Composite Honeycomb Cores

Ksenia Jegorova

Degree Thesis
Plastics Technology
2014

DEGREE THESIS	
Arcada University of Applied Sciences, Helsinki, Finland	
Degree Programme:	Plastics Technology
Identification number:	14661
Author:	Ksenia Jegorova
Title:	Composite honeycomb cores
Supervisor (Arcada):	Rene Herrmann
Commissioned by:	Mathew Vihtonen

Abstract:

This thesis demonstrates how a certain type of a sandwich core - honeycomb is manufactured and post-processed, in case if it was made from composite material itself. Any sandwich structure consists of three essential elements: two faces, core and joints. The core represents good ability to carry shear loads. That part of the sandwich is incredibly significant, since it assures that sandwich is not just light but also stiff enough. Honeycomb core is one of the most structurally efficient core constructions, especially in stiffness-critical applications, which is provided with minimal density and high out-of-plane compression and shear properties. As it follows from its name, honeycomb core consists of hexagon-shaped cells, which are completely identical to each other. That core structure is an anisotropic one, which means it is anisotropically loaded inside the sandwich. That follows that honeycomb core could be made of an anisotropic material performing a maximum strength to mass ratio. Traditional honeycomb constructing methods include corrugation and expansion manufacturing processes as well as expansion combined with dipping into phenolic resin. Corrugation was chosen as a basis manufacturing process used to create honeycomb cores in the experimental part of this work. The process consisted of the following steps: prepreg glass fibre and carbon fibre sheets were shaped with a use of aluminium mould, heat and pressure and then sliced and glued together in order to create a composite honeycomb core. Post-processing by milling did not result in shear overload and delaminating of skins or delaminating of layers from each other. As a result some composite honeycomb cores and composite honeycomb sandwich panels were made. Macroscopic density (approx. 0.4 g/cm^3) and price (at least 160.04 euro/kg) of the made products were competitive with Ultracor samples (approx. 0.3 g/cm^3 and 16000 euro/kg). However these made products would have more performance if bonding between layers inside the honeycomb core would be stronger with less adhesive used.

Keywords:	Sandwich panels, composites, honeycomb core, anisotropic cores, anisotropic materials.
Number of pages:	43
Language:	English
Date of acceptance:	26.11.2014

CONTENTS

Figures

Tables

FOREWORD

First of all, I would like to give my greatest thanks to my supervisor Rene Herrmann, who suggested to me this interesting and challenging idea for my thesis work. I would like to thank him for his guidance and advice during the writing and experiments stages of my work, and for arrangement of a trip to Neuhäuser Contox – Precision Cutting Tools (Prüm, Germany) for post-processing milling.

This thesis work would not be possible without technical help of Erland Nyroth, who modeled and manufactured moulds for the experiments phase.

I would like to thank Neuhäuser Conrox – Precision Cutting Tools (Prüm, Germany), and Vasco Schumann in particular, for performing of the milling post-processing stage and for organization of the trip to Euro-composites (Echternach, Luxembourg) for slicing of the honeycomb block.

I would also like to thank excellence centre of Euro-composites for performing the slicing of the honeycomb block with their band saw.

And last but not least I would like to thank Arcada University of Applied sciences and the Department of Energy and Materials Technology for financial support of my post-processing stage trip to Germany.

LIST OF SYMBOLS (SI units)

D – flexural rigidity

E – Young's modulus [Pa]

I – second moment of inertia

E_f – Young's modulus of faces [Pa]

E_c – Young's modulus of a core [Pa]

b – width [m]

t – thickness of one face / thickness of honeycomb's wall [m]

c – thickness of the core [m]

d – distance from the middle of one face till the middle of another one [m]

h – height [m]

F – force [N]

M – moment

σ – stress [Pa]

L – length [m]

A – area [m^2]

ε – strain

τ – shear stress [Pa]

γ – shear strain

G – shear modulus [Pa]

Q – shear force

M – bending moment

N_n – column in honeycomb, where **n** is a number of the column

1 INTRODUCTION

This thesis work is focused on a research of desired mechanical properties of a core part of a sandwich structure. Possibilities to manufacture a composite honeycomb are also studied. This part is written in order to state a problem and hypothesis of this thesis work, and explain which method is used here.

1.1 Background

Any sandwich structure consists of three essential elements: two faces, core and joints, and that can be clearly seen in Fig. 1.1.

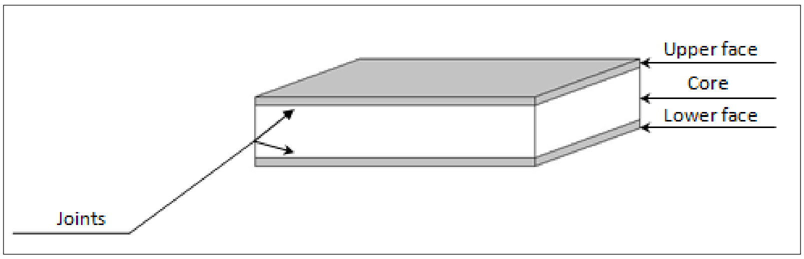


Figure 1.1. Sandwich structure

The aerospace and commercial industries widely use sandwich structures and there is a reason for that. Sandwich panel is a very lightweight construction with high stiffness. A core represents a good ability to carry the shear loads. It is a part of the sandwich which assures that sandwich is not just light but also stiff enough. A honeycomb core is one of the most structurally efficient core constructions, especially in stiffness-critical applications. (Campbell, 2010) Honeycomb core consists of hexagon-shaped cells, which are completely identical to each other.

Figure 1.2. Example of a honeycomb cell

1.2 Hypothesis

A honeycomb is an anisotropic core structure. Since it is anisotropically loaded inside the sandwich, the honeycomb core could be made of an anisotropic material performing a maximum strength to mass ratio.

1.3 Method

This thesis work includes research of literature about mechanical properties of a sandwich structure, its core and a honeycomb core. Ways to manufacture the honeycomb and manufacturing of honeycomb using anisotropic materials are studied too. A practical part is represented with an experimental production of composite honeycomb, its testing and comparing to existing results concerning other types of honeycomb cores.

2 THEORY

This chapter is written in order to show and explain existing theories and conclusions concerning physical properties of sandwich construction, core part of sandwich and honeycomb core. Possibilities to manufacture composite honeycomb are also studied.

2.1 Sandwich deflection

This chapter gives an understanding about a flexural rigidity in a sandwich construction and its definition. There are also discussed stresses presented in a sandwich beam.

2.1.1 Flexural rigidity

According to Sandwich Concept by DIAB AB, the theory of engineering stresses in beams can be modified and adapted in order to use it for a sandwich beam. According to the beam theory flexural rigidity D is given by

$$\mathbf{D = E * I} \ ,$$ *Eq. 2.1 (DIAB AB, 2003, p.6)*

where E is Young's modulus and I is second moment of inertia.

However, since sandwich beam consists of few different parts, its *D* is a sum of flexural rigidities of these parts:

$$\mathbf{D = E_f * bt^3/6 + E_f * btd^2/2 + E_c * bc^3/12}$$ *Eq. 2.2 (DIAB AB, 2003, p.6)*

Fig. 2.1 shows a cross section of the sandwich beam and dimensions for the equation above.

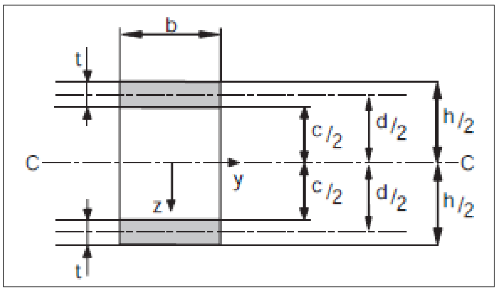


Figure 2.1. Sandwich beam cross section (DIAB AB, 2003, p.6)

The first term in equation (2.2) is flexural rigidity about centroidal axes of the faces. The second term is the first term, which was transposed far a bending about the centroidal axis of the sandwich beam entire cross section. The third term is flexural rigidity of the core, which is the same about its own cenroidal axis as well as about centroidal axis of the entire cross section. Generally sandwich has thin faces. When $d/t > 5.77$ the first term amounts are less than 1%. At a ratio $d/t > 11.55$ the proportion is less than 0.25%. If it is assumed that the faces are thin, then the first the first term could be ignored. When $(E_f/E_c) * (td^2/c^3) > 16.7$ the third term amounts are less than 1% of the second term amounts, and they can be ignored. Thus expression of D can be reduced to

$$\mathbf{D = E_f * btd^2/2}$$ *Eq. 2.3 (DIAB AB, 2003, p.8)*

(DIAB AB, 2003)

2.1.2 Stress types in sandwich

Sandwich beams loaded in different ways are studied in order to find out stress types presenting in a sandwich beam. First case is shown on fig. 2.2, it is the sandwich beam loaded in the middle.

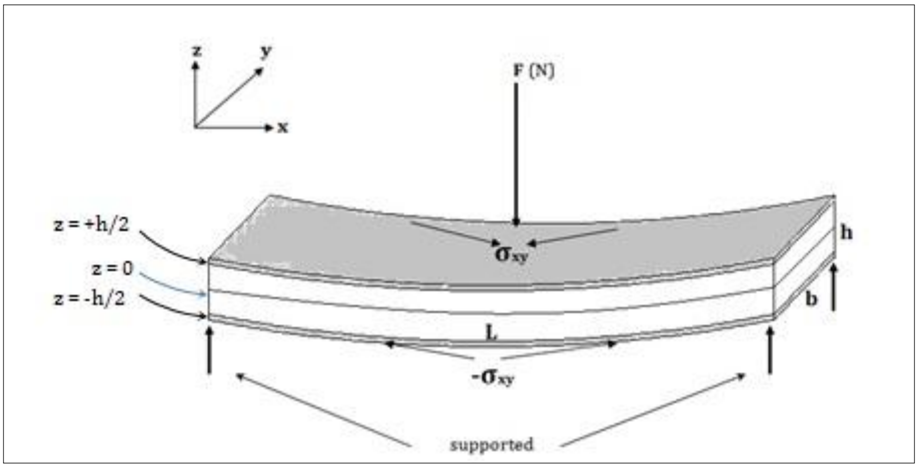


Figure 2.2. Loaded sandwich beam

So in a case when force is applied in the middle there is compression in the upper part of the beam and tension in the bottom part. Stresses in this case can be written as

$$\boldsymbol{\sigma_{xy}(z = +h/2) = +\sigma_{xy}(max)}$$ *Eq. 2.4 (DIAB AB, 2003, p.7)*

$$\boldsymbol{\sigma_{xy}(z = 0) = 0}$$ *Eq. 2.5 (DIAB AB, 2003, p.7)*

$$\boldsymbol{\sigma_{xy}(z = -h/2) = -\sigma_{xy}(max)}$$ *Eq. 2.6 (DIAB AB, 2003, p.7)*

Since theory for engineering stresses in beams with few modifications can be used to determine stresses in the sandwich beam, sheet stresses value is

$$\boldsymbol{| \sigma_{xy}(max) | = (Mc/D) * E_f},$$

$$\text{where } \boldsymbol{M = F * L}$$

$$\text{and } \boldsymbol{Ef = 2D/btd^2},$$

$$\text{so } \boldsymbol{| \sigma_{xy}(max) | = (2FLc)/(btd^2)}$$ *Eq. 2.7 (DIAB AB, 2003, p.7)*

In a case when the sandwich beam is loaded uniformly, as it is shown on fig. 2.3, compressive stress occurs in it. In this case classical beam theory can be applied and the stress can be calculated as that is shown in equation 2.8.

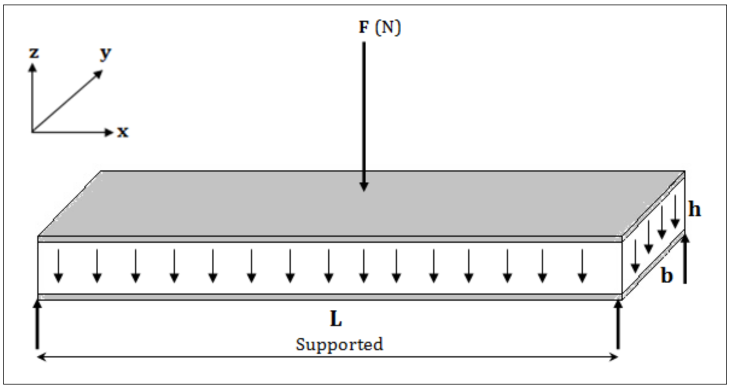


Figure 2.3. Uniformly loaded sandwich beam

$$\boldsymbol{\sigma_z = F/A = F/bL}$$ *Eq. 2.8 (PhysicsNet.co.uk 2010-2014)*

The next case is shown on fig. 2.4, representing vertical shear stress in a sandwich beam.

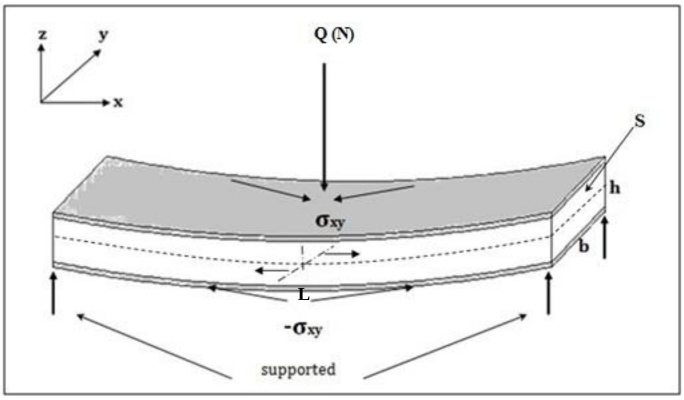


Figure 2.4. Sandwich beam under shear load

Shear stress can be calculated using the equation below.

$$\tau = G * \gamma,$$

where $\gamma = Q / G * bh$,

so $\tau = Q / bh$ or $\tau = Q / S$ *Eq. 2.9 (DIAB AB, 2003, p.9)*

2.2 Core of sandwich

This chapter is written in order to explain stresses, which may present in a core of sandwich. There are also discussed possible core failures and desired properties of the core.

2.2.1 Stress types in core

According to the previous chapter there are sheet stresses, compressive and shear stresses can occur in a sandwich beam under different types of load. Two of them, compressive and core stress, can be defined as core stresses, since they occur in a core of the sandwich beam.

2.2.2 Types of core failure

There are few types of core failures, which can be caused by stresses mentioned before. They are different types of buckling characteristics: general buckling shear crimping, wrinkling and dimpling. All of them can be clearly seen on the fig. 2.5.

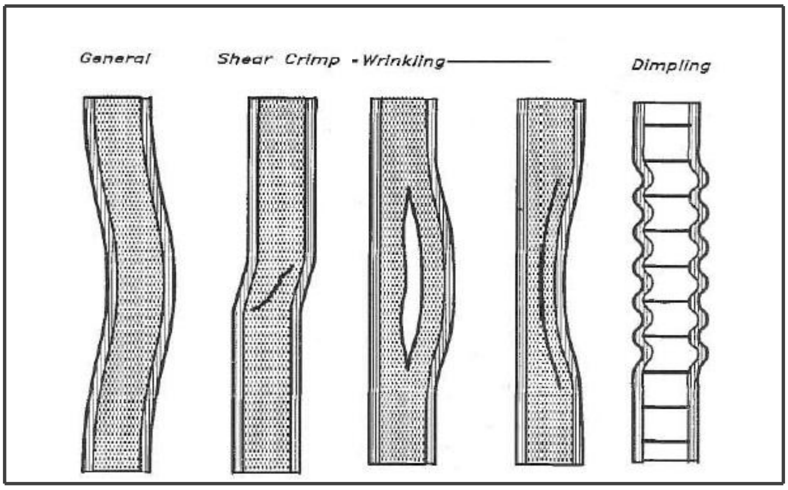


Figure 2.5. Core failures (Larsson & Eliasson, 2000, p. 263)

Possible core failures are studied via placing sandwich panels into compression perpendicular to their plane. That way buckling characteristics can be studied. Possible results of that kind of testing are shown on fig. 2.5. According to Principles of Yacht Design by Larsson and Eliasson, general buckling is mainly caused by reduced thickness of the sandwich panel, which causes bending of the whole structure. Shear crimping is caused by vertical shear overload, which means that core is weak in shear. Wrinkling happens because of different reasons. In first case the problem is caused by a horizontal shear overload, which affects core neutral axis. In second case the problem is caused by compressive overload. The last type of failure called dimpling happens in case when cell-structure core like a honeycomb is used for the sandwich construction. In case with the honeycomb the core and faces of the sandwich are joined at the honeycomb cells' edges. For this reason faces of the sandwich panel can undergo buckling in the free spaces within the cells, when the compressive load is applied.

2.2.3 Prevention of the core failures

Table 2.1. Prevention of core failures

Type of core failure	Prevention method
General buckling	Use a stiffer core Increase thickness of the core
Shear crimping	Use a stiffer core Increase thickness of the core
Wrinkling	Use of core with better elastic properties
Dimpling	Use of core consisting of smaller cells

2.3 Honeycomb core

This chapter is written in order to explain concept of a structure of a honeycomb core and different ways to manufacture honeycomb. Stresses, which can be in that type of core and ways of minimizing them are studied too. In addition there is presented a research of attempts to manufacture honeycomb core of a composite material.

2.3.1 Honeycomb core loading

Honeycomb core provided with minimal density and high out-of-plane compression and shear properties. Example of a honeycomb core is shown below on fig. 2.6.

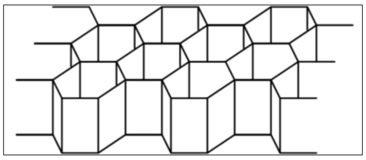


Figure 2.6. Honeycomb structure (Composite Machining, 2014)

Dimensions of one wall of the honeycomb are assumed as it is shown on fig. 2.7. It is also assumed that thickness of the walls is uniform in the whole structure.

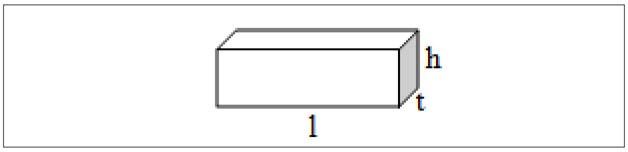


Figure 2.7. Dimensions of one wall of honeycomb

Different parts of the honeycomb are taken and studied in order to understand which stresses are held by which part. First of all a segment of honeycomb, where three walls meet together, is taken and a load it handles is shown. That can be found on fig. 2.8.

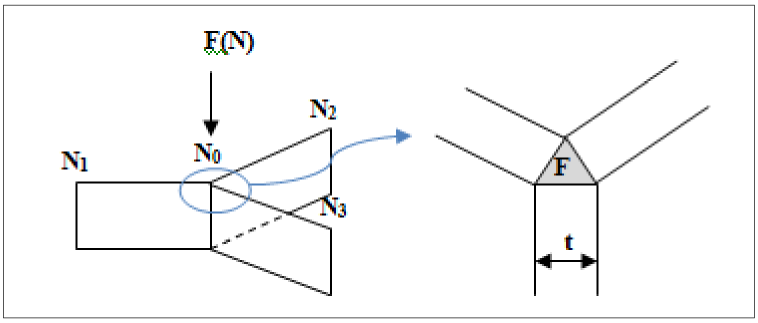


Figure 2.8. Force to the column N_0

There is compressional stress in a column N_o. Force applied to N_o leads to buckling of the column. This stress causes elastic deformation can be described as

$$\sigma = E * \varepsilon = F/A(t) * \varepsilon = F/(t^2\sqrt{3}/4) * \varepsilon = 4F/(t^2\sqrt{3}) * \varepsilon \qquad \textit{Eq. 2.10}$$

Next topic of discussion is a stress at z = 0

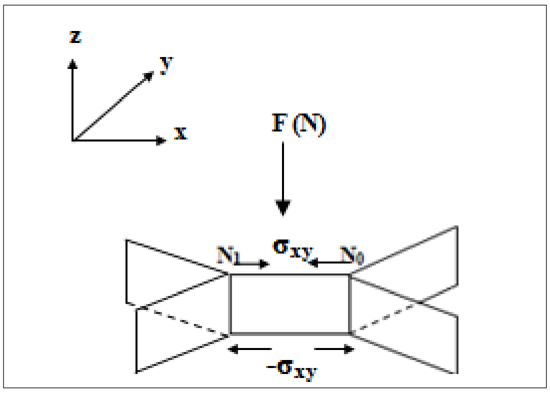


Figure 2.9. Stress in honeycomb core at z=0

In a case shown on fig. 2.9 applied force causes buckling of the wall. Stress values in that case can be found according to the equation below.

$$\boldsymbol{\sigma_{zy} = Mc/I}\text{ , where }\boldsymbol{I = th^3/12} \qquad \textit{Eq. 2.11}$$

Talking about the whole sandwich structure made using honeycomb as a core of it, one more stress should be considered. That stress is shear stress in a bonding between the core and faces. That case is shown on fig. 2.10.

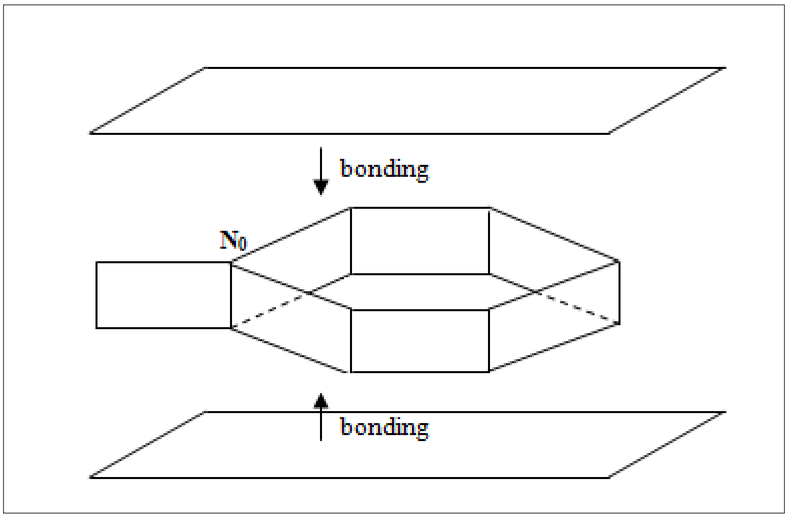


Figure 2.10. Shear stress in a bonding of honeycomb sandwich

So shear stress here can be calculated as

$$\boldsymbol{\tau = Q/ A = Q/ 6tl}\text{, where}$$

$$\boldsymbol{A = Q/ \tau}\text{ or }\boldsymbol{A = Q/ G * \gamma} \qquad \textit{Eq. 2.12}$$

G in that equation is a shear modulus of a joint (glue or bonding agent) used to connect the core and faces. At the same time that equation can be used in order to find the most appropriate area of the cell. According to equation 2.12 the smaller area means smaller stress value. So size of the cells should be small in order to reduce stress at z = c/2.

2.3.2 Ways to minimize stresses in honeycomb

According to the previous chapter all the stresses mentioned there can be placed to figure in order to analyze them easier.

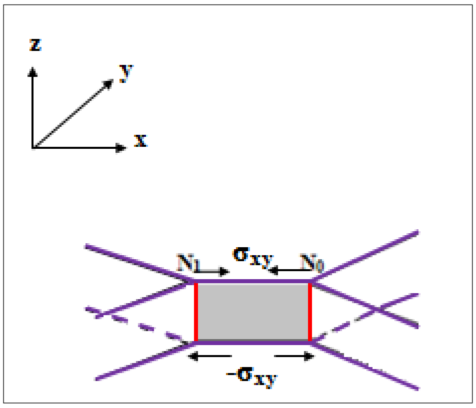


Figure 2.11. Different stresses of honeycomb core

Different colours on fig.2.11 show different stresses in honeycomb core. According to all this stresses the desired properties of the honeycomb core can be stated.

- Compressional strength of the columns
- Large area of bounded interface represented by big amount of small cell per m^2
- Prevented stress at z = 0

It means that ideal honeycomb core should have columns strong enough to withstand stress, and there has to be a lot of small cells in it. That honeycomb core should also have good stiffness properties in order to be able to prevent stress at z = 0.

2.3.3 Traditional ways of manufacturing of honeycomb

Honeycomb can be made by expansion or corrugation process. Expansion process means that layers of materials with printed adhesive lines are first glued together. After that the block, consisting of a few layers of that material, is sliced into pieces of the required size. Finally each piece is expanded and several honeycomb cores are received. Corrugation process means that first material is corrugated or folded into certain shape, after what shaped layers are glued into honeycomb block. The block can be then sliced into pieces of the required size. Both the processes can be understood easier from figures 2.12 and 2.13.

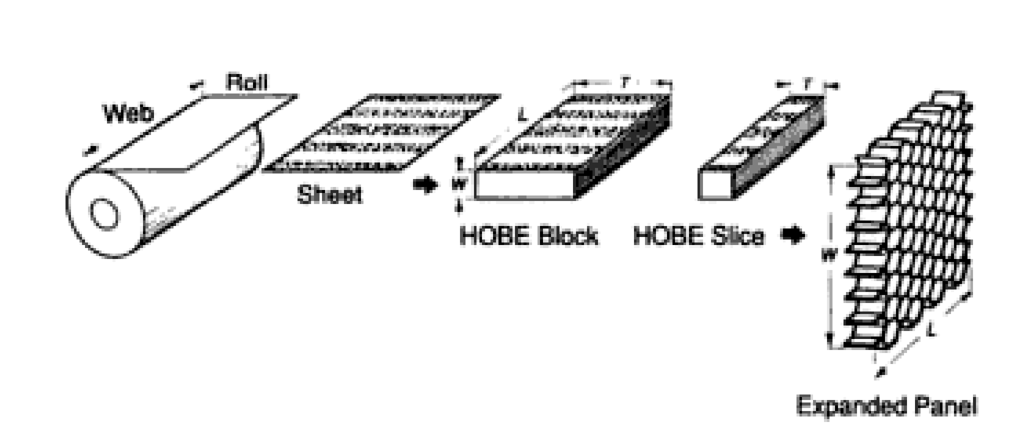


Figure 2.12. Expansion manufacturing process (Campbell, 2010, p.260)

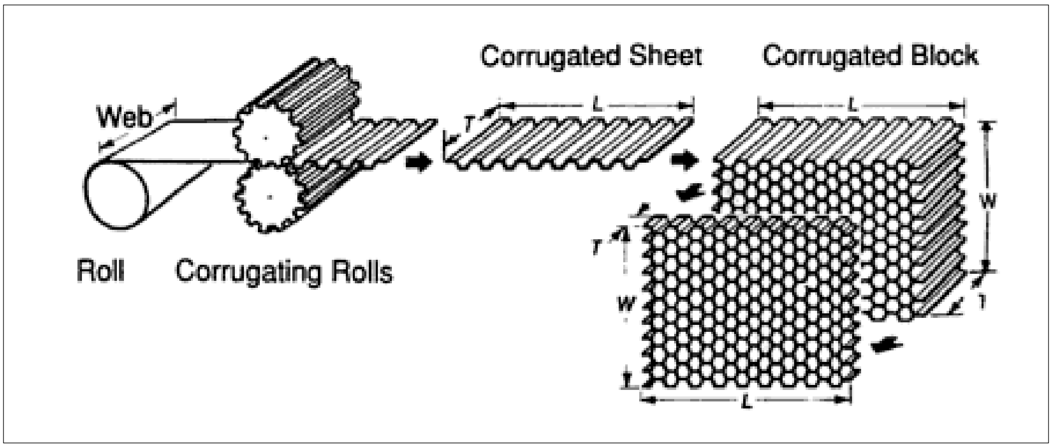


Figure 2.13. Corrugation manufacturing process (Campbell, 2010, p.260)

Expansion process can be described in five stages, which are roll, sheet, HOBE (honeycomb before expansion) block, HOBE slice, expanded honeycomb panel. Corrugation manufacturing in turn consists of roll, corrugating rolls, corrugated sheet, corrugated block, honeycomb panel.

Another known technique is used to create Nomex honeycomb. Expansion manufacturing method is used there as a basis. The process starts the same as traditional expansion manufacturing method, where layers of material with printed adhesive lines are glued together. After that these glued layers are expanded into honeycomb block which is preheated afterwards in order to stay in that shape. The block is dipped several times into phenolic resin then and after that it is heated in the oven so that the resin could cure. As a result Nomex honeycomb block is received and it can be cut or milled into required shape.

Nevertheless neither of the processes described above can be performed without special equipment, which is not available at the place of experiment. Therefore in the experiment for this work the corrugation manufacturing process was taken as a base, but step with corrugating rolls was replaced with lamination, after that there was a slicing stage and finally secondary bonding step was performed in order to build a honeycomb.

Two samples of carbonfibre honeycomb production were available for observation before the experiment. Those samples were manufactured by some unknown American laboratory and they were received through Neuhäuser Controx – Precision Cutting Tools.

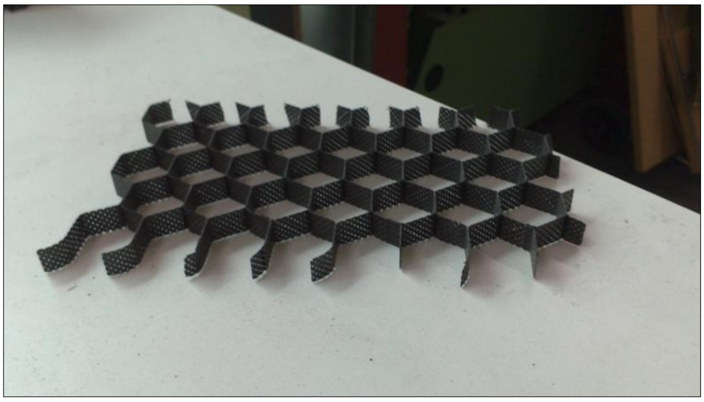


Figure 2.14. Carbon fibre honeycomb core sample from unnamed American lab

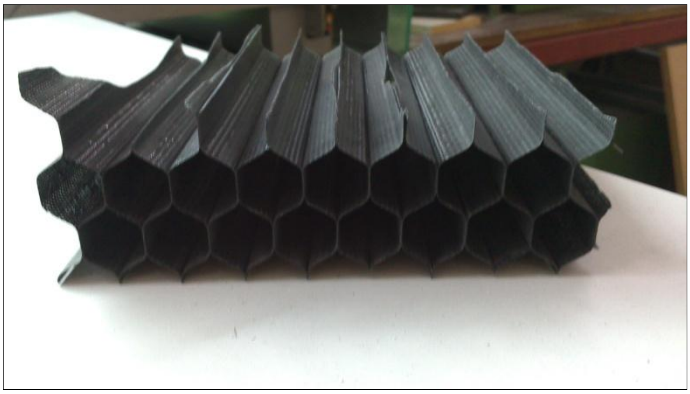


Figure 2.15. Carbon fibre honeycomb block sample from unnamed American lab

Sample from the figure 2.14 was representing hexagons with very sharp corners in cross-section, which would be rather suggesting an idea of corrugation manufacturing processes used as a basis for creating of that honeycomb. However with that flat and shiny surface of the lamina and completely invisible bonding between layers, it looks even more like layers were heated and pressed together in order to get that perfect bonding and shape. Second sample (fig. 2.15) on the other hand has hexagons, which have slightly rounded shape at the corners next to the bonding line between layers. It seems more likely that expansion manufacturing process was used in order to make that honeycomb block.

3 METHOD

3.1 Constructing of composite honeycomb

The aim of the experiment was to find an optimal way to build composite honeycomb using equipment, which was available for this particular work. Corrugation manufacturing process was taken as a basis of the experiment. On the other hand it would be useful to mention that steps of the process were slightly different from the corrugation. So the honeycomb making procedure consisted of the following steps:

- Lamination of layers for honeycomb
- Slicing of the layers
- Secondary bonding or constructing of honeycomb

Two last steps swapped places in one of the experiments.

3.1.1 Lamination of layers

Experiment 1

From beginning there was an idea to perform lamination step using a grooved plastic mould and vacuum for impregnation of fibreglass with epoxy resin.

Mould

Material: POM (Polyoxymethylene)

Dimensions: 66.5 *15 * 4 (cm)

Description: 5 grooves, each 1.5 * 0.8 * 1 (cm) in cross-section

Figure 3.1. POM mould for experimental lamination of a layer for honeycomb

Materials for lamination

Matrix material: fibreglass, 20 * 66.5 (cm)

Resin: epoxy

Additional materials

- Release agent
- Aerofix – to place fibres into the grooves
- Peel-ply – for good secondary bonding
- Release film
- Flow mat
- Plastic film
- Vacuum tape
- Elastic tubes and plastic valves

Equipment

Vacuum pump

Requirements

Full curing time: 24 hours

The lamination procedure

- Applying of Aerofix adhesive spray to a surface of the mould
- Placing of peelply, so that it has a shape of the grooves on the mould
- Additional layer of Aerofix
- Placing of glassfibre textile on the mould surface and making sure that the textile repeats shape of the mould surface
- Layer of Aerofix
- One more layer of peel-ply
- Layer of Aerofix
- Layer of release film
- Layer of Aerofix
- Flowmat
- Vacuum tape is placed around the mould
- Vacuum pipe and resin delivery pipe are attached to opposite sides of the mould
- Plastic film is attached to the vacuum tape, in such a way that it covers the surface of the mould and the pipes
- Vacuum on
- Check for the holes
- Impregnation started
- Product is left until the curing is finished

The peel-ply layers were used on both sides of the fibres layer in order to get a product with a surface, which would be better for secondary bonding.

Figure 3.2. Vacuum impregnation of fibre glass with epoxy resin

After that the film was removed in order to obtain the results. The results were not the desired ones. Product was with a poor quality, the grooves looked more like waves. So there was a conclusion that this lamination method does not suit for this case.

The main problem to solve was a placement of the fibres in to the grooves. So the first thought was to change the way of placing the fibres. One of ideas was a use of some additional equipment, for example rolls, in order to create the sheets with required grooves for honeycomb construction. However, creation of this kind of rolls would be at least time and material consuming process. So another idea has appeared. That was an idea to use pre-preg sheets instead of using fibres and resin separately. Pre-pregs take a shape of the mould when the temperature and pressure are applied, which meant that metal mould with heaters and press could be used in this case.

For the following experiments 2, 3 and 4, parts: additional materials, equipment and requirements, have the same content, so these parts are mentioned in Experiment 2 only.

Experiment 2

The mould with a single groove was made in order to check if this way of lamination would work. Ability of fibres to keep a shape of the groove was to be checked as well.

Mould

Material: Aluminium

Dimensions: 3 *8 * 16 (cm)

Description: two parts, 1 groove in each, groove cross-section – half-circle D = 1.2 cm, metal bar (core) – circle in cross-section D = 1 cm, length = 20.5 cm.

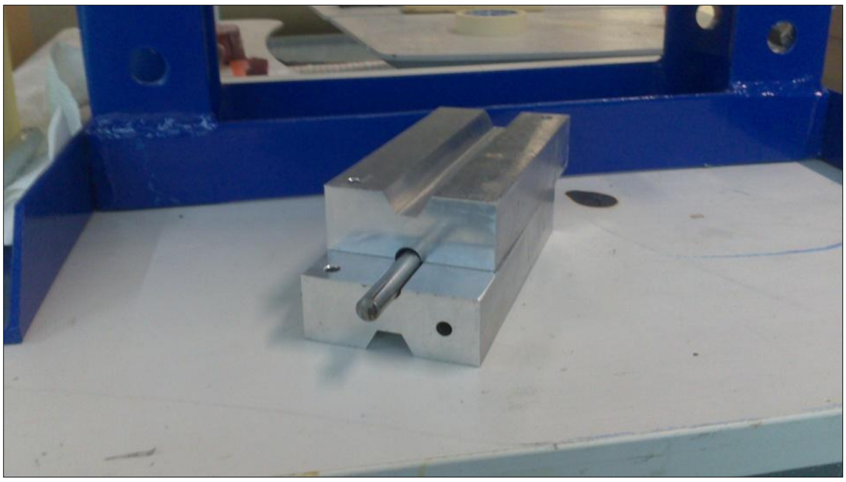


Figure 3.3. Mould for the Experiment 2

Materials for lamination

Fibreglass – prepreg(epoxy), 8 * 15 (cm)

Carbon fibre – prepreg(epoxy), 8 * 15 (cm)

Additional materials

- Release agent
- Peel-ply – for good secondary bonding
- Plastic film
- Spacing material – soft paper or textile

Equipment

Hydraulic press

Heater with 2 heating elements and 1 temperature detector

Requirements

Curing temperature: fibre glass prepreg – 150^{o}C, carbon fibre prepreg – 125^{o}C

Pressure: 2 tonnes

Full heating + curing + cooling time: 8 hours

The lamination procedure

- Treatment of the both moulds' surfaces with release agent
- Bottom part of the mould
- Layers: plastic foil, peel-ply, prepreg, peel-ply, plastic foil
- The core bar is placed in the middle
- Layers: plastic foil, peel-ply, prepreg, peel-ply, plastic foil
- Upper part of the mould is placed on the top

There may be additional layers added after second peel-ply, for example peel-ply, prepreg, peel-ply, prepreg, peel-ply etc. So the main thing is to have a peel-ply layer between each layer of prepreg, in order to be able to separate laminated layers from each other. Amount and presence of a spacing material may vary depending on how many layers of prepreg are to be laminated.

Figure 3.4. Samples recieved after Experiment 2

As a result samples with a good surface were received after that experiment. That followed to the conclusion that the chosen method has worked.

Experiment 3

Nevertheless in order to laminate a layer for honeycomb block construction another kind of mould is needed. There is needed a mould which would have a few grooves in it, and the grooves should have a half-hexagon shape in the cross-section.

So the next step in moving forward to the desired mould was an experiment with the mould, which had one groove of the required shape. That was done in order to see if the material would be placed nicely inside the mould and take a shape of the groove.

Mould

Material: Aluminium

Dimensions: 8 *16 * 3 (cm)

Description: two parts, 1 groove in each, groove cross-section – half-hexagon 1.1* 2.2 * 1 (cm), metal bar (core) – hexagon in cross-section with side length = 1cm, length = 22.5cm.

Materials for lamination

Fibreglass – prepreg(epoxy), 8 * 15 (cm)

Carbon fibre – prepreg(epoxy), 8 * 15 (cm)

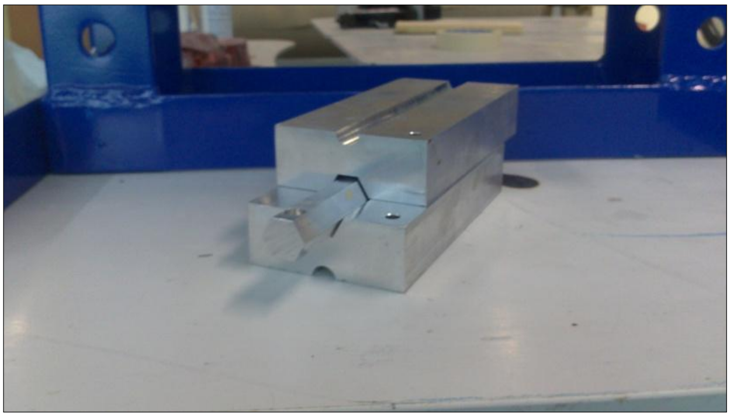


Figure 3.5. Mould used for Experiment 3

Lamination procedure

Steps of the lamination procedure in the experiment 3 were identical to the steps of the experiment 2.

Figure 3.6. Example of the product obtained in Experiment 3

Finally samples with expected surface qualities and having a shape of the groove were received. Since the results were satisfying the experimenting could move forward.

Experiment 4

So for the experiment 4 there was used mould with five grooves. Aim of the experiment was to check if the created mould would be suitable to laminate layers for honeycomb construction using it.

Mould

Material: Aluminium

Dimensions: 16 * 16 * 3 (cm)

Description: two parts, 5 grooves in each, groove cross-section – half-hexagon 1.1*2.1*1 (cm), 5 metal bars (core) – each one is a hexagon in cross-section with side length=1cm and bar length = 22.5cm.

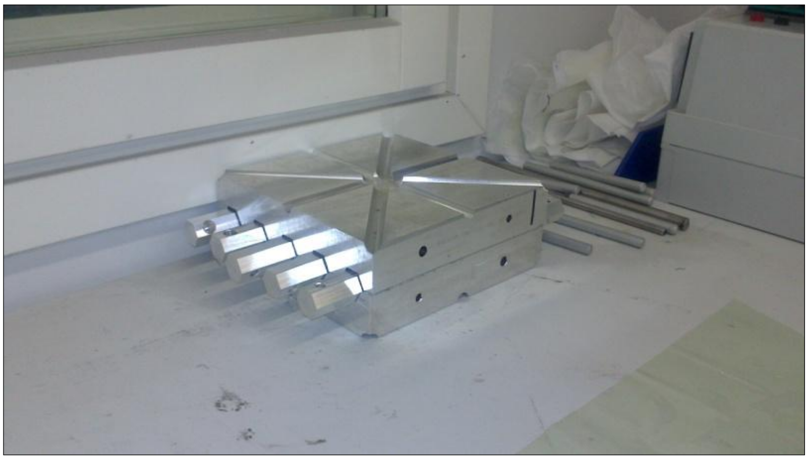


Figure 3.7. Mould used for the Experiment 4

Materials for lamination

Fibreglass – prepreg(epoxy), 160mm * 160mm

Carbon fibre – prepreg(epoxy), 160mm * 160mm

Lamination procedure

Steps of the lamination procedure in the experiment 4 were identical to the lamination steps of the experiments 2 and 3.

Figure 3.8. Mould under press and heating

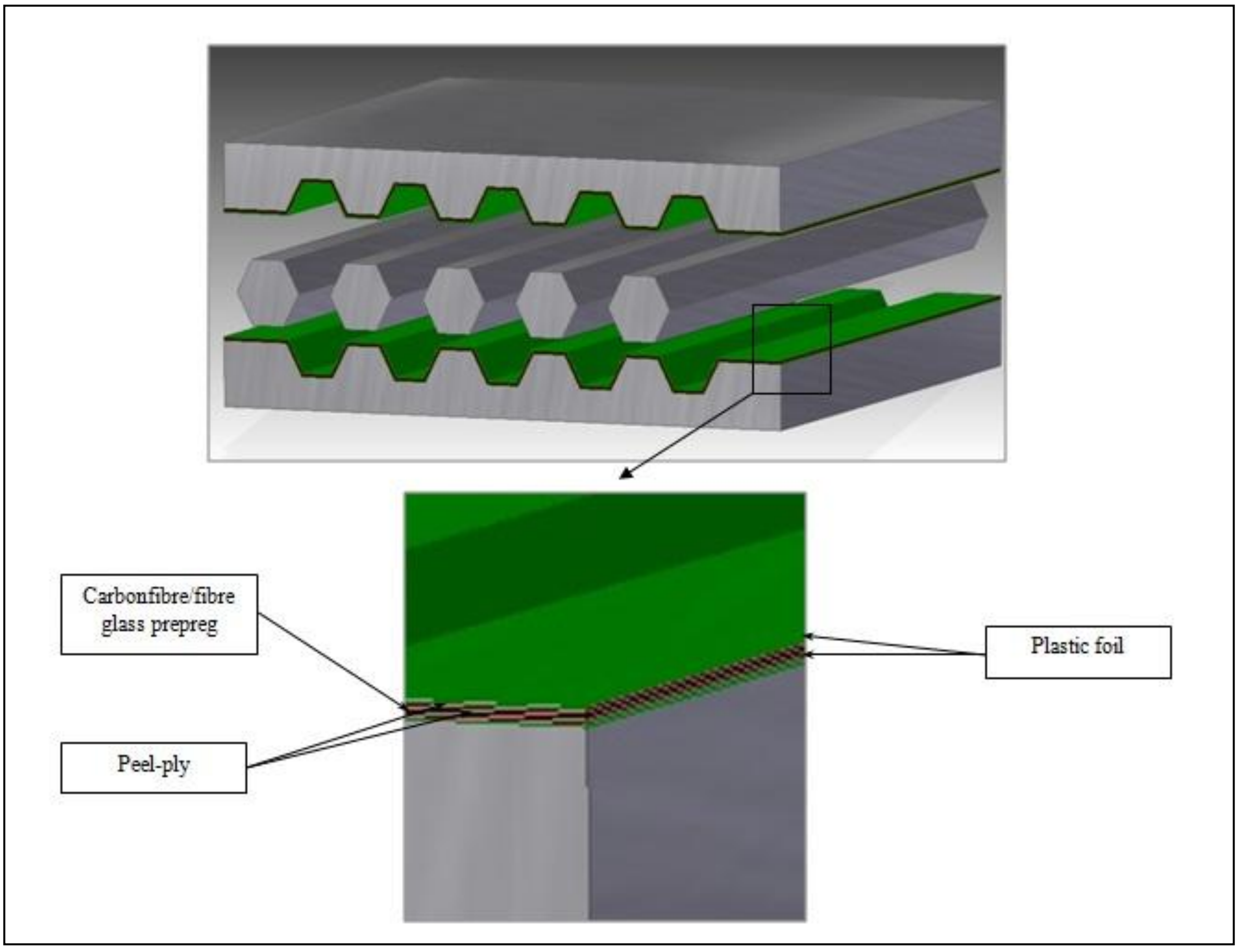


Figure 3.9. Layers inside the mould

The way layers of prepreg and other assisting materials are placed inside the mould can be seen from the figure 3.9. It can be also seen there that the top part of the mould has the same amount of layers on its surface and these layers are placed the same way. As a result the laminates of the required shape were received.

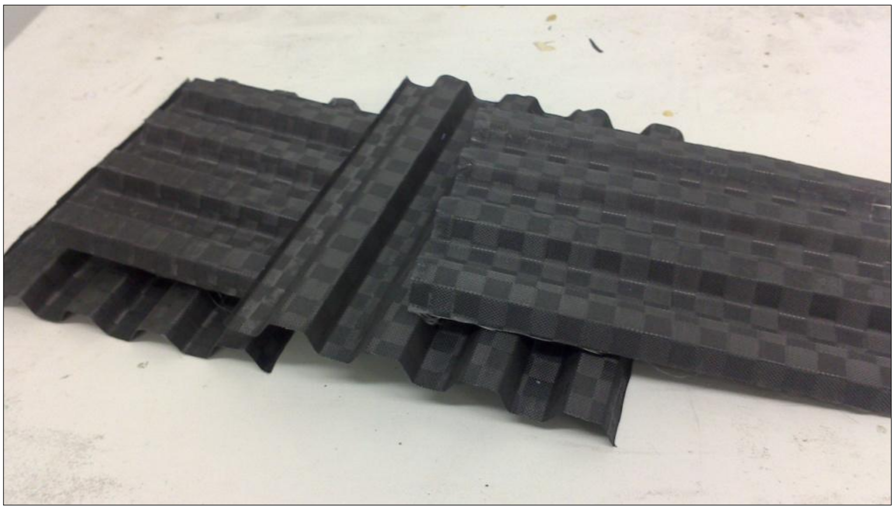


Figure 3.10. Some of the samples recieved in the Experiment 4

3.1.2 Slicing

After the layers are laminated a way of building the honeycomb is to be considered. As that was mentioned before, in corrugation manufacturing method corrugated sheets are first glued together, after what created honeycomb block can be sliced in order to create honeycomb core sandwich panels. However that order of the steps was not possible in this experiment because of the lack of necessary equipment. Bend saw, which was used for the experiment, would break the block, so it was decided to slice the corrugated sheets before building honeycomb of them.

The procedure of slicing was quite tricky because a blade on the bend saw, which was used for that purpose, was not meant for composite materials. Another task was to find a way to prevent the sheets from wobbling during the cutting procedure.

First issue was solved by using a brand new blade and high tool speed. Second problem was solved by using one side of the mould in order to keep a corrugated sheet stable and be able to cut the sheet into stripes of the required width. It was decided to cut carbon fibre sheets into 4 cm stripes and fibreglass sheets into 2 cm stripes.

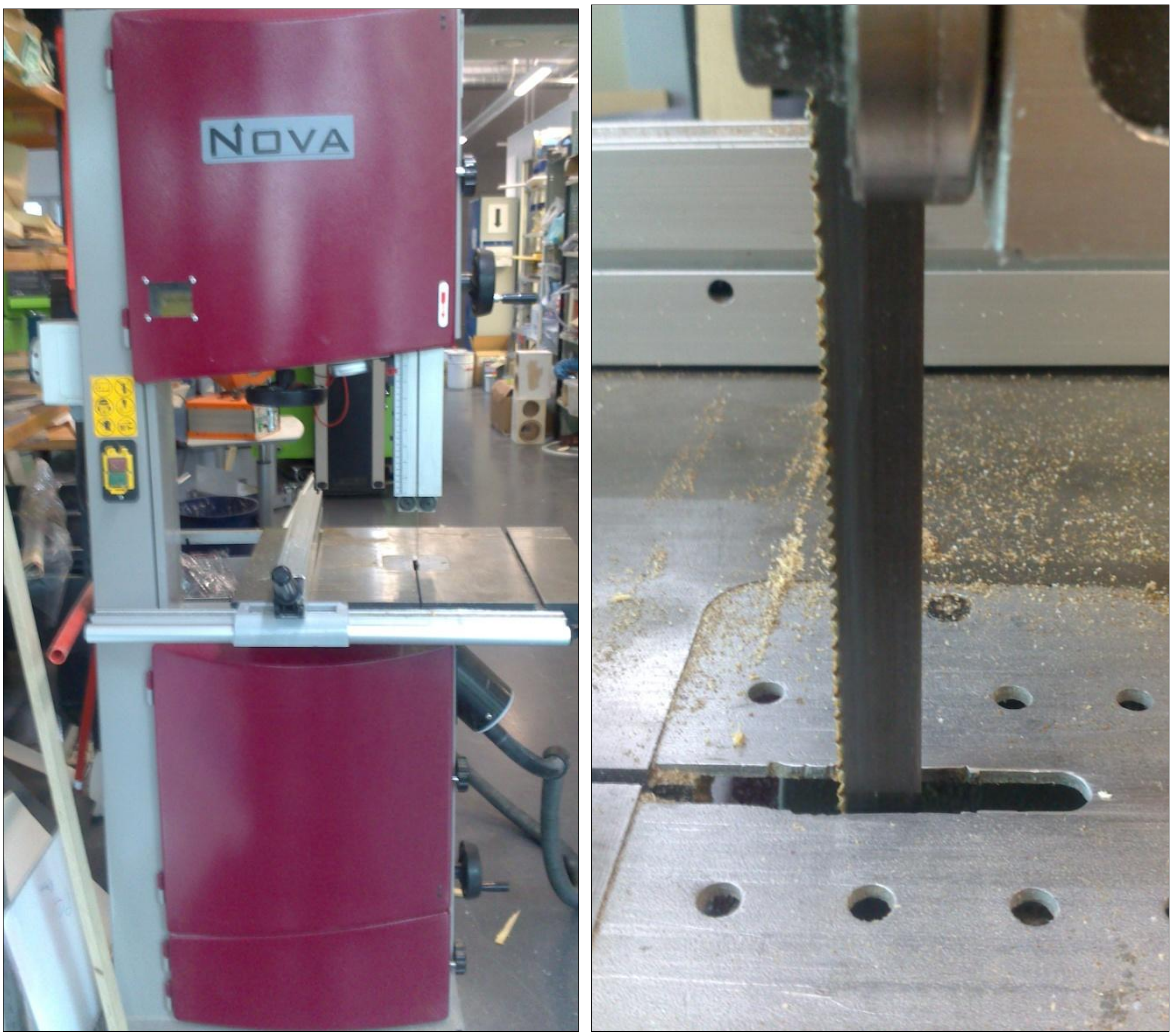


Figure 3.11. Bandsaw and the blade used for slicing of the layers

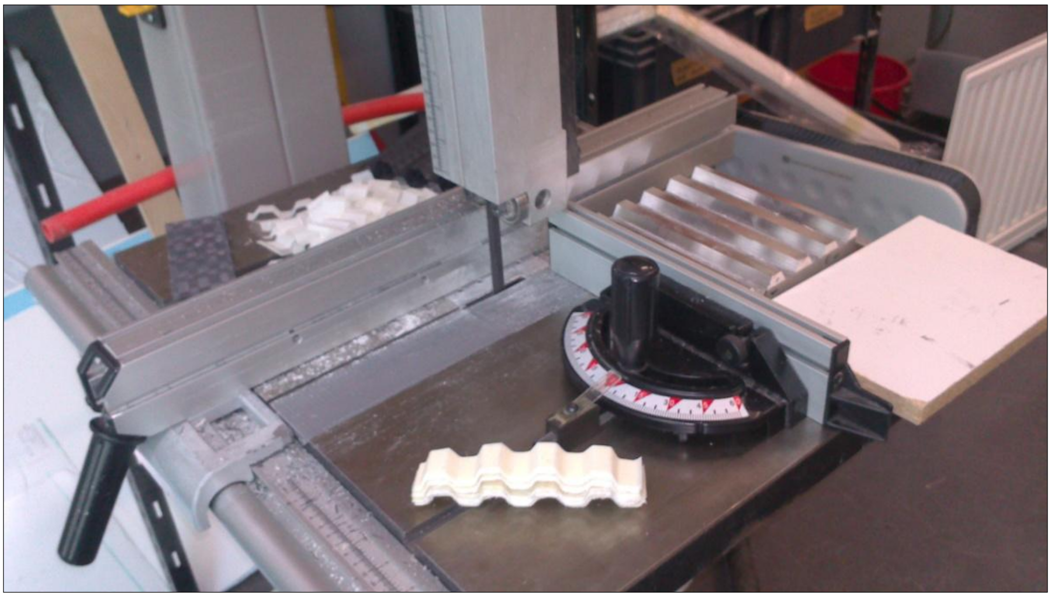


Figure 3.12. Sliced layersfor the honeycomb construction

Finally stripes of the required width were received. Edges of those stripes were not smooth and completely straight, so sandpaper was used in order to create the required smooth and straight surface of the edges. It is important to make sure that edges have a required condition because of the way chosen to build the honeycomb and for building the honeycomb sandwich panels.

3.1.3 Building of the honeycomb

The stripes received after the previous stage were to be glued together in order to get honeycomb core. At least two very important issues were to be considered there: choice of an adhesive and the way of gluing.

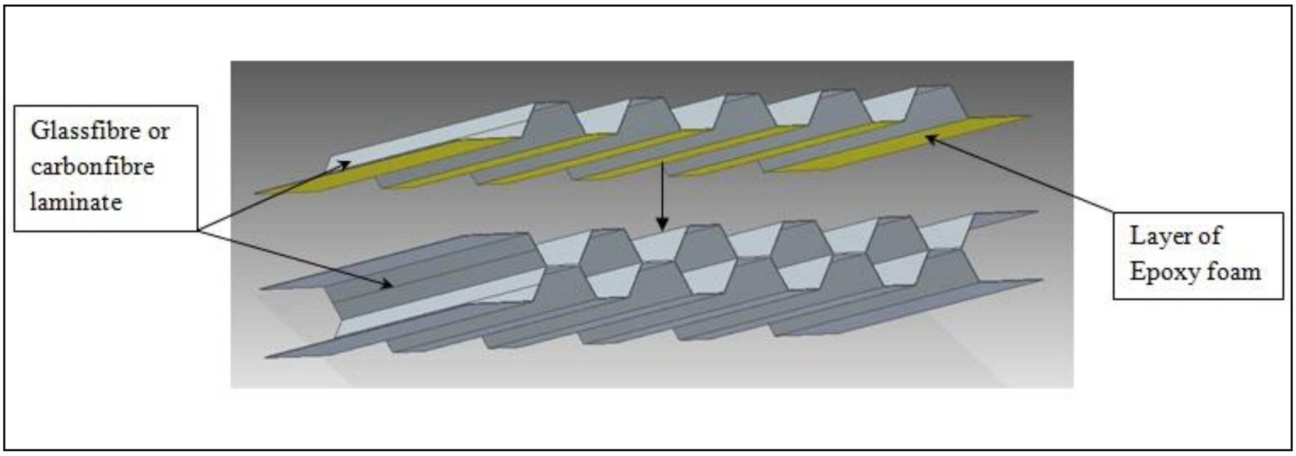


Figure 3.13. Joining of honeycomb layers to each other

So it was decided to use epoxy foam as an adhesive, because it was available, easy to use, light and suitable for the chosen method of gluing. The honeycomb was constructed as follows. First stripe was taken and placed vertically on its longer side next to some stable flat vertical surface. Second stripe was dipped into the epoxy foam and attached to the first one. It was repeated until all the stripes of the same material and size were attached to each other. At the end of the construction the last stripe was supported by some weight with a flat vertical surface.

Figure 3.14. Building of the carbon fibre honeycomb core

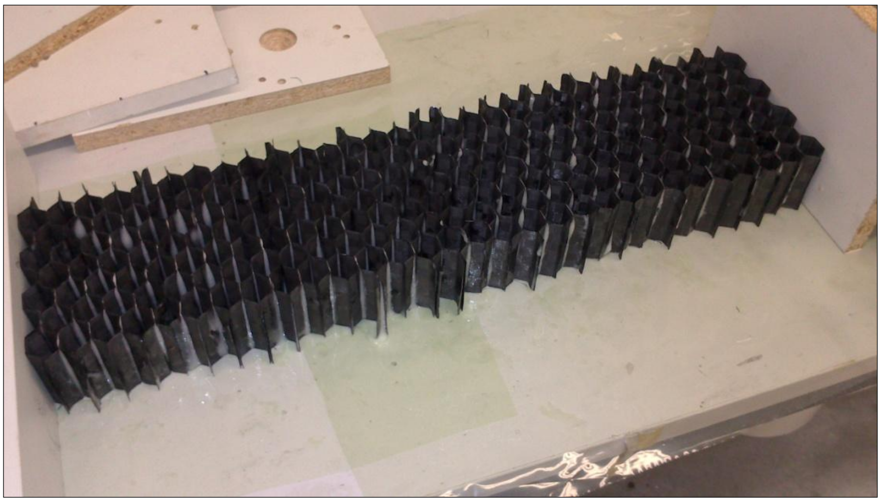


Figure 3.15. Preparation to curing of the carbon fibre honeycomb core

After that the construction was covered with a plastic film and there was a weight placed on the top of it. In twenty four hours honeycomb cores were solid and ready for next stages of processing. Finally four honeycomb cores were built using that adhesive and gluing method.

Figure 3.16. Composite honeycomb cores obtained

3.2 Constructing of composite honeycomb sandwich panel

When the honeycomb cores are ready, honeycomb sandwich panel can be constructed then. That constructing process consists of two following steps:

- Lamination of skins

- Gluing of the skins and core together

Figure 3.17 schematically shows the process of constructing of honeycomb sandwich panel. It is important to mention that usually there is only one step. That step includes both lamination and attaching of skins to the core. It is performed using prepreg as a material for the skins. However in this case skins and core between them would have to be heated. That would be critical in case with this experiment because of the epoxy foam which was used for constructing of the honeycomb core. So the two steps mentioned above were used in order to construct composite honeycomb sandwich panel.

3.2.1 Lamination of skins

Skins for the panels were prepared using vacuum resin infusion process. Choice of matrix materials was not very significant for this experiment, so available materials were chosen for creation of the skins.

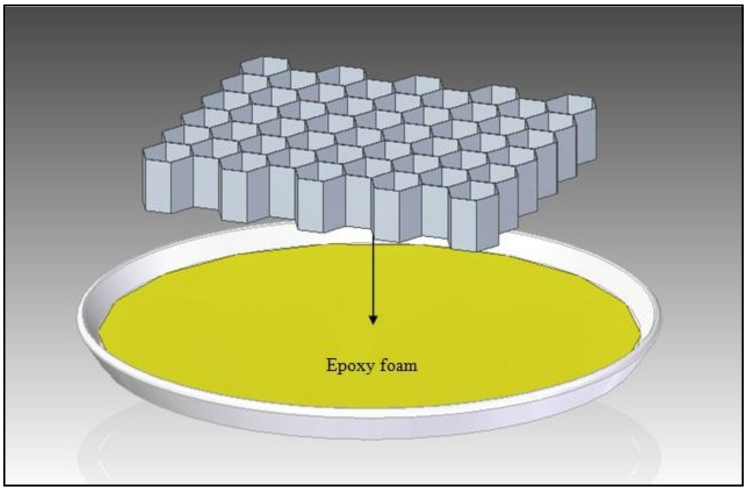
Matrix materials: carbon fibre, carbon fibre/Kevlar mixture.

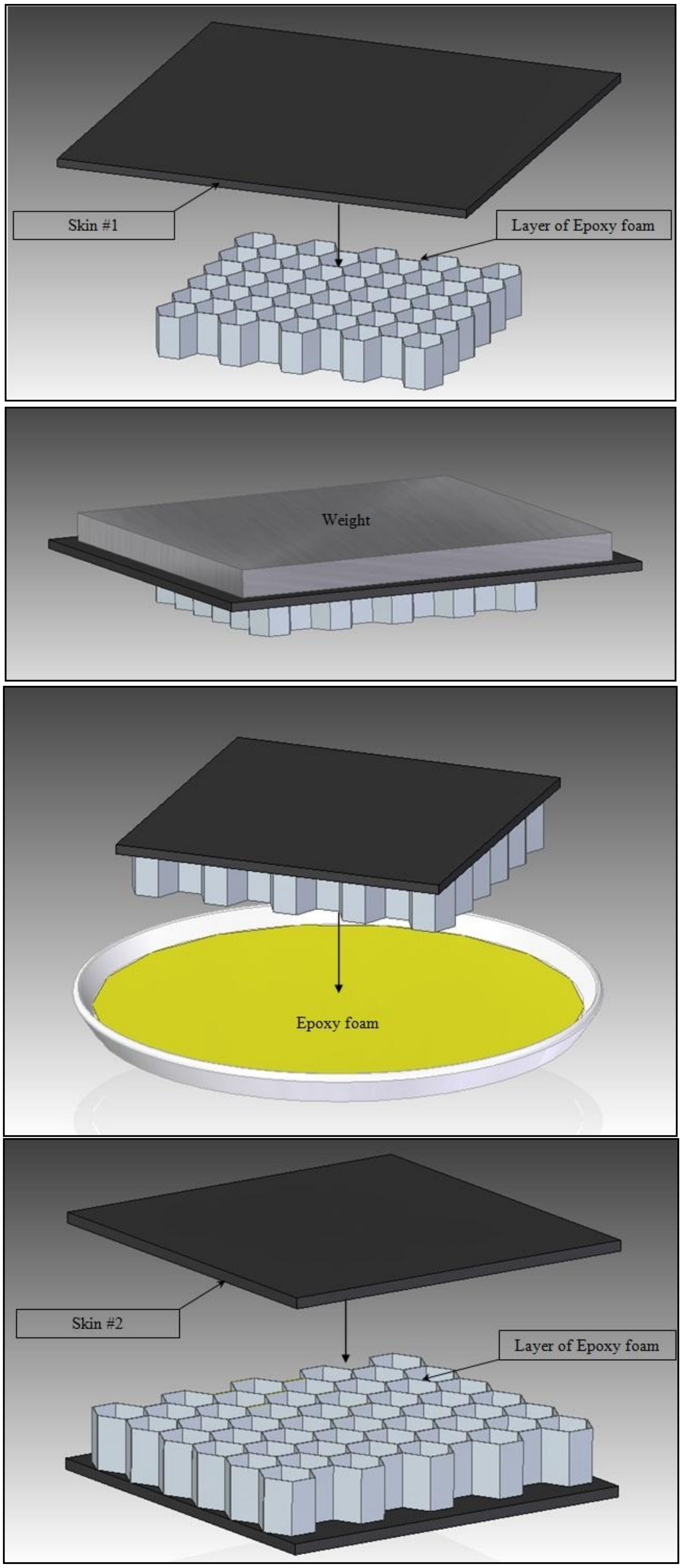
Resin: epoxy.

In addition already laminated piece of glassfibre was taken to make two skins for fibreglass core.

3.2.2 Making of the panels

The panels were made by dipping both sides of the honeycomb core into epoxy foam, then placing it in between to laminated skins and pressing that construction by placing weight on the top of one of the skins. All the steps of that process can be seen from the fig. 3.17.




Skin #1
Layer of Epoxy foam
Weight
Epoxy foam
Skin #2
Layer of Epoxy foam

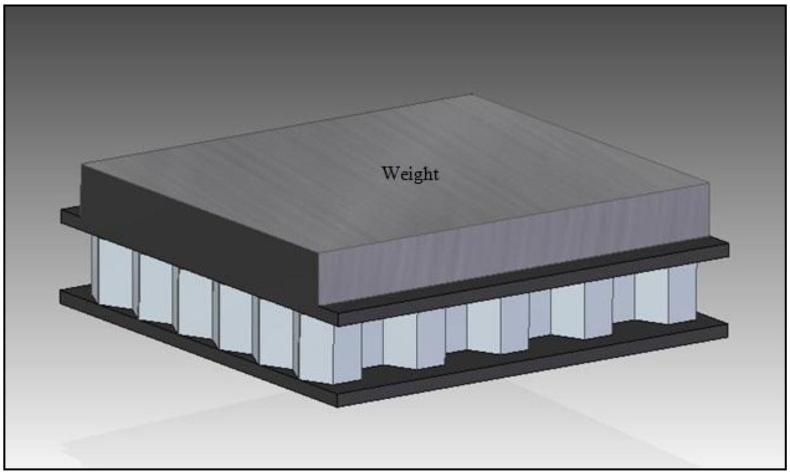


Figure 3.17. Stages of building of composite honeycomb sandwich panel

This procedure was repeated with all the prepared cores and skins. Finally after twenty four hours the resin completely solidified and four composite honeycomb sandwich panels were received.

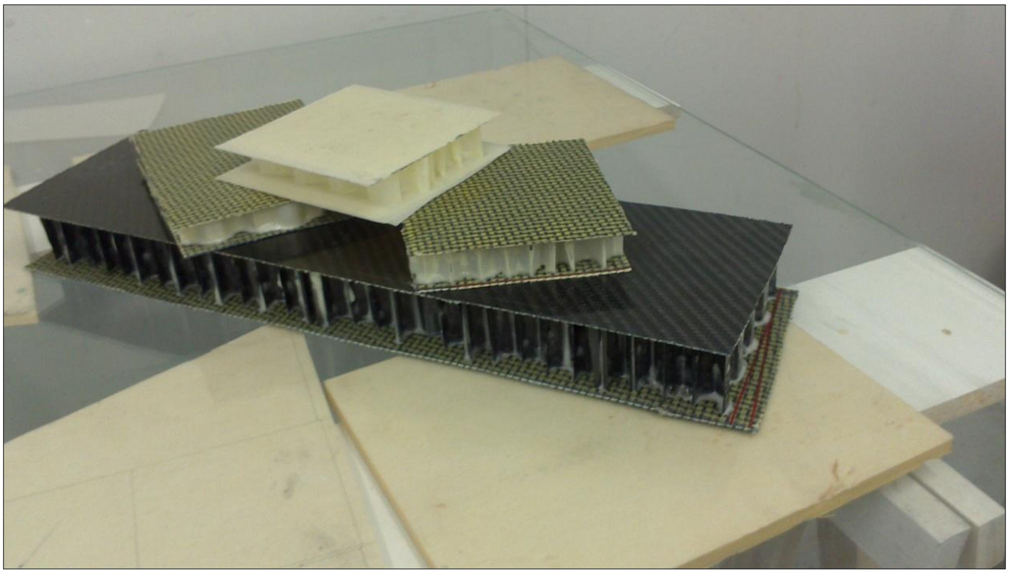


Figure 3.18. Composite honeycomb sandwich panels obtained

4 RESULTS

As a result of the experiment four composite honeycomb sandwich panels were obtained. The table below shows properties and components of each one of them.

Table 4.1. Properties and components of created honeycomb sandwich panels

	1	2	3	4
Core's components	Carbon fibre prepreg (carbon fibres + epoxy resin); epoxy foam (resin + hardener)	Glass fibre prepreg (glass fibres + epoxy resin); epoxy foam (resin + hardener)	Glass fibre prepreg (glass fibres + epoxy resin); epoxy foam (resin + hardener)	Glass fibre prepreg (glass fibres + epoxy resin); epoxy foam (resin + hardener)
Core's weight (g)	177.91 (28.97g of epoxy foam + 148.94g of carbon fibre prepreg)	27.00 (7.84g of epoxy foam + 19.16g of glass fibre prepreg)	16.40 (6.48g of epoxy foam + 10.88g of glass fibre prepreg)	15.73 (5.84g of epoxy foam + 9.89g of glass fibre prepreg)
Core's dimensions (cm)	49.50*19.00*4.40	17.00*12.50*2.00	13.00*12.50*2.30	14.00*9.00*2.50
Core's macroscopic density (g/cm^3)	$177.91g/4138.20cm^3$ **0.04**	$27.00g/425.00cm^3$ **0.06**	$16.40g/164.80cm^3$ **0.10**	$15.73g/315cm^3$ **0.05**
Skins' components	Carbonfibre + Kevlar + epoxy resin	Kevlar + epoxy resin	Kevlar + epoxy resin	Glass fibre + epoxy resin
Skins' weight (g)	Skin 1: 74.60 + Skin 2: 68.20 142.80	Skin 1: 17.09 + Skin 2: 22.15 39.24	Skin 1: 15.09 + Skin 2: 14.96 30.05	Skin 1: 7.42 + Skin 2: 6.20 13.62
Panel's weight (g)	Skins: 142.80 + Core: 177.91 + Epoxy foam: 68.39 389.10	Skins: 39.24 + Core: 27.00 + Epoxy foam: 23.86 90.10	Skins: 30.05 + Core: 16.40 + Epoxy foam: 24.55 71.00	Skins: 13.62 + Core: 15.73 + Epoxy foam: 25.35 54.70
Panel's dimensions (cm)	52.50*15.00*4.70	18.00*13.50*2.20	14.50*13.00*2.50	16.00*13.00*2.7

5 POST-PROCESSING STAGE

After obtaining the results of the experiment it was decided to check if that would be possible to mill those composite honeycomb sandwich panels. It was also agreed to test if that would be possible to slice honeycomb block in order to create cores for sandwich panels. The equipment in the workshop, which was used for the experiment, was not suitable for the purposes mentioned above. However it was possible to perform those tests with help of two companies: Neuhäuser Controx – Precision Cutting Tools (Prüm, Germany) and Euro-composites (Echternach, Luxembourg). First of them was ready to help with milling tests, the second one allowed to try to perform slicing of the composite honeycomb block. The milling test was needed in order to check if skins would delaminate from the core or if layers inside the core would delaminate from each other during the milling process.

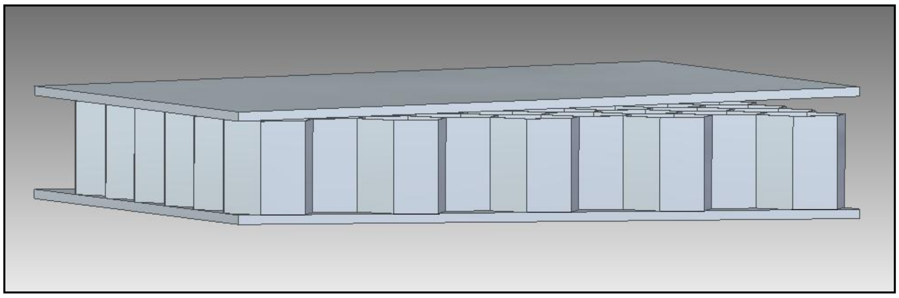


Figure 5.1. Delamination of top skin from the core

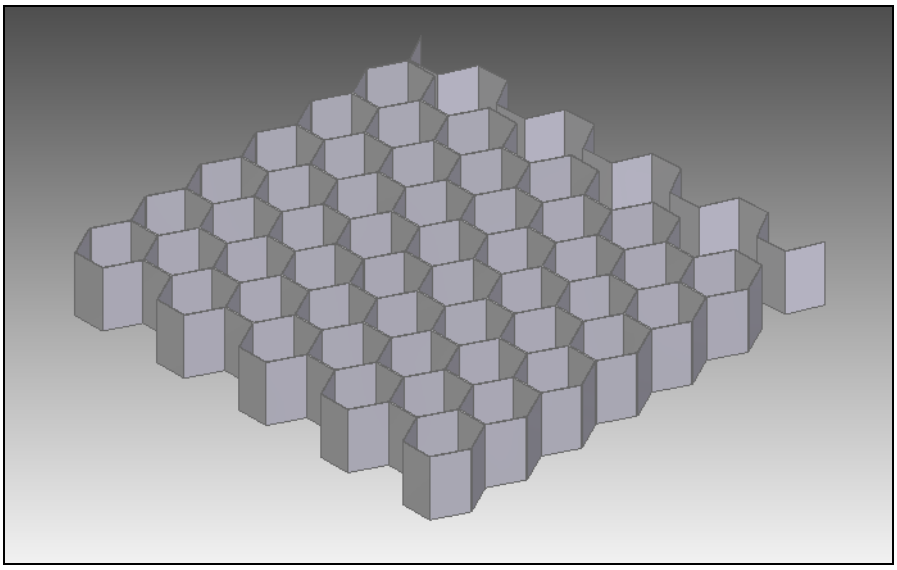


Figure 5.2. Delamination of one of the honecombcore’s layers

Slicing of already made honeycomb block was to be performed in order to find out if layers of the honeycomb would delaminate from each other during the cutting procedure. If slicing of the ready honeycomb would be possible that would make a process of composite honeycomb sandwich panel’s creation simpler and faster.

Experiment 1

First experiment – milling, was performed in Neuhäuser Controx – Precision Cutting Tools using five axes milling machine and some specific tools, such as circular knives, core cut, pocket cut and panel cut.

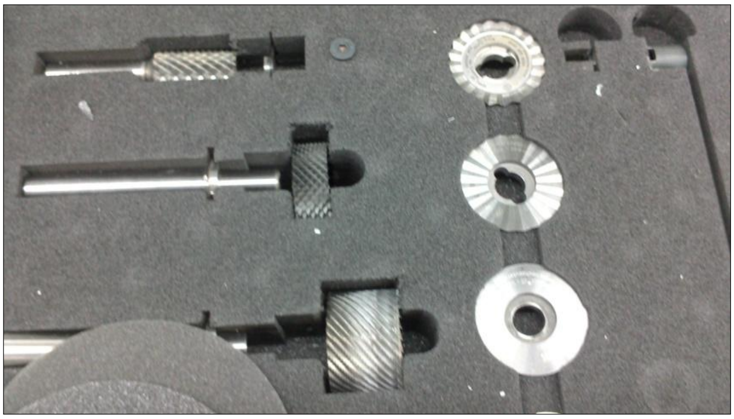
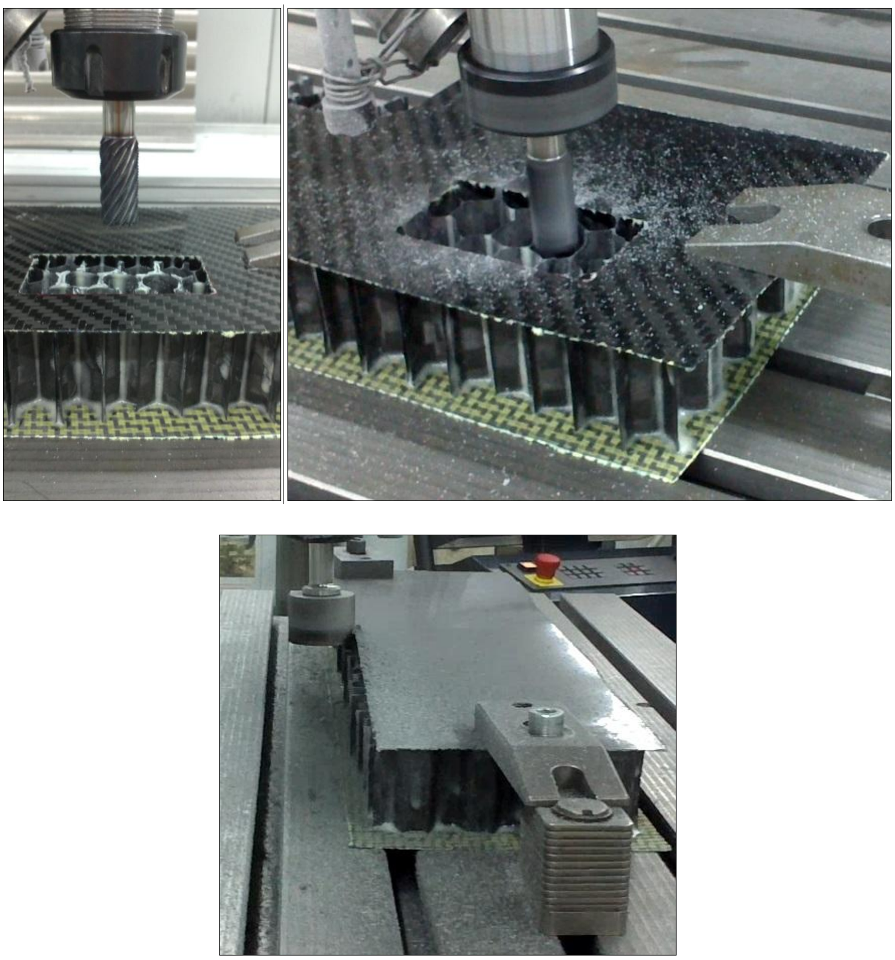


Figure 5.3. Precision cutting tools used for milling in Experiment 1

There were two main tasks in that experiment: milling of the honeycomb panel from the side and creation of the pocket inside the panel.



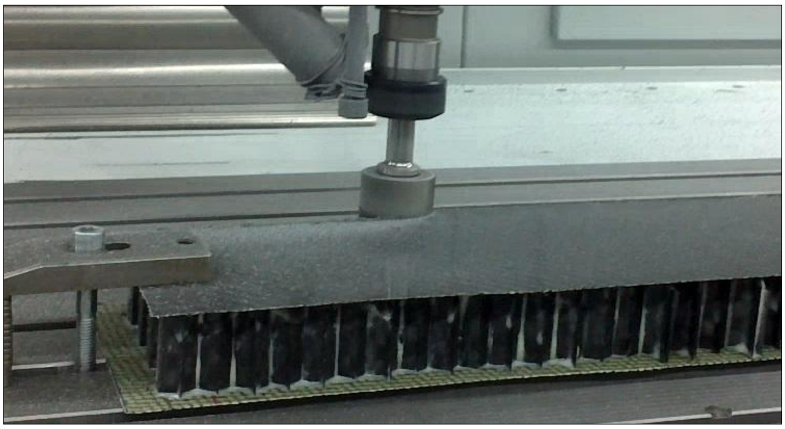


Figure 5.4. Different stages of milling in Experiment 1

As a result both actions were performed and finished successfully. Panel's skins did not delaminate as well as layers of the honeycomb core stayed together. All the received surfaces were completely smooth and ready to use if that would be required.

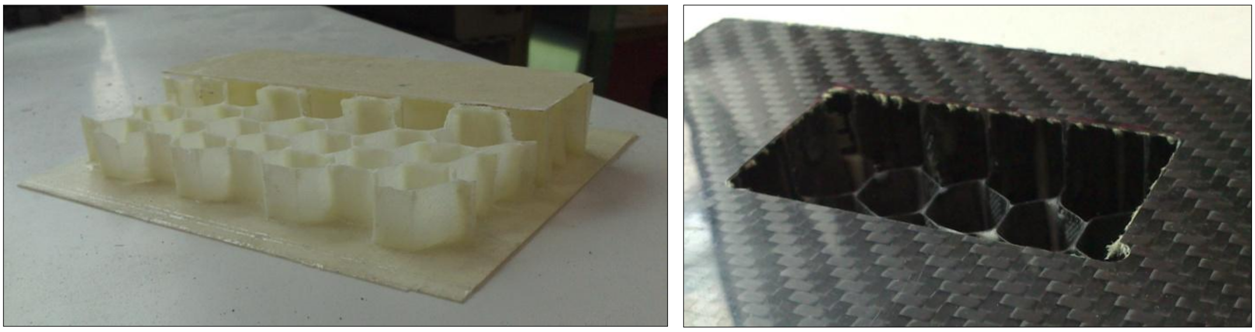


Figure 5.5. Examples of surface finishes obtained after Experiment 1

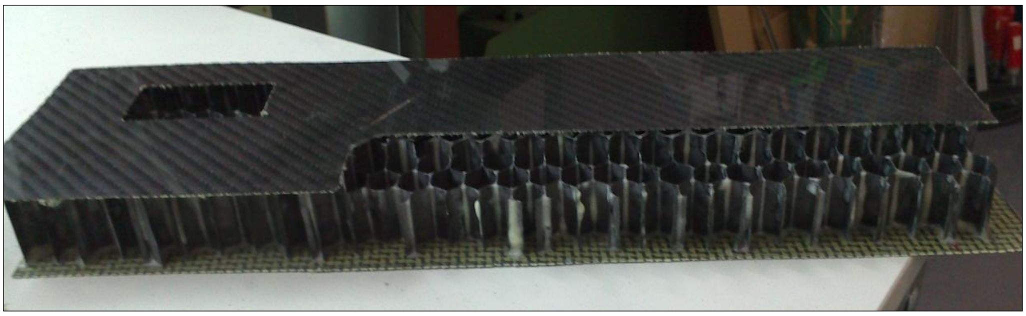


Figure 5.6. Examples of side and pocket milling inside the kevlar/carbon fibre sandwich panel

Experiment 2

In order to perform the experiment glass fibre honey comb block was made using the steps' order described earlier in chapter 3. However there was no a cutting/slicing stage, and a brush was used to place epoxy foam on glass fibre layers before gluing. The brush was used instead of dipping in order to reduce amount of Epoxy foam used and make the honey comb as light as possible. Some parameters of that fibreglass honeycomb block can be found from the table below.

Table 5.1. Parameters of the fibreglass honeycomb block

Fibreglass honeycomb block's Components	glass fibre prepreg (fibreglass + epoxy resin) + epoxy foam
Amount of layers	12
Weight (g)	133.13 (16.13 g of epoxy foam + 117g of fibreglass layers)
Dimensions (cm)	13.73*10.02*16.02
Macroscopic density	$133.13g/2203.95cm^3 = 0.06g/cm^3$

The experiment with slicing of the block was performed in Euro-composites performance testing laboratory using a band saw equipped with a blade meant for Kevlar.

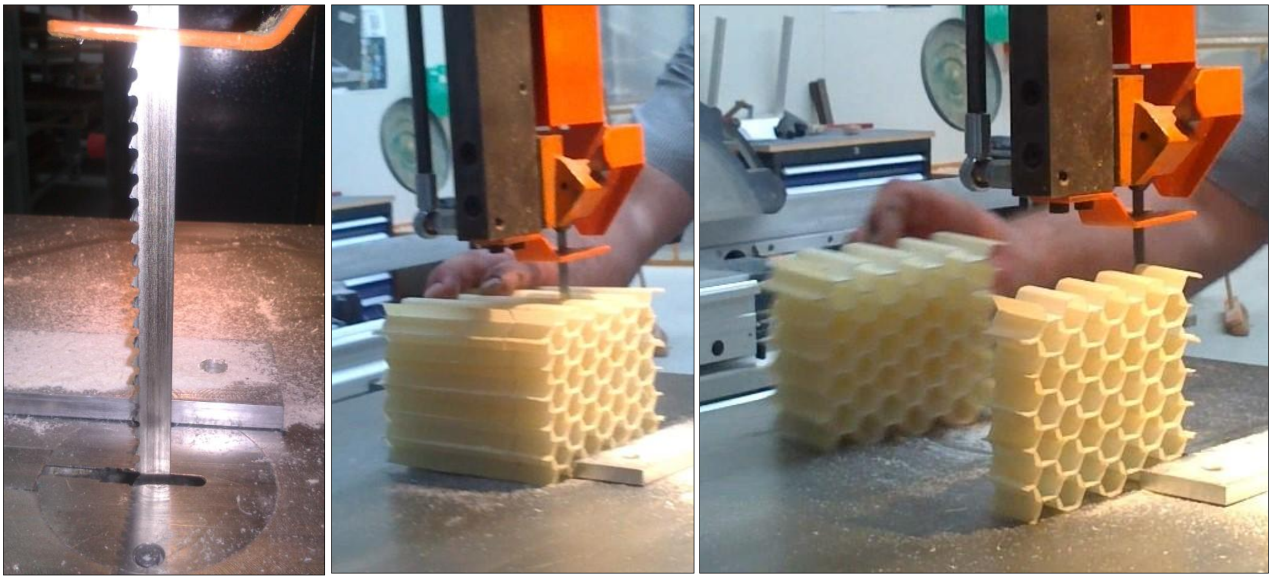
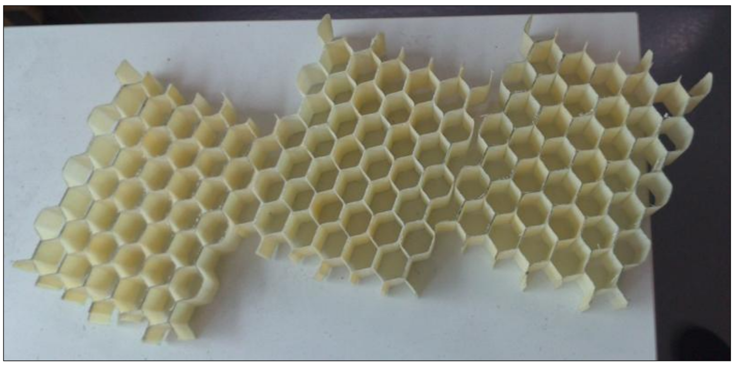


Figure 5.7. Band saw blade form Experiment 2 and fibreglass honeycomb block slicing proceedure

As a result five slices of the block were received all of them having smooth surfaces. Only some areas of layers with weak bonding were delaminated from each other during the cutting procedure.



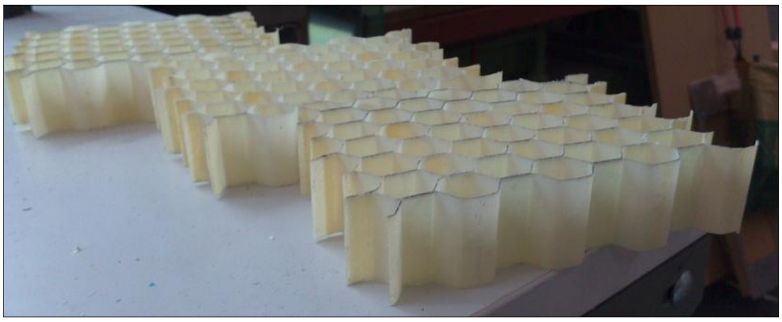


Figure 5.8. Examples of specimens recieved after slicing of fibreglass honeycomb block

6 DISCUSSION

There were different samples of honeycomb structures received from Ultracor. So macroscopic densities of Ultracor samples and those made composite honeycomb cores could be compared to each other. Tables below show these values.

Table 6.1. Macroscopic density of the samples crated for this work's experiment

	Dimensions (cm)	**Weight (g)**	**Macroscopic density (g/cm^3)**
Carbon fibre sample	49.50*19.00*4.40	177.91	177.91g/4138.20cm^3 **0.04**
Fibreglass sample 1	17.00*12.50*2.00	27.00	27.00g/425.00cm^3 **0.06**
Fibreglass sample 2	13.00*12.50*2.30	16.40	16.40g/373.75cm^3 **0.04**
Fibreglass sample 3	14.00*9.00*2.50	15.73	15.73g/315cm^3 **0.05**
Fibreglass sample 4	13.73*10.02*3.01	25.39	25.39g/414.10cm^3 **0.06**
Fibreglass sample 5	13.73*10.02*3.77	28.87	28.87g/518.66cm^3 **0.06**
Fibreglass sample 6	13.73*10.02*3.05	24.62	24.62g/419.60cm^3 **0.06**
Fibreglass sample 7	13.73*10.02*3.20	25.22	25.22g/440.24cm^3 **0.06**
Fibreglass sample 8	13.73*10.02*3.01	23.65	23.65g/414.10cm^3 **0.06**

Table 6.2. Macroscopic density of the Ultracor samples

	Dimensions (cm)	**Weight (g)**	**Macroscopic density (g/cm^3)**
Quartz / cyanate ester	9.00*6.30*12.85	3.33	3.33g/728.60cm^3 **0.005**

Carbon / cyanate ester	6.48*5.76*6.40	0.81	0.81g/238.88cm^3 **0.003**
Carbon / epoxy resin	7.75*6.90*1.27	2.26	2.26g/67.91cm^3 **0.03**
Kevlar / cyanate ester	7.80*6.87*1.33	2.60	2.60g/71.27cm^3 **0.04**
Glass / phenolic	9.43*5.84*4.70	2.21	2.21g/258.83cm^3 **0.009**

According to these tables Ultracor samples in general have macroscopic density values which are much smaller than those values of the samples created for this work's experiment. However if two particular values for similar materials would be compared, that could be obtained that macroscopic density value of Carbon /epoxy resin sample (0.03 g/cm^3) is very close to Carbonfibre/epoxy resin/epoxy foam one (0.04 g/cm^3). Moreover, price comparison shows that products made using the method represented earlier in this work would be much cheaper comparing to Ultracor products (16000 euro/kg comparing to approx. 81.04 euro/kg for carbon fibre prepreg + 50-80 euro/kg for Epoxy foam).Of course that approximate price of the manufactured honeycomb cores does not include any other expenses apart of the materials used, but still materials cost for samples manufactured during this work is around 160 euro/kg and it is very far away from the price of the Ultracor products. Thus, it follows that manufacturing method described in this work can be used to produce competitive and quite cheap composite honeycombs.

Another issue is a speed of production of the composite honeycomb core. There are at least two things, which could be done in order to increase the production speed. First of that was proven in experiments that there is a possibility to make a composite honeycomb block first, and slice it into pieces of the required size. Of course that can be only possible with use of specific – composite meant blades. Second issue is that the process of gluing of honeycomb block's layers together could faster and more efficient if some sort of robot or mechanism would be created in order to perform that action.

7 CONCLUSION

The experiments of this thesis can be considered successful because of the positive results, which were obtained in them. The samples created during this work are relatively competitive, comparing to ones from Ultracor, however they would have more performance if bonding between layers inside the honeycomb core would be stronger with a use of less adhesive. It would be possible to do mass production of composite honeycomb cores and sandwich panels using the manufacturing method described in chapter 3 if some parts of that manufacturing process would be modified. First of the process would become faster and more efficient if there would be a way to place adhesive between layers in a quicker way and make that payer of adhesive thinner and more uniform. One of the possible ways to perform that could be a use of a grooved roller as it is shown on fig. 7.1.

The process would also give better results if there would be a way of holding and pressing layers of honeycomb while the layers get glued together. One of possible constructions and weights which could be used for the purpose described above are shown on fig. 7.2.

Epoxy foam could also be kept in cold before the gluing process, so that a foaming of it does not begin too fast.

Finally the right type of blade for a band saw should be used in order to perform slicing stage after constructing of the honeycomb block.

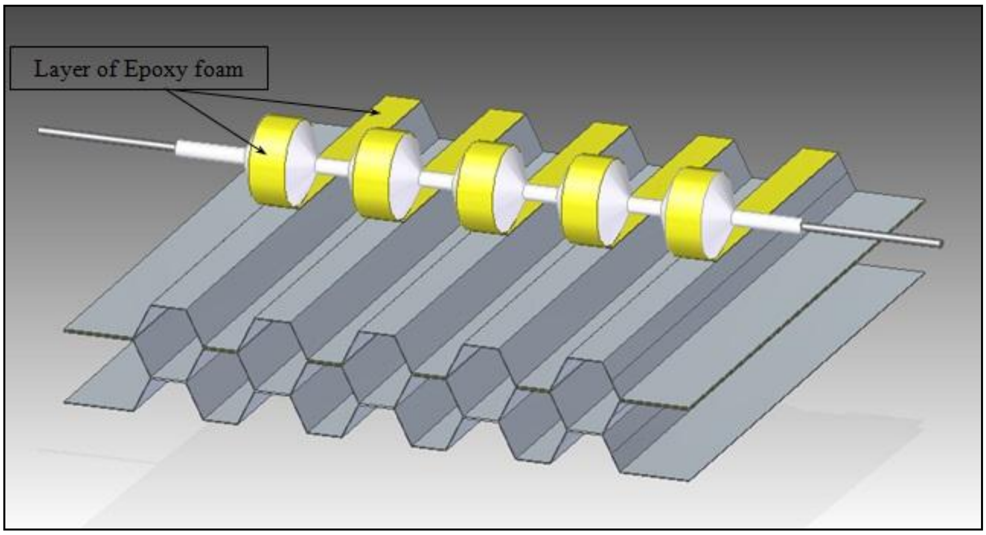


Figure 7.1. Use of a grooved roller for Epoxy foam placing

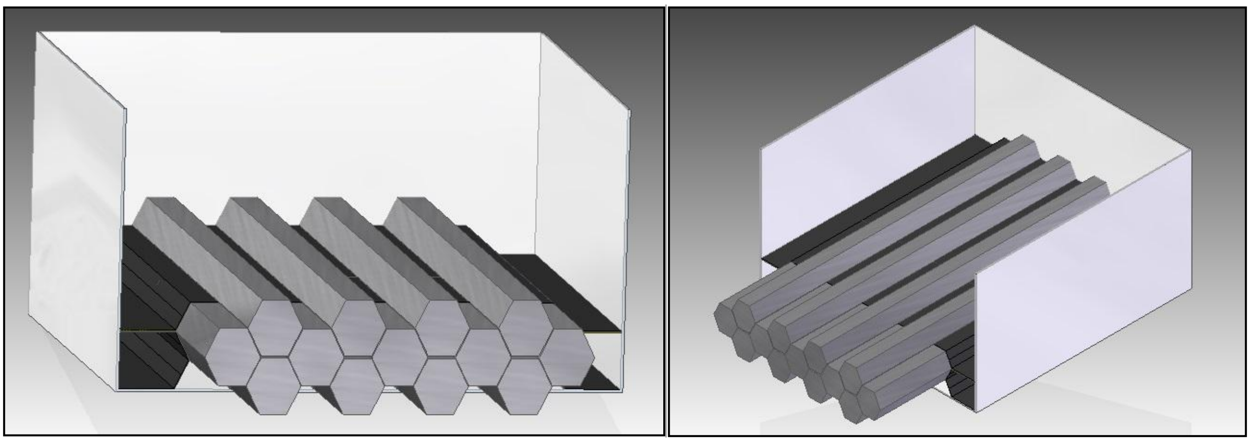


Figure 7.2. Use of supporting walls and weights for constructing of honeycomb block

If all the points mentioned above would be considered in updating of created manufacturing process, then it would be possible to create competitive composite honeycomb. That honeycomb would need less specific and expensive equipment for its manufacturing and would cost much less than existing similar products.

REFERENCES

- Campbell, F. C. (2010). *Structural Composite Materials*. USA: A S M International. pp 255-261.
- DIAB AB (2003). *DIAB SANDWICH HANDBOOK*. Sweden: DIAB AB. pp 1-20.
- Larsson, L., Eliasson, R. E. (2000). *Principles of Yacht Design*. 2nd ed. London: Adlard Coles Nautical. pp 250-268 .
- PhysicsNet.co.uk. (2010-2014). *Stress & Strain.* Available: http://physicsnet.co.uk/a-level-physics-as-a2/materials/stress-strain/. Last accessed 30th Oct 2014.
- Sandvik AB. (2014). *Honeycomb composites.* Available: http://compositemachining.org/honeycomb-composites/. Last accessed 30th Oct 2014.