gelation there is a viscosity window within which, if resin would be impregnated it will flow within and between tow. However it was difficult to control exact timing after mixing, after degassing and before impregnation. Hence specific conclusion from trend of flow velocity values was arduous.

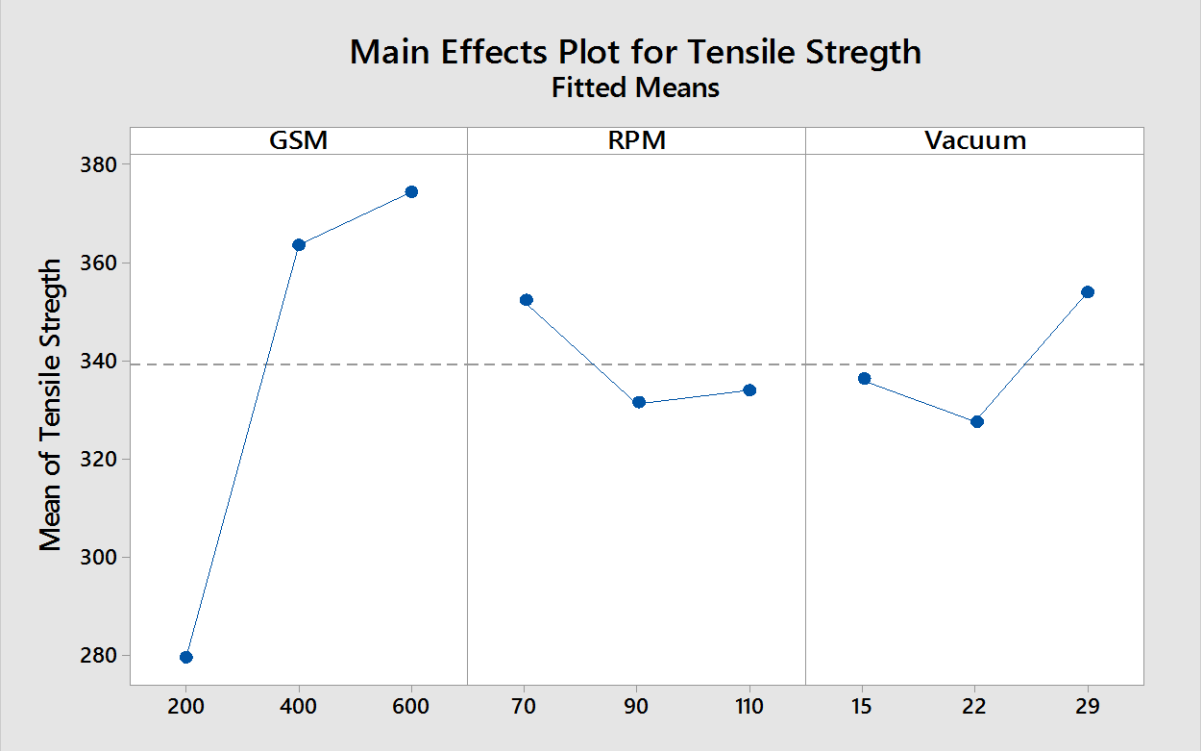


Figure 32 Main plot for tensile strength (MPa)

As shown in Figure 32 as GSM of fabric is most significant parameter for achieving high tensile strength. Also as RPM reduced, tensile strength increased and as vacuum increased tensile strength increased. As per interaction plot, shown in Figure 33, only GSM and vacuum has interaction with each other. It is important to note that, GSM and vacuum together founds to be significant contributor.

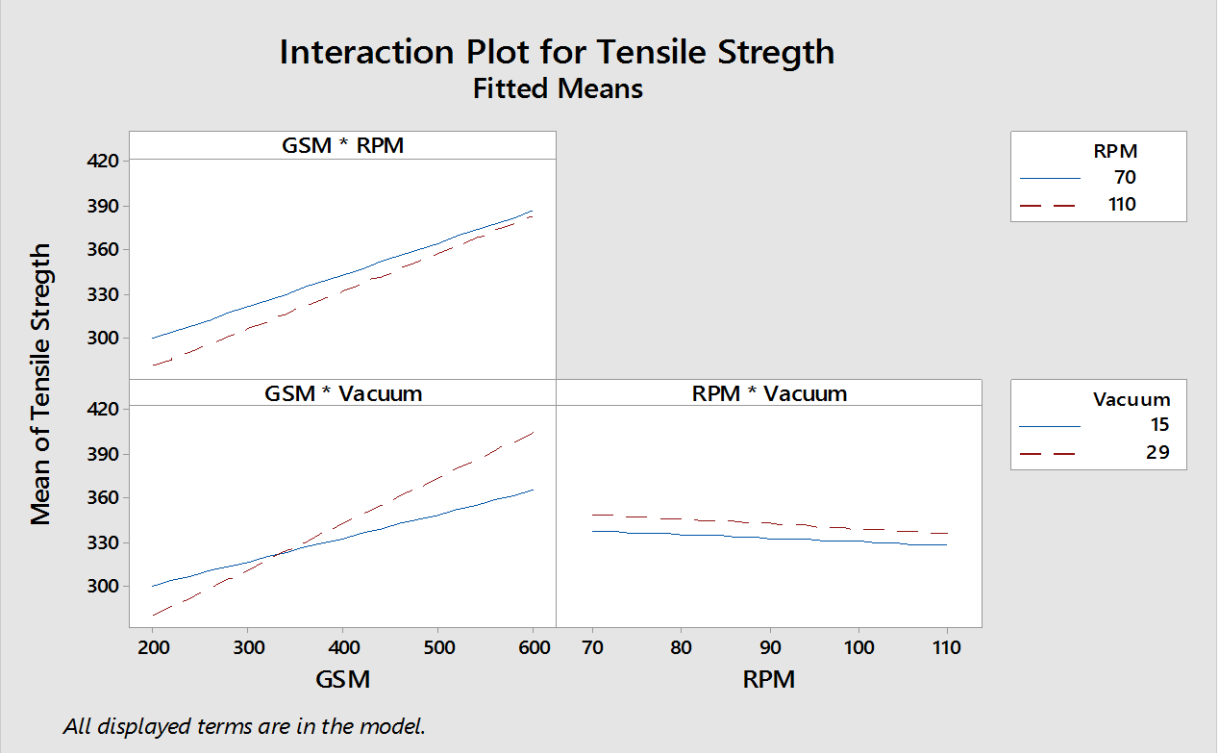


Figure 33 Interaction plot for effect of tensile strength (MPa)

ANOVA analysis has been performed to identify significant input parameters and their interaction affecting the VARTM process. As shown in Table 7, P value is less than 0.005 for 95% confidence interval for GSM and GSM *Vacuum.

Table 7 Analysis of Variance for Tensile strength (MPa)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	44401.7	7400.28	27.28	0.000
GSM	1	117.7	117.68	0.43	0.003
RPM	1	104.0	103.97	0.38	0.543
Vacuum	1	239.0	239.02	0.88	0.359
GSM*RPM	1	180.2	180.18	0.66	0.425
GSM*Vacuum	1	2726.9	2726.93	10.05	0.005
RPM*Vacuum	1	5.5	5.49	0.02	0.888
Error	20	5425.3	271.26		
Total	26	49826.9			

Model Summary:

S	R-sq	R-sq(adj)	R-sq(pred)
16.4701	89.11%	85.85%	80.59%

Regression Equation:

$$\text{Tensile Strength} = 372.8 - 0.087\,GSM - 0.561\,RPM - 3.18\,Vacuum + 0.00097\,GSM * RPM + 0.01077\,GSM * Vacuum - 0.0048\,RPM * Vacuum$$

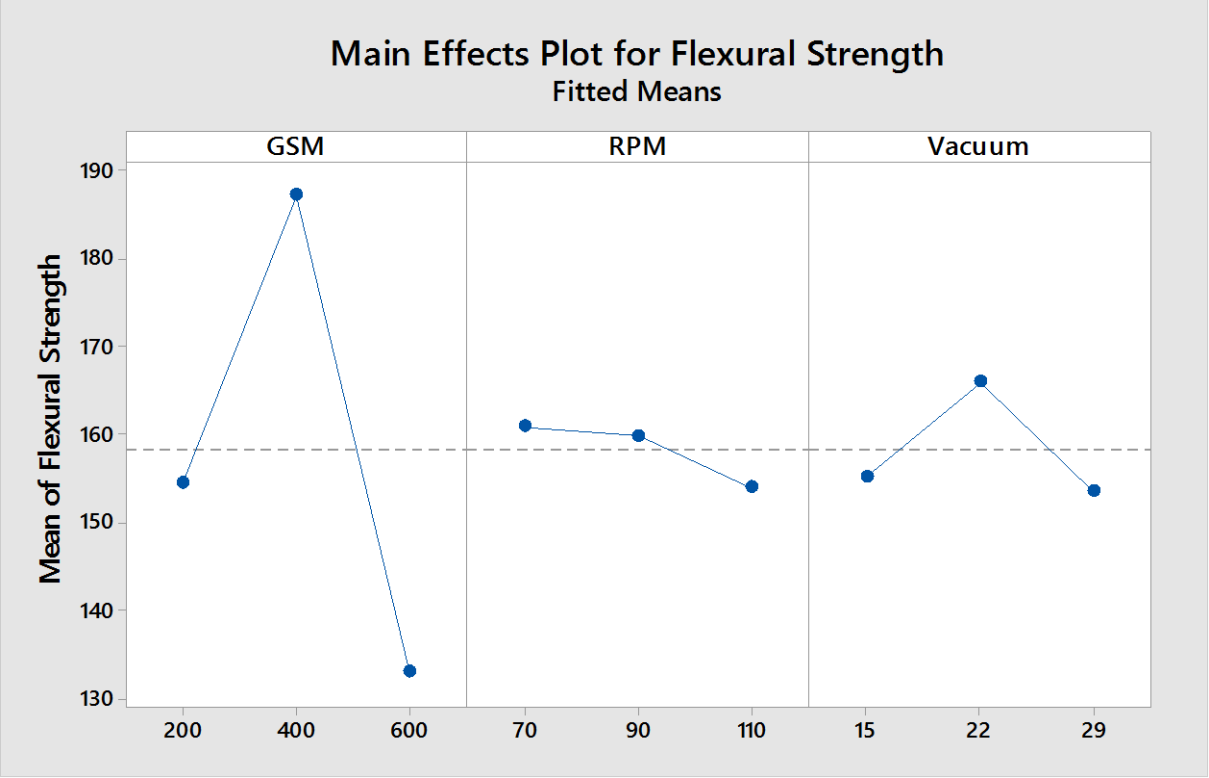


Figure 34 Main plot for effect of flexural strength (MPa)

Major parameter contributing to flexural strength was GSM of fabric. Flexural strength was high for 400 GSM, as shown in Figure 34. Less variation in flexural strength observed for RMP and vacuum. Interaction was found between all parameters as shown in Figure 35. Effect of interaction was found between RPM - GSM and RPM - Vacuum as shown in ANOVA Table 8.

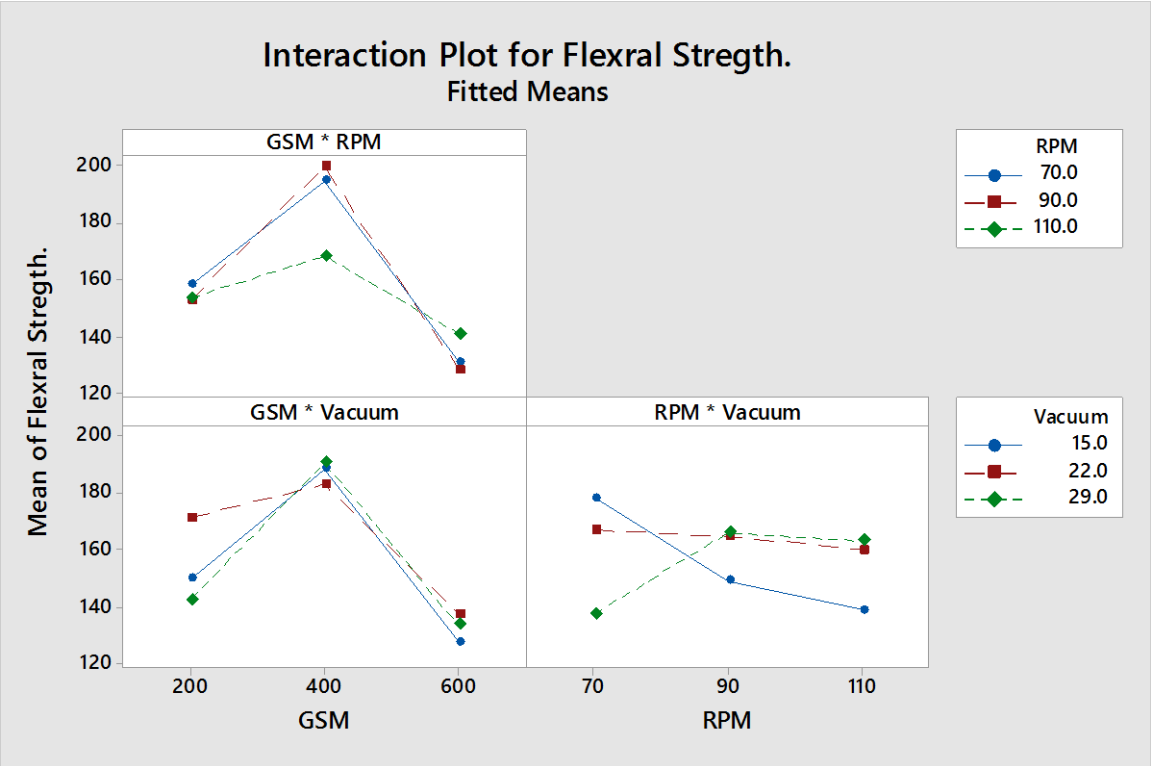


Figure 35 Interaction effect of flexural strength (MPa)

Table 8 Analysis of Variance for flexural strength (MPa)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	18	20665.6	1148.1	9.82	0.001
Linear	6	14050.0	2341.7	20.02	0.000
GSM	2	13372.5	6686.3	57.17	0.000
RPM	2	249.4	124.7	1.07	0.389
Vacuum	2	428.1	214.0	1.83	0.222
2-Way Interactions	12	6615.6	551.3	4.71	0.018
GSM*RPM	4	1766.6	441.6	3.78	0.052
GSM*Vacuum	4	1106.6	276.6	2.37	0.140
RPM*Vacuum	4	3742.4	935.6	8.00	0.007
Error	8	935.6	117.0		
Total	26	21601.2			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
10.8145	95.67%	85.92%	50.66%

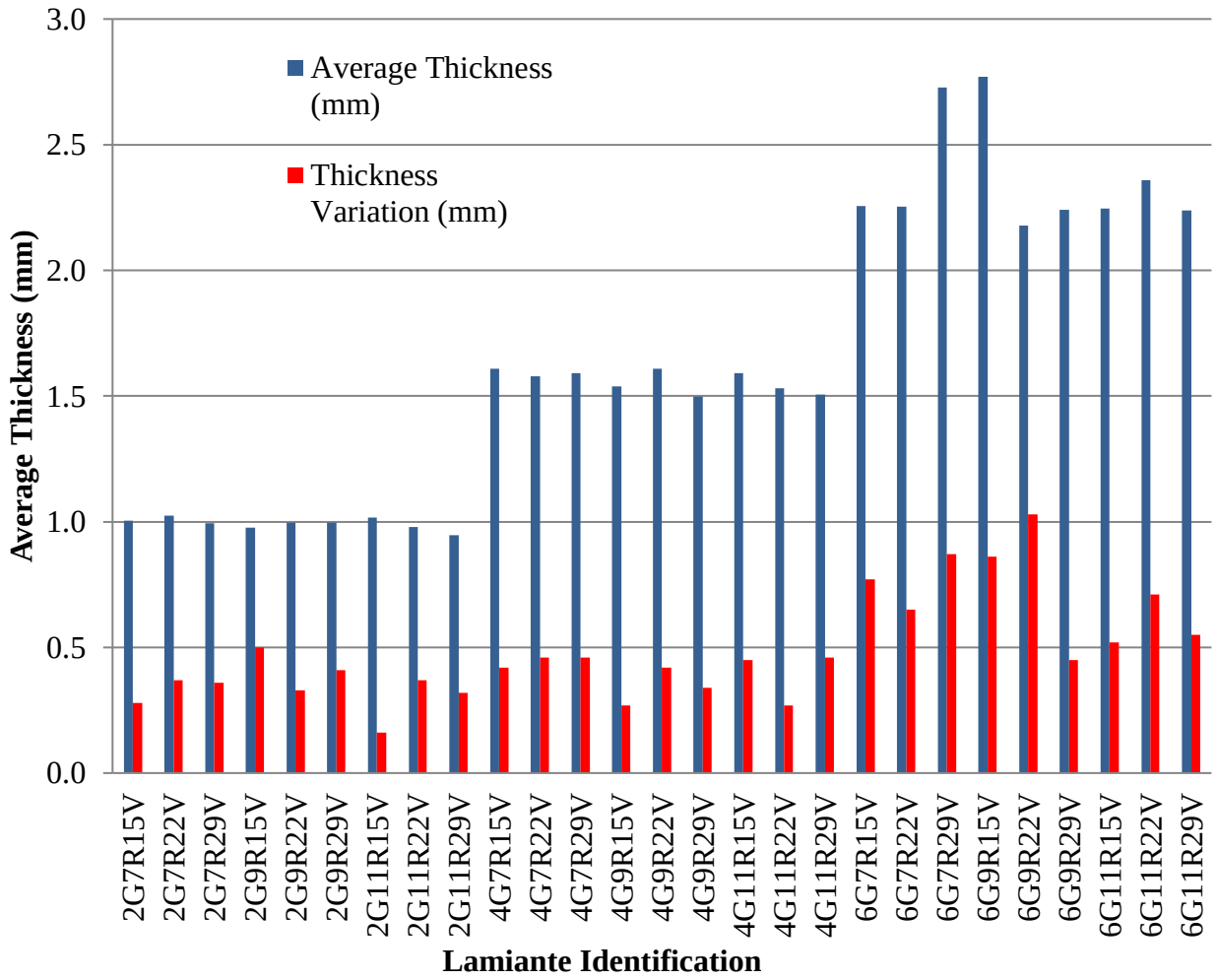


Figure 36 Average thickness and thickness variation of all laminates

As shown in Figure 36, thickness variation increased as fabric GSM increased. The maximum thickness variation was observed 1.03 mm in 6G9R22V laminate, whereas minimum thickness 0.28 mm was observed in 2G7R15V laminate. Laminate made up to 400 GSM, the variation does not increase much but for 600 GSM the variation increased up to 1 mm.

The Fiber volume fraction increased as GSM increased. Fiber volume fraction varied from 34% to 57 % with increased GSM.

7. Conclusion and Future Scope

From the above results, conclusion for sets of experiments conducted and future scope for VARTM process has been discussed in this section.

7.1 Conclusion

Among various manufacturing process for making FRP composites, VARTM is one of the popular manufacturing techniques, applicable for large scale FRP composites.

Preliminary experiments were conducted by developing basic experimental set up and learning from these experiments were used to conduct further sets of experiments.

It is identified that VARTM process involves many important parameters, which may be interdepended also.

Research review was performed to identify various parameters affecting VARTM process and critical parameters have been categorised as pre-process, in-process and post–process parameters. Among all these parameters, total 8 parameters were selected for conducting experiments which includes effect of number of layers, location of resin supply, position of vacuum supply, effect of degassing, effect of inclination of table, amount of vacuum supply, GSM of fabric and RPM of peristaltic pump.

Experiments were performed in four sets, excluding preliminary experiments. For every set of experiments, three parameters with three levels were chosen, except for degassing experiments, only two variables with three levels were chosen.

Indigenous experimental setup was designed and developed to perform these experiments. The learning while preforming experiments were well observed noted and incorporated in next set of experiments. Learnings have been highlighted in materials and method chapter.

Various designs available to conduct experiments were learnt by studying the concept of design of experiment. Taguchi L(9) and full factorial design were used to design experiments. Minitab 17 software was used to design and analyse experiments.

Process sheet and check list were developed before performing experiment to ensure conducting experiments error free. This can be used by any researcher working on VARTM.

For the use of natural fiber, jute fabric was chosen as reinforcement for conducting three sets of experiments. Glass fabric with different GSM was used, as reinforcement, for the last set of experiments. Polyester resin was used as matrix for all sets of experiments. The selection of materials was based on availability.

The response measurement was performed in two ways, in-process and post-process measurement and testing. During in-process measurement flow velocity, flow rate and thickness variation during flow was measured. For post-process tensile strength, flexural strength, thickness variation of cured laminate, microscopic examination, density measurement and fiber volume fraction were performed with applicable ASTM standards.

From the investigation of input parameters number of layers, position of resin supply and location of vacuum supply, it was concluded that,

- The maximum tensile strength was observed when numbers of layers were 5, position of resin supply from middle and vacuum supply location was from edge.
- As number of layers increased, better mechanical characteristics was achieved, however proper impregnation of resin is must otherwise chances of generating low quality laminates and variation in thickness increases.
- It has been found that by increasing flow velocity there is no effect on tensile strength.
- It is important that the resin should flow between and within the tow, to transfer the load.
- Solvent method was used to find fiber weight fraction for jute laminate and up to 70% fiber weight fraction was achieved.

From the investigations on degassing and number of layers following conclusions were derived.

- The flow velocity reduced after degassing. The flow velocity was higher at resin supply location and gradually reduced at vacuum supply side. The flow velocity gradient was observed in thick laminate with more numbers of layers. Top layer side velocity was higher compared to bottom.
- Mechanical properties improved after degassing. It was observed that the tensile strength increased by 6%, 23% and 1% for 5, 10 and 15 layers with degasing. Flexural strength increased by 10%, 4% and 7% for 5, 10 and 15 layers respectively with degasing.
- Thickness variation during resin flow was observed for laminate with more number of layers. Effect of degassing was not observed on thickness variation; however, as number of layers increased thickness variation increased in cured laminate.
- Void inside the laminate had reduced significantly after degassing which was observed in micrographs by 180X microscope.

From the investigations on number of layers, inclination of table and amount of vacuum supply, following conclusions were derived.

- Tensile strength was high when numbers of layers were 8, table inclination was at 0° and vacuum supply was 29 in Hg. For higher layers, more leak rate was observed near sealant tape and due to this tensile strength might have reduced at higher layers.
- Flexural strength was high when numbers of layers were 4, table inclination was at 0° and vacuum was 15 in Hg. As number of layers reduces, flexibility increases and hence flexural strength was found high in 4 layers.
- It was observed that flow velocity mostly depends on the amount of vacuum supply. It was very high when vacuum was 29 in Hg and low when amount of vacuum supply was 15 in Hg. This concludes that the flow velocity can be controlled by amount of vacuum supply.
- For 4 layers and 8 layers, there was no variation in the thickness, however for 12 layers there was variation in part thickness during the resin flow for 0° inclination of glass table.
- It was observed that as supply vacuum increases up to 29 in Hg, the variation in part thickness reduces in cured laminate.

From the investigations on variation in GSM of glass fabric, RPM of peristaltic pump and amount of vacuum supply, following conclusions were derived.

- For tensile strength, vacuum played major role, whereas GSM and vacuum to gather founds to be significant contributor.
- For flexural strength as GSM increases, flexural strength increased and less variation observed in RPM and vacuum. Interaction between variables was high, however high effect of interaction was found between GSM - RPM and GSM - Vacuum.
- The Fiber volume fraction increased as fiber GSM increased. Fiber volume fraction varied from 34% to 57 % with increased GSM.
- Laminate made up to 400 GSM, the thickness variation did not increase beyond 0.5 mm but for 600 GSM the variation increased up to 1 mm.
- For last set of experiments where glass fabric was used, the flexural strength was less than tensile strength, but for all other sets of experiments where jute fabric was used the flexural strength was higher than tensile strength. This shows that the jute fabric laminate have more flexural strength then tensile strength.

VARTM has many applications starting from bot hull to aerospace. To use VARTM process for a particular application, one should have knowledge of composite materials, parameter affecting the process, properties required in product, process requirements and acceptable variation in product out come in terms of strength, thickness and aesthetic. VARTM is still a challenge as for each product, there will be some process variation, and the best product can only be achieved by detail study of this process. It is necessary to choose the parameters wisely to have products with required quality. Lot of things have been done and still lot many things need to be done to improvise this process. This research is contribution to improve part quality of VARTM process for jute polyester composites with controlling some important parameters. Based on the above discussion future scope has been highlighted below.

7.2 Future scope

1) To identify suitable method to monitor and control flow velocity for VARTM process.
2) Preparation of hybrid composites using developed VARTM set up.
3) To study complex curvature components with VARTM process.

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