INTERNSHIP REPORT

Complex Shaped Mold Manufacturing by Means of Laminate Object Manufacturing

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ABSTRACT

Complex shaped composite parts are needed for many applications. The base of every complex shaped part is a mold that represents the shape. However, the fabrication of a mold is very expensive and requires a high amount of skills, money and labor time.
Therefore, a low cost, flexible and fast process is needed. Rapid prototyping processes such as Laminate Object Manufacturing (LOM) can reduce cost and time.
But is this process, based on sensitive paper, can be used to build molds?
The goal of this project is to evaluate the manufacturing process of a paper baser LOM mold and to improve the strength of such a mold in order to increase its durability.

RESUME

Les pièces en composites de formes complexes sont de plus en plus demandées dans l'industrie, pour de nombreuses applications. Pour fabriquer une telle pièce, un moule, représentant la géométrie, est nécessaire.
Cependant, la construction d'un moule nécessite un investissement important en moyen, et en temps. C'est pourquoi, des procédés de prototypages rapides comme « Laminate object Manufacturing » (LOM) peuvent être utilisés.
L'objectif de ce projet est d'évaluer le procéde de fabrication d'un moule fabriqué à partir de papier et d'améliorer sa durabilité.

KEY WORDS

Laminate Object Manufacturing (LOM), rapid prototyping, VARTM, composite manufacture

ACKNOWLEDGEMENT

Working in the Center for Composite Material was interesting. During these six months of internship, I learnt a lot on composite science, especially on composite manufacturing processes like RTM or VARTM.

I have to thank Dr Aurimas Dominauskas for advising me during this project.

Therefore, I am grateful to the people in the CCM for the chance to make this experiment. I especially want to thank Professor Suresh Advani and Docteur Gilles Ausias for giving me the possibility to attend the Center for Composite Materials.

Further on, I want to thank the students and interns in the CCM who made this demanding time joyful but always efficient.

CONTENTS

I - INTRODUCTION

A - Presentation of CCM

1 - The University of Delaware

The University of Delaware has grown from its founding as a small private academy in 1743 to a major university.

The University enrolls over 16,000 undergraduates and nearly 3,000 graduate students. Since 1921, the University has been accredited by the Middle States Association of Colleges and Secondary Schools. Professional accreditation also is held in Accounting, Agricultural Engineering/ Engineering Technology, Athletic Training, Business Administration, Chemistry, Clinical Psychology, Dietetics, Education, Engineering, Family and Community Services, Medical Technology, Music, Physical Therapy, Public Administration and Nursing.

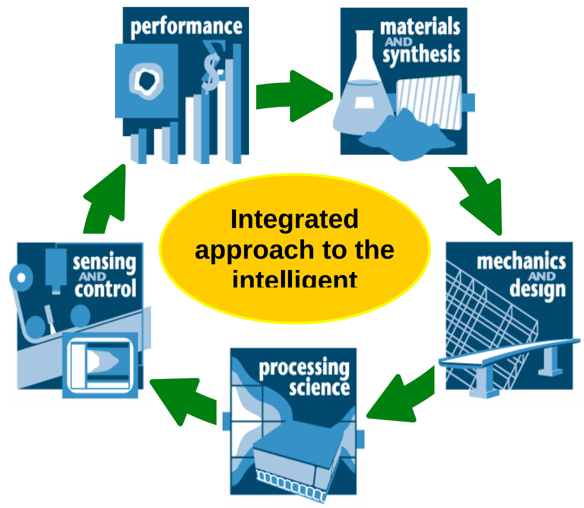
The state of Delaware sits in the heart of the mid-Atlantic seaboard, halfway between Washington DC and New York City.

2 - Center for Composite Materials (CCM)

Founded in 1974 within the University of Delaware's College of Engineering, the Center for Composite Materials (CCM) is an internationally recognized, interdisciplinary center of excellence for composites research and education. CCM's 34,000-square-foot Composites Manufacturing Science Laboratory houses some $8 million worth of composites manufacturing, characterization, testing, and computational equipment used by students, faculty, staff, visiting scholars, and industrial and Army interns from both the United States and abroad.
CCM educates engineers, conducts basic research, and provides prompt technology transfer for the composites community. More than 25 faculty members, 75 students, and a dozen professional research staff are currently affiliated with the Center. The students earn their degrees in engineering, materials science, physics, business, or chemistry.
CCM began working with materials suppliers and end users in the aerospace, automotive, civil engineering and durable goods industries in the mid-1970s. Since then, the Center has collaborated with well over 100 international companies through consortium membership or contracts and grants.

a. Research

Center researchers take a "holistic" approach to composites research, with the work ranging from materials and synthesis, mechanics and design, and processing science to sensing and control and performance evaluation.
During its history, which spans over a quarter of a century, CCM has developed core competencies in a number of composites science and engineering areas, including liquid molding (resin transfer molding, vacuum-assisted resin infusion), textile preforming, novel thermoset processing (e-beam, UV, visible light), thermoplastic processing, joining, composites from renewable sources, interphase science, sensing and control, and cost modeling.



b. Partners

These core competencies are applied to the Center's many research programs, which are supported by a variety of funding sources, including the u.s. Army Research Laboratory (ARL), the Army Research Office (ARO), the Office of Naval Research (ONR), industry (100+ companies representing materials suppliers and end users in the aerospace, automotive, civil engineering, and durable goods industries), the Defense Advanced Research Projects Agency (DARPA), the National Academy of Science (NAS), the National Science Foundation (NSF), and the State of Delaware.

c. Education

Students and faculty in the Center are affiliated with the University of Delaware departments of Chemical, Civil & Environmental, Materials Science & Engineering, Mechanical Engineering, Physics & Astronomy, Chemistry & Biochemistry and the College of Business & Economics.

B - Presentation of the project

CCM is pursuing many projects in Resin Transfer Molding and Vacuum Assisted Resin Transfer Molding. Mainly, these technologies are associated with fabrication of flat composite parts. Furthermore, today many applications require complex shaped geometries.
Therefore, complex shape part manufacturing processes are needed.

The goal of this project is to develop a mold manufacturing process that has several features such as:

- **Low cost,**
- **Flexible,**
- **Rapid,**
- **Repeatable.**

The use of Rapid Prototyping (RP) techniques seems to offer new possibilities in manufacturing very accurate molds at low costs. The costs of the RP techniques are still high, so researches for more low-priced manufacturing process are still necessary. Laminate Object Manufacturing (LOM) is one of the several RP techniques. It uses paper that is cut in shape by a laser and laid up layer by layer to create a three dimensional part. The use of paper provides the manufacturing of low-cost parts. Only few researches can be found which consider LOM as mold manufacturing process.

This research develops a process for LOM mold manufacturing for the Center for Composite materials. The Center is not equipped with a LOM machine but a laser cutter. This offers the creation of a LOM process. The steps of the process will be explained. Further on, this research evaluates the general properties of LOM molds and is focus on the strength improvement of a paper-based mold.

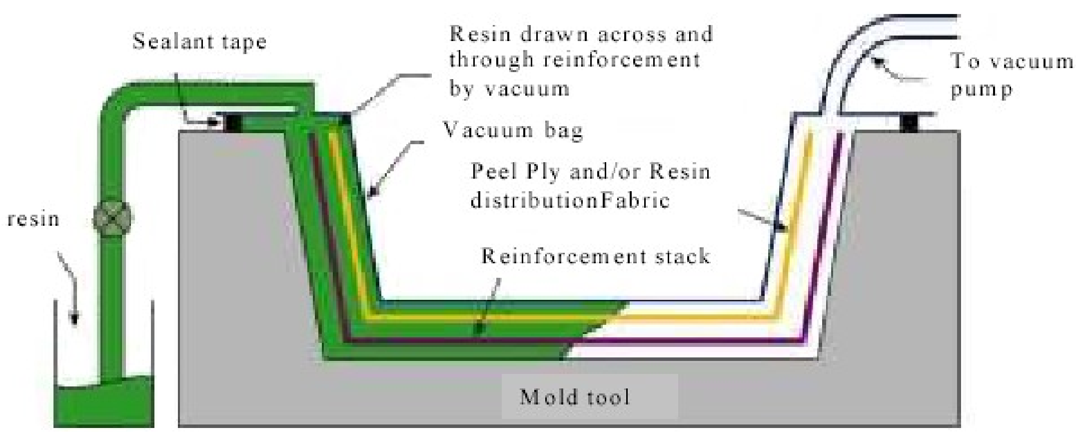
II - THE LOM PROCESS

A - Manufacturing process for composite parts

Vacuum Assisted Resin Transfer Molding (VARTM) is one of the most used composite manufacturing process. Indeed, this process allow to easily manufacture complex shape part, because only one mold is necessary.
The manufacturing of molds for composite parts requires knowledge about the production process of composite parts and the curing process of resin.

1 - The VARTM process

VARTM is a manufacturing process for composite parts witch uses vacuum instead of pressure. Fabrics are laid up in a mold as in RTM. The fiber stack is then covered with peel ply and a knitted type of non-structural fabric. The whole dry stack is then vacuum bagged, and once bag leaks have been eliminated, resin is allowed to flow into the laminate. The resin distribution over the whole laminate is aided by resin flowing easily through the non-structural fabric, and wetting the fabric out from above.



Most of the time, the resin use is epoxy, polyester or vinylester.

Advantages:
- Much lower tooling cost due to one half of the tool being a vacuum bag, and less strength being required in the main tool.
- Large components can be fabricated.
- Standard wet lay-up tools may be able to be modified for this process.
- Cored structures can be produced in one operation.

Disadvantages:
- Relatively complex process to perform well.
- Resins must be very low in viscosity, thus comprising mechanical properties.
- Unimpregnated areas can occur resulting in very expensive scrap parts.
- Patents cover some elements of this process.

2 - Curing process of resin

The use of a certain tool and a certain tooling material greatly depends on the resin used for the composite part. Every resin exhibits a different curing behavior depending on the environmental conditions. Therefore, it is necessary to consider the general curing behavior of resins and the influence of mold properties on the curing of the resin.
The detailed curing behavior of resin strongly depends on the resin itself. Nevertheless, the first effect during curing is an exothermic reaction. Every resin evolves heat during curing and the amount of heat of a resin is always the same. The difference is the rate of heat evolution and therefore the peek temperature. The faster the resin cures the more heat are evolved. This greatly influences the properties of a part and it is therefore desired to control the heat evolution of a resin. The heat evolution can be controlled by the amount of catalyst or accelerator or by external change of the tool temperature. Especially high temperature curing resins need hot tool and equal heat distribution to cure without failure.
While curing, the viscosity of the resin increases and changes from a fluid state to a solid state. The gel point describes the point where the resin changes its state. The exact definition of the gel point is still a subject of discussions. Nevertheless, this point can be described as the state where the resin cannot flow anymore. It shows a rubber similar appearance. Cooling down the resin at this point leads to a change of the state of the material at a temperature defined as the glass transition temperature (T_G). Continuing curing in the solid state without cooling increases T_G.

B - Presentation of Rapid Prototyping

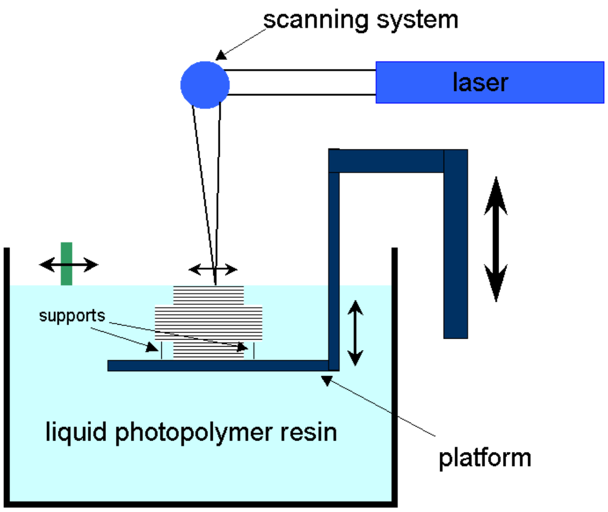
Rapid prototyping (RP) is the process of building up a physical model directly from a 3D triangulated representation of a CAD model.
RP is a new area of technology involving the automated fabrication of geometrically complex and dimensionally accurate solid objects directly from CAD files.
A CAD model of the part is sliced and downloaded to a rapid prototyping system to get a three-dimensional print of the part.

There are several types of RP available in the market currently. The systems are:

- Stereolithography (SLA)
- Fused Deposition Modeling (FDM)
- Selection Laser Sintering (SLS)
- Laminated Object Manufacturing (LOM)

1 - Stereolithography (SLA)

The SLA used a laser beam to solidify the layer of resin. In the process, the designs created on a CAD system is converted into .STL format. In this format, the object is sliced into 2D cross section with a slice thickness ranging from 0.0015” to 0.005”. (=0.0038 mm to 0.127 mm)



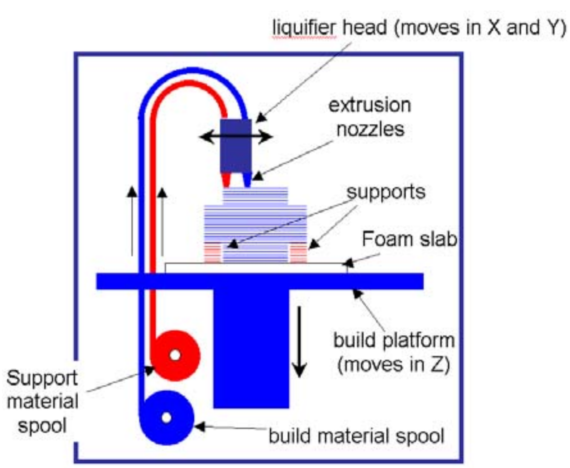
Advantages	Disadvantages
High resolution No limitation of geometry Large selection of machines	Post curing (To complete the solidification process) The part may melt if it exposed to high temperature Limited material

Applications:

Master models for tools that can be used for pre series production tests.
Medical models, form-fit functions for assembly tests.

2 - Fused Deposition Modeling (FDM)

FDM builds by extruding molten plastic that hardens layer-by-layer to form a solid part. The building material, in the form of a thin solid filament, is fed from a spool to a movable head controlled by servomotors. When the filament reaches the head, heaters melt it. The molten material is then extruded through a nozzle onto the part surface.

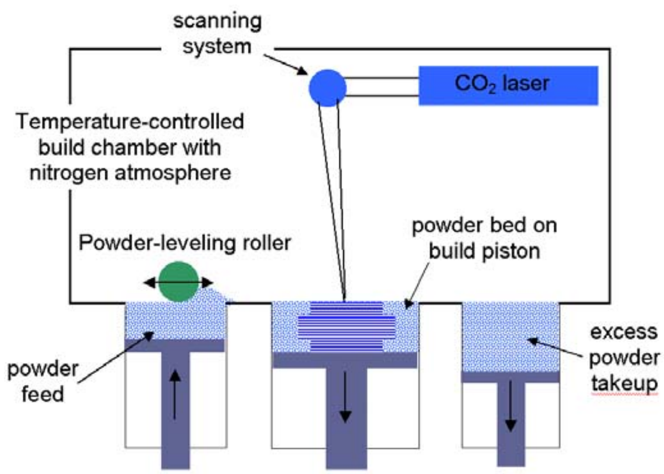


Advantages	Disadvantages
No post curing Temperature (80 – 100 °C) Wax (No powder and so no messy cleanup)	Limited part complexity Restricted accuracy Post-processing for support removal

Applications:
Conceptual modeling, fit, form and functional models for further manufacturing procedures like investment casting, injection molding, vacuum casting, metal injection molding, and fine casting.

3 - Selection Laser Sintering (SLS)

Laser-sintering machines build each layer by first spreading a shallow layer of powder onto a building platform and then scanning a cross section of the part on the powder with a CO_2 laser. Everywhere the laser touches, its energy heats the powder grains, causing them to adhere to their neighbors. Once a layer is complete, the building platform, which is mounted on a moveable piston, lowers by a single layer's thickness, from 0.004" to 0.006" (0.10-0.15 mm) — and a new layer of loose powder is spread across the top of the growing part.



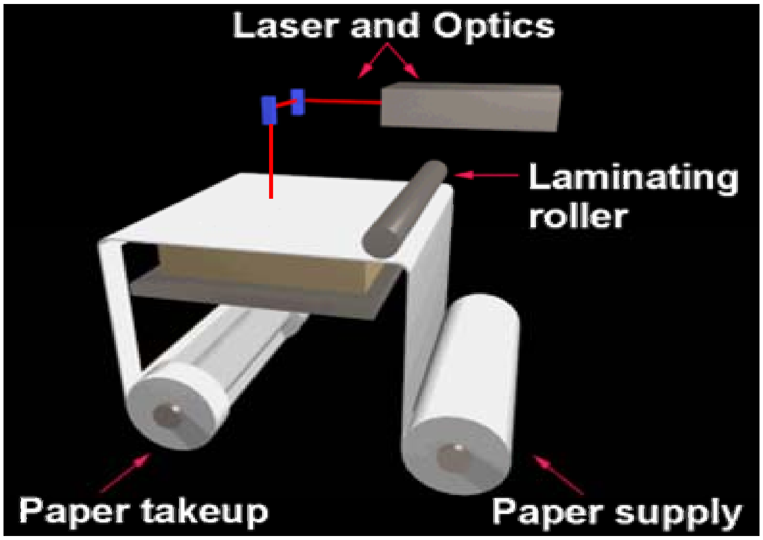
Advantages	Disadvantages
Unattended operation (The system is fully automated)	Post curing (To complete the solidification process)
Good accuracy	War page (The part may melt if it exposed to high temperature)
High detail	
Surface finish	Limited material
Industry presence	Support is needed when the parts are "printed".

Applications:
- Visual representation and functional tough prototypes.
- Cast metal parts (by use of wax).
- Short run and soft tooling.
- For design, technical, and functional studies

4 - Laminated Object Manufacturing (LOM)

LOM technology in brief:

- CO2 laser used to cut the shape of each layer and cut waste material into cubes.
- The paper is bonded to the previous layer using a heated roller, which melts a plastic coating on the bottom side of the paper.
- After manufacture the waste material is broken away to reveal the required 3D structure.



Advantages	Disadvantages
Materials (Paper, plastic, composites)	Quality (Sensitive to wet environment)
Properties (Durable structure)	Strength (The parts are weak when subjected to stress in the direction perpendicular to lamination)
No post curing	Geometry (Limited by the size of access hole)
Cost (No special polymer or wax)	
Stress	

Applications:

- Conceptual design, used for large bulky models as patterns for sand casting
- Models for silicon molds, injection molding, tools fabrication.

C - Presentation of LOM

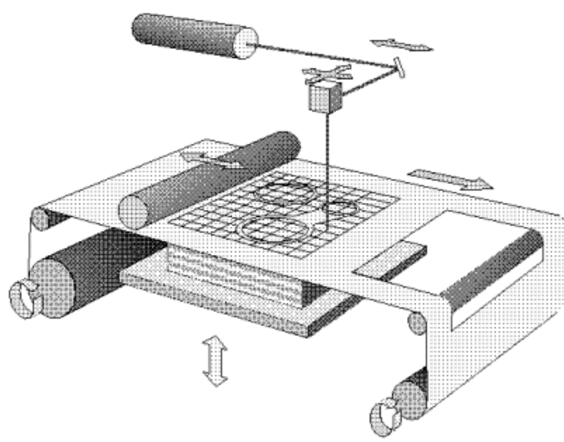
1 - General definition of LOM

All the RP process have been studied and compared for the composite mold manufactured.

The LOM process has been chosen for different reason:

- CCM has major components of the LOM system
- LOM is an inexpensive manufacturing technology
- Technology is flexible regarding to shape complexity
- LOM is a repeatable method of manufacturing
- Surface quality depends on thickness of paper

Helisys Inc. developed laminated Object Manufacturing at the beginning of the 90s. It uses a 3D drawing, which is sliced into layers of the thickness of the utilized thin sheet material. The adhesive coated sheet material is rolled up on spools. Then the sheet is placed on top of a platform where the laser cuts the outline of the layer. Now the platform moves downwards and a new layer is placed above the previous one. A heated roller bonds a new layer to the old one and the laser starts cutting. This process is continued until the part grew up layer by-layer. The additional paper that must be removed surrounds the part.

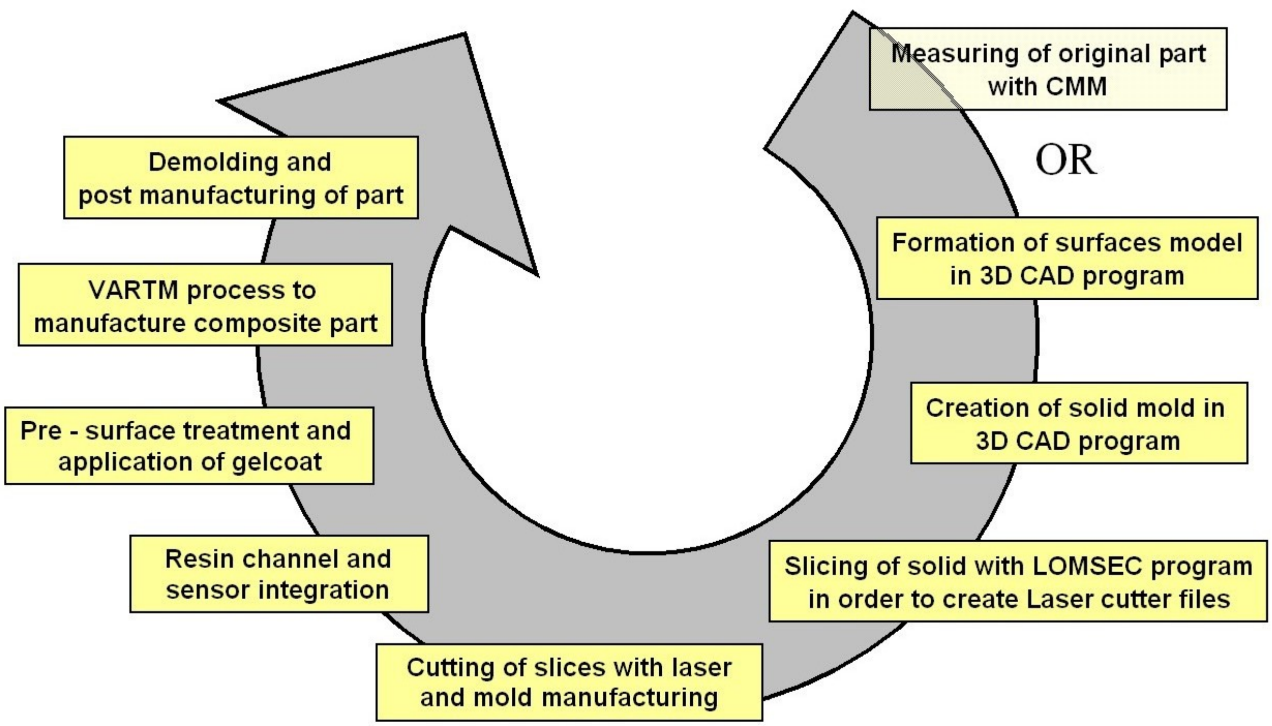


To prevent damage of the part by permeating moisture it is necessary to seal the part with a varnish or a coating. The biggest advantage of LOM is the use of the low cost material paper. Although paper has certain negative characteristics that prevent using LOM parts for functional purposes, the parts are very expedient to analyze the part design.

LOM provide several advantages that make the process faster than other RP techniques. LOM parts do not need postcuring to increase the stability. They don't show shrinkage or warpage, what supports dimensional stability of the part. Complex shapes are possible and undercuts need no support because the paper supports the structure itself. Problems are the sensitivity of paper towards moisture. The stability of the part results from the stability of the bonding layer and the paper. The materials used for LOM show a wide variety. It is not only possible to use paper; almost every cut able sheet material can be used. Recent studies already research the use of LOM for direct composite or ceramic (SiC) part manufacturing. The biggest available LOM machine can already manufacture parts of the size 813 x 559 x 508 mm.

2 - The CCM LOM process

CCM doesn't have a LOM machine. Therefore, LOM molds manufacturing process in the CCM is quite different:



3 - Mold Materials

The following chapter describes the three materials that composed a LOM mold for composite.

a. *Paper*

The most important material in the mold is the paper, and it has the most important influence on the properties of the mold.

Paper is a porous, fibrous material consisting of cellulose fibers connected by hydrogen bonds.
Pulp is the main ingredient in the papermaking process. Pulp can be made from a variety of materials: wood pulp, recycled paper, cotton, flax, straw, and bamboo.
Paper is also a very used material that can be found everywhere.

It is described by its grammage and its thickness. Information about mechanical properties of paper is usually difficult to find. Indeed, paper manufacturers don't study all properties of their paper, because customers are not interested in these facts. Furthermore, the determination is very complicated.

The mechanicals properties of the paper are dependent on environmental conditions.
The values for paper are usually measured during ambient conditions. That is about 25 ºC and relative humidity of 50%. Since paper is very sensitive to moisture and temperature the values can decrease up to 50%.

The "Schrafel Paper Company" fabricates the paper used in the CCM. It is a 0.5 mm thick "Newsprint" paper with one clay-coated side. Its density is about 420 kg/m^3. This paper is originally used as packaging material.

b. *Adhesive*

(i) Basics of adhesion

The mechanism of adhesion has been investigated for years; several theories have been proposed in order to explain the adhesion phenomena. However, no single theory explains adhesion in a general, comprehensive way.

The bonding of an adhesive to a surface is the result of many mechanical, physical, and chemical forces:

- Adsorption: Adhesion results from intimate intermolecular contact, and involves surface forces developed between the atoms in the two surfaces. The most common surface forces that form at the adhesive-adherent interface are Van der Waals forces.

- Chemisorptions: The chemical bonding mechanism suggests that primary chemical bonds may form across the interface. Chemical bonds are strong and make a significant contribution to the intrinsic adhesion in some cases.

- Mechanical interlocking: Good adhesion occurs only when an adhesive penetrates into the pores, holes and crevices and other irregularities of the adhered surface of a substrate, and locks mechanically to the substrate.

- Diffusion: Attributes the adhesion of polymeric materials to the inter-penetration of chains at the interface. The major driving force is due to mutual diffusion of polymer molecules across the interface. This theory requires that both the adhesive and adherent are polymers, which are capable of movement and are mutually compatible and miscible.

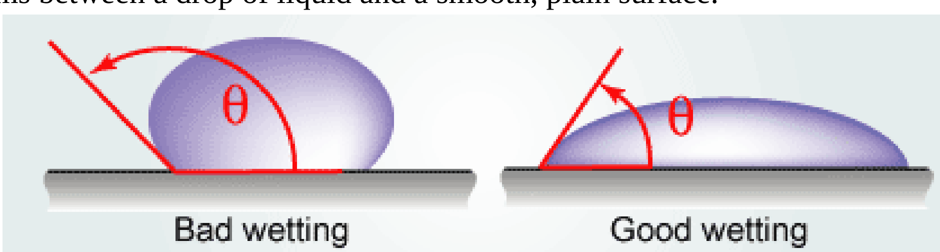
- Electrostatic: The basis of the electrostatic theory of adhesion is the difference in electro-negativities of adhesing materials. Adhesive force is attributed to the transfer of electrons across the interface creating positive and negative charges that attract one another.

(ii) Factors that influence the adhesion

The following factors have a predominant importance in the adhesion process:

- Wetting of the surface:

To enable the adhesive bonds between the adhesive and the surface, the adhesive must first wet the surface; in other words, it must be applied in the liquid form (as a solution, dispersion, or hot-melt). A measure for the wettability of a surface is the angle of contact that forms between a drop of liquid and a smooth, plain surface.



- Surface treatment:

All surfaces exposed to the normal atmosphere undergo gas and water adsorption in the molecular range. To ensure a good adhesion it is sometimes necessary to carry out, expensive mechanical or chemical pre-treatment.

- Structure of the material:

Besides the surface condition, the structure of the materials to be bonded is also of decisive importance. Porous materials (e. g. wood, paper, and textiles) absorb low viscosity adhesives.
The results of this adhesive's penetration are thin, uneven joints that often impair the strength of the bond. On the other hand, the capillaries absorb the more volatile, i.e. low molecular substances preferably.

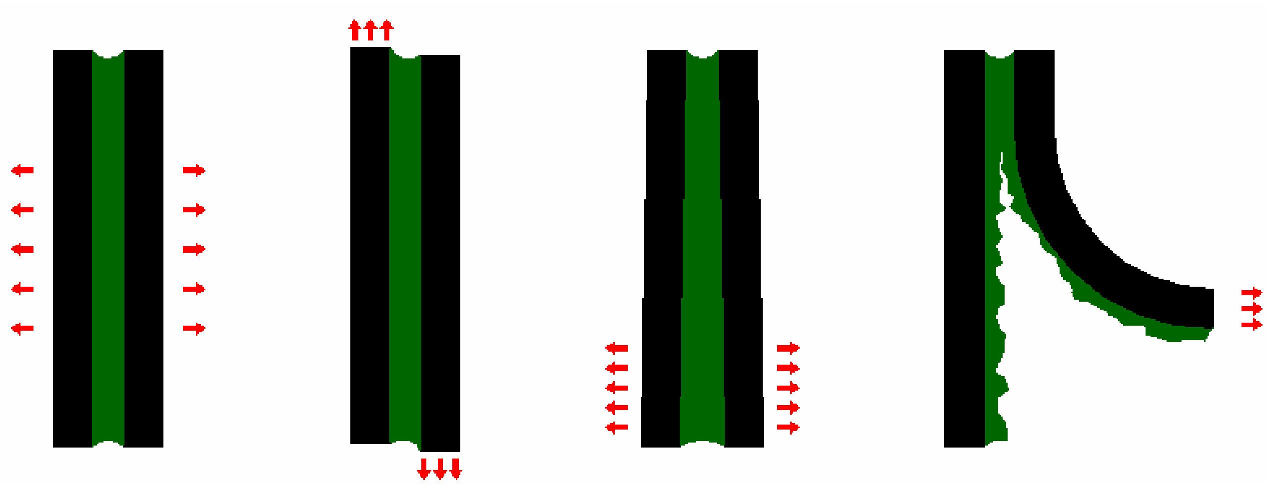
- Structure of the joint:

An important prerequisite for the successful use of bonding technology is that the respective parts be suitably designed for bonding, as distinct from welding, for example. Care must be taken to provide a sufficiently large bonded area, such as a large area of overlap of the mating parts. The ideal bonded joint is one under all practical loading conditions the adhesives is stressed in the direction in which it most resists failure. Favorable stress can be applied to the bond by using proper joint design.

(iii) Stress resistance

One of the primary benefits of adhesive is that it holds something together resisting the stress to pull it apart.

- **Tensile stress** is exerted equally over the entire joint straight and away from the adhesive bond.
- **Shear stress** is across the adhesive bond. The bonded materials are being forced to slide over each other.
- **Cleavage stress** is concentrated at one edge and experts a prying force on the bond.
- **Peel stress** is concentrated along a thin line at the bond's edge. One surface is flexible.



Tensile Shear Cleavage Peel

In the case of a LOM composite mold, we need an adhesive that has good mechanicals properties with shear, cleavage, and compression stress.

c. *Gelcoat*

The gelcoat is necessary to prevent the penetration of moisture in the paper and to simplify the demolding. This chapter deals with the mechanical properties and especially its dependence on the temperature.

(i) General description

Most gelcoat consists of polymeric materials. The used gelcoat also consists of polymers in this case vinyl ester. Polymers show certain characteristics that dictate its use. The characteristics of polymers are described by the same parameters as used for metal. Problems usually result from the sensitivity of polymers to chemical environment and temperature. The elastic modulus of polymers ranges from 10 MPa up to 7 GPa. The tensile strength can be up to 100 MPa.

(ii) Curing behavior of the coating

The coating is cured by the use of a catalyst. The amount of catalyst is determined by the manufacturer. In the case of the used vinylester tooling gelcoat the amount of catalyst is 2% of the amount of the coating. The gel time is determined by the manufacturer to be 15-21 min. However, the curing time essentially depends on the curing conditions. The evaluation of these values was carried out by the use of a curing measurement system. This test was especially made to determine the gel time. The gel time of the tooling gelcoat was determined to about 38-40 min.

(iii) Contact between paper and coating

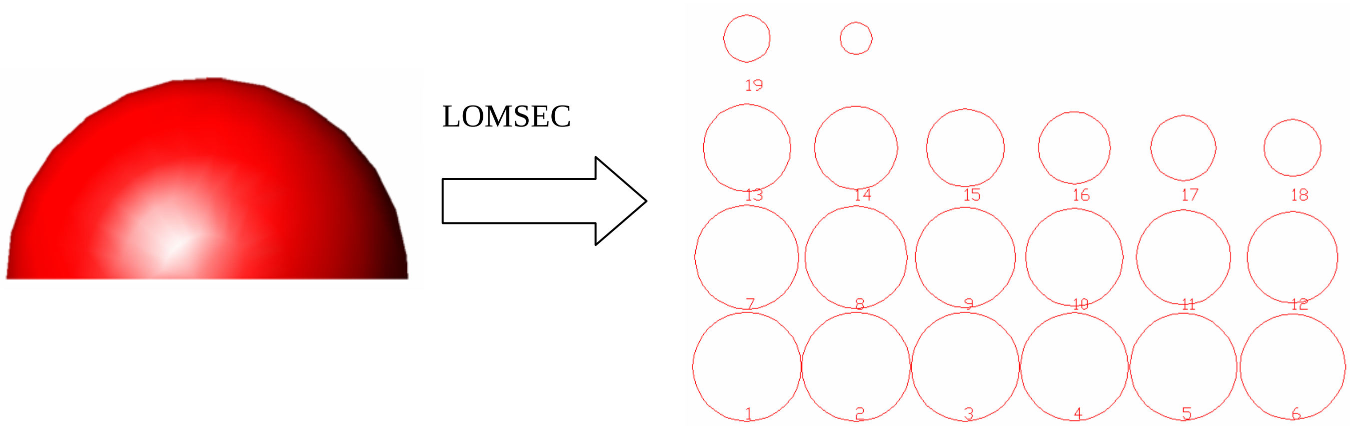
To achieve a stable and long time usable mold it is necessary to evaluate the cohesion between paper and coating. The coating shall provide maximal cohesion to the paper and minimal cohesion to the resin. The stability of the coating depends on two different factors. First, the chemical cohesion between paper and coating is important. This value can be defined as the maximal possible strength of the cohesion. Second, the surface of the coated material is important. If the coating is not able to bond directly to the base material, the bonding will not be strong. This can occur if the surface of the base material is dirty or coated with another weaker material.

D - Goals of the project

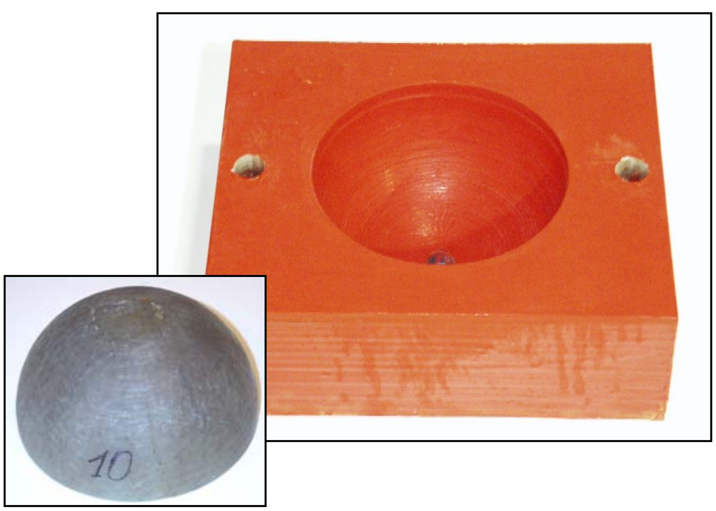
1 - Presentation of previous works

a. LOMSEC program

The cutting laser can only read DXF files created by a 3D-CAD software. AutoCAD is used for this research.
A self-written AutoLISP program makes the creation of the sections for the laser cutter. This “LOMSEC” program cuts the solid in sections with the former determined distance between the sections. The cutting direction is always the z-direction of the “World coordination system”. Afterwards the sections are copied into a 2D pattern with the size of the paper.



b. Half sphere mold



A mold was manufactured to evaluate the durability of LOM molds. The cavity of the mold forms a half sphere.

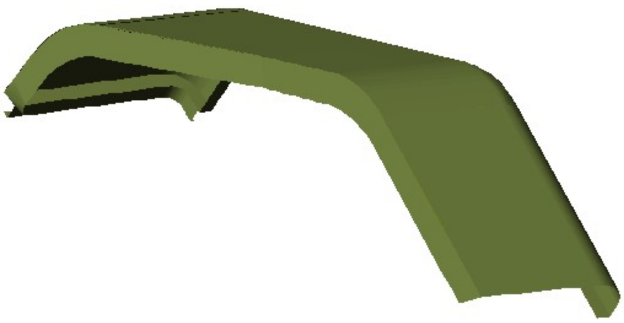
Ten demoldings were possible without significant damages.

Despite the part shape simplicity, this mold shows that that using a paper based LOM mold is possible.

c. Fender mold

Based on the equipment in the CCM a mold manufacturing process must be developed. This process shall be able to reproduce existing parts as well as manufacturing parts that are design in a CAD system. To evaluate the developed process a sample part was chosen that seems possible to be created by means of LOM.

To evaluate the manufacturing process and the abilities of LOM molds a fender truck was chosen: (see appendix 3)



The fender is a part of a truck. The size of the part is about 900 x 300 x 200 mm. Lengthwise the part is bended twice. One side is bended about 90º to mount the fender at the vehicle. The opposite side is arched. At one of the shorter ends of the part, an angular channel is placed to mount this part to the main part of the fender. To strengthen the part at different areas stringers are affixed.
I worked on this mold and on the two first composite manufactured parts during the first month of my internship.

The first demolding damaged the mold. It shows the problem of the strength of the mold. Different reasons can explain this fragility:

- Adhesive used
- Adhesion of the gelcoat to the paper
- Compression strength was low
- Not optimum designed

2 - Goals of the project

The fender mold shows that manufacturing a complex shape part with a paper based LOM mold is possible. However, strength improvement of such a mold has to be done.

First of all, it is important to test the mechanical properties of the material used, in order to choose better adhesive or gelcoat. The adhesive used for the fender mold was a cheap multipurpose spray adhesive. It can be replace by a better or a high temperature one. Paper can also be replace by a stronger material sheet, for example a fiberglass sheet. Three materials have to be studied:

- Adhesive
- Gelcoat
- Paper

However, the goal of the LOM process is to have a low cost mold. As a consequence, prices of materials have to be compared. A fiberglass sheet is around ten times more expensive than a paper sheet.

It can be interesting to improve the strength of a paper based LOM using stiffeners inside the mold. These stiffeners can be made of steel, or of resin and can be placed in a weak area of the mold.

Then, evaluations of the process have to be done. It’s important to know exactly the accuracy of the process. The laser measurement system of the CCM could be used. It is also important to know the application range of a paper based LOM mold in order to know in which case it is possible to choose the LOM process (temperature, shape, number of part…).

III - STRENGTH IMPROVEMENT OF LOM MOLDS

A - Test of adhesives

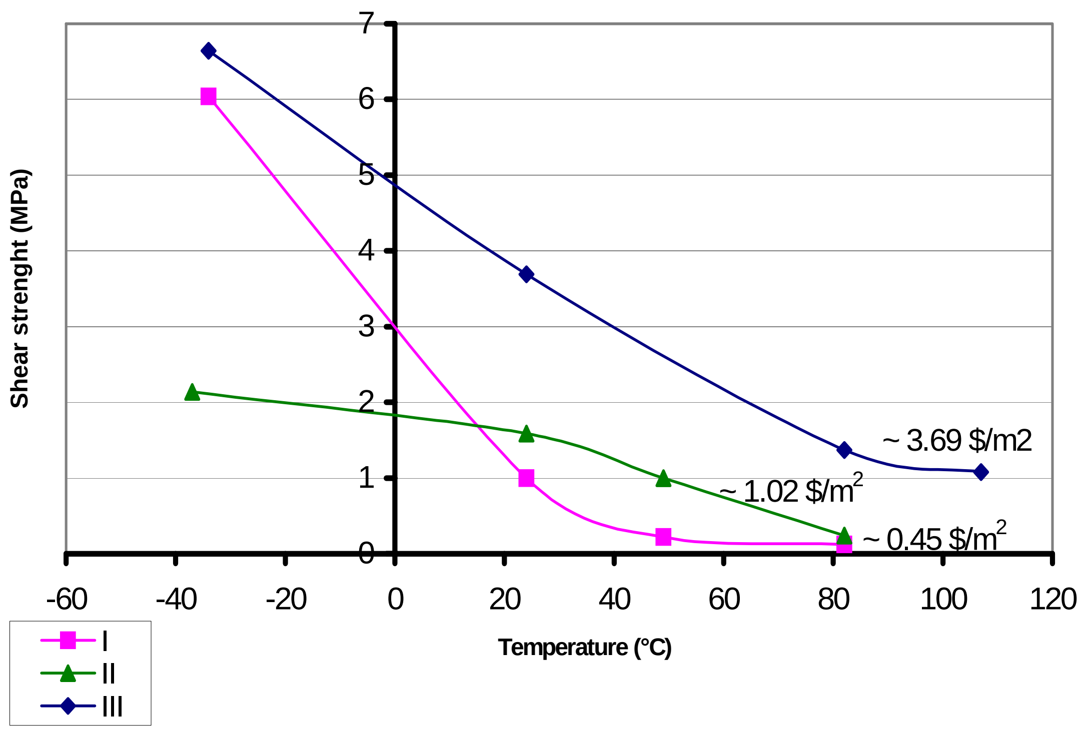
1 - Presentation of the three adhesives

Researches have been done to improve the mechanical properties of the adhesive.
The goal of the LOM project is to manufacture inexpensive composite molds. Therefore, we have to compare the prices and the mechanical properties of different adhesives.

Three different kinds of adhesive have been compared:
- I: 3M™ Multipurpose 77 spray adhesive
- II: 3M™ Hi-Strength 90 spray adhesive
- III: 3M™ Scotch grip 1357

Adhesive	I	II	III
Application	Spray	Spray	Brush
Shear strength (at 20°C)	1	1.59	3.69
Price ($/m^2)	~ 0.45	~ 1.02	~ 3.7
Chemical type	Synthetic Elastomer (trade secret)		Polychloroprene

The goal of this comparison is to choose the adhesive that have the best ratio between the quality and the price.



Adhesive is a viscoelastic material that is sensitive to heat. The more it is heat resistant, the more it is expensive. The graph shows that the used adhesive (I) allows the use of the mold only in ambient temperature.

The adhesive used before was the Multipurpose 77. This cheap adhesive can easily bond lightweight materials such as paper. These mechanicals properties of this adhesive will be compared to two adhesives.
3M High Strength 90 is also an easy to use spray adhesive. The difference between both is the price and the mechanicals properties. Indeed, (I) is more than twice cheaper than II.
The adhesive (III) is a polychloroprene based contact adhesive that has good high heat resistance. As a consequence, it is more expensive than the two others.

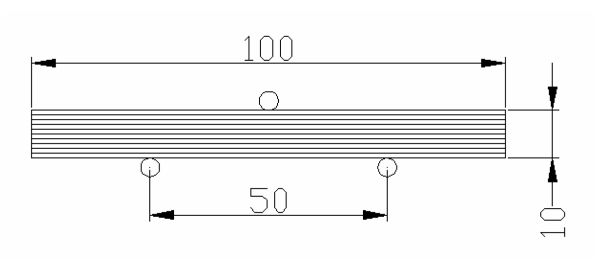
Different tests have been studied, in order to compare quantitatively the three adhesives:

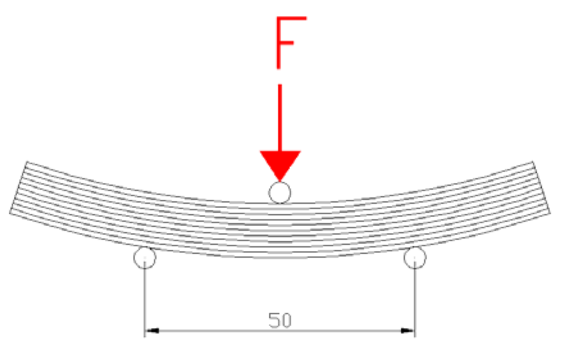
- Three points bending tests
- Shear test
- Compression test

2 - Three points bending test

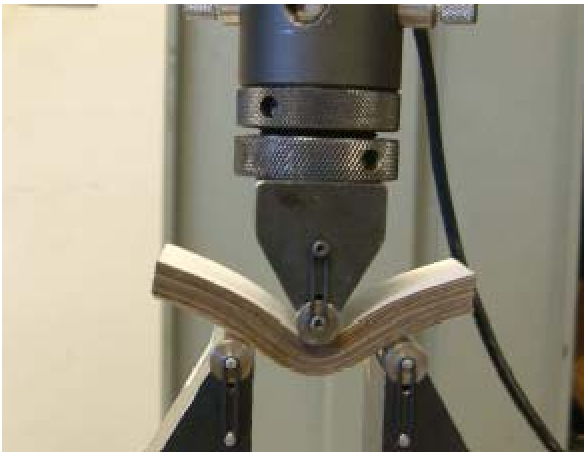
a. Description of the test:

The comparison of the three adhesives is made with a three-points bending test. The goal of this test is to compare the stiffness of the adhesives.
Therefore, three beams of each adhesive were manufactured with 20 layers of paper in the length direction:





The three-points bending test was used to acquire a force-deflection curve of the beam. Then, results were also compared with the theoretical curve calculated with the 3D laminate theory. (see appendix 1 and 2).

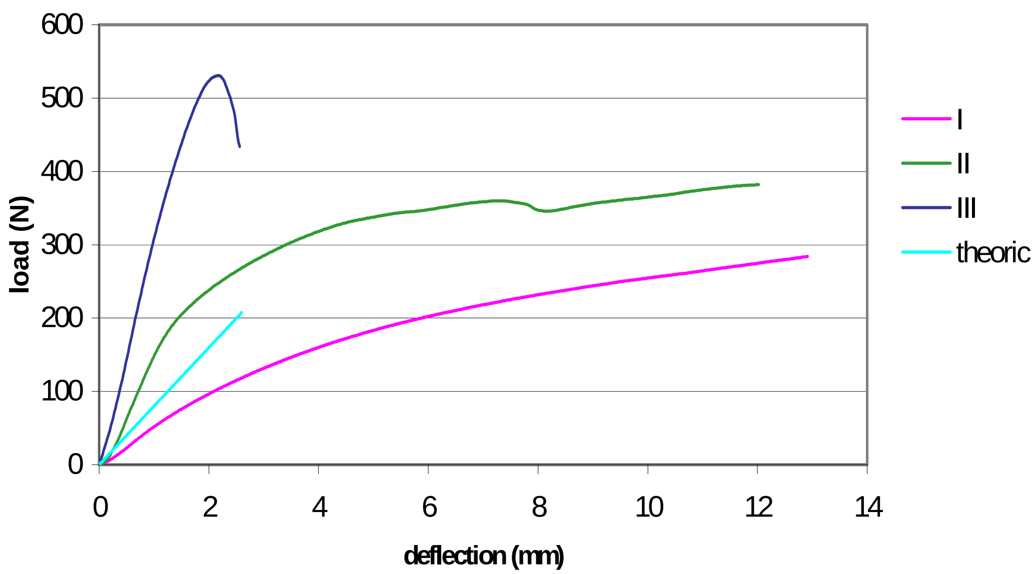


All the layers of paper were made with the cutting laser of the CCM.
The adhesive is applied on one side of paper, and then a pressure of 3.5 kg was applied on the sample so as to have a good compression of paper.

b. Results:

During the test, the deflection in the middle of the beam, and the force are measured. It will be possible to compare the stiffness of the three adhesives used and the theory.

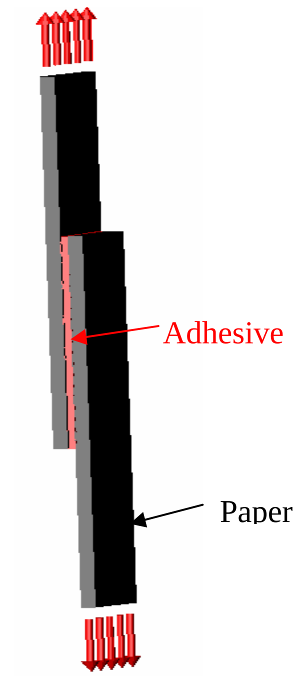
Adhesive	**I**	**II**	**III**	**Theory**
Displacement (F=50 N)	0.97	0.44	0.21	0.63
Displacement (F=100 N)	2.01	0.72	0.38	1.25



This graph shows that the three adhesives don't have the same mechanical behavior. (III) is a brittle adhesive; as a consequence, in a first part, it has a high stiffness, and after the snap, the load decrease quickly.
Adhesives (I) and (II) have a similar behavior, but the stiffness of (II) is higher. However, for our purpose, only a small strain (<2 mm) is interesting.

3 - Lap shear

a. *Description of the test:*



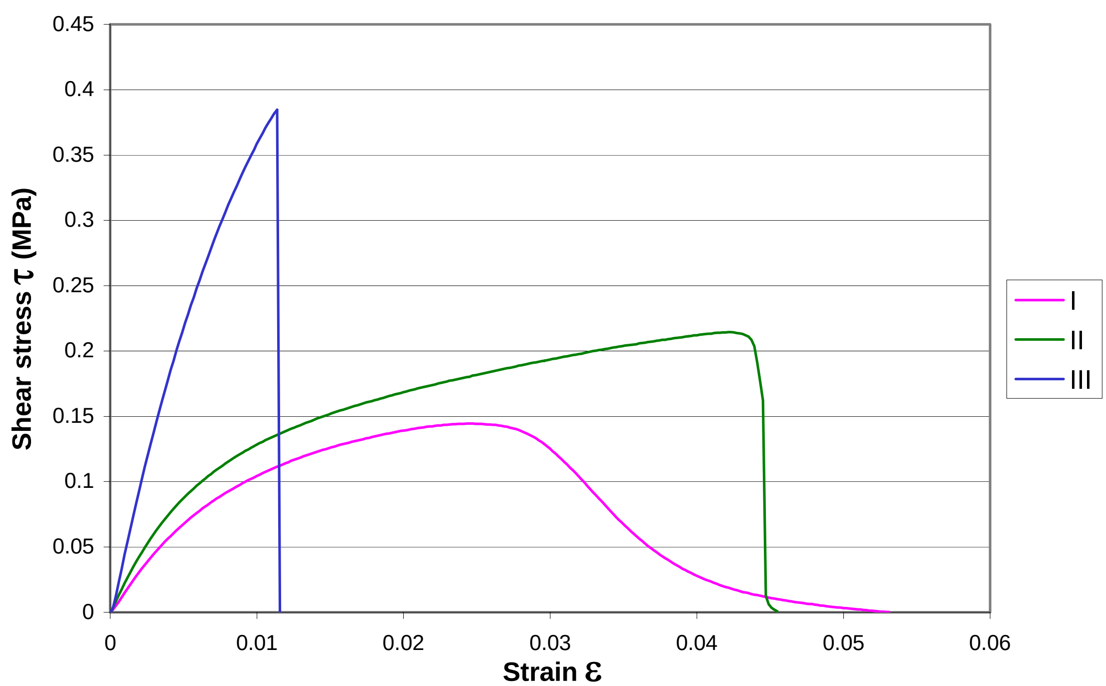
Lap shear determines the shear strength of adhesives for bonding materials.
This test used the ASTM D3163 (standard test method for strength properties of adhesives in shear by tension loading of single-lap-joint).

The testing machine control loads and speed of movement of the two paper sheets glued together. That displacement is the displacement of the adhesive.

The cure of the adhesives on the papers has been performed in the same controlled atmosphere of 20 °C and humidity of about 50% for 48 hours.

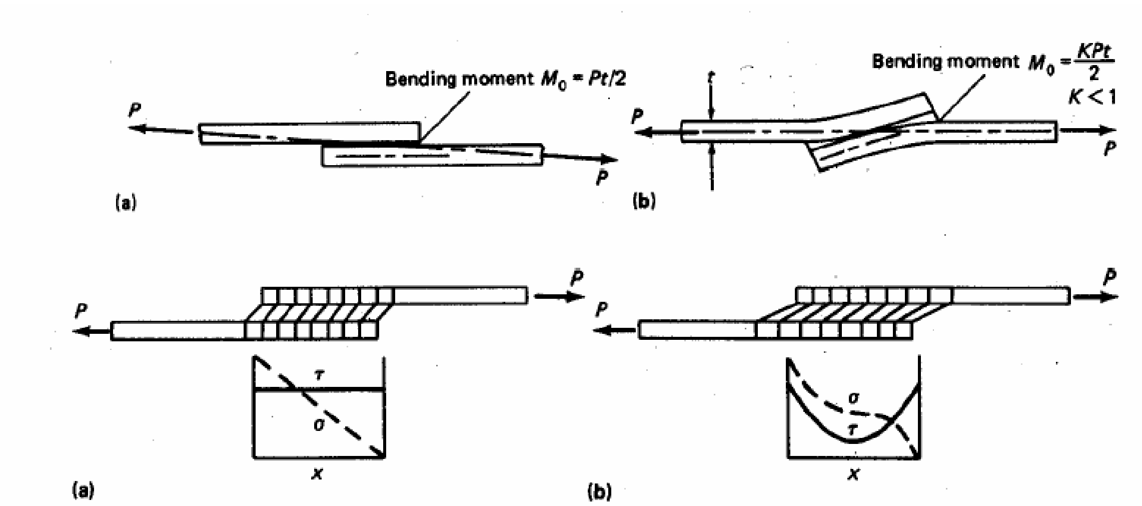
b. *Results:*

The graph shows that there are two different behaviors for these adhesives. The adhesive (I) has a strange behavior. There is no snap in the sample, and both paper sheet slide on each other after the maximal stress.



For adhesives (II) and (III), we have a rupture in the substrate, so the resistance of these adhesives is better than the paper.
It means that the overlap between the two samples of paper was too big and if better curves were needed, the overlap should be reduced.

Consideration has to be done for the interpretation of the results between rigid and elastic adherends.
Rigid adherends create constant shear lap strength along the thickness of the adhesives, but in this case, it is elastic adherend that creates a variable stress.



Exaggerated deformations in loaded single lap joint showing the adhesive shear stress and the adherend tensile stress.

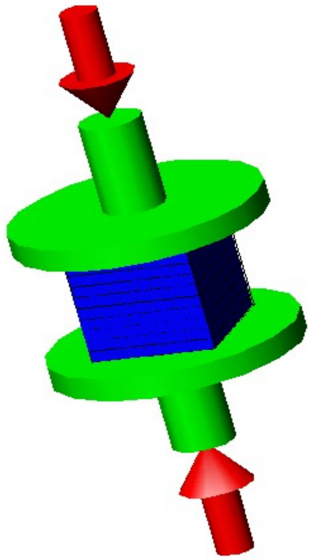
(a) With rigid adherends
(b) With elastic adherends

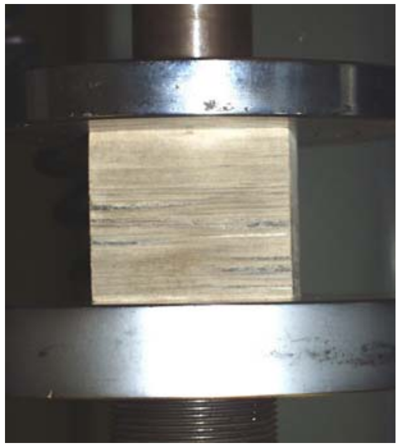
4 - Compression test

a. *Description of the test:*

The goal of these compression tests is to compare the compression behavior of three adhesives. Three samples of each adhesive have been made in the same conditions.

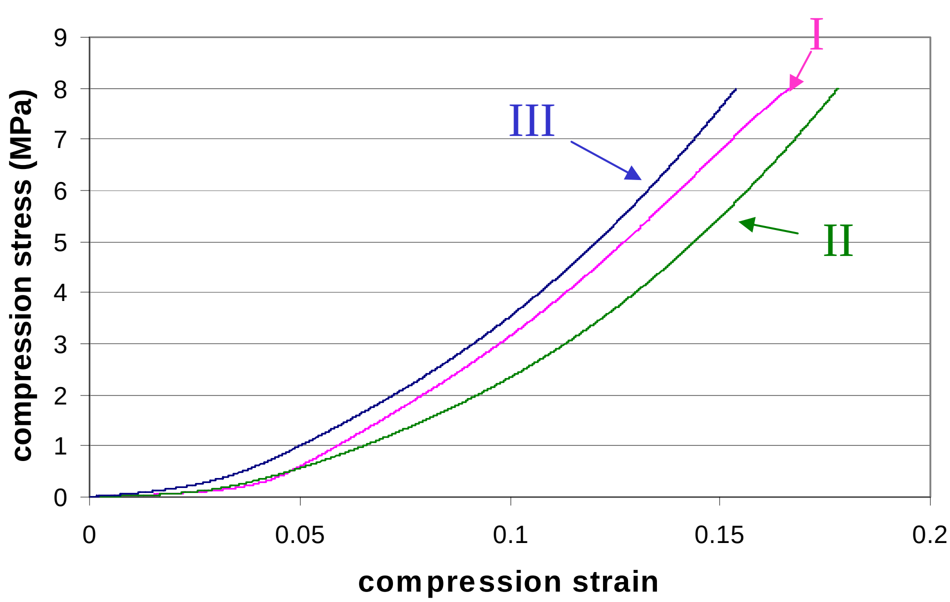
I used 100 layers of 60x60 mm squares of paper cut with the laser cutter.





b. *Results:*

The testing machine control load and displacement, then it is possible to have the compression stress versus compression strain.



The graph shows that all adhesives have the same behavior under compression loading. As a matter of fact, the compression strength of adhesives is not really important for our project.

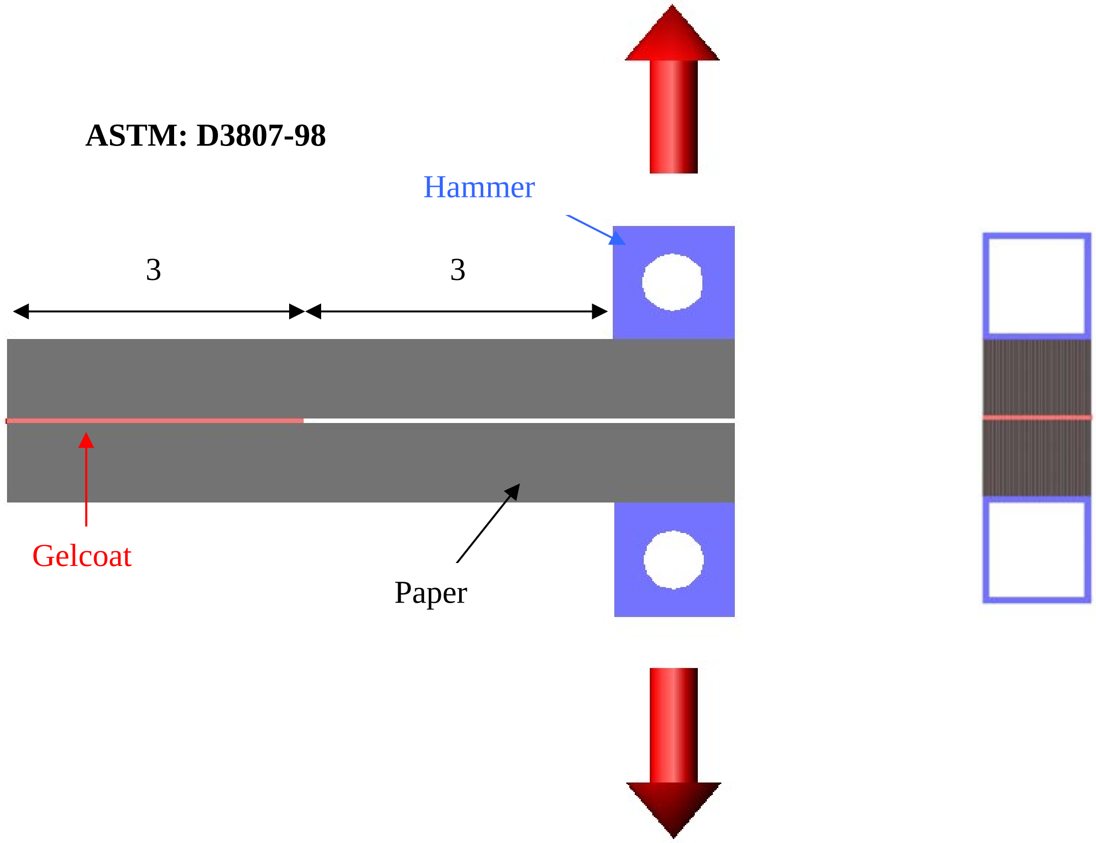
5 - Conclusion concerning adhesive

These three mechanical tests allow the choice of the best adhesive. One of the goals of the LOM process is to manufacture a low cost mold. As a matter of fact, we have to choose the adhesive with the best ratio between mechanicals properties and price.
Three points bending tests show that adhesive properties are important for the stiffness of a paper beam.
The adhesive (II) has good mechanicals properties and has a low price. This adhesive has been chosen. In the case of the fender mold, using this adhesive would increase the total price of the mold of 30%.
This adhesive can also be applied with a pumping system that decreases the price.

B - Test of gelcoat

1 - Description of the test

ASTM D3807-98 has been choosen to test the quality of the gelcoat. This test method determines strength properties of adhesives in cleavage peel by tension loading. It allows the comparative testing of cleavage/peel strengths of bonded engineering thermoplastic adherends.

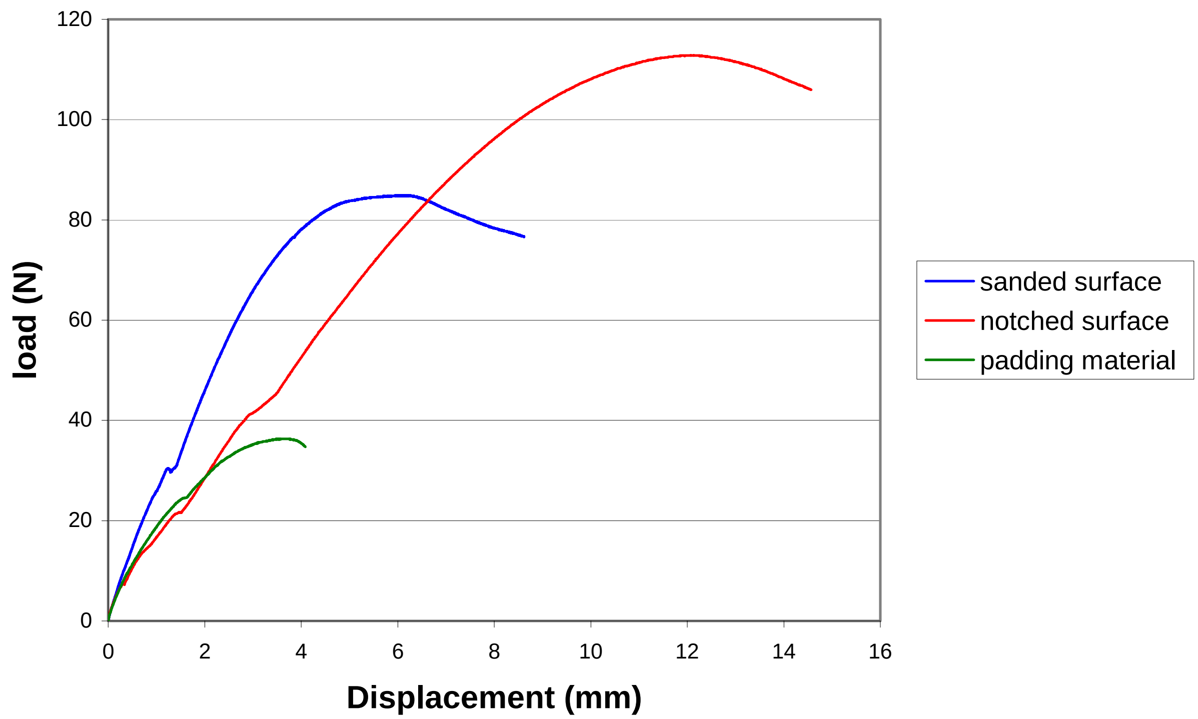


The goal of this test is to compare different gelcoat and different way to apply it. I made 9 samples of 48 layers of paper in order to have a thickness of 1 inch. All this samples have been prepared in the same conditions and with the same adhesive.

The three first samples were manufactured with the vinyl ester tooling gelcoat apply in the interface of the two paper beams. Then, three other samples were made with the same gelcoat, but with a bad surface of paper (made with a steel brush). The last three samples were made with a padding material in the interface between the paper and the gelcoat. The goal of this material is to have a smoother surface and to improve the accuracy of the process.

2 - Results

The testing machine can measure the load applied on the sample, while the displacement. As a consequence, it's possible to know the load (N) versus the displacement (mm).



All the samples have the same geometry, so I can use the load (N) and I don't have to convert in stress (MPa).

Sample	Sanded surface	Notched surface	Padding material
Average of max load (N)	90	112	41

With this test, it's possible to compare the three different way of application of the gelcoat. Apply the gelcoat on a notched surface seems to have better mechanicals properties.

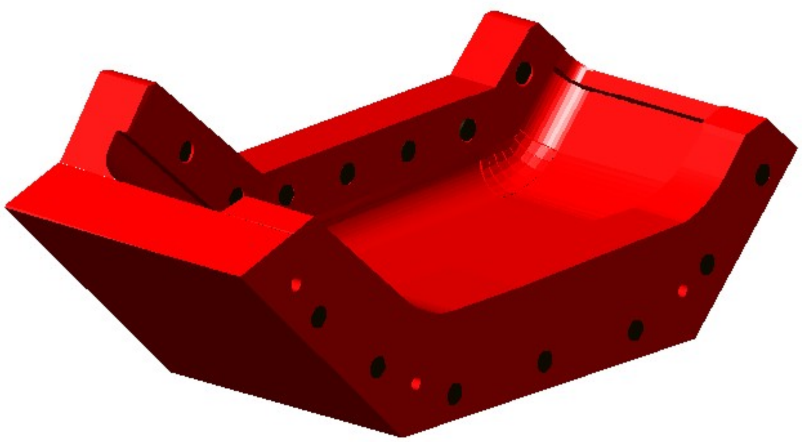
Increase the roughness has two direct incidence:

- A better mechanical anchoring,
- A rise in the contact's surface (10 to 100 times higher).

From these tests, it seems that sanding the surface of the mold before applying the gelcoat is not necessary.

C - Improvement of the stiffness with resin

The goal of this part is to create stiffeners inside the mold in order to improve the mechanical properties of a paper based mold.
The idea is to build a kind of composite mold made with paper and resin. As a consequence, channels in the mold can be filled with resin.



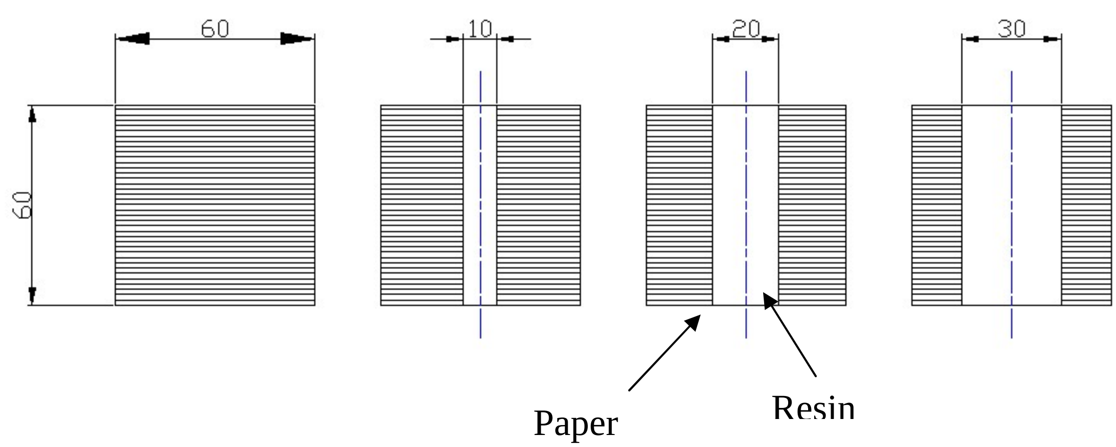
For the fender mold, creating stiffeners in the weak part would allow a better demolding.

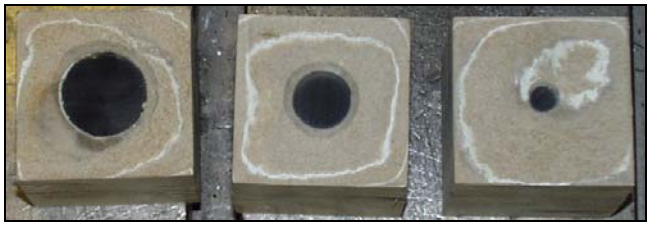
Different test has been made to compare the resin used. Vinyl ester resin has been chosen because epoxy resin has problem to cure with the paper. It seems that paper absorbs the part B of this resin and, as a consequence, the resin can’t cure.

In order to choose the optimum channel diameter and to study the feasibility of this kind of stiffeners, compression test have been done.

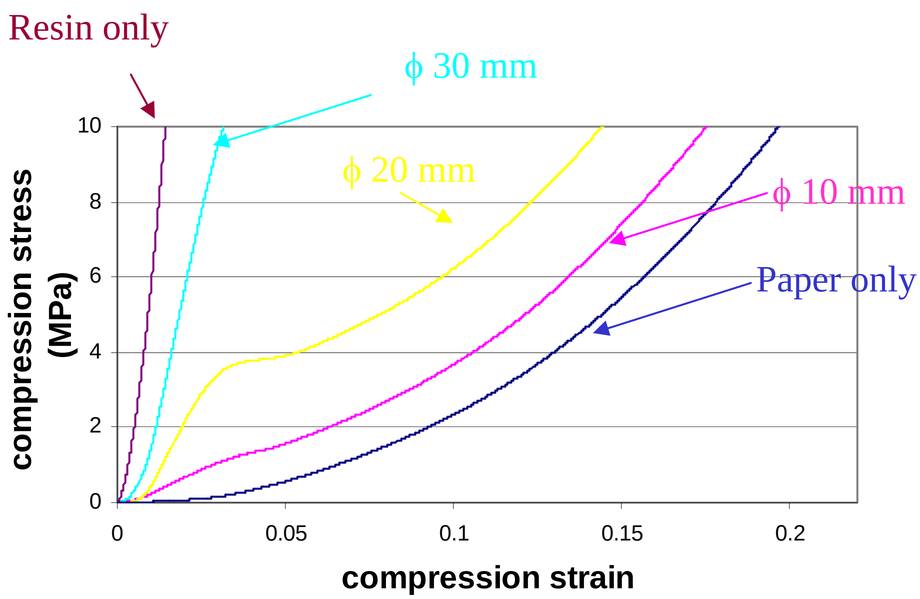
Five kinds of sample have been manufactured:

- With resin only
- 10mm diameter channel
- 20mm diameter channel
- 30mm diameter channel
- Only with paper





The compression test shows the compression stress versus the compression strain:



From these curves, it's possible to choose the optimum diameter. However, this compression test is far from the reality of a LOM mold. Indeed, in a mold, there is not only compression stress. Further on, the proportion of resin in the paper is not the same for each sample.
A diameter of 20mm seems to be enough for a paper based mold.

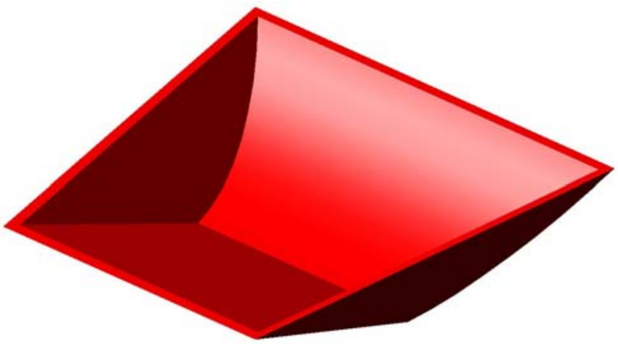
IV - EVALUATION OF MANUFACTURING PROCESS

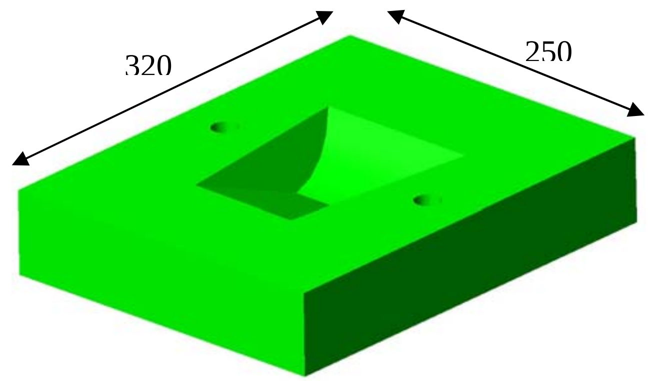
A - Small mold manufacturing

In order to validate strength improvements and durability, a simple shaped, paper based mold has been manufactured.

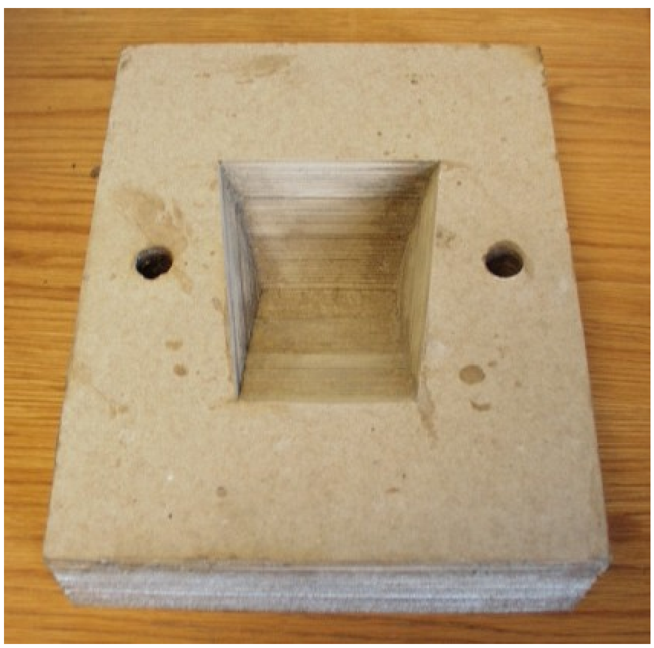
To make this mold, the CCM LOM process has been used:

1. Formation of surfaces model (AutoCAD)
2. Creation of solid mold (AutoCAD)





3. Creation of DXF files for Laser Cutter (LOMSEC program)
4. Cut of the 140 layers and assembling using the assembling device (see appendix 6)



5. Surface treatment and application of the gelcoat

B - Deviation measurement

1 - Description of Faro Arm and Geomagic software

Reverse engineering processes require a system to measure the geometry of the first part. In the CCM, the data for model are collected with the Faro Arm and Geomagic software.

The FaroArm is a multiple-axis measurement arm. It uses six different joints to ensure data collection in a spherical working volume. The user-software acquires the data and creates the geometrical object. The points a measured by a Perceptron Contour Probe laser mounted at the end of the arm. (appendix 4).

Scan clouds can be used for the following purposes.

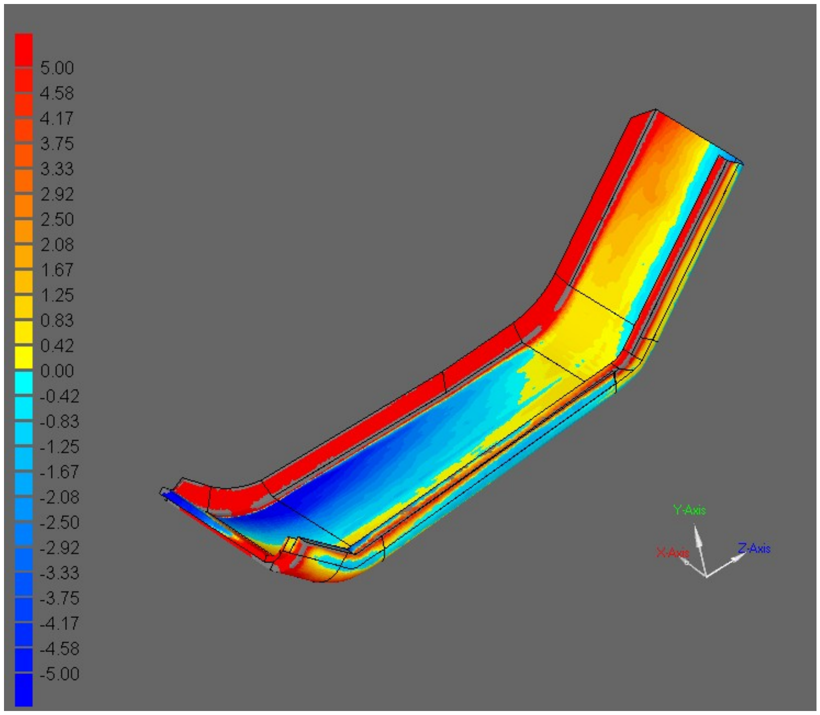
1. *Reverse Engineering*: Produces a CAD model that describes a sample part. Reverse engineering software is used to import a ScanWorks scan cloud, and then mathematically smooth and combine the scan data until representative NURB surfaces are generated.
2. *Copying*: Produce a duplicate of a sample part directly from the scan cloud data. CAM (Computer Aided Manufacturing) is used to read the ScanWorks scan cloud and produce machining instructions for CNC tools.
3. *Rapid Prototyping*: Produce a duplicate of a sample part from a CAD representation of the part. This represents a combination of reverse engineering and copying.
4. *Inspection / Validation*: Check a manufactured part to ensure it conforms to the part's design intent. There are many different levels of checks that may be performed.

    - Presence / Absence - Ensure that an assembly contains all of the necessary parts.
    - Feature Measurement - Measure the location of a feature (hole, edge, slot, etc) and compare it to the designed nominal location.
    - Contour Measurement - Compare part contours to their corresponding CAD models. This comparison may be conducted as 2D cross sectional cuts, or 3D part topographical mapping.

Then, Geomagic Software allows graphical comparisons between CAD models and as-built parts for first article inspection, tool validation, and wears analysis; and it can also processes scan data from a physical part to generate highly accurate models for manufacturing.

2 - Deviation of the fender

In order to study the accuracy of the LOM process, the first composite fender part manufactured has been scanned. Around 4 millions points have been scanned on the part. Then, it is possible to compare the CAD file and the cloud data in order to know the accuracy of the LOM process.

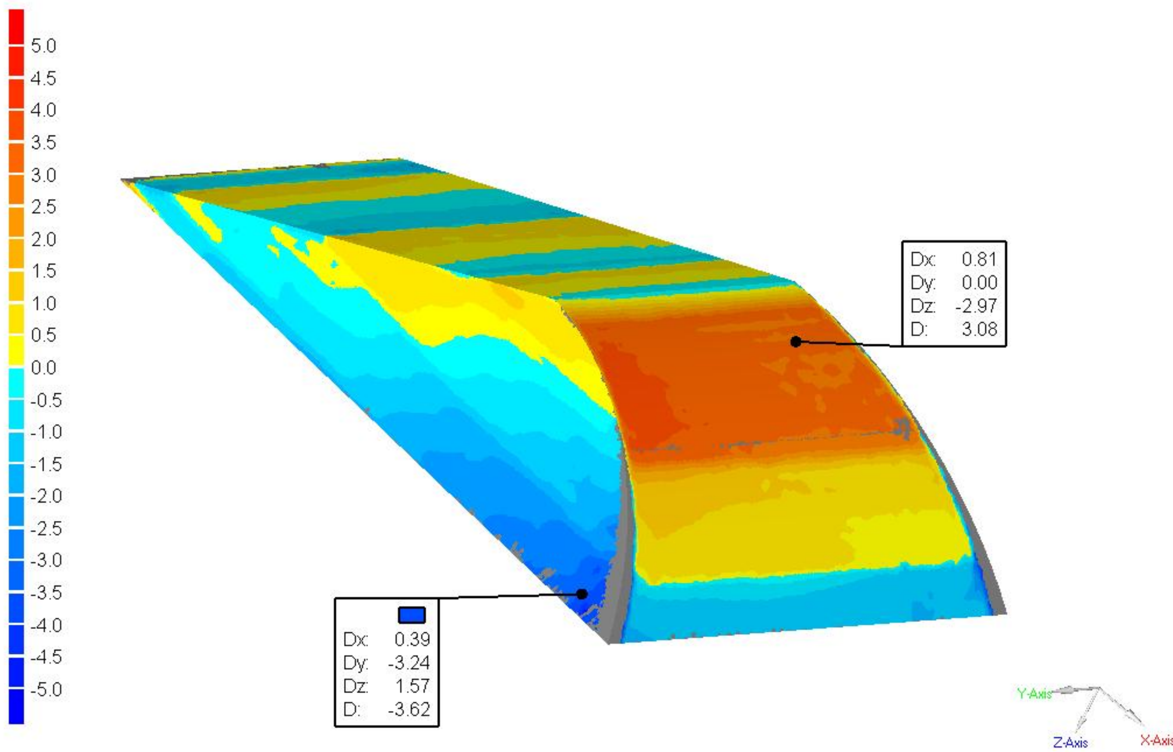


The software shows that the average distance between the part and the CAD file is 0.67 mm. As shown on the picture, the maximal deviation is around 5 mm.
This result can be explained by the fact that to remove the part from the mold, a high stress has been applied on the part. As a consequence, the part is deformed.

This picture shows that the highest deviation is in the corner of the fender. Indeed, this geometry was hard to manufacture because a two-parts mold was needed.

3 - Deviation of the small part

The small mold has been scanned with the FaroArm and the cloud data was compared with the nominal file with Geomagic.



This drawing shows the deviation between the cloud data of the mold (after gelcoat application) and the nominal CAD file. The software gives a maximal deviation of 4.2 mm and an average deviation of ±0.57 mm. These results are important for this kind of small part.
Grey areas on the part come from the fact that there was not enough point in the cloud data in these areas.

4 - Conclusion on the deviation

The accuracy of a paper-based mold is not really good. Parts of the fender have a deviation of around 5 mm. The thickness of the laminate (paper + adhesive) is inconstant and uncertain; as a consequence, parts always have a big deviation in the z direction.

Several tests have been done to measure the thickness of one layer of paper and adhesive. I manufactured 4 cubes of 20 layers of paper, and I found a thickness of 0.511 mm (see appendix 5). However, the thickness of adhesive can change with the quantity used, and the thickness of paper is influenced by a lot of parameter, like humidity.
The mass used to compress the mold is also very important.

C - Application ranges

Several molds were manufacture by means of the described process. Each mold was manufactured to determine certain properties of LOM molds.
Previous molds show that LOM process can be used for thin vinylester part, without post manufacturing. The goal of this part is to discuss of the different applications of the LOM process.

1 - Temperature limit

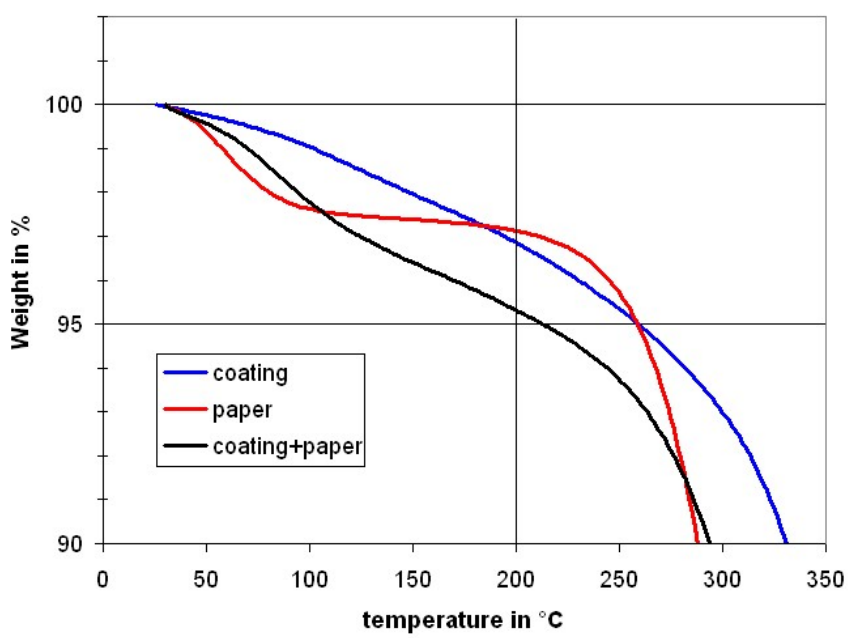
a. *Limit of the gelcoat*

Paper based molds are very sensitive to temperature and moisture. Applying a gelcoat reduce this problem and improve the surface quality.
The used coating is a vinylester tooling gelcoat from "Cook Composite and Polymer". Because vinylester is a polymeric plastic its elevated temperature behavior has to be research to determine the maximal usable temperature.

The coating shall be used below the glass transition temperature, to achieve constant behavior and protection. The coating was tested for its temperature behavior to predict the maximal usable temperature. The manufacturer of the gelcoat promised a maximal heat distortion temperature of 62ºC (144ºF) without post curing of the coating and a maximal heat distortion temperature of 88ºC (189ºF) with postcuring. In a DSC (Differential scanning calorimetry) measurement these values were proved.

b. *Limit of paper and adhesive*

The following figure shows the results of a measurement to determine the heat sustainability of the mold materials. A small piece of paper was placed in a DSC measurement device and the weight loss was measured while heating the specimens.



Besides, the coating and the paper with coating were tested. It can be seen that the paper shows weight loss in the beginning up to 100ºC. Thereafter the weight stays constant. The moisture in the paper causes the weight loss. This can be concluded from several references. Manufacturers heat their paper to 105ºC to reduce its moisture content. At about 230ºC the paper itself starts to lose weight. This indicates the starting vaporization process. The results of the measurement fit to the expected behavior of paper. The gelcoat was also tested in this DSC measurement. It starts loosing weight from the beginning of the heating process. At a temperature of 200ºC the gelcoat already lost about 4% of its weight and the weight lose rate increases with increasing temperature.

Adhesive has not been tested for its thermal behavior, but the manufacturer promised a maximal using temperature of 70ºC (160ºF).

As a conclusion, the process describe in this report can be use at room temperature and not over 70ºC. However, many composite parts need a postcuring, especially for epoxy resin.
In this case, new materials have to be found to improve the heat resistance of the mold. For example, the adhesive 3M 1357 Scotch-Grip tested before, has a maximal temperature of 120ºC (250ºF). But, using this kind of material will seriously increase the price of the mold. In the case of the fender, the price of the mold was around 510$ and with the high temperature adhesive the price would be around 1500$.
Furthermore, it is also possible to replace the paper by another material, for example a composite sheet. But, most of the low price composite sheets, such as a fiberglass and polyester composite, have a maximal using temperature of 60ºC and will tolerate temperatures to 120°C (250°F) for short periods of time (eg. postcuring). Prices for these kinds of panels are around 20$/m^2, instead of 0.6$/m^2 for paper.
Then, high temperature epoxy resin can be used at a temperature of 150ºC, but in this case, the price is around 60$/m^2 (polymer plastic corporation) and we are far from a low cost process.

2 - Dimensional limits of LOM mold

The limits of the mold are determined by the process itself and by the limits of the materials. Further on the properties of the paper and the adhesive influence the limits.

Very small features are not possible to manufacture because these feature would not withstand the stresses during the demolding. The maximal size of a part is determined by the size of the laser cutting system (1300 x 1700 mm) and handling of the part. Theoretical the maximal size is not limited. Objects like engine hoods can be assembled from several parts. Limits always result from the stability of the paper.
In general, the use of LOM for mold manufacturing is appropriate for mid-sized parts with low number of detailed features.

3 - Evaluation of durability

In order to evaluate the durability of LOM molds a small half sphere was manufactured. The durability test with this simple mold example shows that 10 demolding are possible. Considering simple non-complex shapes, the limiting factor is not the stability of the paper laminate but the quality of the tooling gelcoat. Failures appeared at the surface.
This test shows that it's possible to use the LOM process for a small production and not only for prototyping.
But this test has been made on a simple shape. In case of a complex shape, as well as the fender, LOM process can be used to manufacture a master mold. Therefore, the first part manufactured with the LOM mold can be used as a mold. In this case, the LOM mold can be destroyed after.

4 - Application ranges

Application range of a paper based LOM mold described in this report:

Paper based LOM mold	
Shape	Simple or complex (less durability)
Part dimension	Mid size (<1300 x 1700 mm)
Number of manufactured part	<10 without repairing the mold
Temperature range	0 - 70ºC

Nevertheless, it's possible to use different materials for high temperature applications or for many demoldings.
In this case, it's possible to use composite sheets made of fiberglass and polyester resin, and a high temperature adhesive. This plate is stiffener than paper sheets, and as a consequence, it's possible to decrease the bonding surface.

This table shows the price of the process for a square foot layer of adhesive and sheet.

Material	Max temperature (ºC)	Adhesive ($)	Sheet ($)	Total ($)
Paper + Hi strength 90	70	0.095	0.061	0.16
Composite + Scotch grip 1357	120	0.34	0.95	1.29

However, paper and composite sheets don't have the same thickness, as a consequence, it is important to compare the price of a volume of this laminate.

This table shows the price of the process for a one-foot cube of laminate.

Material	Number of layer (thickness mm)	Adhesive ($)	Sheet ($)	Total ($)
Paper + Hi strength 90	617 (0.4945 mm)	58.6	37.6	96.2
Composite + Scotch grip 1357	384 (0.7945 mm)	130.56	364.8	495.4

The price of high temperature mold is around five times higher than a paper based LOM mold. But composite sheets based LOM molds are stronger and have a better durability. As a consequence, more research is necessary to study and improve such a mold.

V - CONCLUSIONS

The use of LOM for complex shaped parts could be proven in this report. The number of producible parts largely depends on the complexity and the stability of the mold. Paper based LOM molds can be used for composite parts manufacturing. However, this process has a bad durability (depending of the shape's complexity), and a bad accuracy. Because of the paper, it's not possible to use this process for small production series. However the LOM process can be used to manufacture prototype, or to build a mastermold. This is probably the most appropriate application of a paper based LOM mold.
For high temperature applications, it's possible to replace paper by composite sheets. In this case, the strength of the mold is improved.

For the LOM process in the CCM, several improvements have to be done. For example, the LOMSEC program that draws the slice of the part has to be improved.

In general the process is able to manufacture very fast complex shaped molds. The stability of the mold largely depends on the complexity of the part.

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Fundamental of adhesion:
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Material property database:
http://www.matweb.com/

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http://www.cs.hut.fi/~ado/rp/rp.html

APPENDIX

APPENDIX 1: Calculation of the mechanicals properties of a laminate beam with the

Evolution of the mechanicals characteristics of a 20 layers laminated beam with the thickness of paper

Paper thickness	0.35	0.375	0.4	0.425	0.45	0.475	0.5	0.75	1	2
E_X	4257	4272	4286	4298	4309	4318	4327	4383	4412	4456
E_Y	1703	1709	1715	1719	1724	1728	1731	1753	1765	1782
E_Z	22.6	22.6	22.5	22.5	22.5	22.5	22.4	22.3	22.2	22.1
NU_{YZ}	0.07	0.06	0.06	0.06	0.06	0.06	0.05	0.04	0.04	0.03
NU_{XZ}	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.02	0.02
NU_{XY}	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
NU_{ZY}	9E-04	8E-04	8E-04	8E-04	7E-04	7E-04	7E-04	5E-04	5E-04	4E-04
NU_{ZX}	3E-04	2E-04	2E-04	2E-04	2E-04	2E-04	2E-04	1E-04	1E-04	8E-05
NU_{YX}	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
G_{YZ}	18.8	19.6	20.4	21.1	21.8	22.5	23.2	28.6	32.4	40.6
G_{XZ}	20.9	21.9	22.9	23.9	24.8	25.7	26.6	33.9	39.5	52.7
G_{XY}	1183	1187	1191	1194	1197	1200	1202	1218	1226	1238

Evolution of the mechanicals characteristics of a laminated beam with the number of layer (0.5 mm thick)

Number of layer	1	3	5	10	20	40	80
E_X	4500	4000.63	3857.96	3601.27	3601.14	3601.14	3601.14
E_Y	1800	1600.68	1543.74	1441.33	1441.23	1441.23	1441.23
E_Z	22	23.29	23.68	18.11	24.42	24.42	24.42
NU_{YZ}	0.21	0.12	0.14	0.13	0.19	0.19	0.19
NU_{XZ}	0.008	0.09	0.12	0.11	0.16	0.16	0.16
NU_{XY}	0.15	0.15	0.15	0.15	0.15	0.15	0.15
NU_{ZY}	1.84	0.002	0.002	0.002	0.003	0.003	0.003
NU_{ZX}	1.52	0.001	0.001	0.001	0.001	0.001	0.001
NU_{YX}	0.32	0.06	0.06	0.06	0.06	0.06	0.06
G_{YZ}	55	11.08	9.02	14.42	6.76	6.76	6.76
G_{XZ}	80	11.74	9.44	15.43	6.98	6.98	6.98
G_{XY}	1250	1111.28	1071.64	1000.73	1000.30	1000.30	1000.30

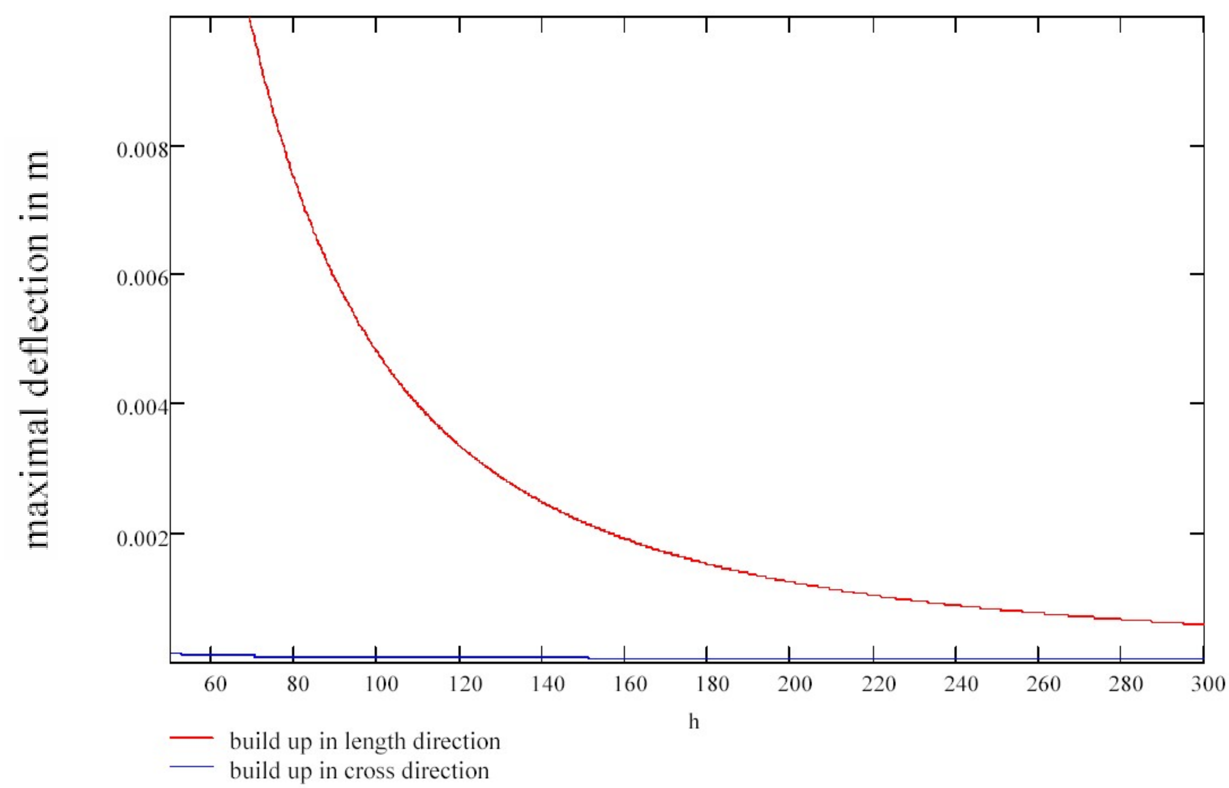
To calculate these data a Fortran-program “Lam3D” was used.

APPENDIX 2: Calculation of the deflection of a laminate beam with 20 layers of paper for three point bending.

$$U_b(x) = \frac{qL^4}{24EI}\left[\left(\frac{x}{L}\right)^4 - 2\left(\frac{x}{L}\right)^4 + \left(\frac{x}{L}\right)\right]$$

$$U_s(x) = \frac{3}{2}\frac{q}{G.A}\left[\frac{L}{2}x - \frac{x^2}{2}\right]$$

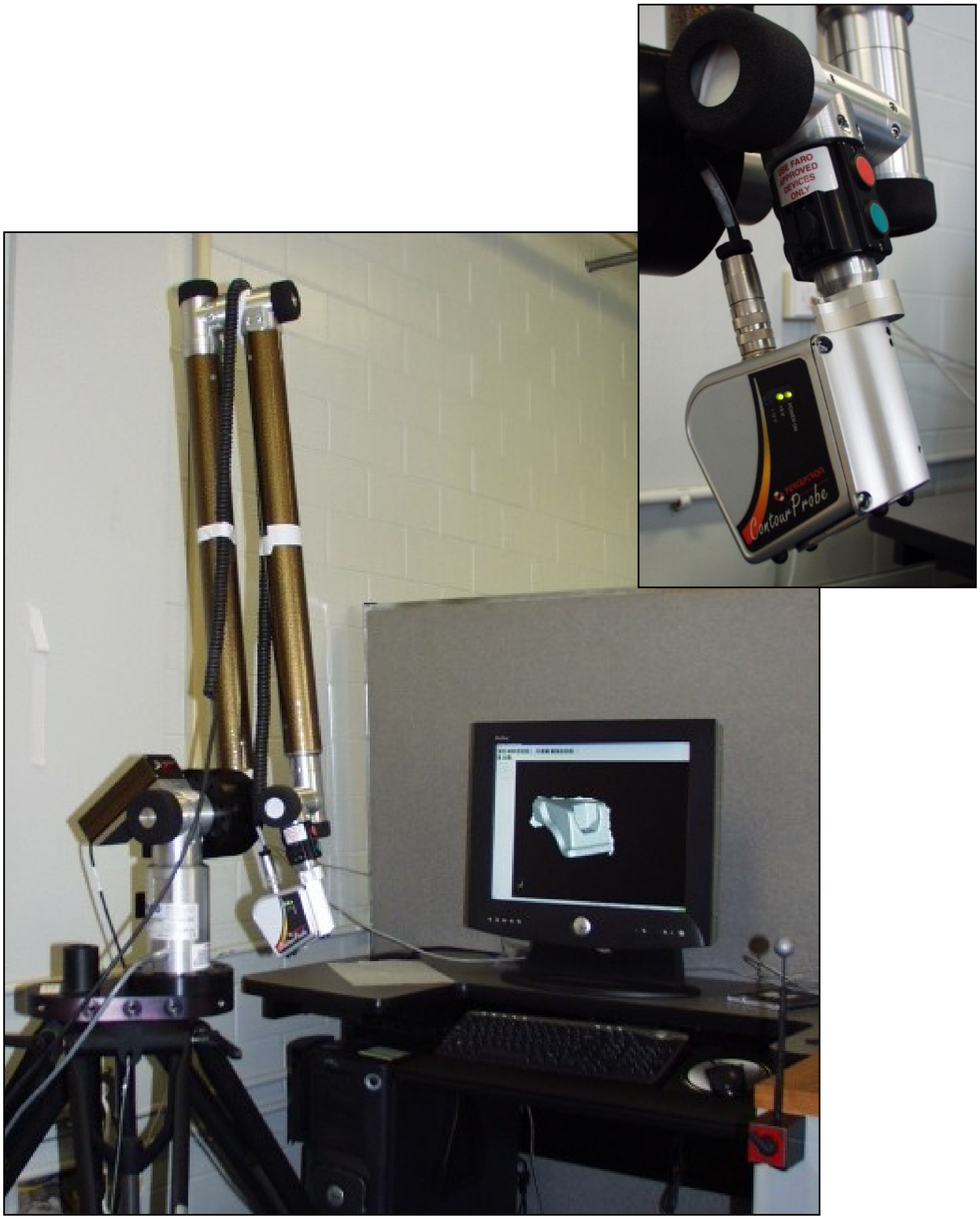
$$U_{MAX} = U\left(\frac{1}{2}\right) = U_b\left(\frac{1}{2}\right) + U_S\left(\frac{1}{2}\right)$$



Maximal deflection over thickness

APPENDIX 3: **Comparison between the original fender and the manufactured part.**

APPENDIX 4: The FaroArm and the Perceptron Laser.



APPENDIX 5: Measurement of the thickness of one layer of laminate (paper +adhesive)

Sample	Adhesive used	Number of layer	Thickness after adhesive application (mm)	Thickness of one layer (mm)
1	High strength 90	20	10.21	0.511
2	High strength 90	20	10.24	0.512
3	High strength 90	20	10.23	0.512
4	High strength 90	20	10.20	0.510

Parts have been compressed with a 3.5 kg mass.

APPENDIX 6: Assembling device