Cost Analysis on L-Shape Composite Component Manufacturing

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ABSTRACT

Cost Analysis on L-shape Composite Component Manufacturing

Ruoshi Tong

In this research, the cost analysis of L-shape composite parts by using Autoclave and Out-of-Autoclave (OOA) techniques was made. The L-shape components were made using convex mold and concave mold respectively. In addition, production time, manufacturing process and product quality are considered in the cost analysis. The considered cost includes material cost, labor cost, tool and equipment costs (purchasing, maintenance and depreciation cost) and energy consumption cost. The cost analysis results indicate that the production time and production cost can be reduced by using parallel steps. The results of the cost analysis conclude that using OOA will lead to least cost production cost. Quality tests, include stretch test, void content test and compression test, on the manufactured composites were conducted in this research. We also developed a mathematical model for optimal production planning based on the studied manufacturing techniques.

Keywords: *Cost Analysis; L-shape Components, Composites manufacturing, Aggregate Production Planning*

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Chapter One

Introduction

1.1 Foreword

Applications of composite materials have had rapid growth in recent years due to technological advances and much improved manufacturing processes. Composite materials have a series of excellent features such as light weight, high mechanical properties among others. These features make them widely used in modern product structures. Composites are used in aerospace, automotive, marine, boating, sporting goods and other industries. Improved manufacturing technologies have reduced the cost of composite materials in aerospace industry. However, costs of composites in general are still higher than equivalent metal materials in most applications (Mazumdar, 2002). In order to further reduce manufacturing cost, many researchers have made significant efforts in developing new manufacturing techniques and tools for producing composite materials and products. For example, out-of-autoclave (OOA) composite manufacturing method was developed to reduce manufacturing cost, due to the low cost of equipment (oven) compared to autoclave method. In this research, we compare the cost of making L-shape components cured by autoclave and OOA processes. Quality of these composite products was analyzed and compared. An aggregate production planning model for optimal composite production was also developed.

1.2 Introduction of Composite Materials

This section presents a general introduction to composite materials.

1.2.1 Constituents of Composite Materials

Advanced composites are made of three main constituents: fibers, matrix and interface between fibers and matrix. Fibers, usually glass, carbon or Kevlar, provide strength and stiffness to the composite materials. Matrix can be polymer, metal, or ceramic, all of which serve several functions in the composite structure for satisfactory performance of the structure (Hoa, 2009).

1.2.2 Applications of Composite Materials

Composites have fast growing market share because of their light weight, good damage tolerance and corrosion resistance. Composites are widely used in aerospace, energy, automotive and other industries.

1.2.3 Composites Manufacturing Technology

Modern composites manufacturing techniques include autoclave molding, filament winding, pultrusion, liquid composite molding, and thermoplastic composites (Hoa, 2009). In this study, we focus on autoclave and out-of autoclave (OOA) layup techniques.

OOA is a manufacturing technique that has received much attention over the past several years. The main difference between autoclave manufacturing and OOA is that pressure is applied in autoclave while only vacuum is used in OOA. Ovens used in OOA process are less expensive than autoclave.

Raw materials, machines, layup methods and curing cycles for autoclave and OOA are different. In this research, materials used in autoclave are unidirectional graphite/epoxy prepregs. Material used in OOA in this study is woven carbon/epoxy prepregs. Materials used in OOA can provide autoclave-type material performance with the benefit of lower processing costs and better manufacturing flexibility. Layup methods and curing cycles are also different for autoclave and OOA.

1.2.4 Composite Manufacturing Cost Analysis

Composite materials are more expensive comparing to traditional materials due to higher cost of raw materials and extensive labor costs involved in composite manufacturing (Mazumdar, 2002). Cost of composite products may be reduced by selecting proper raw materials, using efficient production process and improving product quality. Many cost models have been developed for cost analysis of composite manufacturing. These models usually include labor cost, materials cost, equipment cost, energy cost and tool cost. In this research, a cost analysis model for autoclave and OOA composite manufacturing is developed to compare manufacturing costs of different processes. Several composite samples were made for the purpose of cost and quality analysis.

1.3 Quality Test

Quality of L-shape composite components fabricated by different methods is tested and analyzed in this research. The quality tests in this study include tensile test, compression test, and void content test. The results are compared. Stronger compression strength is an important requirement for many applications. Void formation can cause stiffness and strength reduction. It is crucial to measure the void content of composite products.

1.4 Aggregate Production Planning

Aggregate production planning is the process of designing a production scheme to meet the medium to long term forecasted demands. Its purpose is to allocate different manufacturing resources to satisfy the demands and to minimize production costs in the planning time horizon. In developing an aggregate production planning model, production variables such as production level and inventory level are determined to accommodate production capacity in each period (usually weeks, months, or seasons) over the planning time horizon (usually 6 months to 18 months). In this research, a multi-product aggregate production planning model is developed.

1.5 Scope of the Thesis

In this thesis, cost analysis in connection with quality of L-shape composite parts made by autoclave and OOA techniques was carried out. The cost components include material cost, labor cost, tool and equipment costs (purchasing, maintenance and depreciation costs) and energy cost. Quality test results for the components by different manufacturing methods are compared. A multi-product aggregate production planning model is developed to decide the optimal production quantity and inventory level.

1.6 Research Contributions

A detailed analysis on L-shape composite manufacturing process is developed. The developed model is for comprehensive cost analysis of manufacturing L-shape composite products. The model can be easily modified for cost analysis on similar products manufactured by composite materials in aerospace or other industries. In addition, an aggregate production planning model is proposed for optimal allocation of resources to satisfy demand.

1.7 Organization of the Thesis

This thesis is organized into eight chapters. Following the introductory Chapter 1, Chapter 2 provides a review of the literature in cost analysis models, composites manufacturing, quality testing, and production planning. Chapter 3 presents an introduction of L-shape composites manufacturing process using out-of-autoclave and autoclave. Details about L-shape composite manufacturing cost breakdown and analysis are presented in Chapter 4. Mechanical property tests and comparisons are presented in Chapter 5. A composite bus seat (a practical example) production process and cost analysis are presented in Chapter 6. Problem description, model formulation and result analysis of aggregate production planning are presented in Chapter 7. Chapter 8 presents concluding remarks and discusses possible future research topics in this area.

Chapter Two

Literature Review

2.1 Introduction

Many different composite manufacturing processes have been developed to improve product performance and to reduce production cycle time and production cost. In recent years, composite manufacturing process using oven and vacuum bags was utilized. In this chapter, research articles on the following topics will be reviewed as they are related to the work conducted in this research:

- Out of Autoclave Composites Manufacturing Technique.
- Cost Analysis Techniques in Composites Manufacturing
- Manufacturing Cost Estimation
- Quality Tests Techniques for Composites

2.2 Out-of-Autoclave Composites Manufacturing Technique

Dang *et al* (2011) presented several composite components produced by out-of-autoclave (OOA) process. They are equivalent to those made of 90 psi autoclave prepreg system. The baseline sample using autoclave process was fabricated from IM7/8552 material. This same part was remade using CYCOM 5320 OOA prepreg. The research focused on two autoclave methods of fabrication: hand layup and automated layup. The OOA part with hand layup used the male tool with Torr reusable vacuum bag. Mechanical testing results showed that the OOA system is mechanically comparable to that of the IM7/8552 system. The laminate quality was acceptable, and there were no observed ply wrinkling, voids and resin pooling.

Gao and Stevenson (2007) investigated the influence of different composite manufacturing processes on the drop-weight impact damage in woven carbon/epoxy laminate. Autoclave and the Quickstep processes were compared. Quickstep is an OOA process to produce high-quality composite parts at lower cost. The laminates were inspected by visual observation, dye-penetrant X-ray technique and optical microscopy observation. With these testing methods, voids, fiber/resin debonding and cracks can be detected. The damage of composite laminate under drop-weight impact loading was evaluated. The responses to this low velocity impact loading of composite laminates produced by Quickstep process and autoclave process were compared.

Davies *et al* (2006) assessed the Quickstep method for composite parts manufacturing and compared physical properties of the cured laminates with those produced by autoclave. Details about the Quickstep material, Quickstep and autoclave cure and Quickstep vacuum bag process were described. Due to the increased ramp rates the cure cycle time was significantly reduced by Quickstep process. The effect of cure cycle heat transfer rates in the cure cycle on physical and mechanical properties of the composite products was presented. The mechanical test results of autoclave and oven cured processes were compared and analyzed.

Akayet *et al* (1996) explored the non-autoclave vacuum-bag process for certain sandwich structures. They observed that the non-autoclave process of honeycomb sandwich structures have poor compaction and high porosity of the skins with decreased skin-core adhesion. The honeycomb inside pressure was measured. An optimal range of pressure inside the honeycomb was found. And an optimum process window was determined for time frame determination leading to an optimal initial honeycomb pressure level.

2.3 Composites Manufacturing Cost Analysis

Verrey *et al* (2005) used the TCM (technical cost model) approach to carry out cost analysis for thermoplastic and thermoset RTM (resin transfer molding) processes. Cost segmentation and comparison for thermoplastic RTM and thermoset RTM were made. The comparison was made using a cost breakdown diagram. Alternate strategies were also studied. Their study showed that reduction in non-crimp fabric scrap can lead to major cost savings.

Ǻkermo and Ǻström (1999) developed a program to predict component cost for different component sizes and complexities. The raw material cost strongly dominates the component costs. The compression molding manufacturing process for thermoplastic composite and sandwich component were described. Other related issues were discussed including the formula and the expression of how to calculate the cost.

Klanšek and Kravanja (2005) presented a method for manufacturing cost estimation and optimization for different composite floor systems. Details of each cost component were described. An approximation function was proposed for processing time and material consumption calculation. Structural optimization was applied for precise comparison of three different composite floor systems.

Stockton *et al* (1998) presented a time estimate model for advanced composite manufacturing cost analysis. They conducted the cost analysis for various activities, such as mold development and automated tape laying. The developed model can also be used for component designs and process optimization.

Rajadurai and Thanigaiyarasu (2008) presented structural analysis, failure prediction and cost analysis of different materials for manufacturing wind turbine blades. They proposed that some properties should be considered during material selection. A finite element analysis was made for turbine blade failure prediction. The cost analysis showed that certain type of blades are structurally efficient and offer the least expensive solution in all loading cases.

Pantelakis *et al* (2009) introduced a method for manufacturing composite components with regard to product quality and cost. This method was applied in making thermoplastic composite helicopter canopies. Quality and cost sensitivity were analyzed to derive material dependent quality functions and process dependent cost estimation relationships.

2.4 Quality Test Techniques for Composites Samples

Lomov*et al* (2007) used auniaxial tensile test to characterize damages in textile composites. The test was applied to different textile composites: carbon/epoxy triaxial braids, quasi-UD woven, and NCF. The tensile test was accompanied with acoustic emission (AE) and full-field strain mapping. The sample was examined by X-ray and ultrasonic C-scan. X-ray was used to detect very fine matrix cracks occurred within the yarns. Ultrasonic C-scan test was used to reveal the overall damage pattern. Cross-sectioning and microscopically examination of samples identified local damage modes.

Bhatnagar *et al* (2006) developed a low-cost method for biaxial tension tests for loading an in-plane reinforced composite laminate. Different experimental techniques and specimen shapes were used in their study. Details about the design and development of biaxial tensile testing fixture were illustrated. The load measurement and the assembly of the test fixture were also described. The equi-biaxial and non-equi-biaxial stresses with different stretch ratios can be incorporated in this new biaxial fixture design. The fixture can be used to estimate the interaction of the coefficients between the two principal stresses in an orthotropic or fiber-reinforced material system.

Bech *et al* (2008) developed a compression test method under static and fatigue loading. The new MCL (mechanical combined loading) fixture was described in detail. Quasi-static compression and compression-compression fatigue tests were performed on unidirectional carbon/epoxy and glass/polyester laminate specimens. The result of these experiments indicated that the MCL fixture is stable and reliable for industrial use and the test can measure compressive fatigue parameters.

Tant (1993) analyzed mini-sandwich specimen compression test using finite element method with quadrilateral isoparametric elements. The initial and final tangent properties were presented. He used nonlinear analysis in an iterative way with incremental loading. It reveals that considering the final tangent or secant material properties is important for obtaining accurate stress distributions of the specimen.

Gao*et al* (2006) presented an experimental program to characterize the effect of voids on the strength of composite laminates. In the void content measurement experiments, C-scan ultrasonic inspection and microscopic images were used to analyze void content and characterize the void shape, location and size. Interlinear shear strength flexure strengths and tensile strength were measured to assess the effect of voids. The effects of cure pressure conditions and dwell times on the critical void contents were described.

Paciornik and Almeida (2009) used digital optical microscopy techniques to measure volume fraction and distribution of voids in composite parts. Volume fraction was measured by using object measurement technique and mosaic images formed by assembling low magnification fields. Quantitative measure of void spatial distribution was provided to reveal homogeneity or clustering of the void population. The results provide a global view of the complex microstructure of the material.

2.7 Summary

In this chapter, many research works were reviewed. The literature covers the area of autoclave and OOA composite manufacturing processes, manufacturing cost analysis and aggregated production planning. Among the reviewed articles, a few of them have researched on cost analysis of OOA process. We used both autoclave and OOA processes to manufacture L-shape composite parts and made cost analysis based on these processes. A cost analysis model will be established to compare the total cost of different parts and combined with aggregate production planning for multiple products. Moreover, tensile test, compression test, and void content test are conducted in our research for testing the mechanical characters of the samples.

Chapter Three

Manufacturing the L-Shape Composites Parts

In this chapter, we describe in detail the autoclave and out-of-autoclave (OOA) processes used to manufacturing the components considered in this research.

The autoclave process steps include cutting the materials (NCT 301), preparing tools, laying up prepregs, putting the materials into autoclave and curing, removing the sample from mold, inspecting the products, and finishing the surfaces.

The OOA process steps include cutting the materials (Cycom 5320) and other steps, similar to those of the autoclave process. The only difference is that the raw material and curing cycle are different. In this research, several L-shape samples are made using autoclave and OOA processed. Some of the samples are shown in Figures 3.1 and 3.2.

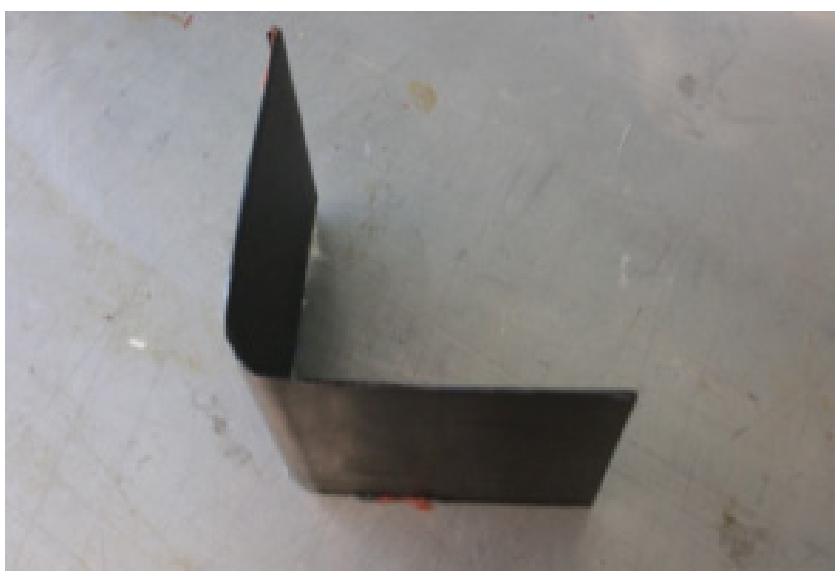

Figure 3.1: Autoclave sample

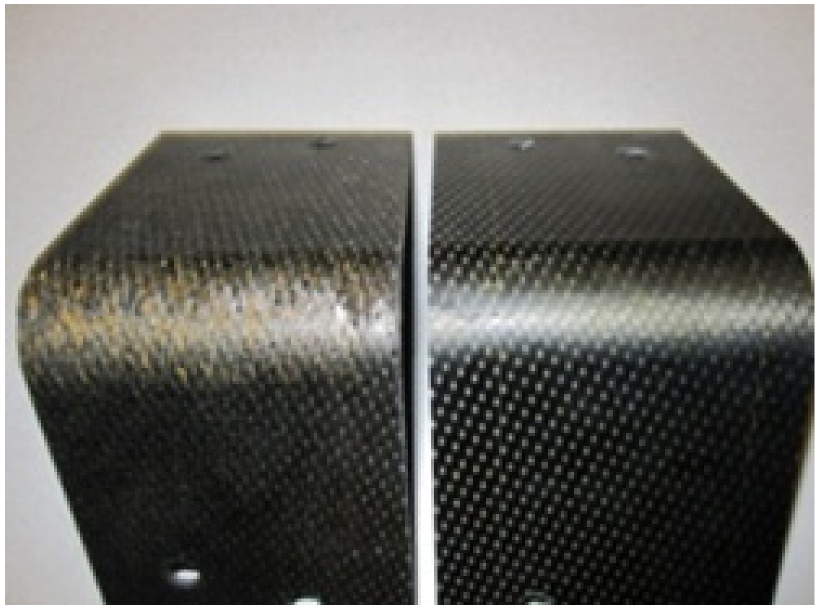

Figure 3.2: OOA concave samples

3.1 The Raw Materials

To manufacture composite samples, we used the following materials at different stages of the process. These materials are provided by suppliers.

- As discussed earlier, different materials are used to make the samples for autoclave and out-of-autoclave processes. Due to the lack of pressure in out-of-autoclave process, it is important that the resin has sufficiently low viscosity to flow and wet the fibers. New types of prepregs need to be available.

- In this study, we used convex and concave sides of a mold to make the L-shape samples. The size of each ply for the convex sample is 12"×4". The size of each ply for the concave sample is 10.5"×4".

- After removing the samples from the mold, some resin usually sticks on the mold. Mold cleaning fluid was used to clean the surface of the mold.

- Release agent was applied on the surface of the mold, in removing the samples from the mold easily. On sample surfaces, release films were applied.
- Bleeder materials were used to absorb the resin that leaks out during the curing process in the autoclave. Normally, bleeder materials are polyester mat, fiberglass, and cotton. For out-of-autoclave curing process, no bleeder material was used.
- A vacuum pump was applied to create a consistent compaction across the structure.
- Sealant tape was used to seal the margin of the mold and the vacuum bag.

3.2 Prepare Prepregs and Cutting

Prepregs are usually stored in a freezer at about -5°C. Before cutting, we need to take out the materials from the freezer and left them in the room temperature for several hours.

3.3 Tools Preparation

In this research, the L-shape concave and convex samples were made with two mold sides using autoclave and out-of-autoclave manufacturing methods. The mold shown in Figure 3.3 is made of aluminum, designed according to the shape of the samples and provides the surface finish for the samples. Autoclave makes the samples using high temperature and pressure. Oven makes the samples with high temperature and normal pressure. After curing, the mold surface may not be smooth. This will affect the quality of next samples to be made by the mold. Mold cleaning fluid is needed for cleaning the mold. Release agent and release films were used for removing the samples from the mold without affecting their surface quality.

3.3.1 Autoclave Process

Tools and equipment used in autoclave processing are autoclave, mold, and vacuum pump.

- An autoclave can be considered as a vessel with heating unit and high pressure. To provide high pressure, the autoclave is usually manufactured as a large cylindrical tube. A door is set up at the end of the tube. Since high temperature must be supplied during the curing process, the autoclave is usually made of welded steel. Commonly, autoclaves are very expensive and their capacities are limited. Figure 3.3 and Figure 3.4 show a schematic drawing of autoclave and a photo of an autoclave (Hoa, 2009), respectively.

- Roller is used for layup to remove the wrinkles. It is also useful to bond the prepreg layers.

- Molds used in autoclave processing are usually made by stainless steel or aluminum. To design the mold, the expansion and contraction of the mold and the part shrinkage must be considered.

- A vacuum pump is used for debulking.

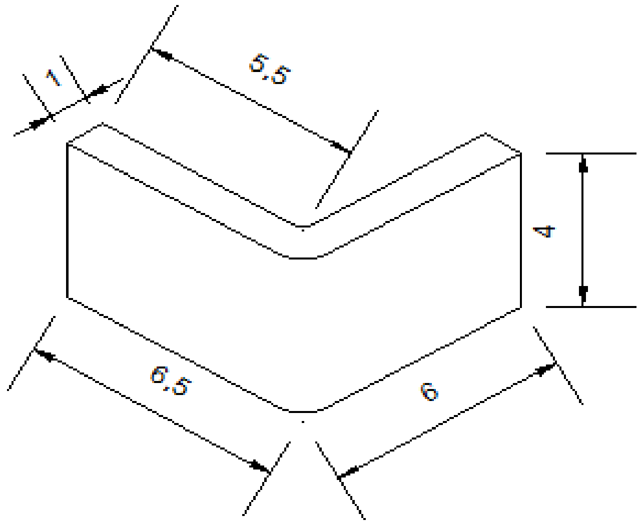

Figure 3.3: L-shape mold size

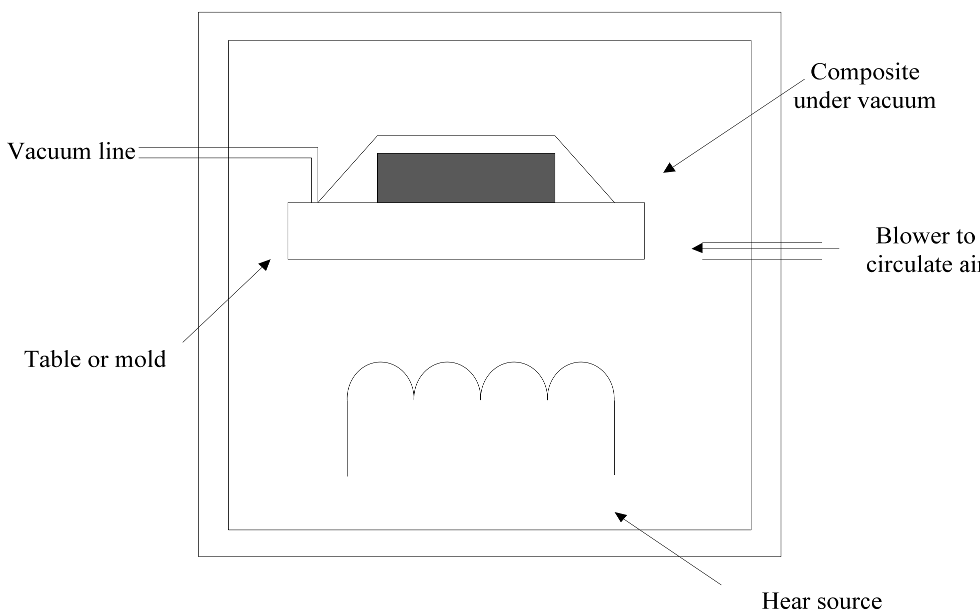

Figure 3.4 Schematic drawing of an autoclave

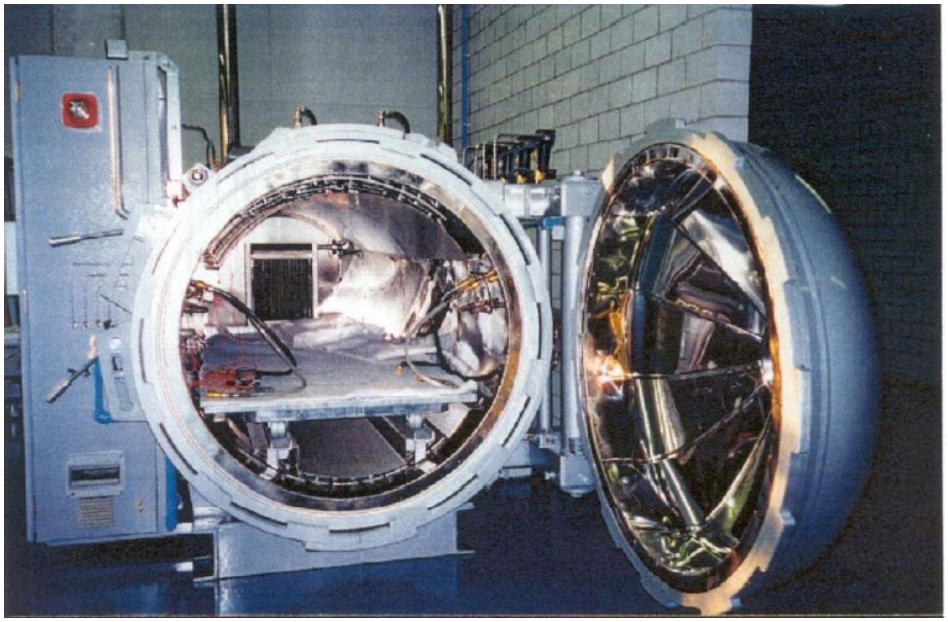

Figure 3.5 Autoclave photo (Hoa, 2009)

3.3.2 Out of Autoclave Processing

Tools and equipment used in the oven process are oven, mold, and vacuum pump.

- An oven can supply high temperature during the curing process. Compared with autoclave, oven cannot supply pressure. The prepreg is debulked by vacuum pump with 28.5 Hg, during oven curing process.
- Roller was used in layup to remove the wrinkles. It is also useful to bond the prepregs layers.
- Molds used in the out-of-autoclave process are the same as the one used in autoclave process.
- A vacuum pump was used for debulking.

3.4 Laying up the Prepregs

Similar to most composite manufacturing, prepregs are placed by hands. The orientations of the laminates of the prepregs cured by autoclave follow the sequence of [0/90/0/90/90/0/90/0]. Material used for OOA samples is Cycom 5320. Cycom 5320 is woven prepregs. To make the OOA samples have the same thickness with autoclave samples, samples cured by OOA follow the sequence [0/90/0/90]. Because the part is L-shape, the corner should be laid up carefully to make the layer smooth and to touch each other closely.

3.5 Vacuum Bag

To breathe the air off the samples and well pack the layers of the prepregs, “debulking” is necessary after certain layers are laid down. For the samples made by autoclave, the 8 layers need to be debulked after laying up every 2 layers. For the samples made by oven, the total 4 layers need to be debunked after laying up each layer. For each “debulking”, the vacuum bag and breather materials were placed. Vacuum was applied using a vacuum pump. We need to place the bleeder materials and breather materials again, after we complete all the layers. During the curing process the vacuum needs to be maintained. Figure 3.5 shows the assembly of all layers (Hoa, 2009). Using the vacuum bag can provide pressure to compact the laminate. Figure 3.6 shows the consolidation with vacuum bag. At the same time, void between laminate can be absorbed. Applying vacuum bag can also make it easy for the resin to flow.

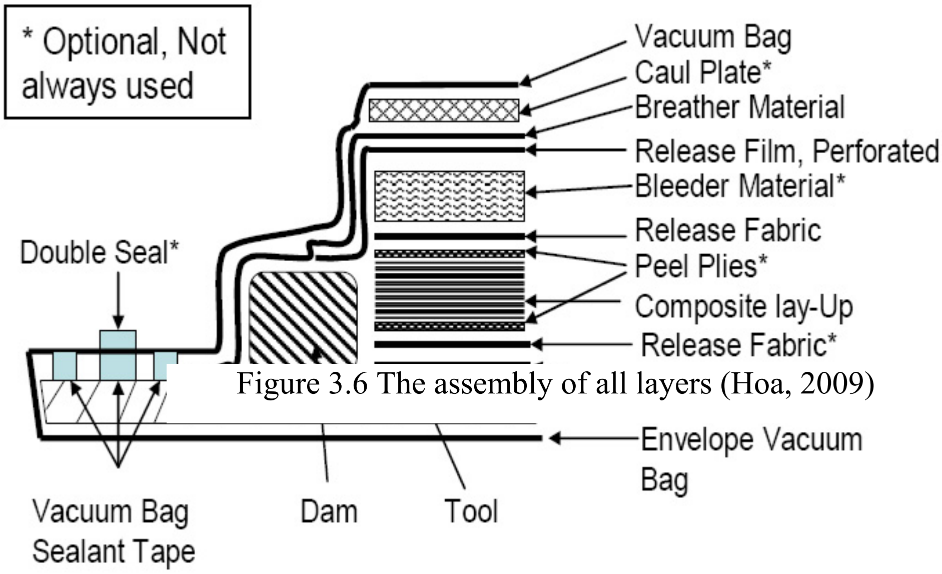

Figure 3.6 The assembly of all layers (Hoa, 2009)

Figure 3.6: The assembly of all layers

Figure 3.7 Consolidation with vacuum bag

3.6 Composite Curing Cycle

The curing cycles of the autoclave technique and OOA technique will be presented below.

3.6.1 Curing in the Autoclave

Autoclave provides high pressure and heat to bond the adjacent layers strongly. Heat transfer and energy balance, resin flow and consolidation, and void suppression are considered for deciding the curing cycle. The composite L-shape sample which is made of NCT 301 materials needs to be cured in the autoclave for 2 hours, the temperature ranges from 24°C to 140°C as shown in Figure 3.7. The pressure is 60 psi.

3.6.2 Curing with OOA

Oven provides high temperature but no pressure for the composite products. To achieve the same quality with samples made by autoclave, the curing cycle for the Cycom 5320 materials was set at 25°C for 2 hours, then at 93°C for 2 hours 45minuts, and at 143°C for 2hour 15minuts as shown in Figure 3.8.

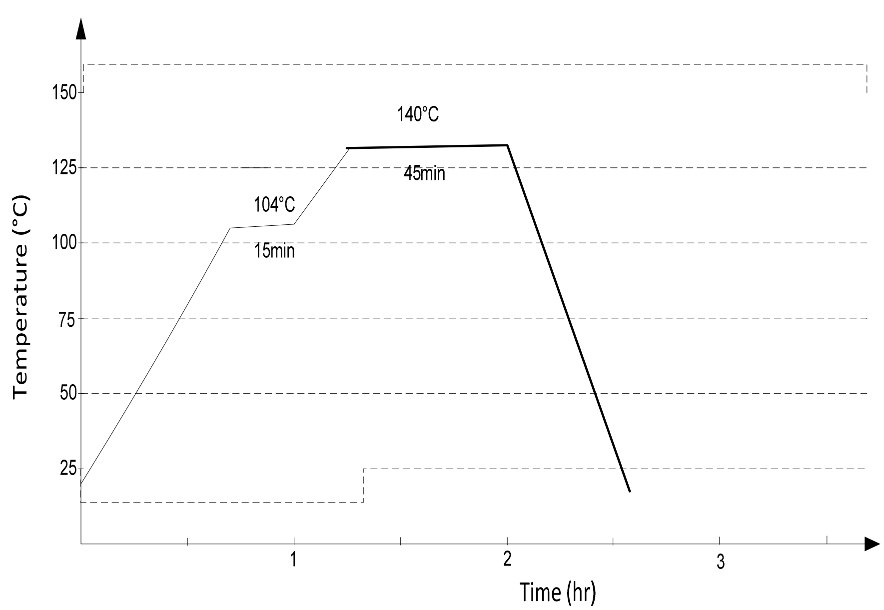

Figure 3.8 Cure cycle of autoclave process

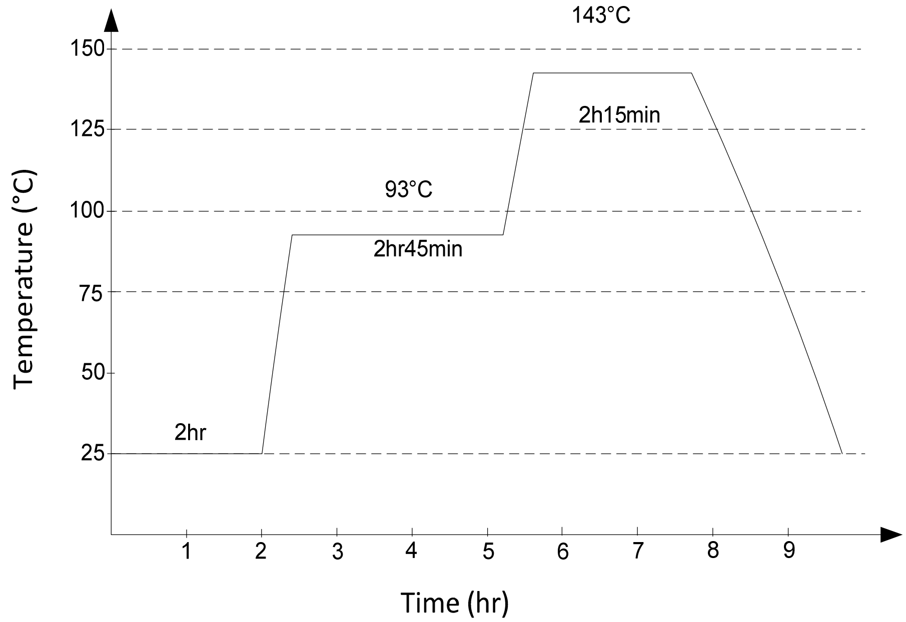

Figure 3.9 Cure cycle of OOA process

3.7 Removing the Part from the Mold, Inspection, and Finishing

The composite samples are removed from the mold after they are cured. The next step is to make the quality test. Void of the composite samples can be detected using microscope inspection. Strength and compression tests should also be conducted to check the sample's mechanical properties.

3.8 Summary

This chapter presents a brief description of the composite manufacturing processes to make the sample components in this study. Information on raw materials, manufacturing steps, equipment and tools which are needed in the manufacturing process is introduced.

Cost analysis for composite samples manufacturing include the costs associated with each step of the manufacturing process. Cost analysis for the concave and convex samples made in autoclave and OOA will be studied and discussed in the next chapter.

Chapter Four

L-Shape Composite Manufacturing Cost analysis

In this chapter, we will discuss composite manufacturing cost analysis and production. Production cost normally includes manufacturing cost and inventory cost. Cost analysis model for composite manufacturing needs to consider material cost, labor cost, tools cost and equipment cost (Ye et al, 2009). In this chapter, we will compare costs of manufacturing concave and convex L-shape composite samples made by autoclave and out-of-autoclave (OOA).

4.1 L-Shape Composite Manufacturing Production Cost Estimation

We will discuss the L-shape composite manufacturing production cost estimation in this section.

4.1.1 Material Cost

Material cost is the sum of the costs of all materials. It includes purchase costs of the prepreg, release agent, bleeder, breather, release film, vacuum bag, and sealant tape. Tables 4.1 to 4.4 present material cost of the four samples.

Table 4.1: Materials cost for OOA concave sample

Raw materials	Supplier	Unit Price	Amount	Cost($)
Prepreg(g)	Cytec	0.1145$/g	86.21	9.87
Release agent (ml)	Airtech	0.148$/ml	8.00	1.18
Breather(sq-ft)	Airtech	0.468$/sq-ft	4.31	2.02
Release film(sq-ft)	Airtech	0.374$/sq-ft	4.31	1.61
Vacuum Bag(sq-ft)	Airtech	0.182$/sq-ft	6.67	1.21
Plastic(sq-ft)	--------	0.1$/sq-ft	10.00	1.00
Sealant Tape	General sealant	4.78$/single	0.50	2.39
Total cost				19.29

Table 4.2: Material cost for OOA convex sample

Raw materials	Supplier	Unit Price	Amount	Cost($)
Prepreg(g)	Cytec	0.1145$/g	98.53	11.28
Release agent (ml)	Airtech	0.148$/ml	8.00	1.18
Breather(sq-ft)	Airtech	0.468$/sq-ft	4.31	2.02
Release film(sq-ft)	Airtech	0.374$/sq-ft	4.31	1.61
Vacuum Bag(sq-ft)	Airtech	0.182$/sq-ft	6.67	1.21
Plastic(sq-ft)	--------	0.083$/sq-ft	10.00	1.00
Sealant Tape	General sealant	4.78$/single	0.50	2.39
Total cost				20.70

Table 4.3: Material cost for autoclave concave sample

Raw materials	Supplier	Unit Price	Amount	Cost($)
Prepreg(g)	Newpote	0.05$/g	51.73	2.59
Release agent (ml)	Airtech	0.0148$/ml	8.00	0.12
Breather(sq-ft)	Airtech	0.483$/sq-ft	0.29	0.14
Release film(sq-ft)	Airtech	0.468$/sq-ft	1.67	0.78
Vacuum Bag(sq-ft)	Airtech	0.374$/sq-ft	0.29	0.11
Plastic(sq-ft)	Airtech	0.182$/sq-ft	6.67	1.21
Sealant Tape	General sealant	4.78$/single	0.50	2.39
Total cost				7.34

Table 4.4: Materials cost for autoclave convex samples

Raw materials	Supplier	Unit Price	Amount	Cost($)
Prepreg(g)	Newport	0.05$/g	59.13	2.96
Release agent (ml)	Airtech	0.0148$/ml	8.00	0.12
Breather(sq-ft)	Airtech	0.483$/sq-ft	0.33	0.16
Release film(sq-ft)	Airtech	0.468$/sq-ft	1.67	0.78
Vacuum Bag(sq-ft)	Airtech	0.374$/sq-ft	0.33	0.12
Plastic(sq-ft)	Airtech	0.182$/sq-ft	6.67	1.21
Sealant Tape	General sealant	4.78$/single	0.50	2.39
Total cost				7.75

4.1.2 Cutting and Layup Cost for Autoclave Samples

In this study, cutting and layup are performed by hand. The cutting and layup time depends on the size and number of the plies, the thickness of the material and the shape of the mode. In this study, the size of the samples made by autoclave is 4”×12”. We need to layup 8 plies of the prepregs following the direction [0/90/0/90/90/0/90/0], and debulk the sample after laying the first ply and then for every 2 plies. The steps and layup time for autoclave concave and convex samples are shown in Tables 4.5 and 4.6.

Table 4.5: Process of autoclave convex sample

Process	Time (min)
Cleaning the mold	5
Cutting Prepregs	5
Cutting Bleeder	2
Cutting Breather	2
Cutting Release film	2
Cutting Vacuum bag	3
Applying release agent	32
Lay up 1st Prepregs	4.45
Applying consolidation bag	15
Consolidation	5
Remove bag	5
2nd and 3rd prepregs down	8.9
Replace bag	5
Consolidation	10
Remove bag	5
4th and 5th prepregs down	8.9
Replace bag	5
Consolidation	10
Remove bag	5
6th and 7th prepregs down	8.9
Replace bag	5
Consolidation	10
Remove bag	5
8th prepregs down	4.45
Preparing Cure Bag	15
Testing bag sealing	5
Placing the tool in the Autoclave	8
Removing The tool from the Autoclave	8
Removing Composite from the Mold	5
Total	212.6

Table 4.6: Layup Steps of autoclave concave sample

Process	Time(min)
Cleaning the mold	5
Cutting Prepregs	5
Cutting Bleeder	2
Cutting Breather	2
Cutting Release film	2
Cutting Vacuum bag	3
Applying release agent	32
Layup 1st prepreg	3
Applying consolidation bag	15
Consolidation	5
Remove bag	5
2nd and 3rd prepregs down	6
Replace bag	5
Consolidation	10
Remove bag	5
4th and 5th prepregs down	6
Replace bag	5
Consolidation	10
Remove bag	5
6th and 7th prepregs down	6
Replace bag	6
Consolidation	10
Remove bag	5
8th prepregs down	3
Preparing Cure Bag	15
Testing bag sealing	5
Placing the tool in the Autoclave	8
Removing The tool from the Autoclave	8
Removing Composite from the Mold	5
Total	202

Labor cost can be obtained by multiplying the labor rate, assuming $15/hour, by the total labor time shown at the end of the table. Therefore, the labor cost for autoclave convex sample is $50.5 and the labor cost for autoclave concave sample is $53.15.

4.1.3 Cutting and Layup Cost for OOA Samples

The size of the samples made by OOA is 4” ×12”. We need to layup 4 plies of woven Cycom 5320 prepregs, and debulk the sample for each ply. The steps and labor cost for OOA concave and convex samples are shown in Tables 4.7 and 4.8.

Table 4.7: Layup process of OOA convex sample

Process		Time(min)
Cutting Prepregs		3
Cutting Breather		1
Cutting Release film		1
Cutting Vacuum bag		1
Cutting Plastic		0.5
Cleaning the mold		5
Applying release agent		32
Layup 1st ,2nd prepreg		8
Applying consolidation bag	Preparing consolidation bag	10
	place bag	5
Consolidation for 10min		10
Remove bag		5
3rd prepreg down		4
Replace bag		5
Consolidation for 10min		10
Remove bag		5
4rd prepreg down		4
Applying consolidation bag	Preparing consolidation bag	10
	place bag	5
Testing bag sealing		5
Placing the tool in the Autoclave		8
Removing The tool from the Autoclave		8
Removing Composite from the Mold		5
Total time		150.5

Table 4.8: Layup process of OOA concave sample

Process		Time(min)
Cutting Prepregs		2
Cutting Breather		1
Cutting Release film		1
Cutting Vacuum bag		1
Cutting Plastic		0.5
Cleaning the mold		5
Applying release agent		32
Layup 1st ,2nd prepreg		10
Applying consolidation bag	Preparing consolidation bag	10
	place bag	5
Consolidation for 10min		10
Remove bag		5
3rd prepreg down		5
Replace bag		5
Consolidation for 10min		10
Remove bag		5
4rd prepreg down		5
Applying consolidation bag	Preparing consolidation bag	10
	place bag	5
Testing bag sealing		5
Placing the tool in the Autoclave		8
Removing The tool from the Autoclave		8
Removing Composite from the Mold		5
Total		153.5

The labor cost can be obtained by multiplying the labor rate, assuming $15/hour, by the total labor time shown at the end of the table. Therefore, the labor cost for OOA convex sample is $37.63 and the labor cost for OOA concave sample is $38.38.

4.1.4 Equipment and Tools Cost

Equipment and tool cost is comprised of energy operation cost, depreciation cost and maintenance cost. Energy cost is the cost of the electric energy which is used during the composite sample manufacturing process. We use the electric rate to multiply the time used in the process. The straight line method is used to calculate the depreciation cost of the machines used to make the samples. The value of the equipment decreases by usage. For this study, the depreciation cost for each sample is the daily depreciation cost of the equipment, because it takes one day to make one sample. The next is the maintenance cost of the equipment. Tables 4.9 to 4.11 show the total equipment related cost. The total equipment related cost is the sum of these three terms:

Equipment and tool cost=depreciation cost + energy cost +maintenance cost (4.1)

Where:

Depreciation cost=(purchase price-salvage value)/(life cycle×300 (days)) (4.2)

Energy cost=electric rate × process time (4.3)

Maintaining cost= annual maintaining cost/300 days (4.4)

Table 4.9: Equipment cost

Process	Equipment	Lifetime(years)	Purchase($)	Salvage($)
Autoclave	Autoclave	20	233500	23350
	Pump	10	1000	100
OOA	Oven	20	19980	2000
	Pump	10	1000	100

Table 4.10: Depreciation and maintenance cost

Depreciation cost ($)		Maintenance cost ($)	
Autoclave and pump	Oven and pump	Autoclave and pump	Oven and pump
35.32	3.33	3.63	0.33

Table 4.11: Energy cost

Process	Equipment	Time (hour)	Cost ($)
Autoclave	Autoclave	2	2.7
	Compression Air	2.67	0.1
OOA	Oven	8	10.8
	Compression Air	8.67	0.33

4.1.6 Total Cost

The total cost for each sample is the sum of material cost, cutting and layup cost and equipment and tool cost (Ye *et al* 2009).

Total cost=material cost+ cutting and layup cost+ equipment and tool cost

=amount of the material× unit cost+ labor rate× total process time+ (purchase price-salvage value)/life cycle+ annual maintaining cost/300+electric rate ×process time (4.5)

4.2 Process Improvement for the Sample Manufacturing

From the manufacturing process steps shown in Tables 4.12 to Tables 4.15, we can find that there is certain waiting time. We can use this time to carry out other steps such as cutting materials and preparing the vacuum bags. Thus, the total manufacturing time could be reduced. Tables 4.12 to 4.15 show the improved manufacturing process. Take the OOA-convex manufacturing process as an example. Table 4.7 shows that it requires 32 minutes to apply release agent, 2 minutes for applying and 30 minutes for waiting. This waiting time can be used to carry out other steps at the same time. Table 4.14 shows that during the waiting time the mold is occupied and one can only operate the steps which do not need the mold. Figure 4.3 shows that the total manufacturing time and cost will be reduced by using parallel process. Table 4.12 shows the improvement of manufacturing process.

Table 4.12: Autoclave convex sample improved manufacturing process

<table>
<tr><th colspan="2">Process</th><th>Time (min)</th></tr>
<tr><td colspan="2">Cleaning the mold</td><td>5</td></tr>
<tr><td rowspan="6">Applying release agent(Time:32min)</td><td>Cutting Prepregs</td><td rowspan="6">32</td></tr>
<tr><td>Cutting Breather</td></tr>
<tr><td>Cutting Release film</td></tr>
<tr><td>Cutting Vacuum bag</td></tr>
<tr><td>Cutting Bleeder</td></tr>
<tr><td>Preparing consolidation bag1</td></tr>
<tr><td colspan="2">Lay up 1st prepreg</td><td>3</td></tr>
<tr><td colspan="2">Consolidation for 5min</td><td>5</td></tr>
<tr><td colspan="2">2nd and 3rd prepregs down</td><td>6</td></tr>
<tr><td colspan="2">Replace bag</td><td>5</td></tr>
<tr><td>Consolidation for 10min</td><td>Preparing consolidation bag2</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">4th and 5th prepregs down</td><td>6</td></tr>
<tr><td colspan="2">Replace bag</td><td>5</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">6th and 7th prepregs down</td><td>6</td></tr>
<tr><td colspan="2">Replace bag</td><td>6</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">8th prepregs down</td><td>3</td></tr>
<tr><td colspan="2">Preparing Cure Bag</td><td>5</td></tr>
<tr><td colspan="2">Testing bag sealing</td><td>5</td></tr>
<tr><td colspan="2">Placing the tool in the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing The tool from the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing Composite from the Mold</td><td>5</td></tr>
<tr><td colspan="2">Total</td><td>158</td></tr>
</table>

Table 4.13: Autoclave concave sample improved manufacturing process

<table>
<tr><td colspan="2">Process</td><td>Time (min)</td></tr>
<tr><td colspan="2">Cleaning the mold</td><td>5</td></tr>
<tr><td rowspan="6">Applying release agent(Time:32min)</td><td>Cutting Prepregs</td><td rowspan="6">32</td></tr>
<tr><td>Cutting Breather</td></tr>
<tr><td>Cutting Release film</td></tr>
<tr><td>Cutting Vacuum bag</td></tr>
<tr><td>Cutting Bleeder</td></tr>
<tr><td>Preparing consolidation bag1</td></tr>
<tr><td colspan="2">Lay up 1st prepreg</td><td>4.45</td></tr>
<tr><td colspan="2">Consolidation for 5min</td><td>5</td></tr>
<tr><td colspan="2">2nd and 3rd prepregs down</td><td>8.9</td></tr>
<tr><td colspan="2">Replace bag</td><td>5</td></tr>
<tr><td>Consolidation for 10min</td><td>Preparing consolidation bag2</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">4th and 5th prepregs down</td><td>8.9</td></tr>
<tr><td colspan="2">Replace bag</td><td>5</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">6th and 7th prepregs down</td><td>8.9</td></tr>
<tr><td colspan="2">Replace bag</td><td>6</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">8th prepregs down</td><td>4.45</td></tr>
<tr><td colspan="2">Preparing Cure Bag</td><td>5</td></tr>
<tr><td colspan="2">Testing bag sealing</td><td>5</td></tr>
<tr><td colspan="2">Placing the tool in the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing The tool from the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing Composite from the Mold</td><td>5</td></tr>
<tr><td colspan="2">Total</td><td>169.6</td></tr>
</table>

Table 4.14: OOA convex sample improved manufacturing process

<table>
<tr><th colspan="2">Process</th><th>Time (min)</th></tr>
<tr><td colspan="2">Cleaning the mold</td><td>5</td></tr>
<tr><td rowspan="7">Applying release agent(Time:32min)</td><td>Cutting Prepregs</td><td rowspan="7">32</td></tr>
<tr><td>Cutting Breather</td></tr>
<tr><td>Cutting Release film</td></tr>
<tr><td>Cutting Vacuum bag</td></tr>
<tr><td>Cutting Plastic</td></tr>
<tr><td>Preparing consolidation bag1</td></tr>
<tr><td>Preparing consolidation bag2</td></tr>
<tr><td colspan="2">Lay up 1st ,2nd prepreg</td><td>8</td></tr>
<tr><td colspan="2">Place the bag 1</td><td>5</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">3rd prepreg down</td><td>4</td></tr>
<tr><td colspan="2">Replace bag</td><td>5</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">4rd prepreg down</td><td>4</td></tr>
<tr><td colspan="2">Place the bag 2</td><td>5</td></tr>
<tr><td colspan="2">Testing bag sealing</td><td>5</td></tr>
<tr><td colspan="2">Placing the tool in the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing The tool from the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing Composite from the Mold</td><td>5</td></tr>
<tr><td colspan="2">Total time</td><td>124</td></tr>
</table>

Table 4.15: OOA concave sample improved manufacturing process

<table>
<tr><th colspan="2">Process</th><th>Time (min)</th></tr>
<tr><td colspan="2">Cleaning the mold</td><td>5</td></tr>
<tr><td rowspan="7">Applying release agent

(Time:32min)</td><td>Cutting Prepregs</td><td rowspan="7">32</td></tr>
<tr><td>Cutting Breather</td></tr>
<tr><td>Cutting Release film</td></tr>
<tr><td>Cutting Vacuum bag</td></tr>
<tr><td>Cutting Plastic</td></tr>
<tr><td>Preparing consolidation bag1</td></tr>
<tr><td>Preparing consolidation bag2</td></tr>
<tr><td colspan="2">Lay up 1st ,2nd prepreg</td><td>10</td></tr>
<tr><td colspan="2">Place the bag 1</td><td>5</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">3rd prepreg down</td><td>5</td></tr>
<tr><td colspan="2">Replace bag</td><td>5</td></tr>
<tr><td colspan="2">Consolidation for 10min</td><td>10</td></tr>
<tr><td colspan="2">Remove bag</td><td>5</td></tr>
<tr><td colspan="2">4rd prepreg down</td><td>5</td></tr>
<tr><td colspan="2">Place the bag 2</td><td>5</td></tr>
<tr><td colspan="2">Testing bag sealing</td><td>5</td></tr>
<tr><td colspan="2">Placing the tool in the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing The tool from the Autoclave</td><td>8</td></tr>
<tr><td colspan="2">Removing Composite from the Mold</td><td>5</td></tr>
<tr><td colspan="2">Total</td><td>128</td></tr>
</table>

Table 4.16: Labor cost for improved process of composite samples manufacturing

	OOA-convex	OOA-concave	Autoclave-convex	Autoclave-concave
Layup time (min)	124	128	158	169.6
Labor($)	31	32	39.5	42.4

4.3 Cost Analysis and Comparison

The total cost for each sample is the sum of material cost, cutting and layup (labor) cost and equipment and tool cost. The cost breakdown for samples OOA-convex, OOA-concave, autoclave-convex and autoclave-concave are shown in Table 4.17 and Figure 4.1.

Table 4.17: Total cost for the four types of samples

Cost($)	OOA-convex	OOA-concave	Autoclave-convex	Autoclave-concave
Material	20.7	19.29	7.74	7.34
Labor	37.63	38.88	50.5	53.15
Equipment	15.09	15.09	41.45	41.45
Total	73.42	73.26	99.69	101.94

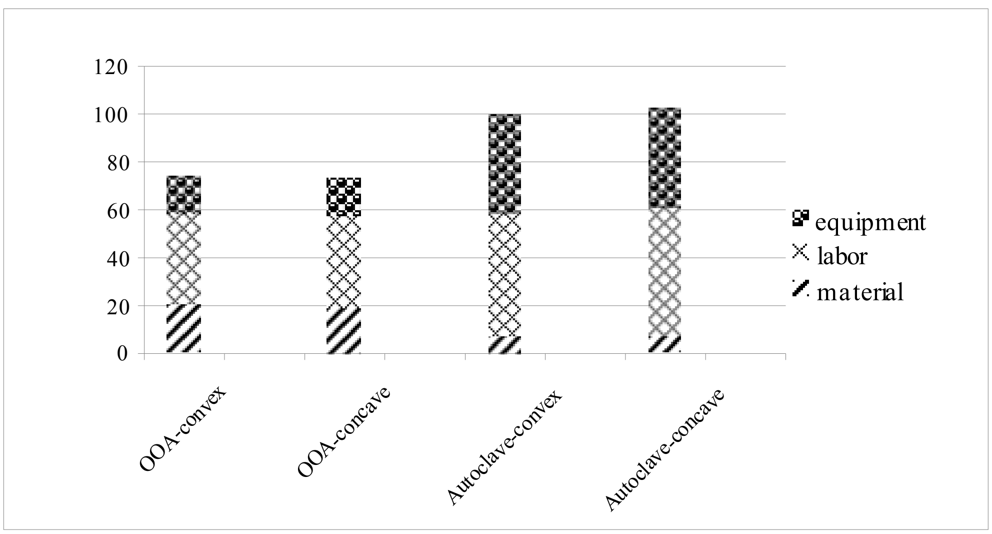

Figure 4.1: Cost breakdown for the 4 types of manufacturing process

Figure 4.1 shows how different cost categories contribute to the total cost. For OOA and autoclave samples, equipment and labor costs dominate the total cost. So decreasing the equipment cost is a crucial factor to reduce the total manufacturing cost. The results show that OOA has lower total cost due to lower equipment and labor cost, though material cost is higher than autoclave parts.

From the cost breakdown shown in Figure 4.1 and Figure 4.2, one can find that for each type of manufacturing method, labor cost occupies a large part of the total cost. Thus, improving the layup process is also an important way to reduce the total cost. From the data in Tables 4.12, 4.13, 4.14 and 4.15, we can get the total cost for the 4 samples with improved process where certain steps are done in parallel. The total cost of the process in parallel for each manufacturing process is calculated and shown in Table 4.18. The comparison of the cost for the process with series steps and process in parallel is shown in Figure 4.3.

It shows that the cost can be reduced by using parallel production process. The cost analysis indicates that using parallel steps would save production time and hence processing time related cost. The results of the experiments and analysis conclude that using OOA will lead to least total production cost. The higher material cost associated with the OOA process will be compensated mainly by the savings on equipment cost.

4.4 Summary

A cost estimate model was proposed in this chapter. Cost breakdown for manufacturing the L-shape composites parts was analyzed. The comparison for each cost component and the total cost was conducted. And the comparison between the process in series steps and the process in parallel showed that the total cost can be reduced by using process in parallel.

Table 4.18 Total cost for the 4 samples with improved process

	OOA-convex	OOA-concave	Autoclave-convex	Autoclave-concave
material	20.7	19.29	7.74	7.34
labor	31	32	39.5	42.4
equipment	15.09	15.09	41.45	41.45
Total	66.79	66.38	88.69	91.19

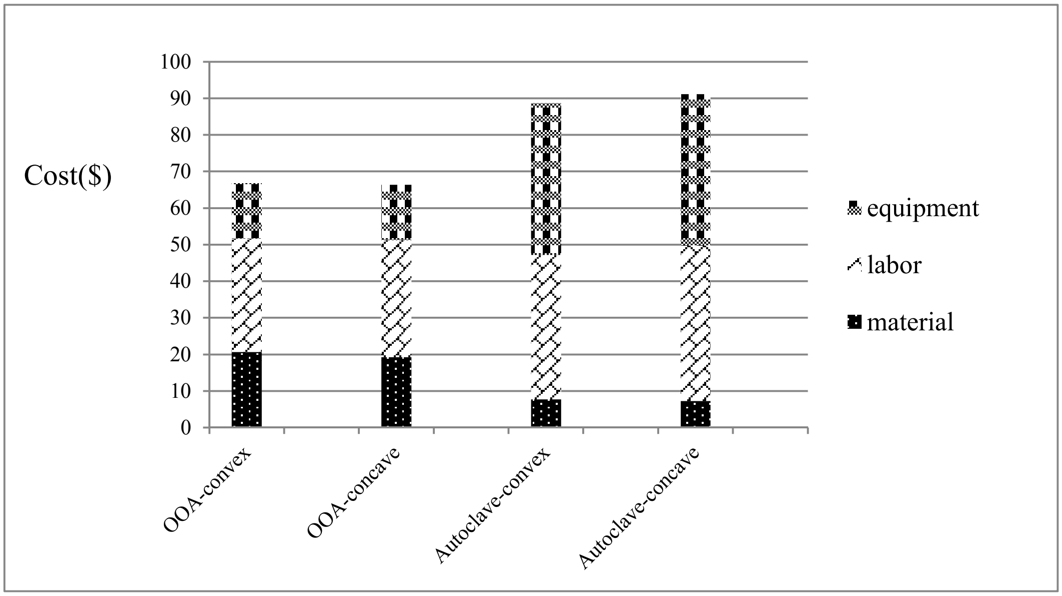

Figure 4.2 Cost breakdowns for the 4 types of improved manufacturing process

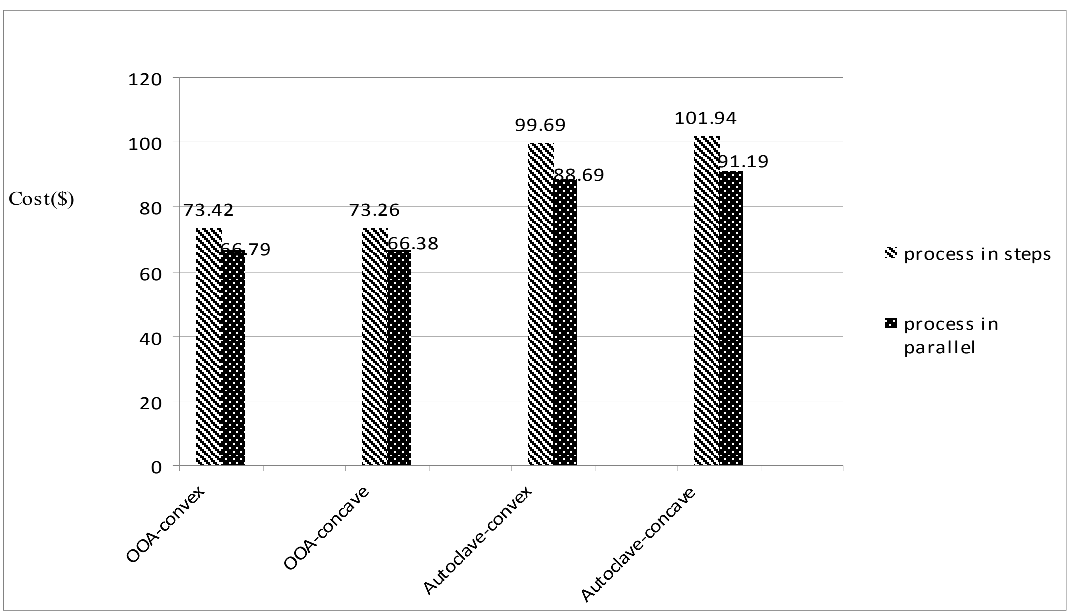

Figure 4.3: Compare of the process in steps and process in parallel

Chapter Five

Quality Test for L-shape Composite Components

Due to light weight and high quality, composite materials have been widely used in a variety of applications. Quality tests are conducted on the samples manufactured in this study. They include tensile test, compression test, and microscope for void content test. The results will be compared and showed in this chapter.

5.1 Tensile Test

In conducting the tensile test, we used the following process.

- Cut the edge of the samples. Measure the thickness of each coupon. The thickness of each coupon is shown in Table 5.1. In this study, one coupon for each sample is used.
- Make two holes on the sample arm for fixture to hold as shown in Figure 5.1.
- Put the coupon accurately on fixture, then tight it with bolts and nuts.
- Fix the above coupon on the Universal Tensile Machine as shown in Figure 5.2.
- Apply the load on the specimen with the speed of 10mm/min.
- Note down the data about Axial Force and Axial Displacement.
- Calculate stress and generate graph using the data.

Table 5.1: Thickness and section area of the sample

Dimension	Autoclave Convex	Autoclave Concave	OOA-convex	OOA-concave
Thickness (mm)	1.28	1.25	1.52	1.54
Area (sq-mm)	97.54	95.25	115.82	117.35

Figure 5.1: Coupon with holes for fixing

Figure 5.2: Setting up the test

The force-displacement data from the 4 tests are plotted in Figures 5.3 to 5.6.

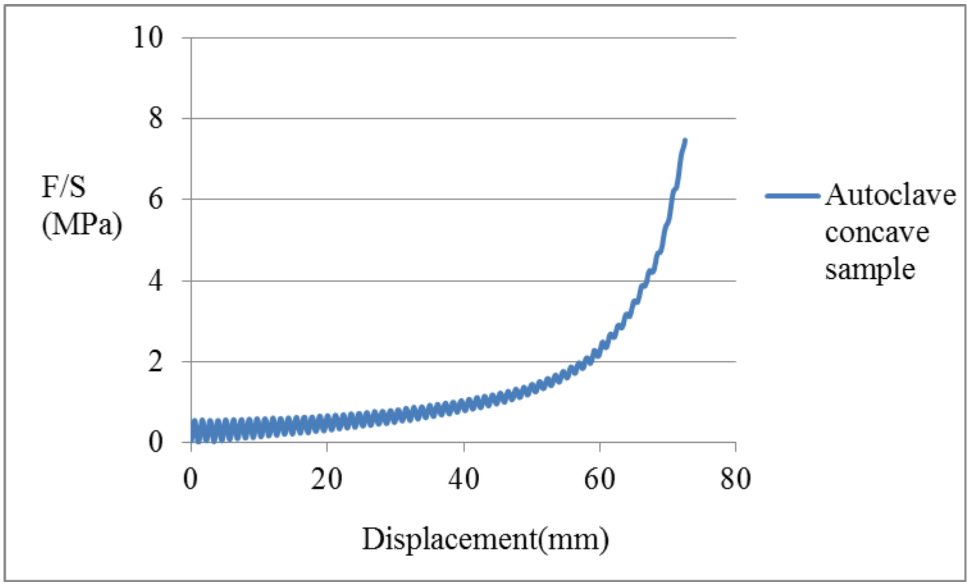

Figure 5.3: Stress for autoclave concave sample

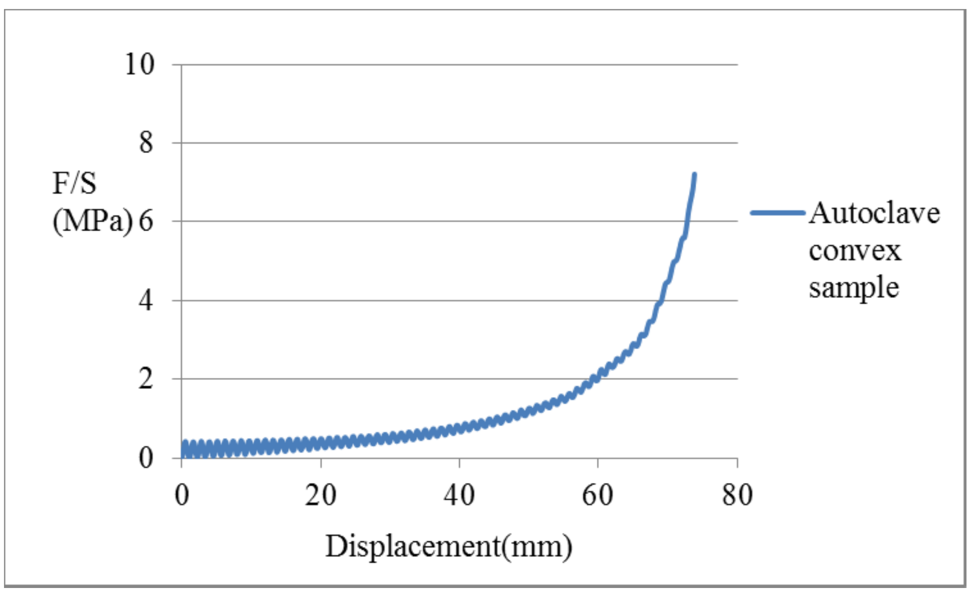

Figure 5.4: Stress for autoclave convex sample

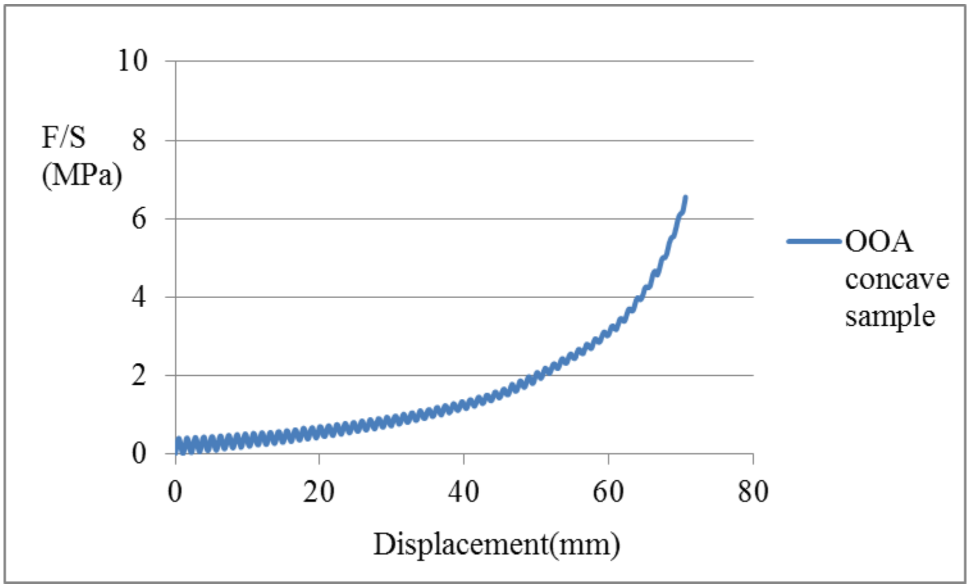

Figure 5.5: Stress for OOA concave sample

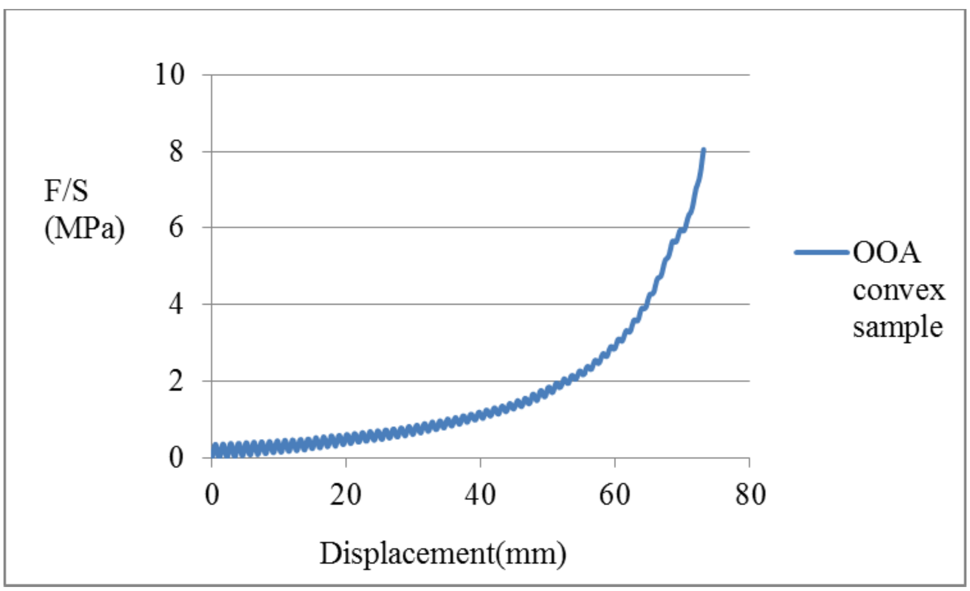

Figure 5.6: Stress for OOA convex sample

It can be seen that the stresses for the four samples are similar.

5.2 Compression Test

Compression tests are done using the same MTS machine with a special fixture. Many L-shape composite parts are used in airplanes, boats and buses. Therefore, compression strength is an important parameter. In this study, we conducted compression tests on the samples following the steps stated below.

- Measure the thickness of each L-shape sample. Cut the arm off from L-shape sample.
- Make the surface of the arms rough. Then, bond tab to the specimen. Applying tab can prevent stripping.
- Cut the coupon of size 0.5” × 4.5” shown as Figure 5.7. The thickness and section area data are in Table 5.2.
- Put the coupon accurately on fixture shown as Figure 5.8, then tight it with Universal Tensile Machine.
- Apply load on the specimen with speed of 1.5mm/min.
- Keep on applying the load until the specimen is broken.
- Calculate stress and plot the data

The force is applied at its longitudinal direction and the resulting displacement is recorded. Compression stress is the load divided by the cross section area. The L-shape sample compression stress graphs are shown in Figures 5.9 to 5.11. The recorded data are presented in Appendix B.

Figure 5.7: Coupon for compression test

Table 5.2: Thickness and section area of the sample

Dimension	Autoclave Convex	Autoclave Concave	OOA-convex	OOA-concave
Thickness(mm)	1.25	1.30	1.54	1.64
Area(sq-mm)	15.88	15.24	19.56	20.83

Figure 5.8: Compression test with MTS

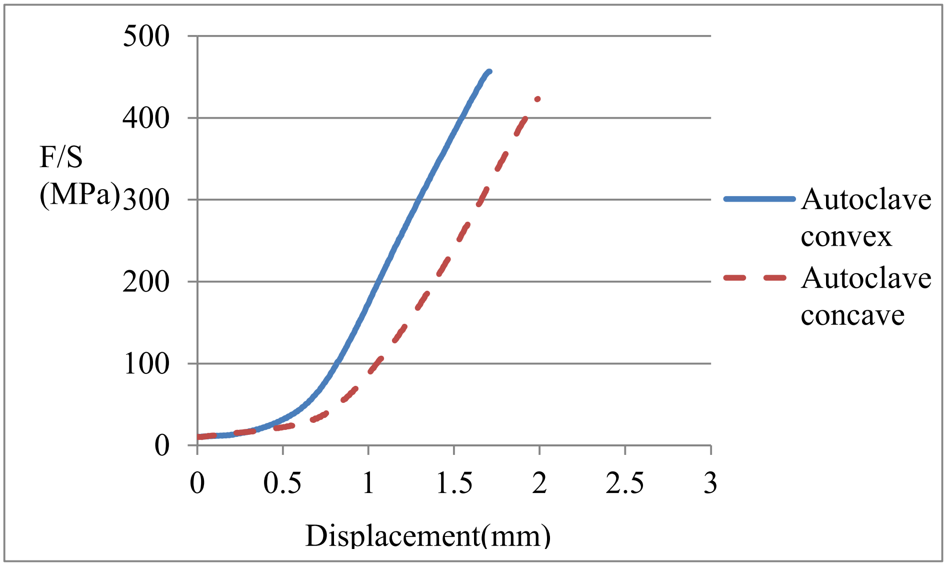

Figure 5.9: Compression stress for autoclave convex and concave samples

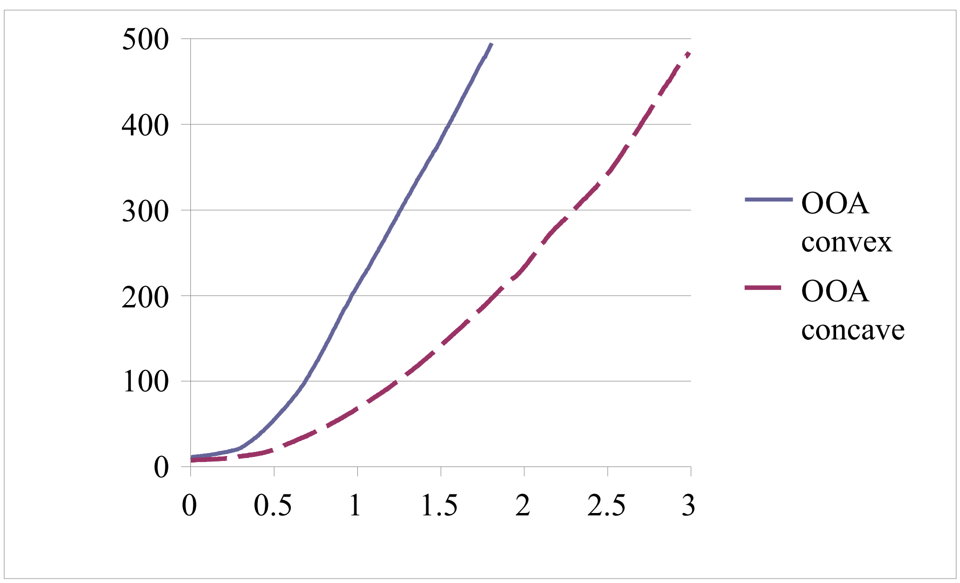

Figure 5.10: Compression stress for OOA convex and concave samples

It can be seen from Figure 5.9, there are differences in compression stress between the samples made by concave and convex molds. Figure 5.9 indicates that the stiffness of the autoclave convex sample is higher than that of the autoclave concave sample. Convex sample is easier to layup and autoclave can supply the pressure to the sample, so stiffness of autoclave convex is higher than that of the autoclave concave sample. Also we can see that the stiffness of the OOA convex sample is higher than that of the OOA concave sample, as shown in Figure 5.10.

As shown in Figure 5.11, autoclave-convex sample is the stiffest amount the four samples. Although autoclave manufacturing method can result in higher quality, the properties of the raw materials can also affect the product quality. Figure 5.11 shows that the OOA convex sample has smallest displacement under compression force. This is because that OOA prepregs (Cycom 5320) are probably stronger than that of autoclave prepregs (NCT 301).

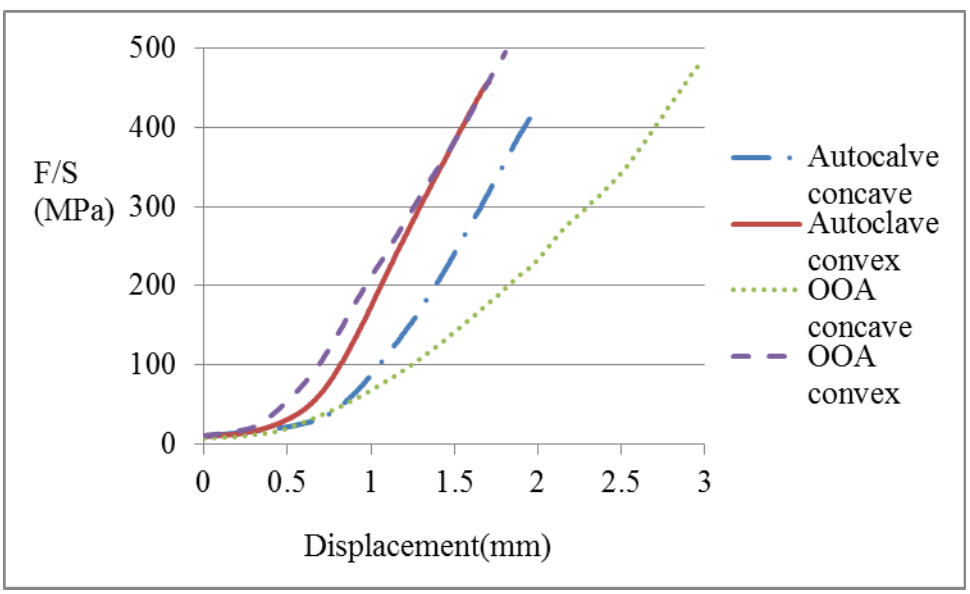

Figure 5.11: Compression stress for OOA and autoclave samples

5.3 Void Content Test for L-shape Composite Components

Void inside of L-shape composite components comes from wandering tow, broken fibers or air pockets and wrinkles created during the layup process. The void formation can cause stiffness and strength reduction (Grunenfelder and Nutt 2010). It is crucial to measure the void content of composite samples. L-shape components are difficult to layup because of the corner. We choose the corner section for void content test.

We followed the steps stated below in conducting the void tests.

- Apply the release agent to surface of the mold shown in Figure 5.12. The purpose to do this is to make it easy to release the sample from the model. Wait 10 minutes for it to completely dry.

- Mix Epon Resin 828 and Cure Agent 3046 with the ratio of 100:45. Pour the mix liquid into the mold for mounting. In this experiment, we cut the sample into several small mounting samples.

- Hold the samples in the vacuum oven at 35ºC for 18 hours. Then take the samples out of the oven and release the samples from the mounting mold. Hold the samples at 100ºC for 2 hours in vacuum oven. Samples after demold are shown in Figure 5.13.

- Automatic grinding machine LECO VP-150 (Figure 5.14) was used for grinding and polishing. #120, #240, #320, #600, and #800 sandpapers were used for grinding. Monocrystalline diamond suspension and polishing cloths were used for initial polishing. Colloidal silica suspension and Imperial polishing cloths were used for final polishing.

- Microstructure of each piece was examined using an optical microscope (Figure 5.15).

Figure 5.12: Model for mounting

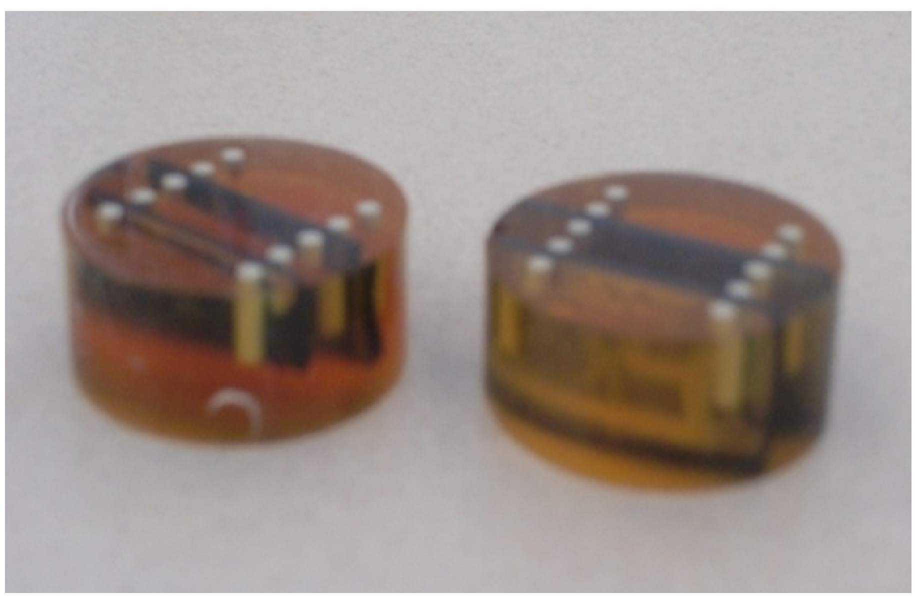

Figure 5.13: Samples after demold

Figure 5.14: Automatic grinding machine LECO VP-150

In this study, the void content percentage was calculated. For the void percentage, we used the void area divided by the sample section area. The results are shown in Table 5.3. Microscope pictures are shown in Figures5.16 and 5.17. We can see clearly the fiber, resin and voids from the microscope images.

Table 5.3: Void content of corner section of composite L-shape samples

Void Content of Corner Section of L-shape Samples				
	Autoclave convex	OOA Convex	Autoclave Concave	OOA Concave
Amount	4	5	9	12
Percentage	0.066%	0.004%	0.022%	0.119%

Figure 5.15: Optical microscope machine

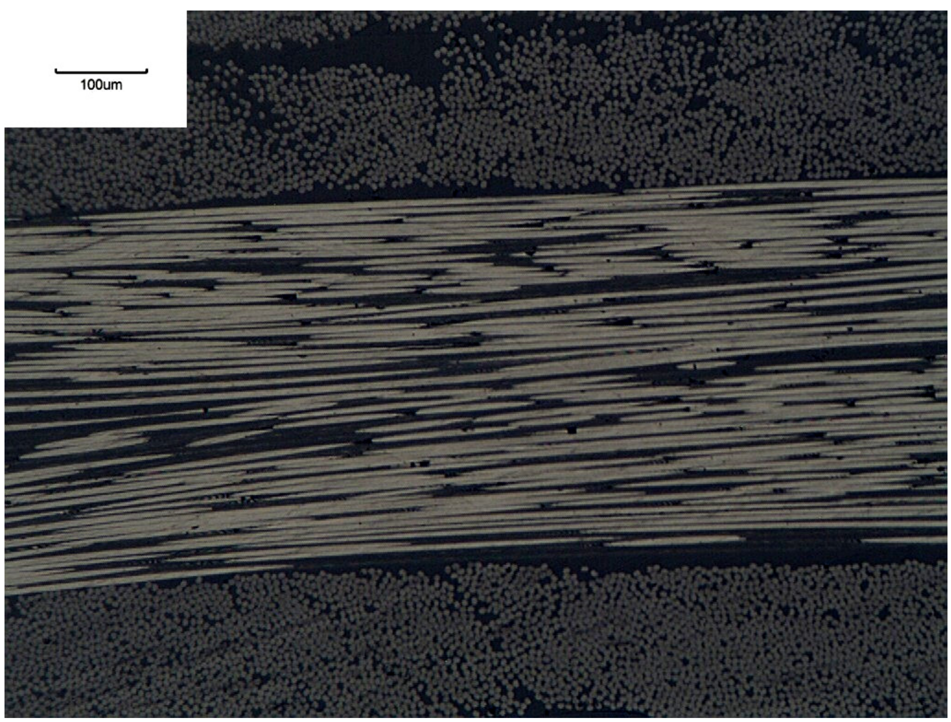

Figure 5.16: Corner section structure OOA concave sample

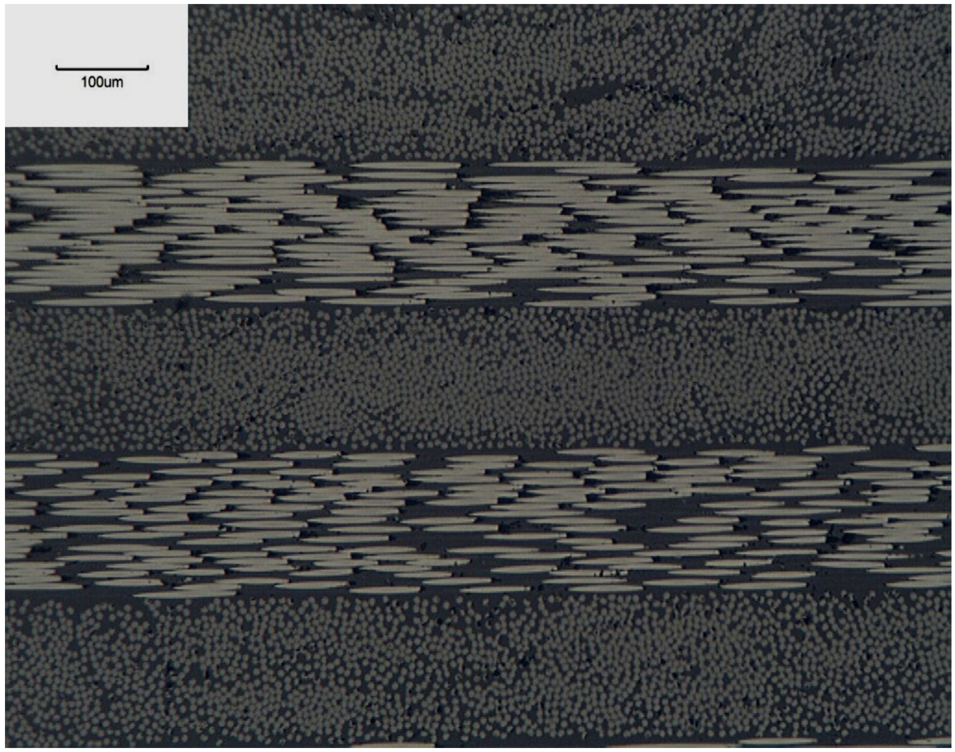

Figure 5.17: Corner section structure autoclave concave sample

5.4 Summary

In this research, we performed mechanical tests on the composite samples. They include tensile test, compression test and void content test. Details of the experiments are illustrated in this chapter. For each test, the results are analyzed and compared. The results show that the samples made using different processes have high mechanical properties and are of good quality.

Chapter Six

Cost Analysis of Composite Bus Seat

In this chapter, a practical example is presented to illustrate the cost analysis models presented in Chapter Four. The example is a bus seat, an L-shape composite product. The bus seat manufacturing experiment is conducted by student from McGill, in this study we complete the cost analysis for the composite bus seat manufacturing. We also compare the manufacturing costs of different composite bus seats made by autoclave and out-of-autoclave.

6.1 Composites Bus Seat

Manufacturing of the bus seat is more complicated than manufacturing the L-shape parts discussed in Chapter Four. As shown in Figure 6.1, there are small corners on the edge of the bus seat. The prepregs were cut into the required shape using a programmable cutting machine.

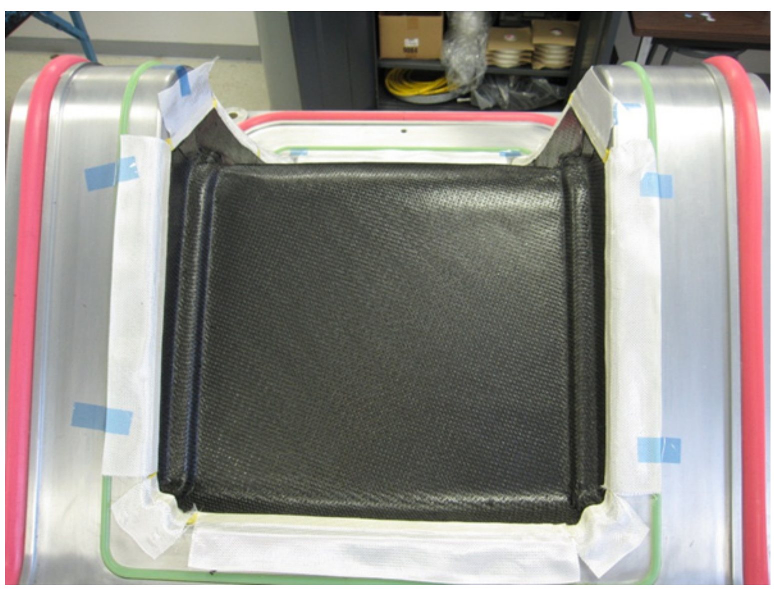

Figure 6.1: Bus seat mold

In total, six bus seats were made using different raw materials and manufacturing methods. These material and method combinations are OOA with MTM 45-1, OOA with MTM 45-1 sandwich, OOA Cycom 5320, OOA Cycom 5320 sandwich, Autoclave Cycom 5276-1 and Autoclave Cycom 5276-1 sandwich. Figure 6.2 shows how the vacuum bag for bus seat is applied. A bus seat sample is shown in Figure 6.3. Sandwich bus seat samples are shown in Figures 6.4 and 6.5.

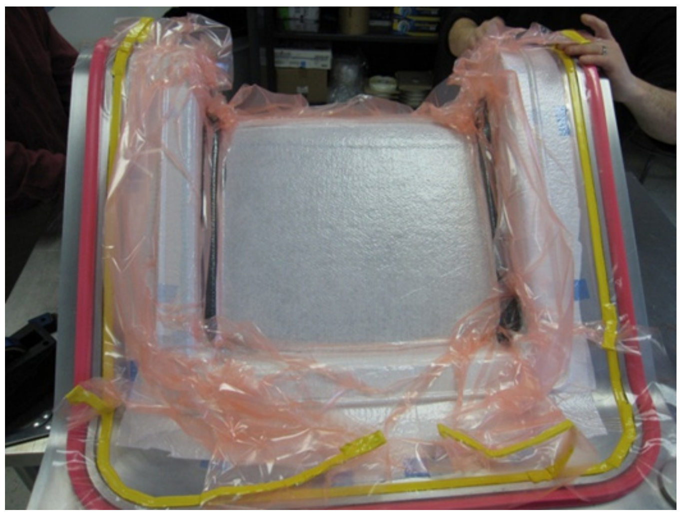

Figure 6.2: Vacuum bag for bus seat

Figure 6.3: Bus seat samples

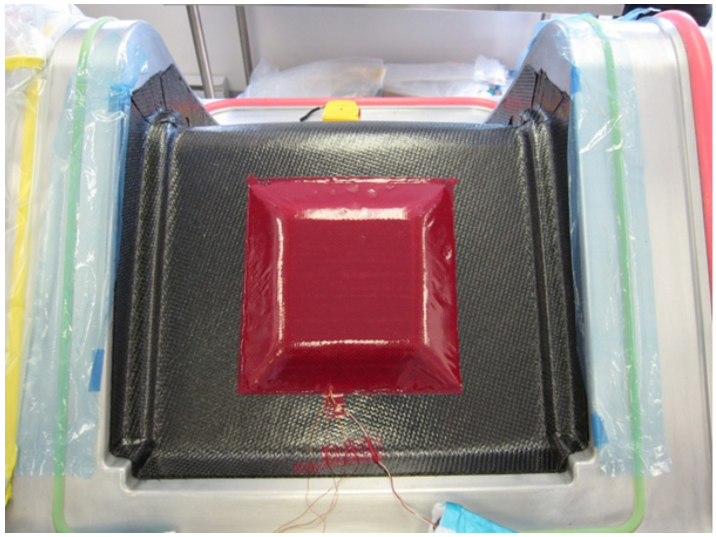

Figure 6.4: Honeycomb application of bus seat layup steps

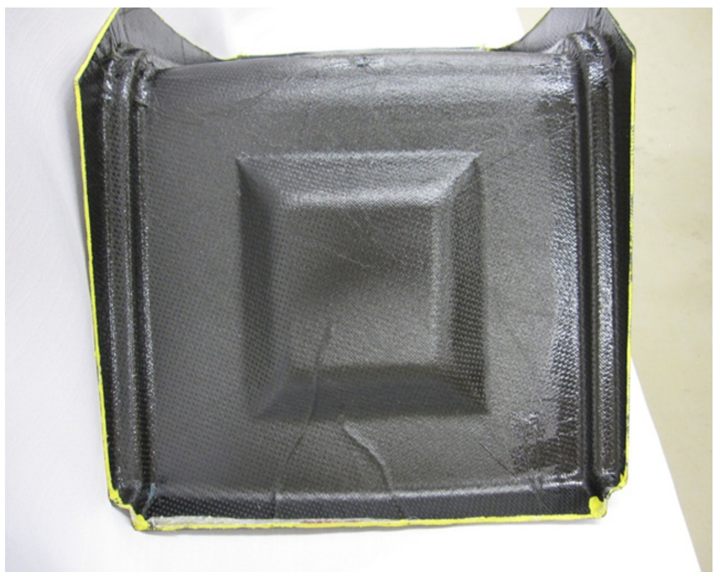

Figure 6.5: Bus seat samples made with honeycomb

6.2 Composite Bus Seat Manufacturing Cost Estimation

The cost components considered in this analysis include: raw material cost, labor cost, tool and equipment costs including purchasing, maintenance and depreciation costs and energy consumption cost.

6.2.1 Material Cost

The raw material cost includes those to purchase the prepreg, release agent, bleeder, breather, release film, vacuum bag, and sealant tape. Tables 6.1 to 6.6 present detailed material cost data to make the 6 bus seat samples.

6.2.2 Cutting and Layup Cost

Layup were performed by hand. Three different woven prepregs were used to make the six types of bus seats: MTM 45-1, MTM 45-1 sandwich, Cycom 5320, Cycom 5320 sandwich, Cycom 5276-1 and Cycom 5276-1 sandwich. Amount them, bus seats made of MTM 45-1 and Cycom 5320 were cured by OOA, and those made of Cycom 5276-1 were cured by autoclave. Detailed layup steps are shown in Tables 6.7 to 6.12. We used $15/hour as the labor wage to multiply the total labor time at the end of Tables 6.7 to 6.12 to obtain the labor costs. These cost values are summarized in Table 6.13.

6.2.3 Equipment and Tool Cost

Equipment and tool cost include depreciation cost and maintenance cost. Energy cost is the cost of electricity used in the manufacturing process sample. Straight line method is used to calculate the depreciation cost. For this study, the depreciation cost for each sample is the daily depreciation cost of the equipment, because it took one day to make each sample. The total equipment and tool cost calculated according to the Equation 4.1 to 4.4.

Tables 6.14 to 6.19 present equipment cost, depreciation cost and maintenance cost for manufacturing the bus seat samples.

6.2.4 Total Composite Samples Cost

The total cost for manufacturing each sample is the sum of material cost, cutting and layup cost and equipment and tool cost. Table 6.20 shows the total costs of the samples made from different materials and processes.

Table 6.1: Materials cost for OOA MTM 45-1 sample

Item	Supplier	Unit Price	Amount	Cost($)
Prepreg(sq-ft)	ACG	0.47/sq-ft	76.50	35.96
Release agent (ml)	Airtech	0.12 /ml	10.00	1.20
Release agent (ml)	Airtech	0.026 /ml	20.00	0.52
Breather(sq-ft)	Airtech	0.20 / sq-ft	38.00	7.60
Release film(sq-ft)	Airtech	0.33 /sq-ft	20.00	6.60
Vacum Bag(sq-ft)	Airtech	0.19 /sq-ft	105.00	19.95
Sealant Tape(feet)	General sealant	0.17 /feet	50.00	8.50
Fiber glass(feet)	-----	0.20/ feet	8.30	1.66
Total Cost				81.99

Table 6.2: Material cost for OOA MTM 45-1 sandwich sample

Item	Supplier	Unit Price	Amount	Cost($)
Prepreg(sq-ft)	ACG	0.47 /sq-ft	76.50	35.96
Release agent (ml)	Airtech	0.12 /ml	10.00	1.20
Release agent (ml)	Airtech	0.026 /ml	20.00	0.52
Breather(sq-ft)	Airtech	0.20/sq-ft	40.00	8.00
Release film(sq-ft)	Airtech	0.33 /sq-ft	17.90	5.91
Vacum Bag(sq-ft)	Airtech	0.19 /sq-ft	36.50	6.94
Strety vacuum bag (sq-ft)	Airtech	0.18 /sq-ft	41.00	7.38
Honeycomb (sq-ft)	-----	17.5/sq-ft	0.70	12.25
Adhesive (sq-ft)	3M	6.2/sq-ft	1.40	8.68
Sealant Tape (feet)	General sealant	0.17 /feet	33.40	5.68
Fiber glass (feet)	-----	0.20 /feet	8.30	1.66
Total				94.17

Table 6.3: Materials cost for OOA Cycom 5320 sample

Item	Supplier	Unit Price	Amount	Cost($)
Prepreg(sq-ft)	Cytec	0.47 /sq-ft	76.50	35.96
Release agent (ml)	Airtech	0.12 / ml	10.00	1.20
Release agent (ml)	Airtech	0.026 /ml	20.00	0.52
Breather(sq-ft)	Airtech	0.20 /sq-ft	25.80	5.16
Release film(sq-ft)	Airtech	0.33 /sq-ft	10.00	3.30
Vacum Bag(sq-ft)	Airtech	0.33/sq-ft	10.00	3.30
Strety vacuum bag (sq-ft)	Airtech	0.18 /sq-ft	90.00	16.20
Sealant tape(sq-ft)	General sealant	0.17 /feet	500.00	85.00
Adhesive (sq-ft)	-----	0.05 /feet	90.00	4.50
Total				155.14

Table 6.4: Materials cost for OOA Cycom 5320 sandwich sample

Item	Supplier	Unit Price	Amount	Cost($)
Prepreg(sq-ft)	ACG	0.47 /sq-ft	76.50	35.96
Release agent (ml)	Airtech	0.12 /ml	10.00	1.20
Release agent (ml)	Airtech	0.026/ ml	20.00	0.52
Breather(sq-ft)	Airtech	0.20/ sq-ft	32.00	6.40
Perforated release film (sq-ft)	Airtech	0.33 /sq-ft	10.00	3.30
Non-perforated release film(sq-ft)	Airtech	0.33 /sq-ft	10.00	3.30
Vacuum bag (sq-ft)	Airtech	0.18 /sq-ft	92.00	16.56
Honeycomb (sq-ft)	-----	17.5/sq-ft	0.70	12.25
Adhesive (sq-ft)	3M	6.2/sq-ft	1.40	8.68
Sealant Tape(inch)	General sealant	0.17/feet	500.00	85.00
Fiberglass tow (inch)	-----	0.05 /feet	90.00	4.50
Total				177.67

Table 6.5: Materials cost for autoclave Cycom 5276-1 sample

Item	Supplier	Price	Amount	Cost($)
Prepreg(sq-ft)	Cytec	0.47 /sq-ft	76.50	35.96
Release agent (ml)	Airtech	0.12 /ml	10.00	1.20
Release agent (ml)	Airtech	0.026/ ml	20.00	0.52
Breather(sq-ft)	Airtech	0.20 /sq-ft	25.80	5.16
Non-perforated release film (sq-ft)	Airtech	0.33 /sq-ft	9.70	3.20
Perforated release film(sq-ft)	Airtech	0.33 /sq-ft	9.70	3.20
Stretchy Vacuum Bag(sq-ft)	Airtech	0.18 /sq-ft	90.00	16.20
Sealant Tape(inch)	General sealant	0.17 /feet	488.00	6.91
Fiberglass tow(inch)	-----	0.05 /feet	90.00	0.38
Total				72.73

Table 6.6: Materials cost for autoclave Cycom 5276-1 sandwich sample

Item	Supplier	Price	Amount	Cost($)
Prepreg(sq-ft)	ACG	0.47/sq-ft	76.50	35.96
Release agent (ml)	Airtech	0.12/ml	10.00	1.20
Release agent (ml)	Airtech	0.026/ml	20.00	0.52
Breather(sq-ft)	Airtech	0.20 /sq-ft	32.00	6.40
Perforated release film (sq-ft)	Airtech	0.33 /sq-ft	9.00	2.97
Non-perforated release film(sq-ft)	Airtech	0.33 /sq-ft	9.00	2.97
Vacuum bag Stretchlon 800 (sq-ft)	Airtech	0.19 /sq-ft	92.00	17.48
Honeycomb (sq-ft)		17.5/sq-ft	0.70	12.25
Adhesive (sq-ft)	3M	6.2/sq-ft	1.40	8.68
Sealant Tape (inch)	General sealant	0.17/feet	524.00	7.42
Fiberglass tow (inch)	-----	0.05 /feet	90.00	0.38
Total Cost				96.22

Table 6.7: Layup steps for MTM 45-1 bus seat

Process	Time(min)
Cut Prepregs	10.00
Cut Breather	2.00
Cut Release film	2.00
Cut Vacuum bag	1.00
Layup 1st ply	36.00
Apply consolidation bag	35.00
Consolidation	10.00
Remove bag	5.00
2nd , 3rd and 4th plies down	85.00
Apply consolidation bag	8.00
Consolidation	10.00
Remove bag	3.00
5th , 6th, 7th and 8th plies	135.00
Edge breathing	63.00
Final Bag	45.00
Test bag sealing	15.00
Place the tool in the Oven	3.00
Remove The tool from the Oven	3.00
Remove Composite from the Mold	5.00
Total time	476.00

Table 6.8: Layup steps for MTM 45-1 sandwich bus seat

Process	Time(min)
Cut Prepregs	10.00
Cut Breather, release film and vacuum bag	10.00
1st ply	25.00
1st debulk (apply bag + debulk + remove bag)	108.00
2nd and 3rd plies	59.00
2nd debulk (apply bag + debulk + remove bag)	29.00
4th ply	23.00
Partial plies	10.00
Honeycomb	15.00
5th ply	27.00
3rd debulk (apply bag + debulk + remove bag)	29.00
6th, 7th and 8th plies	83.00
Edge trimming	60.00
Edge breathing	12.00
Final bag + leak test	71.00
Place the tool in the Oven	3.00
Remove The tool from the Oven	3.00
Remove Composite from the Mold	5.00
Total time	582.00

Table 6.9: Layup steps for Cycom 5320 bus seat

Process	Time(min)
Cut Prepregs	10.00
Cut Breather, release film and vacuum bag	10.00
1st ply	22.53
1st debulk (apply bag + debulk + remove bag)	77.00
2nd ply and 3rd ply	61.06
2nd debulk (apply bag + debulk + remove bag)	29.13
4th ply and 5th ply	70.06
3rd debulk (apply bag + debulk + remove bag)	26.00
6th ply, 7th ply and 8th ply	94.53
Place fiberglass tow	5.00
Final bag + leak test	79.48
Place the tool in the autoclave	10.00
Remove The tool from the autoclave	5.00
Remove Composite from the Mold	5.00
Total time	494.85

Table 6.10: Layup steps for Cycom 5320 sandwich bus seat

Process	Time(min)
Cut Prepregs	10.00
Cut Breather, release film and vacuum bag	10.00
1st ply	28.50
1st debulk (apply bag + debulk + remove bag)	70.90
2nd ply and 3rd ply	57.00
2nd debulk (apply bag + debulk + remove bag)	29.76
4th ply and 5th ply	70.66
Partial plies	10.00
Honeycomb	14.00
3rd debulk (apply bag + debulk + remove bag)	31.85
6th ply, 7th ply and 8th ply	126.48
Place fiberglass tow	5.00
Final bag + leak test	95.00
Place the tool in the autoclave	10.00
Remove The tool from the autoclave	5.00
Remove Composite from the Mold	5.00
Total time	569.15

Table 6.11: Layup steps for Cycom 5267-1 bus seat

Process	Time(min)
Cut Prepregs	10.00
Cut Breather, release film and vacuum bag	10.00
1st ply	23.00
1st debulk (apply bag + debulk + remove bag)	77.00
2nd ply and 3rd ply	58.00
2nd debulk (apply bag + debulk + remove bag)	26.00
4th ply and 5th ply	95.00
3rd debulk (apply bag + debulk + remove bag)	30.00
6th ply, 7th ply and 8th ply	83.00
Place fiberglass tow	5.00
Final bag + leak test	81.00
Place the tool in the autoclave	10.00
Remove The tool from the autoclave	5.00
Remove Composite from the Mold	5.00
Total time	508

Table 6.12: Layup steps for Cycom 5267-1 sandwich bus seat

Process	Time(min)
Cut Prepregs	10.00
Cut Breather, release film and vacuum bag	10.00
1st ply	27.00
1st debulk (apply bag + debulk + remove bag)	76.00
2nd ply and 3rd ply	60.00
2nd debulk (apply bag + debulk + remove bag)	38.00
4th ply and 5th ply	55.00
Partial plies	10.00
Honeycomb	14.00
3rd debulk (apply bag + debulk + remove bag)	37.00
6th ply, 7th ply and 8th ply	101.00
Edge breathing	3.00
Final bag + leak test	95.00
Place the tool in the autoclave	10.00
Remove The tool from the autoclave	5.00
Remove Composite from the Mold	5.00
Total time	546.00

Table 6.13: Labor cost for bus seat samples

	MTM45-1	MTM45-1 with Honeycomb	CYCOM 5320	CYCOM 5320 with Honeycomb	CYCOM 5276-1	CYCOM 5276-1 with Honeycomb
Cost($)	119	145.5	123.71	142.29	136.5	127

Table 6.14: Equipment cost for OOA bus seats

Equipment	Lifetime (years)	Purchase ($)	Salvage ($)
Oven	20	42000	4200
Pump	20	11000	1100
Ply cutter	20	200,000	20,000

Table 6.15: Daily Equipment Depreciation and Maintenance Cost ($/day)

Depreciation Cost (oven+pump+ply cutter)	37.95
Maintenance Cost (oven+pump+ply cutter)	7.00
Depreciation Cost (autoclave+pump+ply cutter)	181.65
Maintenance Cost (autoclave+pump+ply cutter)	33.33

Table 6.16: Equipment cost for MTM 45-1 and MTM 45-1 sandwich bus seat

		Time (hr)	Cost ($)
Energy Consumption Cost	Ply cutter	0.167	0.47595
	Oven	12	81
	Compression Air	22	2.4618
Depreciation Cost			37.95
Maintenance Cost			7
Total			128.89

Table 6.17: Equipment cost for Cycom 5320 and Cycom 5320 sandwich bus seats

		Time (hr)	Cost ($)
Energy Consumption Cost	Ply cutter	0.167	0.47595
	Oven	3.6	24.3
	Compression Air	5	0.5595
Depreciation Cost			37.95
Maintenance Cost			7
Total			63.29

Table 6.18: Equipment for autoclave bus seats

Equipment	Lifetime (years)	Purchase ($)	Salvage ($)
Autoclave	20	1,000,000	100,000
Pump	20	11000	1100
Ply cutter	20	200,000	20,000

Table 6.19: Equipment cost for autoclave bus seat

		Time (hr)	Cost ($)
Energy Consumption Cost	Ply cutter	0.167	0.47595
	Autoclave	5.8	43.5
	Compression Air	7.0	0.7833
Depreciation Cost			181.65
Maintenance Cost			33.33
Total			259.74

Table 6.20: Total cost for bus seats

	MTM45-1	MTM45-1 with Honeycomb	CYCOM 5320	CYCOM 5320 with Honeycomb	CYCOM 5276-1	CYCOM 5276-1 with Honeycomb
Material	81.99	94.17	155.14	177.67	96.22	72.73
Labor	119	145.5	123.71	142.29	136.5	127
Equipment	128.89	128.89	63.29	63.29	259.74	259.74
TOTAL	329.88	368.56	342.14	383.25	492.46	459.47

6.3 Cost Comparison and Analysis

Figure 6.6 shows the different cost components contributing to the total manufacturing cost. For making the bus seats, autoclave equipment cost and labor cost dominate the total cost using MTM 45-1 and Cycom 5276-1. Reducing equipment cost is crucial for reducing the total manufacturing cost. The figure also shows that OOA has lower total manufacturing cost due to lower equipment cost, although material cost is higher than those made by autoclave. Among the 6 combinations in making the sample bus seats, OOA MTM 45-1 has the lowest cost.

Figure 6.6 also shows that for all manufacturing methods, labor cost occupies a large part of the total cost. So improving the layup process is also an important way to reduce the total cost.

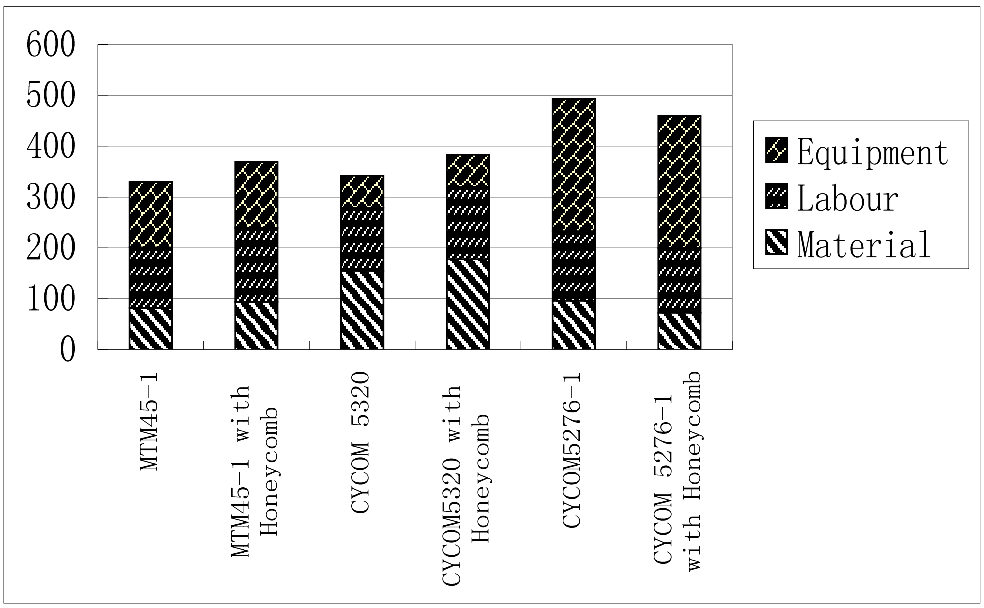

Figure 6.6: Cost breakdown of 6 composite bus seats

6.4 Summary

Cost estimation and analysis for manufacturing composite bus seats are illustrated in this chapter. Cost breakdowns for different processes in making the bus seats are described in detail. The manufacturing process is also presented in detail. In the end, the cost results are compared and analyzed.

Chapter Seven

Aggregate Production Planning for Composite Manufacturing

In this chapter, we propose an aggregate production planning model for composite manufacturing. Production cost analysis presented in Chapter Four is to identify main factors affecting composite production cost. The aggregate production planning model for multiple products presented in this chapter can be used for medium-term (6 to 18 months) production planning. It allocates production resources to satisfy customer demand and minimizes production costs in the planning horizon.

The multi-product production planning problem considered in this chapter is similar to that in Christou *et al* 2007. The problem features are consistent with the cost analysis presented in the previous chapters. In addition, the parameter values used in the example problem are derived from the cost analysis in the previous chapters. Details about the cost structure, assumptions for the model, notations, explanations and model formulation are presented next.

7.1 Problem Definition

In this study, we consider different types of composite components fabricated by different methods. Products by either autoclave process or OOA process can satisfy the customer. The customer requires certain number of products each month. They can be made by autoclave or by OOA. The production planning model is to determine the number of products to produce to satisfy the demand with minimized total cost. The following assumptions are used in formulating the aggregate production planning model.

1. Customer demand may be different in different time periods.

2. Product orders are received at the beginning of each period.

3. Products are delivered at the end of each period.

4. If product delivery is delayed, penalty cost will incur.

The objective function of the model is to minimize total production cost, inventory cost and penalty cost.

7.2 Manufacturing Model

Before the mathematical model is presented, we first give notations used in formulating the model.

Index sets:

错误！未找到引用源。 : Index of product types, 错误！未找到引用源。
错误！未找到引用源。 : Index of time periods, 错误！未找到引用源。

Parameters:

错误！未找到引用源。: Demand in period t;
错误！未找到引用源。 : Unit production cost;
错误！未找到引用源。: Unit inventory holding cost for one period;
错误！未找到引用源。: Unit penalty cost for each month late products;

Decision variables:

错误！未找到引用源。 : Production quantity of product 错误！未找到引用源。 during time period t;
错误！未找到引用源。 : Inventory quantity of product 错误！未找到引用源。 at the end of time period t;
错误！未找到引用源。: Delayed quantity of product 错误！未找到引用源。 at the end of period t;

The objective function of the math model is to minimize total production cost in considered time periods.错误！未找到引用源。错误！未找到引用源。错误！未找到引用源。

$$\text{Min} = \sum_{i}^{I}\sum_{t}^{N} C_i \times P_{it} + \sum_{i}^{I}\sum_{t}^{N} H_i \times I_{it} + \sum_{i}^{I}\sum_{t}^{N} (C_i + C_p) \times L_{it} \tag{7.1}$$

The objective function is to be minimized subject to the following constraint functions:

$$\sum_{i}^{I} P_{it} - \sum_{i}^{I} I_{it} + \sum_{i}^{I} I_{i(t-1)} + \sum_{i}^{I} L_{it} = D_t \qquad \forall (i,t) \tag{7.2}$$

$$I_{it} \in N \quad , \quad P_{it} \in N \ , L_{it} \in N \qquad \forall (i,t) \tag{7.3}$$

$$0 \leq P_{1t} \leq U, \qquad P_{1t} \in N, \quad \forall t \tag{7.4}$$

$$0 \leq P_{2t} \leq U, \qquad P_{2t} \in N, \quad \forall t \tag{7.5}$$

$$0 \leq L_{1t} \leq Q, \qquad L_{1t} \in N, \quad \forall t \tag{7.6}$$

$$0 \leq L_{2t} \leq Q, \qquad L_{2t} \in N, \quad \forall t \tag{7.7}$$

$$0 \leq P_{1t} + L_{1(t-1)} \leq U, \qquad L_{it}, P_{it} \in N, \forall t \tag{7.8}$$

$$0 \leq P_{2t} + L_{2(t-1)} \leq Q, \qquad L_{it}, P_{it} \in N, \forall t \tag{7.9}$$

$$L_{i0} = 0 \qquad \forall i \tag{7.10}$$

Constraint (7.2) ensures that the total production of autoclave and OOA plus the inventory at the end of the previous period plus the delay quantity minus the inventory level in this period is equal to the customer demand in the period. Constraints (7.4) ~ (7.7) ensures that the autoclave production and OOA production are limited by the production capacity. Constraints (7.8) and (7.9) indicate that the sum of production and penalty in the period should not be over the production capacity. Constraint (7.10) shows that the initial value of delayed products is 0.

7.3 Numerical Examples and Analysis

An example problem is presented to test the model. This example problem is based on the information of the composite manufacturing processes discussed in Chapter 3 and Chapter 4. The example problem considers 4 different ways in making autoclave-convex, autoclave concave, OOA –convex and OOA-concave. The end products are considered the same in satisfying customer demands.

The unit manufacturing cost is obtained from the process discussed in Chapter 4. The number of the production period is 7 months. The manufacturing costs of autoclave-convex and OOA-convex component and equipment capacities are shown in Table 7.1. The holding cost is $0.78 per product. The penalty for each delayed product is $7.8. Customer demands for the 7 months are shown in Table 7.2.

Table 7.1: Unit manufacturing cost for each kind of samples

	OOA-convex	Autoclave-convex
Cost ($)	66.79	88.69
Capacities (unit/per month)	20	40

Table 7.2: Product demand for each period

Month	1	2	3	4	5	6	7
Demand(unit)	77	33	25	75	107	100	45

7.5 Solution and Analysis

The example problem is solved using optimization software LINGO. The optimal solution: how many units to product, inventory and how many backlog is shown in Table 7.3. The total production cost is \$ 38,579.10 with manufacturing cost, inventory cost and penalty cost being \$27,233.2, \$66.3 and \$11,279.6 respectively.

Table 7.3: Solution for product quantity for each period

	Solution		Inventory		Backlog	
Period	Autoclave	OOA	Autoclave	OOA	Autoclave	OOA
1	40	20	0	0	0	17
2	40	3	10	0	0	0
3	40	20	45	0	0	0
4	40	20	30	0	0	0
5	40	20	0	0	0	17
6	40	3	0	0	40	17
7	0	3	0	0	22	20

It can be seen that production will be up to the maximum of the capacity, when the customer demand is high. At the same time, inventory will be used and backlog will be occurred. Because OOA-convex is less expensive than autoclave-convex, when demand is not very high, capacity of OOA-convex is always used first. When demand is higher, to satisfy the demand, autoclave-convex will be used first because of its fast production rate. Moreover, the shortage cost occurs only when the customer demand is very high in this problem.

7.6 Summary

A multi-product production planning model was established for allocating production resources to minimize total production costs is composite manufacturing. Production level, inventory level and penalty level of the products were determined to minimize the total cost. Details of the cost structure, assumptions for the model, notations, explanations and model formulation were described. The mathematical model is programmed in LINGO. A numerical example is solved to validate the developed model.

Chapter Eight

Conclusions and Future Research

In this chapter we present a summary of the research conclusion based on the composite manufacturing and the problem modeling presented in the previous chapters. Future research directions in this area are also discussed.

8.1 Research Summary

In this study, out-of-autoclave and autoclave composite manufacturing processes are studied. We proposed a cost model to analyze the costs of manufacturing L-shape composite components. The total manufacturing cost of the OOA L-shape components was compared with the autoclave L-shape components. We identified the factors that have major impact on production cost. The study also shows that the process can be improved if certain manufacturing steps take place in parallel.

Tests were conducted for testing quality of the manufacturing L-shape components. Tensile and compression tests were conducted for testing the mechanical properties. Microscope tests were used in checking the corner section of the samples to detect void content of the corner section.

An aggregate production planning model was developed for large scale production of composite manufacturing. Production cost, inventory cost and penalty cost were considered in the production planning model. We used the L-shape composite manufacturing production as an example. The model was solved using simple linear programming optimization to obtain optimal production quantities and inventory quantities were obtained in this research.

Both the production cost and aggregate production planning model developed in this study can be easily modified for cost analysis on similar composite manufacturing processes in different industries.

8.2 Contribution

Four different kinds of composite L-shape samples were fabricated in this study: autoclave concave, autoclave convex, OOA-concave and OOA-convex. And a multiple product cost analysis model was developed for the composite L-shape manufacturing production.

8.3 Future Research

The research presented in this thesis can be extended in several aspects such as:

1. Consider the uncertainties involved in composites manufacturing.

2. Extend the model to include sensitivity analysis and other post-optimality analysis.

3. Develop cost analysis model which can be used for manufacturing different composite products at the same time.

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APPENDIX A: Tensile Test Load Data

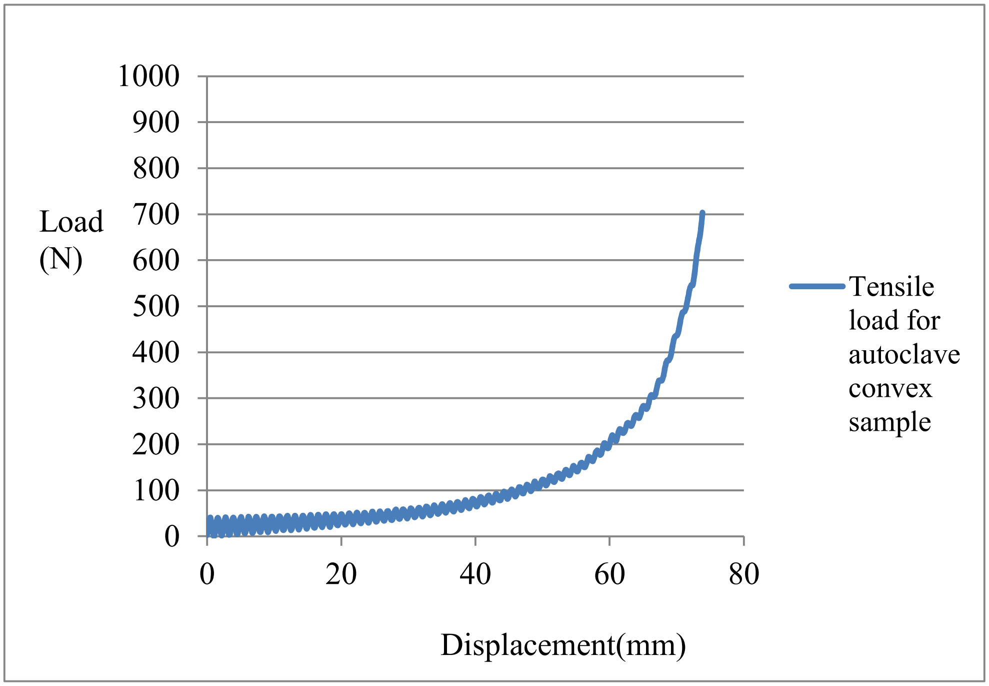

Figure A1: Tensile load for autoclave convex sample

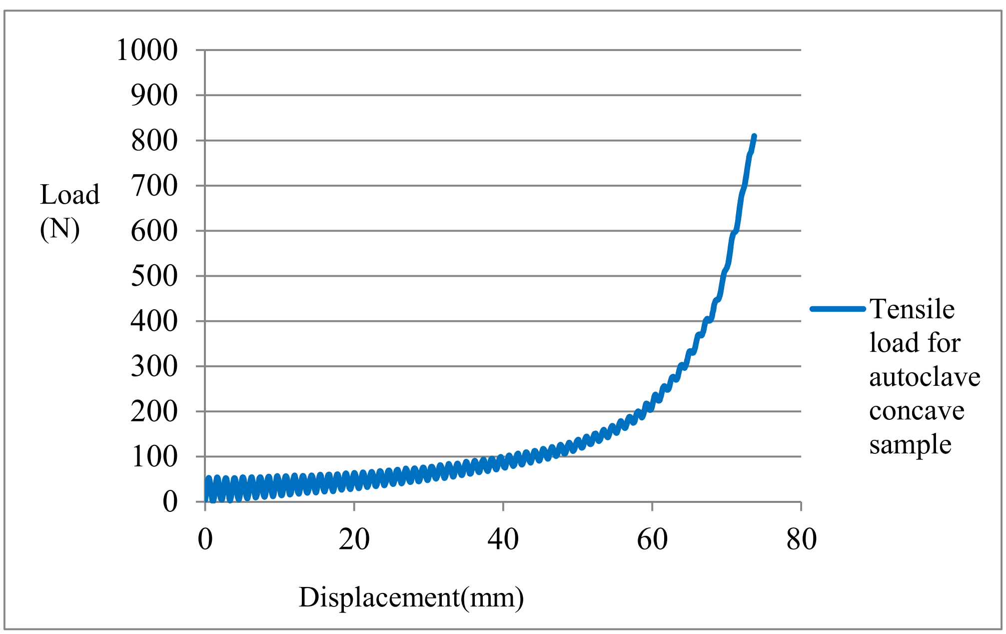

Figure A2: Tensile load for autoclave concave sample

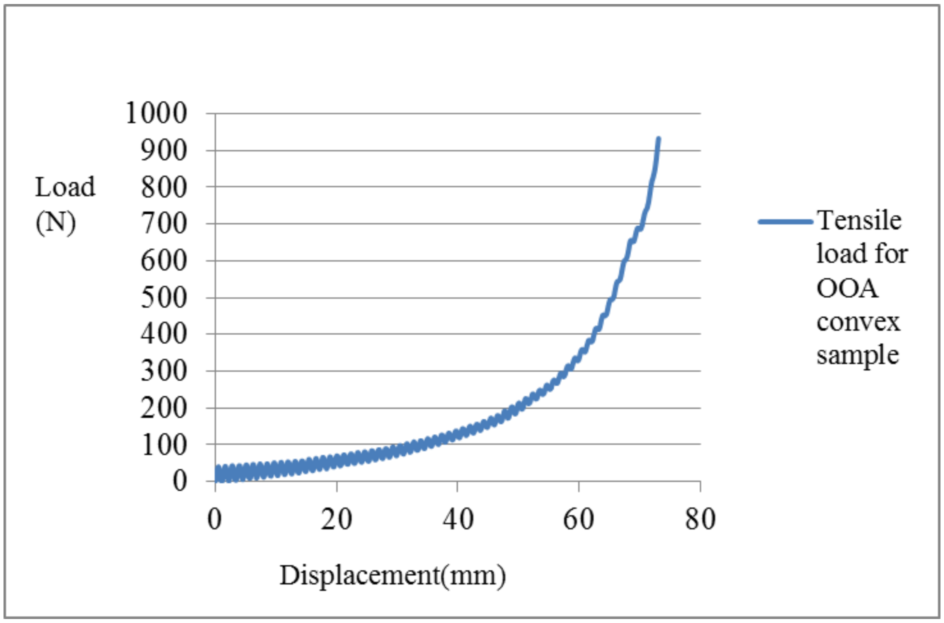

Figure A3: Tensile load for OOA convex sample

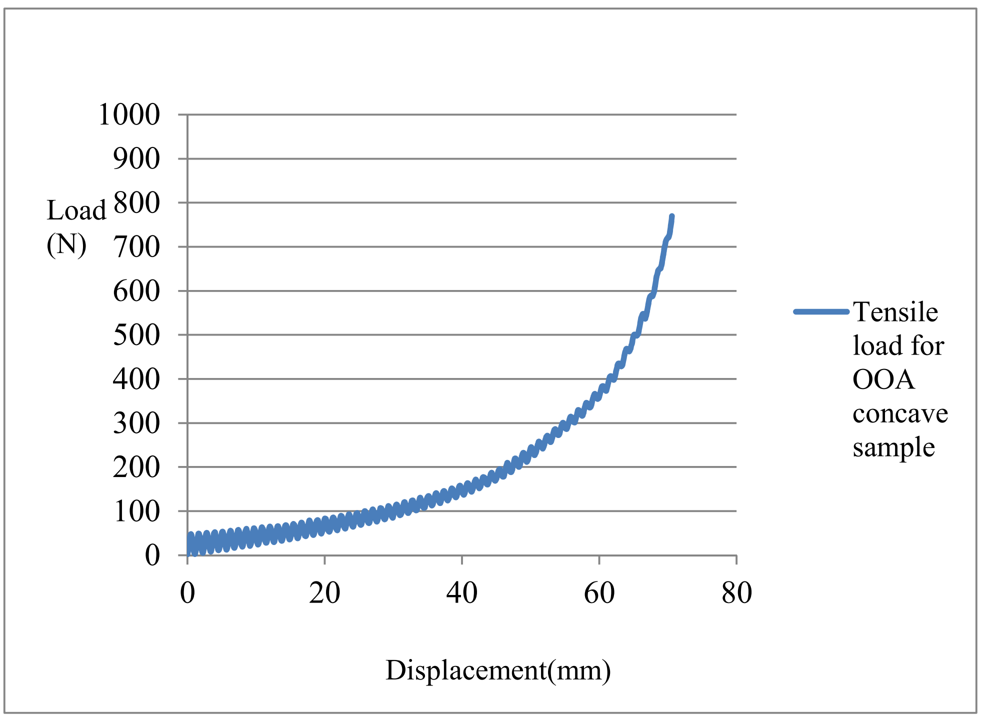

Figure A4: Tensile load for OOA concave sample

APPENDIX B: Compression test load data

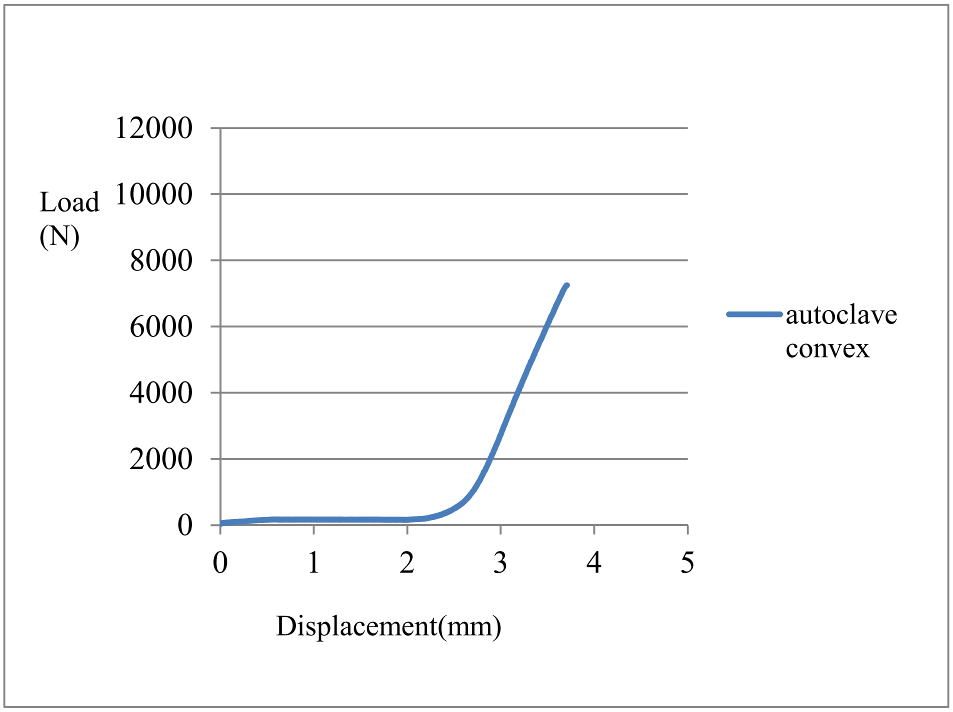

Figure B1: Autoclave convex compression Load

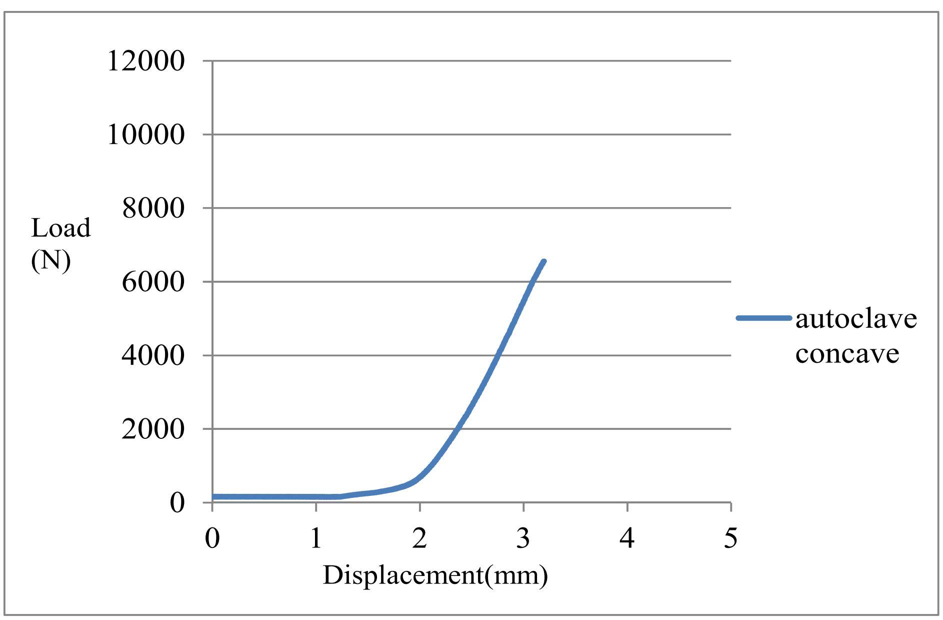

Figure B2: Autoclave concave compression load

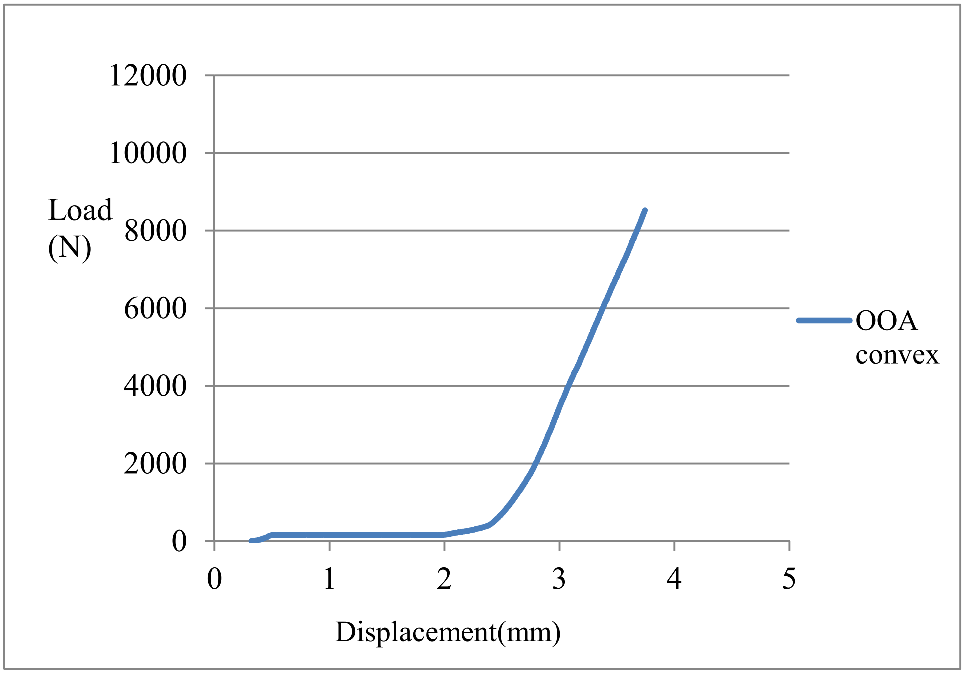

Figure B3: OOA convex compression load

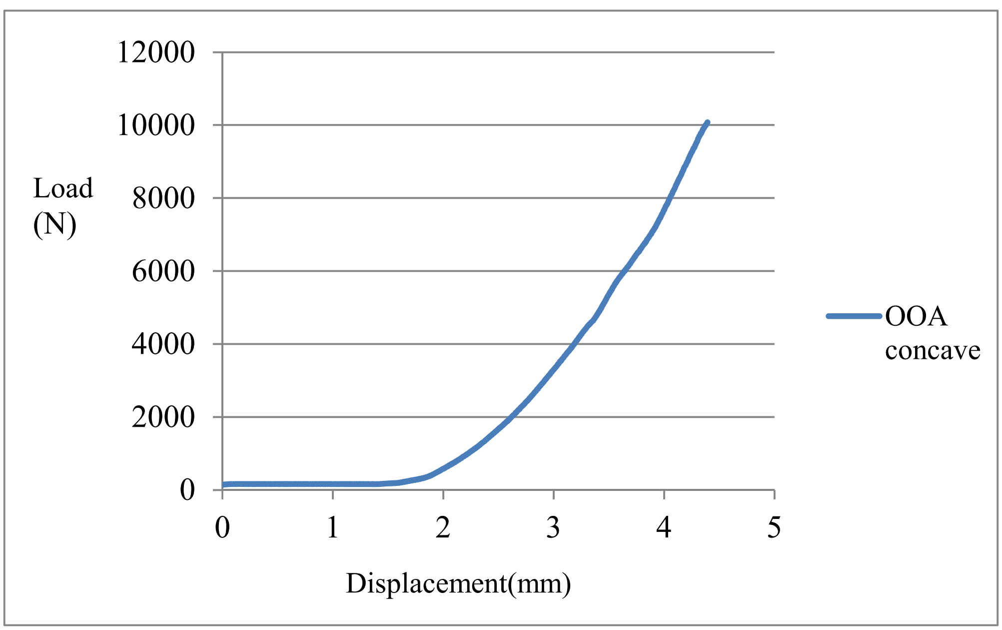

Figure B4: OOA concave compression load