

Manufacturing of aerospace composite material parts using collaborative robots

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Master's Thesis

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Abstract

Throughout the last fifty years, since the introduction of composite systems, a number of industries such as aerospace, automotive, naval and military have been exploiting and investigating these materials due to their specific mechanical properties.

The serial production of composite components using pre-impregnated hand lay-up still faces many challenges. In order to overcome these challenges, alternatives with the aim of producing cost effective parts are being developed, such as Resin Transfer Moulding and Vacuum Assisted Resin Transfer Moulding, however these have not yet been widely adopted. Other more mature alternatives are currently implemented to increase productivity and consistency of manual pre-impregnated lay-up, for instance Automated Tape Laying and Automated Fibre Placement.

This thesis focuses on the automation of the current manufacturing system using a collaborative robot cell, replacing pre-impregnated hand lay-up technologies for mass production purposes. Allowing for higher production numbers and cutting cycle times, decreasing costs.

Three concept grippers are described as possible solutions to the implementation in conjunction with a collaborative robot. However, only one is chosen to be further developed due to being considered the most promising. An initial dimensioning of the components of the gripper is done, as well as the needed supporting elements. The operating procedure is also described in order to allow for a better understanding of its functioning.

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Acronyms

FEUP – Faculty of Engineering of the University of Porto

CAER – Caetano Aeronautic

CFRP – Carbon Fibre Reinforced Polymer

Prepreg – Pre-impregnated

ATL – Automated Tape Laying

AFP – Automated Fibre Placement

OoA – Out-of-Autoclave

RTM – Resin Transfer Moulding

VARTM – Vacuum Assisted Resin Transfer Moulding

Symbols

Normal Stress (σ) [MPa]

Shear Stress (τ) [MPa]

Displacement [mm]

von Mises yield criterion ($\sigma_{\text{von mises}}$) [MPa]

Length [m]

Width [m]

Young's modulus (E) [GPa]

Yield strength (σ_{ys}) [MPa]

Safety factor [SF]

Density [ρ] [kg/m^3]

Poisson's ratio (ν)

Pressure (P) [Pa]

Force (F) [N]

Area (A) [m^2]

Bending moment (M_f) [Nm]

Elastic section modulus (ω) [mm^3]

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1 Introduction

1.1 Project and motivation

The present work appears in the scope of a thesis, in the branch of Production, Conception and Manufacturing of the Master in Mechanical Engineering from the Faculty of Engineering of the University of Porto (FEUP).

This thesis was developed at Caetano Aeronautic S.A. (CAER) where the production process of Carbon Fibre Reinforced Polymer (CFRP) stiffeners is completely manual, due to the complexity of the desired part forms. In serial production, when compared to metal manufacturing, composites are accompanied by long cycle times and high costs. The objective of the project is to develop a practical automated manufacturing system, to be implemented in the production chain, and replace hand lay-up technologies for mass production purposes, thus allowing for higher production numbers and cutting cycle times, decreasing costs.

1.2 Salvador Caetano Group, S.A.



Figure 1 – Salvador Caetano Group head office (http://www.gruposalvadorcaetano.pt/html/grupo__q11__--_3DPT__q20__q30__q41__q5.htm)

“Sempre presente na construção do futuro” (“Always present to build the future”) - Mr. Salvador Fernando Caetano’s motto.

In 1946, Mr. Salvador Fernando Caetano started his activity by establishing “Martins, Caetano & Irmão, Lda”, which became the first coachbuilder in Portugal. We may consider this the beginning of the current Group.

In the year of 1966 that company became Salvador Caetano – Indústrias Metalúrgicas e Veículos de Transport, S.A.R.L.

Years later, an agreement was signed with Toyota Motor Sales and the company became an exclusive distributor of Toyota products in Portugal. By 1996, fifty years after its foundation, over 50 companies in varied sectors of activity had been newly created or acquired.

When, on the 27th of June 2011, Mr. Salvador Caetano passed away the Caetano Group had over 6800 employees and over 150 companies. The Group continues to widen its horizons, having a presence in countries such as Portugal, Spain, United Kingdom, Germany, Cape Verd, Angola, China, Mozambique, Kenya, Tanzania, Uganda, Zambia, Zimbabwe, Malawi, Mauritania, Mali, Niger and Senegal.(Fernandes, Cruz, & Cruz)

1.3 Caetano Aeronautic, S.A.

On August of 2012, Salvador Caetano Group signed an agreement with Airbus Defence and Space, with the presence of the Portuguese Government, which led to the creation of Caetano Aeronautic, S.A. This company is specialized in the manufacturing of both metallic and composite airframes and aims to provide for main aircraft manufacturers and Tier 1 suppliers.

The company started with 40 employees, though the estimate is that this number will grow to 250 in the following years.

In August of 2014, with the objective of insuring its growth, CAER signed an agreement with Aciturri to help improve responsiveness on both companies and reinforce their relation with Airbus and Embraer.

After three short years of operation, Caetano Aeronautic, S.A. has achieved some essential milestones, such as:

- Feb 2014 – Certification EN9100 in metals;
- Apr 2014 – CAER approved as OGMA supplier;
- Jul 2014 – Mechanical FAI approval – Aciturri;
- Feb 2015 – Renovation EN9100 in composites;
- Jun 2015 – Official inauguration;
- Jul 2015 – Certification in composites production – Airbus;
- Set 2015 – Audit EN9100 in composites;
- Nov 2015 – Accredited Nadcap.

(Rodrigues, 2015)

1.4 Thesis outline

The thesis is composed by five chapters.

In chapter one, the project and the motivation behind it are described, with the identification of the main objectives of the present work. This is followed by a brief introduction to the company.

In chapter two, a state of the art is presented regarding industrial robots, specifically the technology used in the fabrication of composite parts, Automated Tape Laying (ATL) and Automated Fibre Placement (AFP), along with a study of current collaborative robots.

In chapter three, a description of the current process steps for pre-impregnated (prepreg) hand lay-up at CAER is made and the problems found when envisioning the process being performed by a collaborative robot are identified.

In chapter four, the concept solutions are presented as well as a more in-depth study regarding the chosen solution, providing a description of the operating procedure as well as a dimensioning of various components needed.

In chapter five, the main conclusions of the study are given along with future work propositions.

2 State of the art

Throughout the last fifty years, since the introduction of composite systems, a number of industries such as aerospace, automotive, naval and military have been exploiting and investigating these materials due to their specific mechanical properties.

Particularly in the aerospace industry, composite systems have been used to replace metal alloys, resulting in aircrafts with better performance, weight and energy consumption. However, the manufacturing process using these materials, when compared to more conventional ones, is much more expensive as a result of being a mainly manual labour (very specialized and time-consuming process) and requiring a high capital investment (eg. for autoclave and cooled storage).(Croft, 2010; Grimshaw, Grant, & Diaz, 2001)

Many researchers have been motivated to consider an out-of-autoclave (OoA) alternative due to the limitations of traditional autoclave curing that include:

- Long cycle time;
- High pressure;
- High investment;
- Costly tooling;
- High footprint;
- High energy consumption.

Therefore, to overcome these challenges, alternatives with the aim of producing cost effective parts in a shorter processing time are being developed, such as Resin Transfer Moulding (RTM) and Vacuum Assisted Resin Transfer Moulding (VARTM). Although these have not yet been adopted by the composite manufacturing industry.(Canal, Benavente, Hausmann, & Michaud, 2015; HSIAO & HEIDER, 2012; Naik, Sirisha, & Inani, 2014; Schlimbach & Ogale, 2012; UDDIN, CAUTHEN, RAMOS, & VAIDYA, 2013)

In order to effectively allow for the production of a higher number of parts an automation of the production chain is required, resulting in a substantial cut in cycle time as well as a decrease in part cost. However, this can only be applied to the production of large parts due to their simple geometry, for which systems like ATL and AFP were created.

Regarding the production of small to medium sized components, no solution has yet been found and it still requires prepreg hand lay-up. To aid this process, collaborative robots are being researched looking to reduce challenges such as large amounts of waste and slow material deposition rates. (Angerer et al., 2010; Beakou, Cano, Le Cam, & Verney, 2011; Dirk, Ward, & Potter, 2012; Grimshaw et al., 2001)

2.1 Resin Transfer Moulding

The process can be separated into two main stages:

- In the first stage, the preforms are placed into a mould cavity. The mould is then closed, compacting the preform to the desired thickness.

- In the second stage, a pre-mixed resin is injected into the mould cavity, at a pressure higher than 2 MPa, infusing the fibres.

Once the part is cured, it is removed from the mould. The RTM process has some limitations that include the entrapment of air within the preform and improper infusing of the fibres.(Naik et al., 2014; Schlimbach & Ogale, 2012)

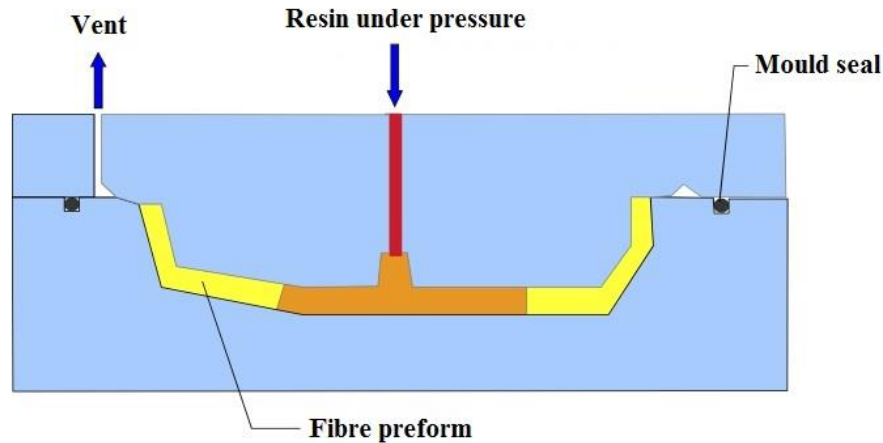


Figure 2 – Schematic of resin transfer moulding (<http://aerospaceengineeringblog.com/composite-manufacturing/>)

2.2 Vacuum Assisted Resin Transfer Moulding

VARTM was developed in order to overcome the limitations of RTM, resorting to the use of a vacuum system. In this process the upper half of a conventional mould is replaced by a vacuum bag, eliminating the need for precise metal mould making. Vacuum lines, connected to a vacuum pump, expel the air from the preform assembly and resin is allowed to flow into the preform. The injection pressures are low, in the order of 0,1 MPa, which result in little movement of the preform producing better quality parts.(Canal et al., 2015; HSIAO & HEIDER, 2012; Song, 2003; UDDIN et al., 2013)

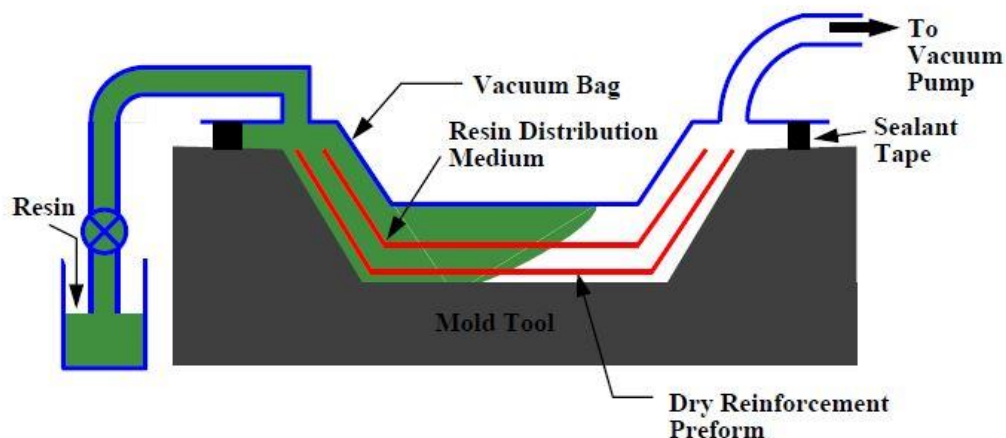


Figure 3 – Schematic of vacuum assisted resin transfer moulding (Song, 2003)

2.3 Industrial robots

With the need to increase productivity, quality and safety the concern with industrial robots rose in the beginning of the twentieth century.

It was after the Second World War, based on knowledge of Computer Numeric Control (CNC) machines, that George Devol and Joseph Engelberger started a company named Unimation Inc., which in turn was the first world industrial robot factory, and produced the first industrial robot seen in Figure 4.

Since then, industrial robots have come a long way, improving in many factors like actuators, sensors, transmissions, control algorithms and grippers. In the last decade, great progress has been made in terms of sensorial and visual capability, that combined with function dedicated grippers allows for better performance from the robots, seeing as they are able to obtain information about the work being done. (Carreira, 2012; Lopes, 2001/2002; Matthias et al., 2011; Olsen & Craig, 1993)

The structure of a robot may vary, but there are essential elements that constitute one:

- Main body - usually six axis of freedom;
- Power unit - provides power to the actuators;
- Controller - controls the movement of the main body and gripper;
- Gripper - designed to interact with the environment;
- Sensors - provide information to the controller (position, speed, acceleration, force feedback or visual);



Figure 4 – First industrial robot (<http://robotssystem.ir/en/history/history/index.htm>)

There are many factors to take into consideration when referring of industrial robots, such as:

Table 1 – Characteristics of industrial robots(Carreira, 2012; Lopes, 2001/2002)

Manners of mounting the main body	Fixed – Where the main body is either on the ground (free standing), on the wall or on the ceiling;
	Mobile – Where the main body is mounted on a rail also on the ground, on the wall or on the ceiling
Configurations of the main body	Vertically articulated;
	Cartesian
	SCARA
	Cylindrical
	Polar
Sensors	Delta
	Velocity
	Acceleration
Actuators	Force and torque
	Pneumatic
	Hydraulic
	Electric

2.4 Automated Tape Laying

In favour to improve productivity and consistency of manual lay-up, ATL systems were developed in the late 1960s. The method of laminating composite tape onto a rotatable base using CNC was first patented in 1971 by Chitwood and Howeth.

In 1974, an automated system capable of delivering 75mm wide tape over a curved surface where the head was able to rotate and withhold material, allowing for greater part complexity, was depicted by Goldsworthy.

Lay-up speeds were given to be 10-20 m/min, which did not affect overall productivity. But above all, ATL reduced errors and by so material wastage, resulting in greater material utilization.

The early 1980s were a time of rapid development of this technology, enabling it to become more widespread and converting it into a more generic process. A lay-up system with a lightweight head that dispensed composite tape, in a similar way to the first patent by Chitwood and Howeth, addressed the issue of higher lay-up speeds, allowing for up to 60m/min.

The basis for all modern commercial single-phase ATL systems was introduced in 1986 by Meier, where direct lay-up force control and head normality over curved surfaces was enabled using tracking system with force-controlled axis.

In the 1990s tape heating was implemented to overcome issues during the production of higher complex parts.

Configuration

Automated tape layers are machines with up to ten axis of movement, configured specifically for plane or somewhat contoured applications. A classic machine, which can be seen in Figure 5, consists of parallel rails, a cross-feed bar that moves on precision ground ways, a ram bar that raises and lowers the material delivery head, and the material delivery head shown in Figure 6.



Figure 5 – ATL configuration (<http://australianaviation.com.au/2010/09/airbus-flight-tests-a350-composite-panel/>)



Figure 6 – ATL material delivery head (<http://www.mmsonline.com/news/coriolis-composites-enters-long-term-partnership-with-dutch-tprc>)

Process description

The process can be considered as a form of additive manufacturing, once the part is built up by addition of material. The head handles the prepreg tape spools, usually 75, 150 and 300 mm wide. In essence the system is a CNC machine that follows predefined paths accurately and repetitively, placing each ply next to one other with a slight gap of 0.5-1 mm, to allow for variations in placement and tape tolerances. At the end of each ply, the head cuts the tape automatically and repeats this process until the part is complete.

Advantages

- Fast rate of material deposition;
- Does not depend on an operator;
- Less labour intensive;
- Less waste of materials;
- Repeatability of results;
- Can handle large structures with ease.

Disadvantages

- High capital cost;
- Relatively new technology;
- Laps and gaps issues;
- Distortion in thermoplastic composite processing.

(Croft, 2010; Dirk et al., 2012; Grimshaw et al., 2001)

2.5 Automated Fibre Placement

AFP first concept was presented in the 1974 patent by Goldsworthy, where he stressed the challenge of conforming tape onto a curved surface. To resolve this problem, the head would be able to split the tape into 3.2mm strips and lay-up them at distinct speeds.

The technology was commercially introduced in the end of the 1980s, with strips of tape being kept in separate tows and independently driven.

Configuration

The current configuration of AFP is very similar to that of ATL, differing only in material form and supply to the lay-up head, presented in Figure 7.



Figure 7 – AFP material delivery head(Jeffries, 2013)

Process description

Unlike the ATL process, AFP systems use tows of material with typical widths of 3.2, 6.4 and 12.7 mm. At the moment, depending on the head configuration, up to 32 tows can be used. Each tow is fed individually by the guide, and can be cut and restarted separately during manufacturing. As a result, each tow can be fed at different speeds, allowing for lay-up over complex geometries.

Advantages

- Allows for steering of fibres;
- More suited for contoured surfaces;
- Less waste of materials;
- Can handle large structures with ease;
- Greater component complexity.

Disadvantages

- Does not reach the same deposition rates as ATL
- High capital cost;
- Relatively new technology;
- Laps and gaps issues;

(August, Ostrander, Michasiow, & Hauber, 2014; Croft, 2010; Dirk et al., 2012; Grimshaw et al., 2001)

2.6 Collaborative robots

In the last decade a growth in the interest of bringing humans and robots closer together in the manufacturing environment could be witnessed. To address this demand, an industrial robot capable of working in collaboration with a worker was developed, to enhance his productivity and reduce stress load from exhaustion. Thus originating a new category of industrial robots named collaborative robots.

The collaborative robots must be harmless to the worker in all situations, requiring no separating safeguards, thanks to the safety features implemented in them. To prevent injury to humans, these robots have integrated sensors, passive compliance or overcurrent detection, which when triggered will stop its movement.

Some also have easy programing, where the robot can learn by hand-guiding, without requiring the need for complex programming methods, and allowing the worker to simply teach points, orientations and paths by demonstration.

Table 2 – Collaborative robots applications and key features(ROBOTIQ, 2015a)

	Key Features	Applications
ABB - YuMI	Padded dual arms	Small part assembly
	Lightweight and easy to mount	Toy industry
	Agile motion	Watch industry
	Dual arm	
ABB - Roberta	Lightweight	Inspection
	Good payload to structural weight ratio	Mobile platforms human-machine interaction
Bionic Robotics – BioRob	Low deadweight	Palletizing
	Compliant drivetrain	Machine tending
	Low energy consumption	Product testing
	Learn by hand-guiding	Laboratory automation
BOSCH – APAS	Protective leather coat	Machine Tending
	Security perimeter that reduces speed	Pick and place
	Integrated vision system	Process Application
	Mobile platform	Assembly
		Packaging
Fanuc – CR-35iA	High payload and reach	Automotive
	Compliant soft rubber skin	Packaging Distribution
	Compatible with Fanuc software and sensors	Metalworking
F&P Personal Robotics – Prob 1R	Soft cover	Quality Control
	Force limited	Assembly
	Learn by hand-guiding	Service Robotic
		Health care
Kawada Industries - NEXTAGE	High precision 3D vision system	Pick and place
	15 axes of freedom	Assembly
	Low power motors	Process Application
	Safety systems for close work environment	
	Dual arm	
KUKA - IIWA	Lightweight	Machine Tending
	Collision detection system	Pick and place
		Process Application
		Assembly
		Packaging

MABI – Speedy 10	Lightweight	Machine Feeding
	High precision positioning	Handling
	Intuitive graphical user interface	Assembly
Precise Automation – PAVP6	Lightweight	Tabletop Applications
	Learn by hand-guiding	
	Embedded controller	
Rethink Robotics – Sawyer	More rigid system	Machine Tending
	More accurate	Circuit Board Testing
	Camera with wide field of view	Material Handling
Rethink Robotics – Baxter	Learn by hand-guiding	Pick and place
	Automatically adjust to changes	Case Packing
	Mobile platform	Kitting
	Dual arm	Process Application
		Packaging
Universal Robots – UR5 & UR10	Learn by hand-guiding	Machine Tending
	Collision detection system	Pick and place
		Process Application
		Assembly
		Packaging

Table 3 – Collaborative robots specifications

	Number of axis	Payload (kg)	Reach (mm)	Weight (kg)	Accuracy (mm)	Speed (m/s)	Starting price (€)
ABB - YuMI	7 (per arm)	0,5 (per arm)	500	38	0,02	1,5	35 000
ABB - Roberta	6	8	800	19,5	0,1	-	28 000 – 33 000
Bionic Robotics – BioRob	4-5	0,8-0,5	956	6	0,2	1,3	29 000
BOSCH – APAS	6	2	911	230	0,5	0,5	-
Fanuc – CR-35iA	6	35	1813	990	0,08	0,75	70 000
F&P Personal Robotics – Prob 1R	6	1,5	771	16	0,1	-	-
Kawada Industries - NEXTAG	6 (per arm)	1,5	-	130	0,03	-	-
KUKA - IIWA	7	7-14	911-931	22,3-29,5	0,1	-	-
MABI – Speedy 10	6	10	1384,5	28	0,1	-	-
Precise Automation – PAVP6	6	2	432	28	-	-	-
Rethink Robotics – Sawyer	7	4	1260	19	0,1	-	25 000
Rethink Robotics – Baxter	7 (per arm)	2,2	1210	75	0,5	1	22 000
Universal Robots – UR5 & UR10	6	5-10	850-1300	18,4-28,9	0,1	1	30 000 - 40 000

2.7 Grippers

The task of grasping and holding a material may appear very simple to a human, however it can be extremely complicated for a robot, requiring the need to establish a secure, robust and reliable gripping.

Numerous principles have been researched over the last decades, depending on various conditions that influence the effectiveness of the gripper, such as:

- Geometry;
- Material type;
- Thickness;
- Rigidity;
- Elasticity;
- Weight;
- Friction;
- Adhesive.

The most widespread are mechanical grippers usually based on friction or form closure. These require either hydraulic, electric or pneumatic drive systems to control the gripper fingers. In order to grasp objects of various geometries, different grippers are used:

(Fantoni et al., 2014; Koustoumpardis & Aspragathos, 2004)

- Regular geometry – dual or more parallel fingered grippers, allowing for full contact with the object and higher friction force, thus providing a stronger grip.

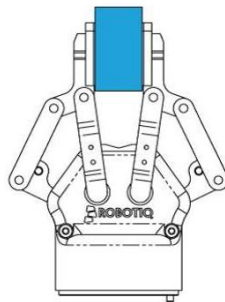


Figure 8 – Parallel gripper(ROBOTIQ, 2015b)

- Cylindrical geometry - dual or more encompassing fingered grippers, surrounding the object creating more contact points.

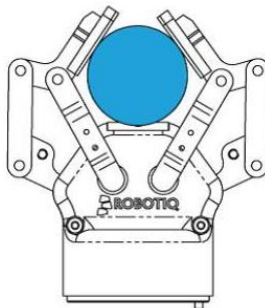


Figure 9 – Encompassing gripper(ROBOTIQ, 2015b)

Regarding the handling of irregular geometry objects, recent years have shown different approaches which, unlike most grippers, use soft and flexible materials that conform to the shape of the object:

- Gripper based on the jamming of granular material - results from the fact that loose grains are free to move inside an elastic bag, deforming around an object

and then harden, due to the increase of particle confinement, when applying a vacuum.(Amend Jr, Brown, Rodenberg, Jaeger, & Lipson, 2012; Brown et al., 2010)

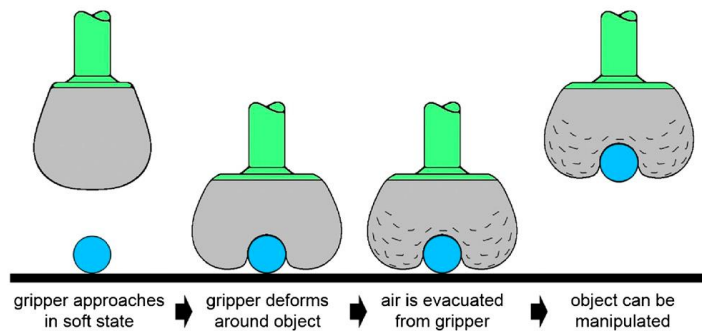


Figure 10 – Schematic of operation of gripper based on the jamming of granular material(Brown et al., 2010)

- Dielectric elastomer minimum energy structures - a prestretched dielectric elastomer membrane bonded with an inextensible but flexible frame, that when voltage is applied changes the equilibrium state resulting in bending actuation and creation of complex forms.(Araromi et al., 2015)



Figure 11 – States of dielectric elastomer minimum energy structures(Araromi et al., 2015)

The manipulation of materials similar to fabrics is an action that only a few dedicated and conventional system can reproduce, requiring a complex and time consuming configuration.

The research into grippers for handling non-rigid materials began in the 1980s, and resulted on the development of grippers based mainly on mechanical principals. During the 1990s, the behaviour of fabric was taken into consideration, and new approached centred on artificial intelligence were investigated.

The approach to handling fabrics can be divided into three main categories:

(Brown et al., 2010; Do, Paton, Herszberg, & John; Fantoni et al., 2014; Koustoumpardis & Aspragathos, 2004)

Mechanical

- **Clamp**

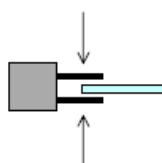


Figure 12 – Clamp gripper(Koustoumpardis & Aspragathos, 2004)

Clamping grippers functioning is based on the normal force between the section of the gripper in contact and the material. By varying the jaw distance between the points of contact, the gripper is able to handle a wide range of sizes. Nevertheless, for these to work, the edge must be approachable.

- **Pinch**

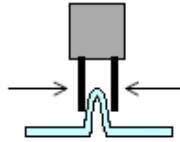


Figure 13 – Pinch gripper(Koustoumpardis & Aspragathos, 2004)

On pinching grippers, the jaws are moved onto the material and then closed, forcing the fabric to be clasped between. These are very efficient although they make the task of placing without forming creases very difficult.

- **Pins/Needles**

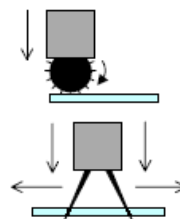


Figure 14 – Pins/Needles gripper(Koustoumpardis & Aspragathos, 2004)

These grippers offer a very accurate positioning, at the cost of damaging the material, by piercing the fabric at an angle.

Pneumatic

- **Vacuum**



Figure 15 – Vacuum gripper(Koustoumpardis & Aspragathos, 2004)

Once contact between the gripper and the material has been guaranteed, the air is removed creating a vacuum, allowing for a secure grasping.

- **Air-flow**

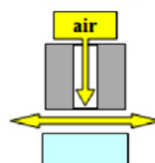


Figure 16 – Air-flow gripper(Koustoumpardis & Aspragathos, 2004)

Air-flow grippers, apply an air-flow between the gripper and the material creating lift.

Adhesive

- **Glue**

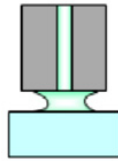


Figure 17 – Glue gripper(Koustoumpardis & Aspragathos, 2004)

The grasping is done by a bonding agent applied on the gripper that, when in contact to the material, creates a binding. These usually affect the quality of the material by leaving part of the bonding agent on the material.

- **Cryo-freezing**

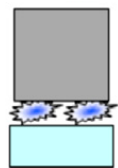


Figure 18 – Cryo-freezing gripper(Fantoni et al., 2014)

These grippers deposit a small amount of liquid on the surface of the material and then freeze it, resulting in ice that produces the required force.

- **Electrostatic**

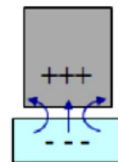


Figure 19 – Electrostatic gripper(Fantoni et al., 2014)

Electrostatic grippers are based on the attraction caused by a charge difference between the gripper and the material.

3 Process and problem

3.1 Process

To ensure that the components produced meet structural quality requirements, the manufacturing process must be well understood and controlled. This process has several essential steps.

Mould preparation

Previous to the manufacturing stage of a component, the mould has to be extensively cleaned of any dirt, dust or residual substances from the previous manufacturing of parts as seen in Figure 20. This is done with the assistance of clean rags with a solvent like acetone and if needed Scotch-Brite (A or S). When cleaned the release agent, FREKOTE, is applied ensuring a uniform layer.

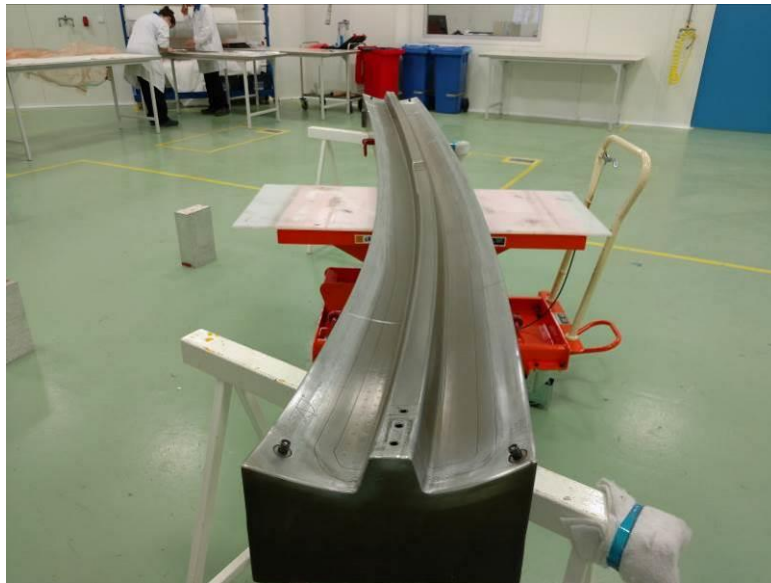


Figure 20 – Part mould

Material preparation

The prepreg material must be stored at temperatures below -18°C , to avoid curing of the resin and maintain material integrity, prolonging its shelf life. Prior to cutting, the prepreg rolls must be removed and allowed to de-freeze in a controlled manner, assuring that no condensation is formed. This is usually done by allowing the fully wrapped and sealed roll to reach room temperature before unwrapping it.

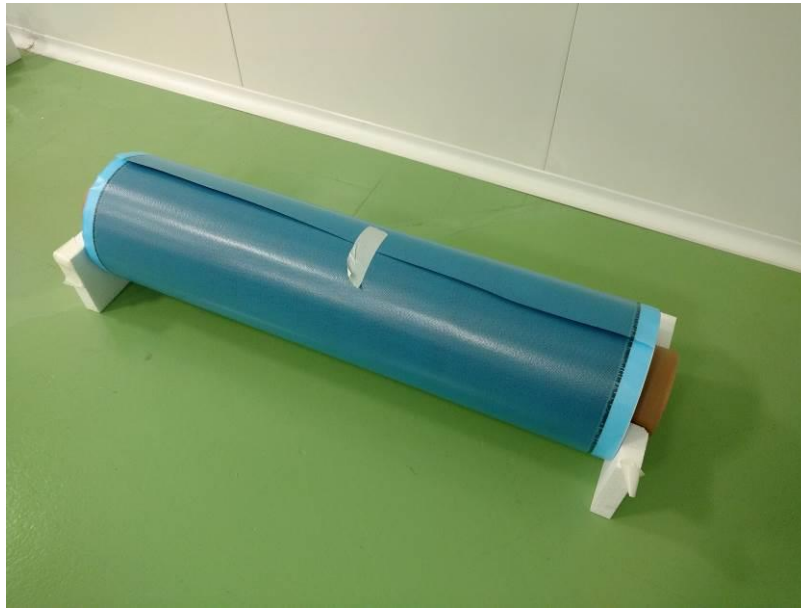


Figure 21 – Prepreg material after de-freezing

Cutting

Once the material has reached room temperature, it is cut into shaped plies, using a computer-controlled cutting table seen in Figure 22, to optimise fabric utilisation. The plies are then labelled to ensure that they are used in the correct sequence, and organized accordingly as shown in Figure 23.

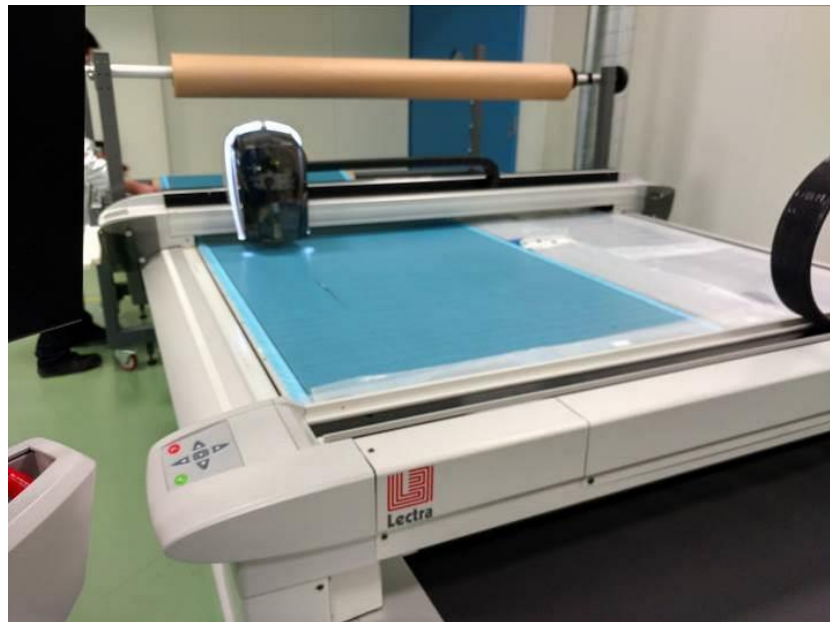


Figure 22 – Automatic cutting table

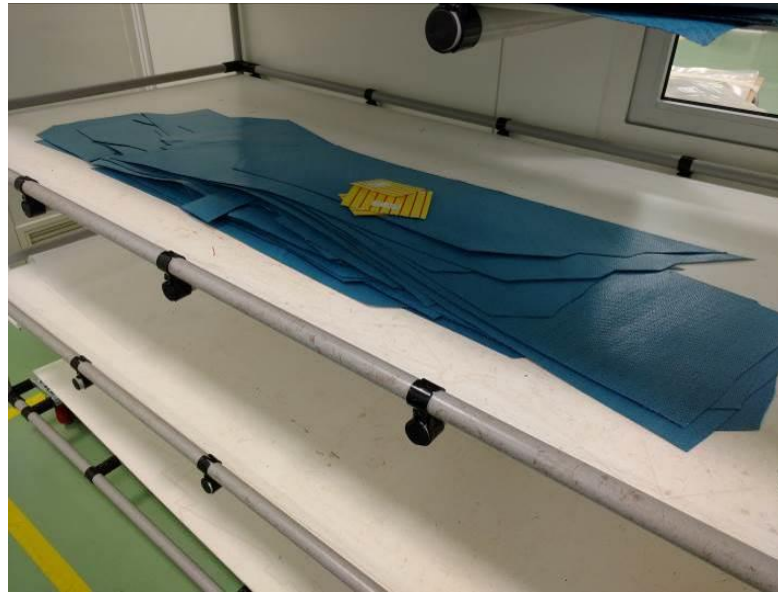


Figure 23 – Organized plies

Prepreg hand lay-up

Before the hand lay-up can begin the protective release films must be removed from the prepreg. Afterwards the ply can be positioned, with the aid of a laser system that projects the ply outline onto the mould to ensure the required accuracy for each lay-up step.

It is important that each ply is joined as tightly as possible in order to avoid large air inclusions and ensure an accurate geometry. Hand lay-up also allows for greater part complexity.

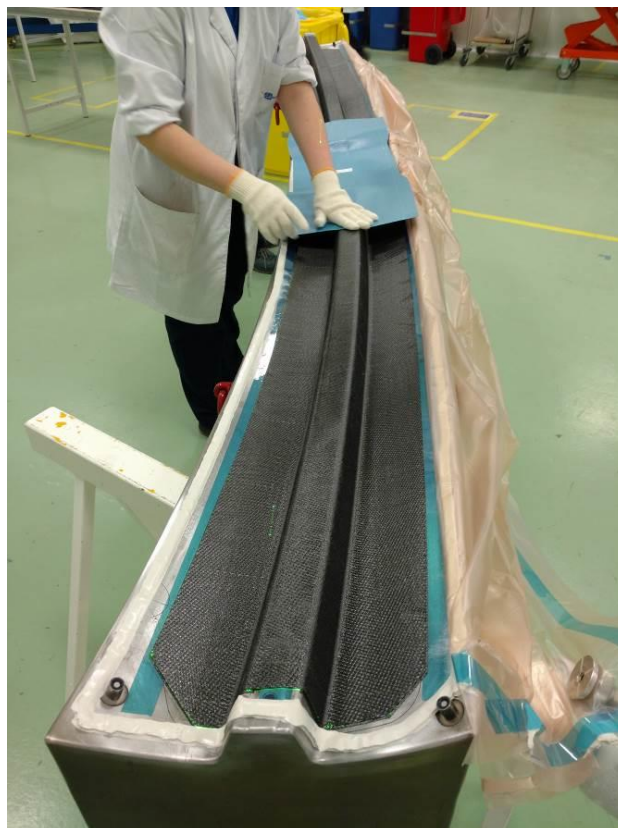


Figure 24 –Prepreg hand lay-up

Intermediate compaction

To prevent defects caused by excessive air inclusions it is essential to perform compaction regularly. To this effect a temporary vacuum bag is applied with pressures presented in Table 4:

Table 4 –Vacuum compaction pressures

With core	76 - 150 mmHg 10 132,5 - 19 998,355 Pa
Without core	530 - 610 mmHg 70 660,855 – 81 326,645 Pa

Final compaction

Once the lay-up is complete, a final vacuum bag is applied, shown in a representation on Figure 25. A typical vacuum bag is made-up of several elements:

- Vacuum bag;
- Vacuum inlet valve;
- Sealant tape;
- Breather;
- Perforated release film;
- Prepreg.

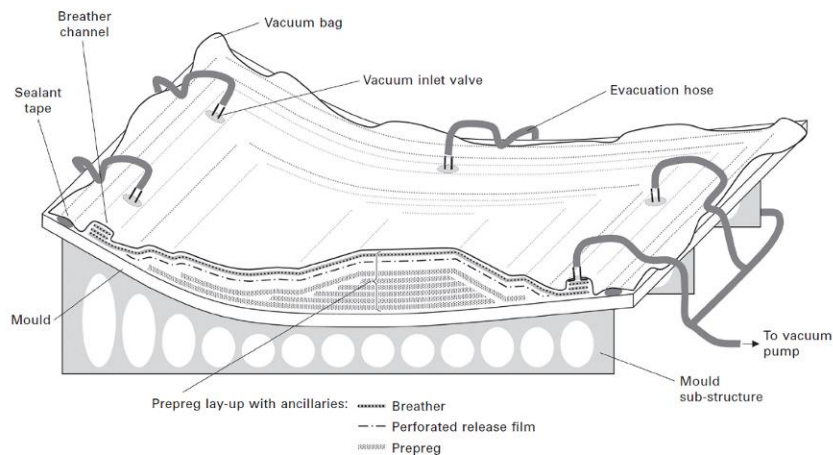


Figure 25 – Vacuum set-up (PanSart & Lloyd, 2013)

An airtightness test is conducted on the entire set-up to ensure the integrity of the seal, before the curing process, by monitoring the rise in pressure through a pressure gauge. If a variation is detected, this indicates a leak that has to be repaired. A new vacuum bag is applied if a repair is not possible.

Cure cycle

To cure the prepreg, the complete assembly is placed in a computer-controlled autoclave which applies a cure cycle designed and programmed to control two parameters, temperature and pressure.

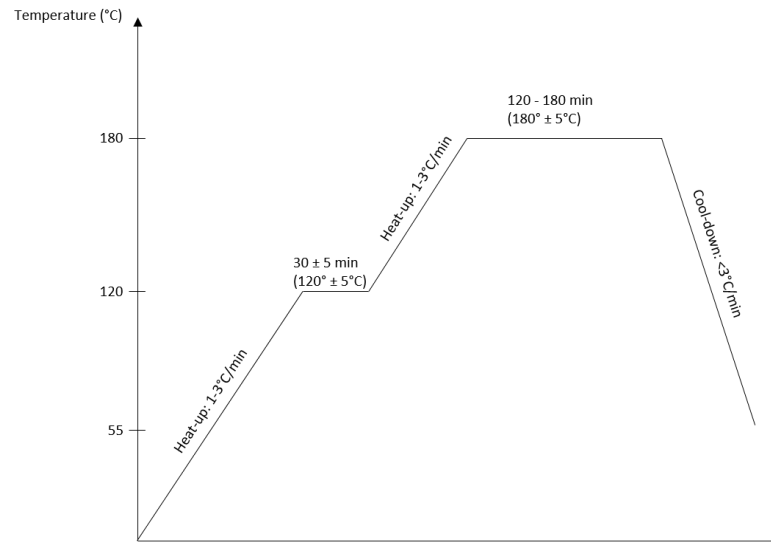


Figure 26 – Cure cycle example

3.2 Problem

The process described above is the basis for the work developed during the time at CAER and the proposed solution in this thesis, which is to implement a collaborative robot cell to obtain CFRP stiffeners. To this end, already qualified materials for mass production purposes should be used in a cost effective way.

As already mentioned, the production process of small to medium size parts presents numerous challenges for an automation technology to which there is still no mature solution available. Of particular interest is the handling, placing into a three-dimensional geometry and compacting the carbon fibre and each step poses different difficulties:

1. Handling, where gripping the ply off the table and transporting has to ensure that it isn't damaged or doesn't fall;
2. Placing, the ply must be placed into the three-dimensional geometry without forming creases;
3. Compacting, in this stage all air inclusions must be removed.

The part chosen to be studied has the following geometry and dimensions shown in Figure 27.

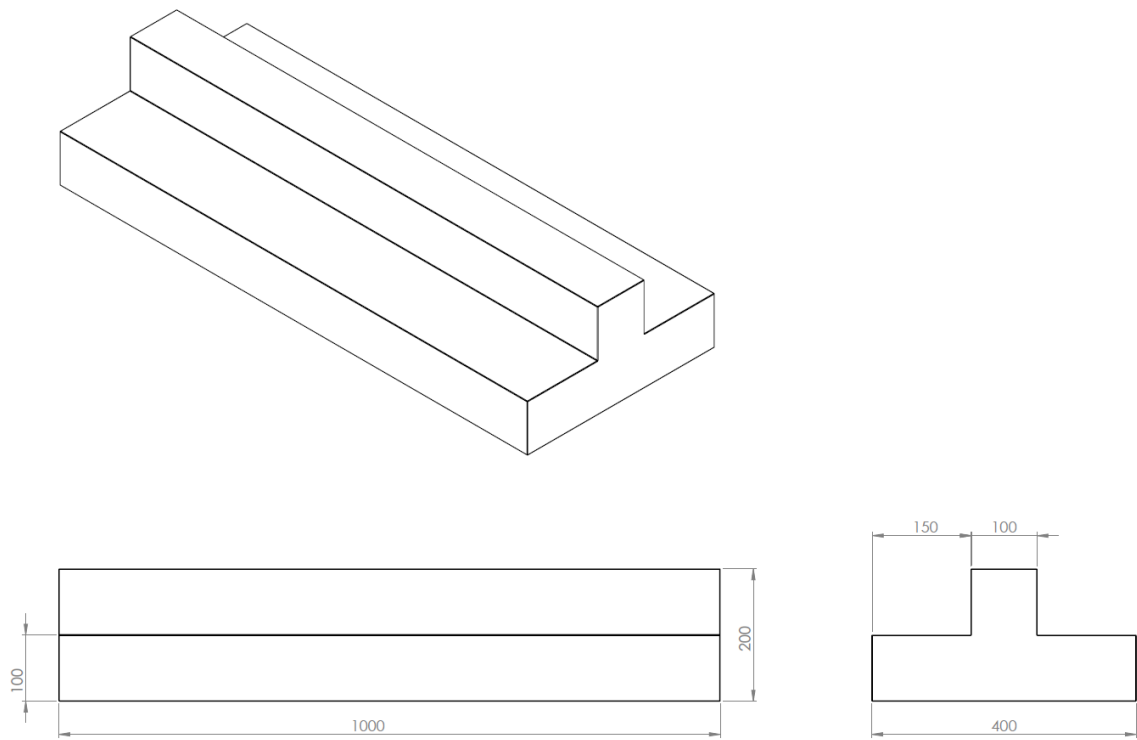


Figure 27 – Part dimensions

4 Concept solution

A replication of the human hand was suggested in an early stage however it quickly became obvious that the hand movement would be very difficult to duplicate and also bring other complications to the study:

- Introduce a higher level of complexity and programing;
- Replicate the same mistakes as the operator;
- Not capable of tensioning the complete ply.

To shorten the technological gap between manual prepreg lay-up and high volume production line, along with resolving the described challenges, a new flexible handling gripper should be developed, since the existing solutions are not capable of answering the current demands.

This gripper should also be implemented with a collaborative robot, which is very flexible and program free, allowing for an automated process with similar results as a manual process and fast deployment.

In order to resolve the aforementioned questions, this thesis introduces and discusses different solutions, and finally focussing on the believed to be the best concept design.

Three concepts where initially modelled and thought, each based in the vacuum principal to grip and handle the plies. The approach to which they used this system where different.

First concept - Vacuum valve grid gripper

In a first approach the vacuum principal was used in a more traditional way, with suction valves to allow for the pick and place operation as presented in Figure 28. The suction valves would be able to be controlled independently, with motor control for each valve, allowing for high mould adaptability. The modular fabrication would also permit for an easy change of component in case of failure.

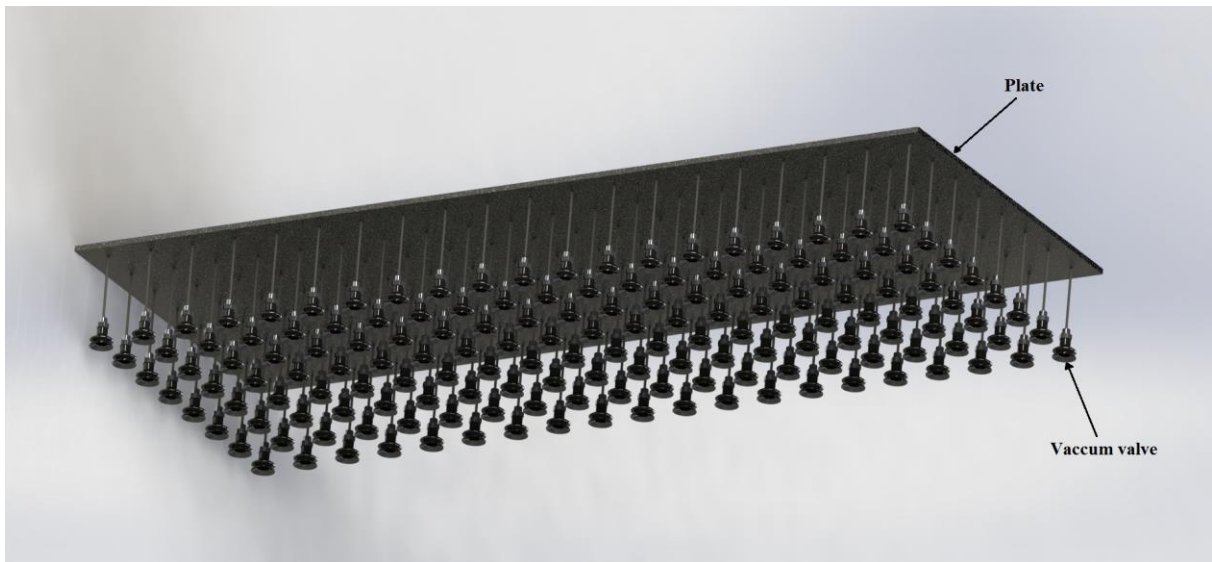


Figure 28 – Vacuum valve grid gripper concept

This model was discarded for two main reasons:

- The modularity of the system introduces a higher level of complexity.
- It would not be able to accomplish the compaction stage uniformly along the ply originating creases.

Second concept - Foam core gripper

In the second concept, the complex valve system was substituted for a semi permeable and shape compliant foam core as shown in Figure 29. This model would be able to pick and place the plies and compact them when pressed against the mould.

However, the fact that the foam core is not able to adapt its geometry without contact with the mould constitutes a problem, due to being unable to control its movement and apply pressure evenly, originating creases.

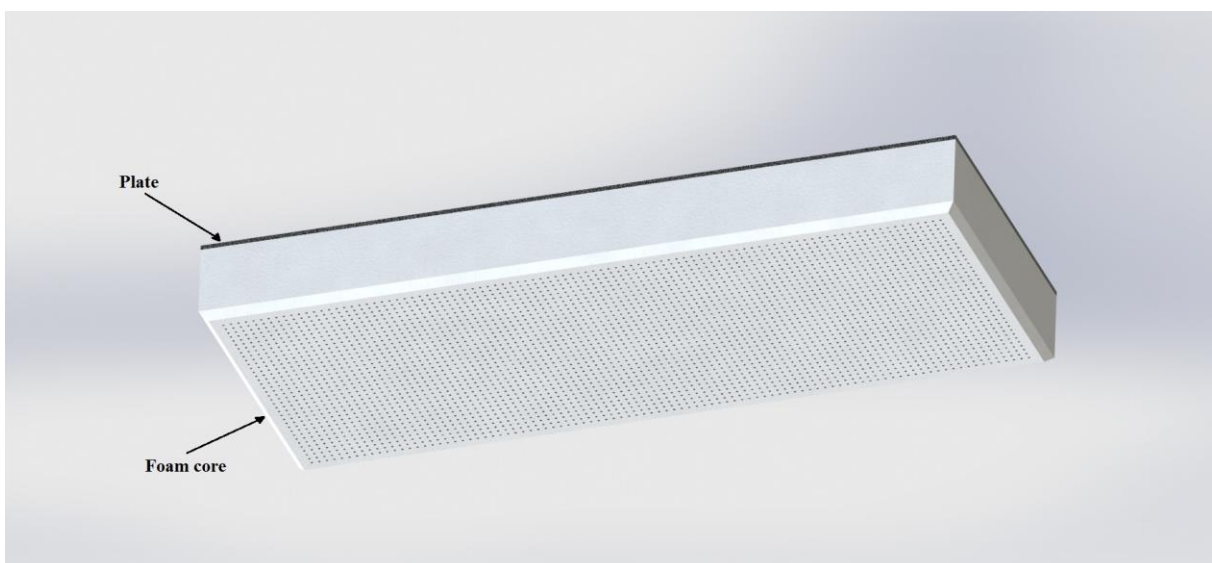


Figure 29 – Foam core gripper concept

Third and final concept - Expandable element gripper of variable geometry

The final concept was the chosen to be further studied, and consists of an expandable element of variable geometry with embedded vacuum structure shown in Figure 30, theoretically capable of performing two actions, pick and place and compaction, without having to change the tool, something very uncommon.

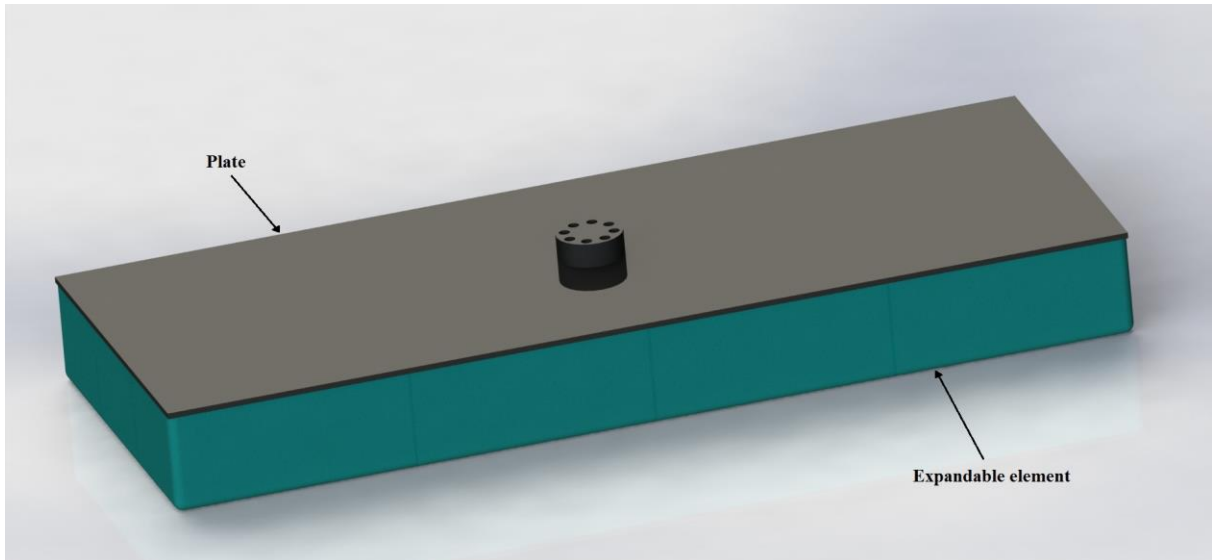


Figure 30 - Expandable element gripper concept

In order to be able to perform the two actions, the expandable element, presented in Figure 31, was designed with vacuum tubes in its interior that allow for the pick and place of a ply and separate interior chambers that, when positioned correctly, inflate compacting the ply against the mould.

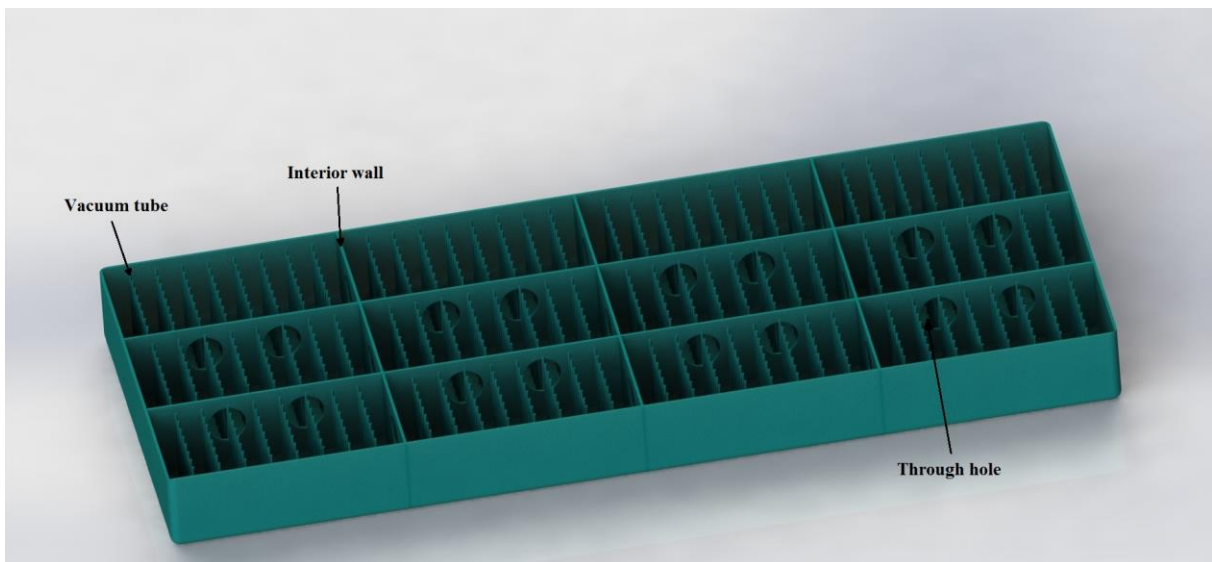


Figure 31 – Expandable element gripper concept interior

The objective of the sectioned interior is to allow for a controlled inflation, according to the geometry of the mould. A through hole has been designed in the interior walls to allow these sections not to be completely independent of each other, to avoid the creation of creases in the fabric.

The gripper is composed of two main parts:

- Plate, which creates a joint between the robot and the expandable element;
- Expandable element.

Expandable element

The material chosen to fabricate the expanding element would have to withstand the maximum pressure of 81 326,645 Pa reached during the compaction stage of the process, as already mentioned in a previous section.

Another property of great importance is the capability of high expansion, minimum of 400%, demanded in order to be able to conform to any geometry required.

To answer these requirements, the material chosen was silicone, which has good mechanical properties for this purpose.

Consulting the Trellerborg manual, for silicone blanket, the main properties to be taken into account are tensile strength (9MPa) and elongation at break (800%) which are considered to be enough.

Plate

In order to determine the thickness of the plate a program was used, developed in Matlab for the discipline Finite Elements Method, with the purpose of determining four nodes quadrangular finite element plate based on the first order shear deformation theory. Using the various properties of the material in this case steel, shown in Table 5. As well as the length and width, the program is able to calculate, as shown through Figure 33 to Figure 44, the deformation, normal stress and shear stress.

Using the obtain results, the von Mises yield criterion can be applied by means of the equation 4.1 so that the condition shown in equation 4.2 can be verified.

In the program a mesh of 45 by 45 elements was defined, as well as boundary conditions which where establish as fixed on all sides and a safety factor of 1,5 was chosen. For steel, the safety factor used is normally between 1,5 and 2.

Table 5 – Plate dimensions and steel mechanical properties

Length [m]	1
Width [m]	0,4
Young's modulus (E) [GPa]	200
Yield strength (σ_{ys}) [MPa]	355
Safety factor [SF]	1,5
Density [ρ] [kg/m ³]	7800
Poisson's ratio (ν)	0,3

Applying:

$$\sigma_{\text{von mises}} = (\sigma_x^2 - \sigma_x * \sigma_y + \sigma_y^2 + 3 * \tau^2)^{(1/2)} \quad (4.1)$$

The calculations must satisfy the following condition:

$$-\sigma_{\text{von mises}} + \sigma_{ys} / \text{Safety factor} > 0 \quad (4.2)$$



Figure 32 – Plate point identification

Thickness 5 mm

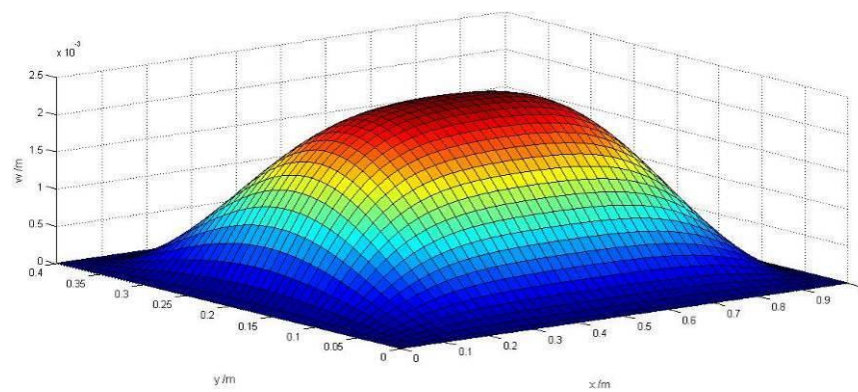


Figure 33 – Displacement 5mm

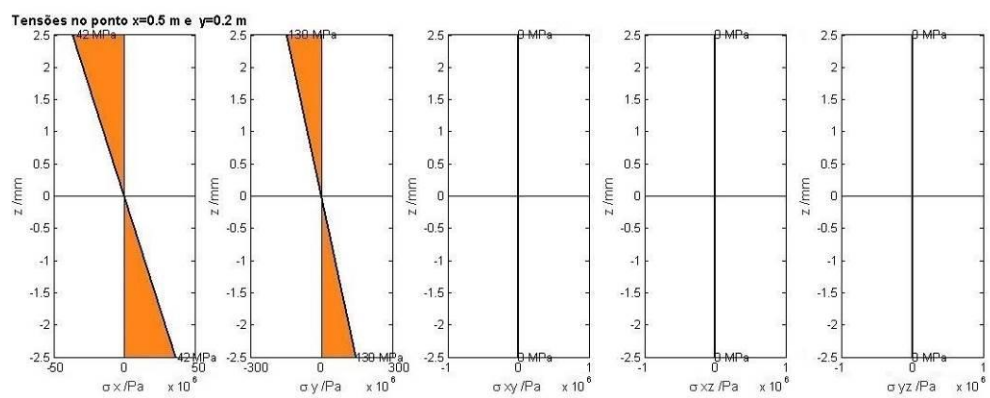


Figure 34 – Stress middle point

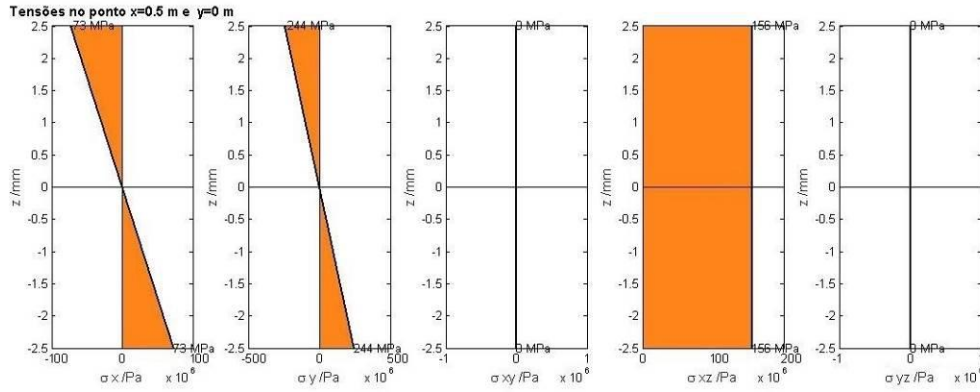


Figure 35 – Stress point A

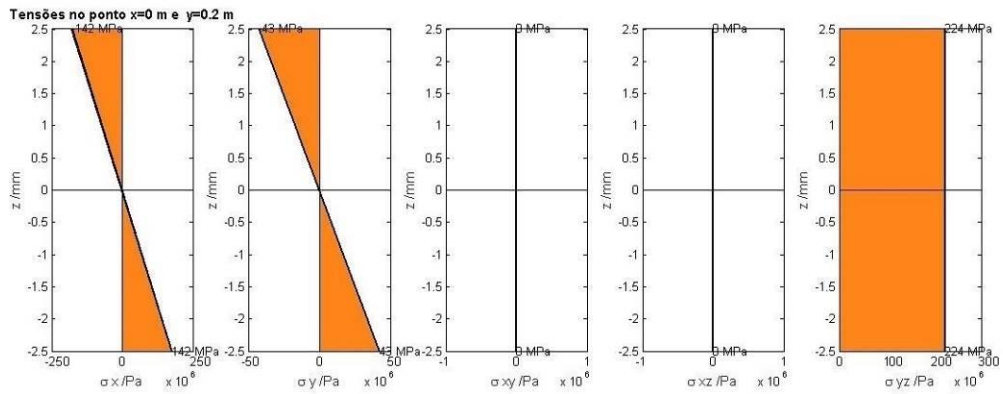


Figure 36 – Stress point B

Table 6 – Results for thickness of 5mm

Point coordinates	Middle (0,5;0,2)	A (0,5;0)	B(0;0,2)
σ_x [MPa]	41,92	73,16	141,93
σ_y [MPa]	130,41	243,88	42,58
τ [MPa]	0	155,61	224,03
Displacement [mm]	2.36		
von Mises [MPa]	114,91	346,50	407,96
Condition (equation 4.2)	118,42	-113,16	-174,63

Thickness 6 mm

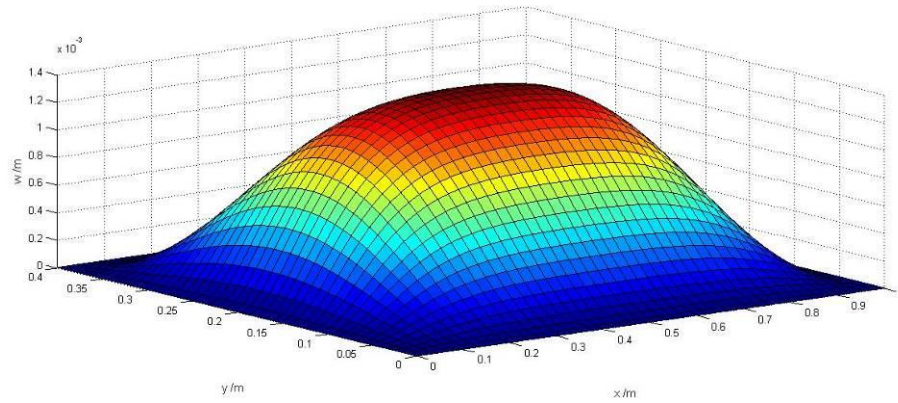


Figure 37 – Displacement 6mm

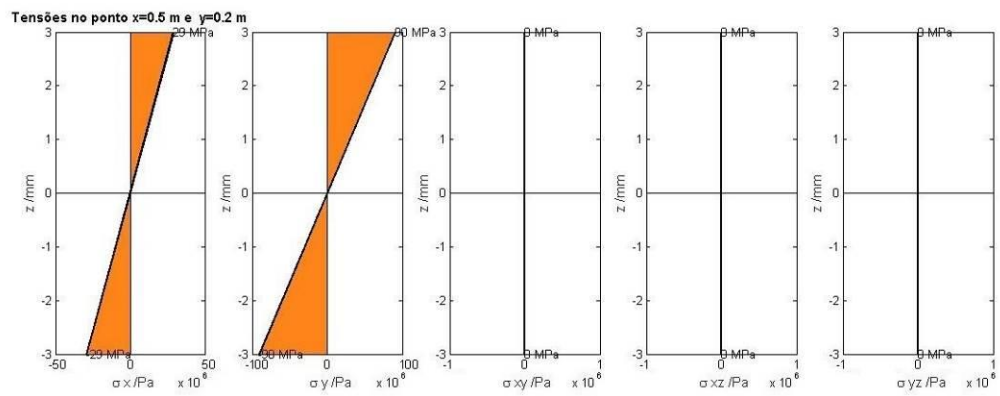


Figure 38 – Stress middle point

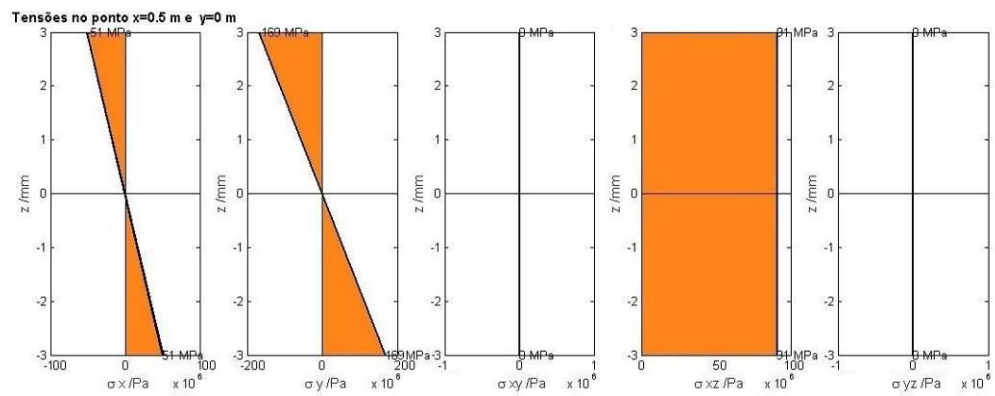


Figure 39 – Stress point A

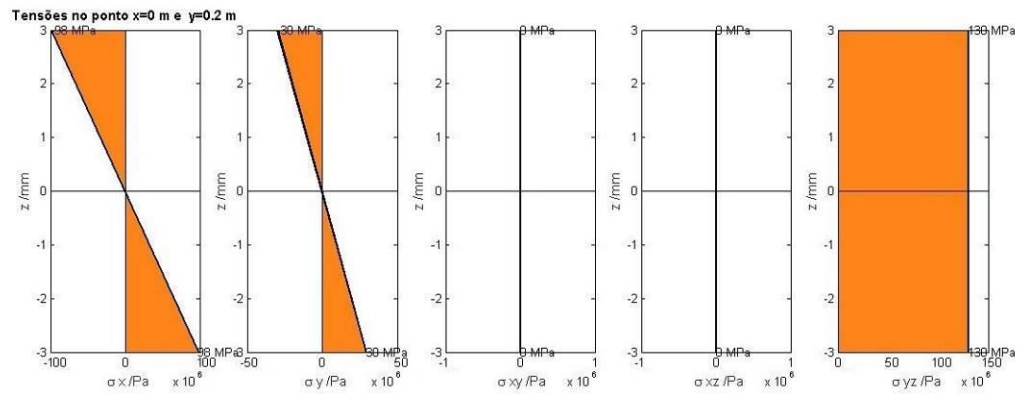


Figure 40 – Stress point B

Table 7 – Results for thickness of 6mm

Point coordinates	Middle (0,5;0,2)	A (0,5;0)	B(0;0,2)
σ_x [MPa]	29,08	50,76	98,46
σ_y [MPa]	90,48	169,20	29,54
τ [MPa]	0	90,95	130,33
Displacement [mm]	1,37		
von Mises [MPa]	79,57	271,68	241,38
Condition (equation 4.2)	153,77	15,65	-8,05

Thickness 7 mm

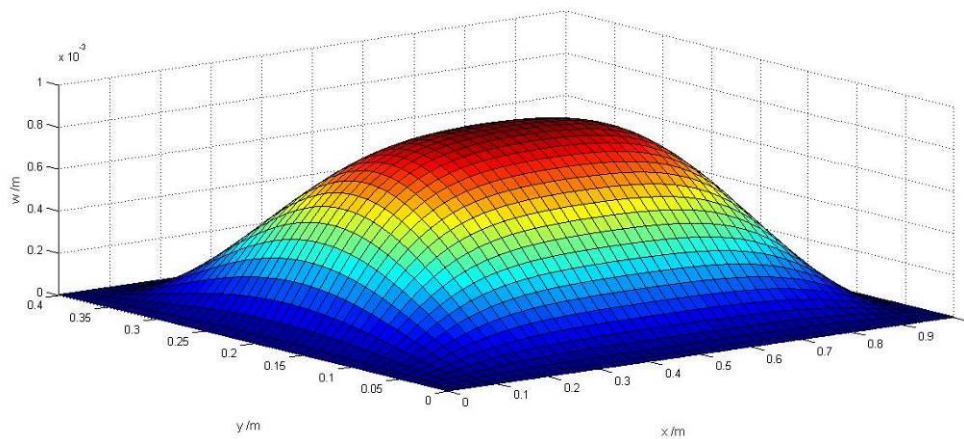


Figure 41 – Displacement 7mm

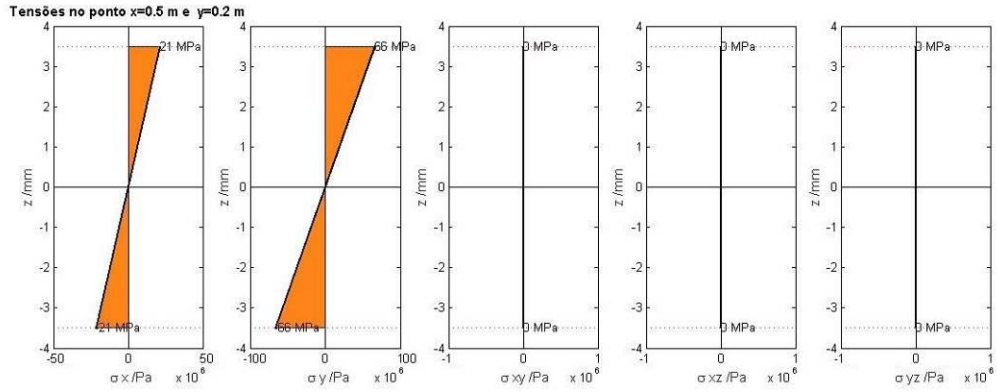


Figure 42 – Stress middle point

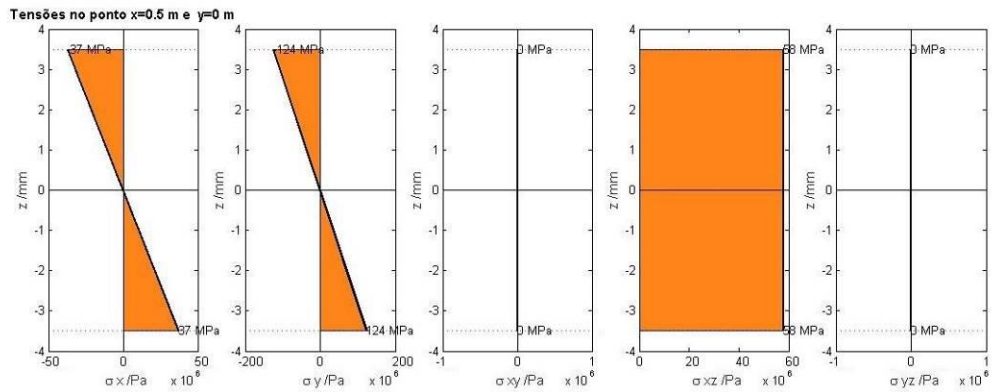


Figure 43 – Stress point A

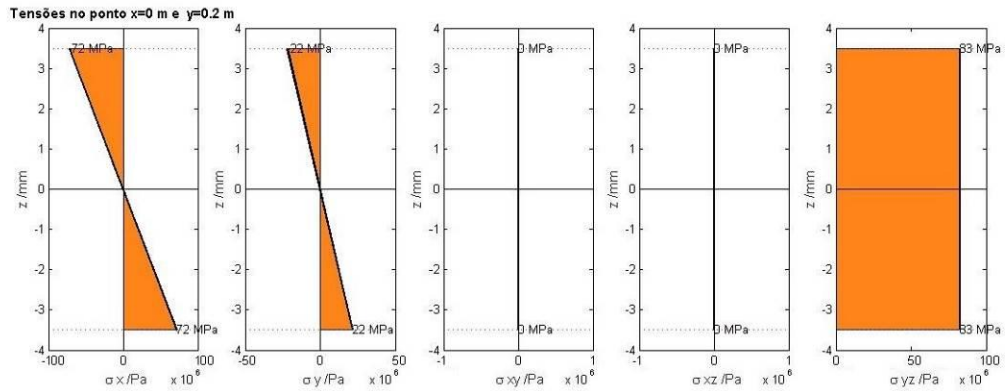


Figure 44 – Stress point B

Table 8 – Results for thickness of 7mm

Point coordinates	Middle (0,5;0,2)	A (0,5;0)	B(0;0,2)
σ_x [MPa]	21,35	37,26	72,25
σ_y [MPa]	66,41	124,20	21,68
τ [MPa]	0	57,95	82,60
Displacement [mm]	0,86		
von Mises [MPa]	58,40	149,16	157,32
Condition (equation 4.2)	174,93	84,17	76,01

The chosen thickness was 6mm, regardless of the stress obtained in point B not satisfying the condition. However, due to the proximity, if the safety factor chosen would be slightly adjusted the condition would have been met without compromising the integrity of the plate. Another possibility is to choose a steel with a higher yield strength.

Once the thickness of the plate is known, its weight can now be determined through the following equation:

$$W_p = A_p * t * \rho \quad (4.3)$$

Where:

F_p , is the plate weight force;

A_p , is the area of the base frame;

t , is the thickness;

ρ , density.

Resulting in a weight of 18,3643 kg.

The weight of the gripper narrows the choice of collaborative robots down to one, the FANUC CR-35iA, the only one able to withstand such payload.

This finding made noticeable that the compaction stage of the process would not be able to be performed only by the collaborative robot, without any other means of supporting the loads resulting from the high pressure.

To resolve this matter a supporting frame and a connection between the frame and the plate was envisioned and dimensioned.

Cylinders

To allow for pressure exerted during the compaction stage of 81 326,645 Pa, the plate is supported by four pneumatic cylinders due to their compatibility with clean room environments. To dimension the size of the cylinders, the total force needs to be determined using the following function:

$$P_{ee} = F_{ee} / A_p \quad (4.4)$$

$$(=) F_{ee} = P_{ee} * A_p \quad (4.5)$$

Where:

P_{ee} , is the pressure exerted by the expanding element;

F_{ee} , is the force exerted by the expanding element;

A_p , is the area of the plate

Since the area is 0,4 [m²], it would result in a force of 32 530,658 N.

Taking into consideration the force exerted by the weight of the plate of 183,643N, the total force results in 32 347,015 N

Given the total force, it can be replaced in equation 4.6 to determine the force per cylinder.

$$F_{pc} = F_t / 4 \quad (4.6)$$

Where:

F_{pc} , is the force per cylinder;

F_t , is the total force.

Which totals, $F_{pc} = 8086,754 \text{ N}$

Once the force per cylinder is known, the area of each cylinder can be calculated resorting to equation 4.7.

$$P_{pc} = F_{pc} / A_{pc} \quad (4.7)$$

Where:

P_{pc} , is the functioning pressure of a cylinder ($5 \times 10^5 \text{ Pa}$);

F_{pc} , is the force per cylinder, and;

A_{pc} , is the area of a cylinder.

$$A_{pc} = F_{pc} / P_{pc} \quad (4.8)$$

And $A_{pc} = 0,01617 \text{ m}^2$

$$A_{pc} = \pi * r^2 \quad (4.9)$$

Where:

r , is the radius of a cylinder

$$r = (A_c / \pi)^{(1/2)} \quad (4.10)$$

Thus $r = 0,07175 \text{ m}$ and the diameter is $d = 0,1435 \text{ m}$

From the SMC catalogue, the cylinder with the closest diameter is the CDS2B160TF-400, with a bore size of 160mm and a stroke of 400mm.

Design of supporting frame

When dimensioning the support frame where the cylinders are attached, presented in Figure 45, the frame was divided into 3 sections to simplify the calculations needed.

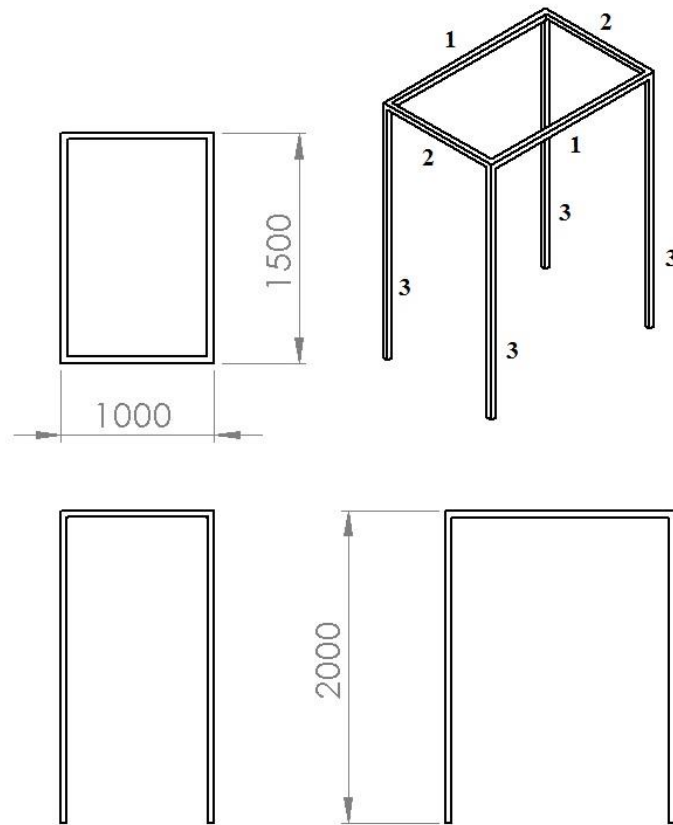


Figure 45 – Support frame

Beam 1 - bend

For the horizontal beams an approximation can be made to a beam with a pinned and a roller support shown in Figure 46.

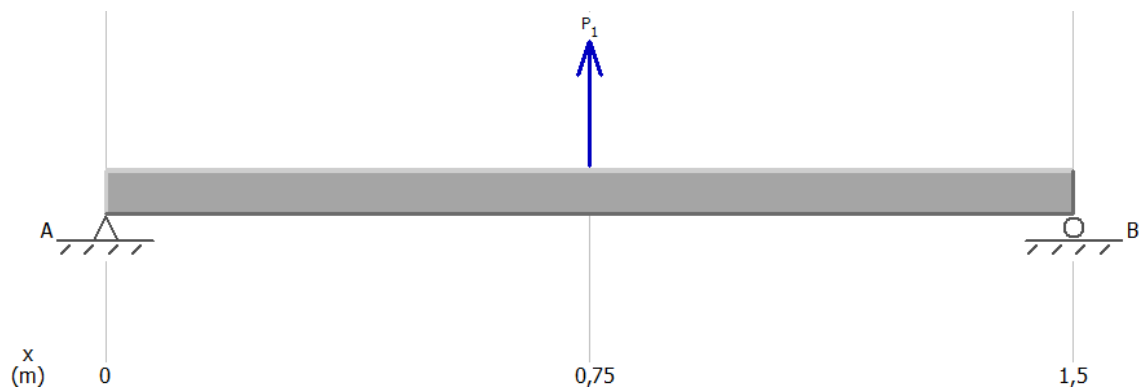


Figure 46 – Load diagram

Using

$$P_1 = (F_t * SF) / 4 \quad (4.11)$$

Where:

P_1 , is the concentrated load;

F_t , is the total force (32 347,015 N);

SF, is the safety factor, mentioned before (1,5)

Resulting in $P_1 = 12130,13 \text{ N}$

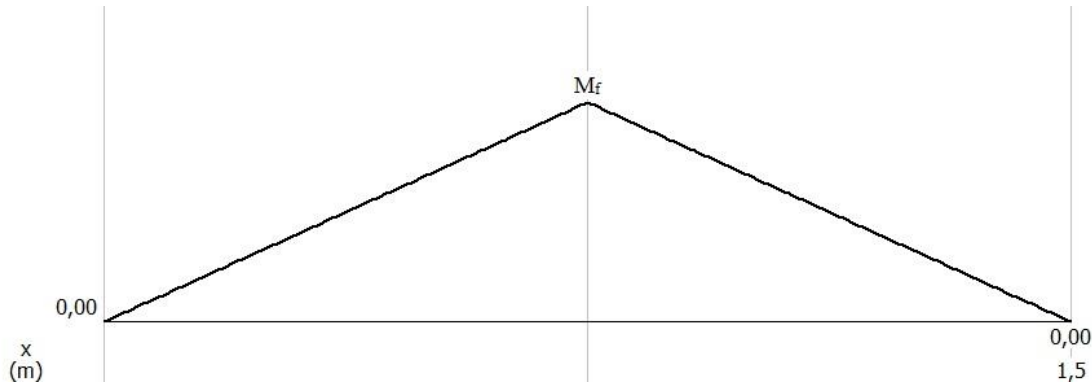


Figure 47 – Moment diagram

$$M_f = (P_1/2) * (l/2) = (P_1 * l)/4 \quad (4.12)$$

Where:

M_f , is the bending moment;

l , is the length (1,5m).

Which totals, $M_f = 4548,799 \text{ Nm}$

Applying:

$$\sigma_{ys} = M_f / \omega \quad (4.13)$$

Where:

σ_{ys} , is the yield strength of the material, in this case S355 Steel (355 MPa);

M_f , is the bending moment (4548,799 Nm);

ω , is the elastic section modulus.

$$\omega = M_f / \sigma_{ys} \quad (4.14)$$

Resulting in, $\omega = 12813,518 \text{ mm}^3$

The selection of steel profile is done by consulting the SZC catalogue and finding a profile with an elastic section modulus superior to the one calculated. The chosen profile VKT square steel tubing, shown in Figure 48, has an elastic section modulus of $\omega = 15200 \text{ mm}^3$ with a width of $b = 45 \text{ mm}$.

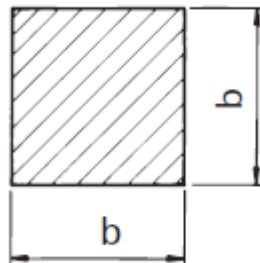


Figure 48 – Square section tube dimensions

The profile can also be RRK hollow square steel tube, seen in Figure 49, which has an elastic section modulus of $\omega = 14500 \text{ mm}^3$, and its dimensions are $b = h = 60 \text{ mm}$ and $t = 4 \text{ mm}$.

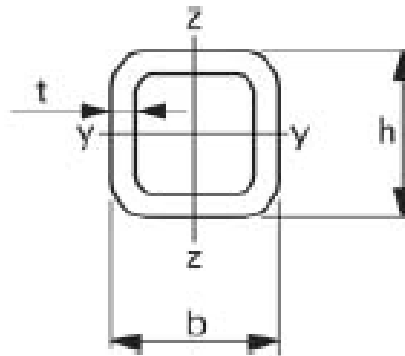


Figure 49 – Hollow square section tube dimensions

Beam 2 – bend

Once again, for the horizontal beams an approximation can be made to a beam with a pinned and a roller support, demonstrated in Figure 50.

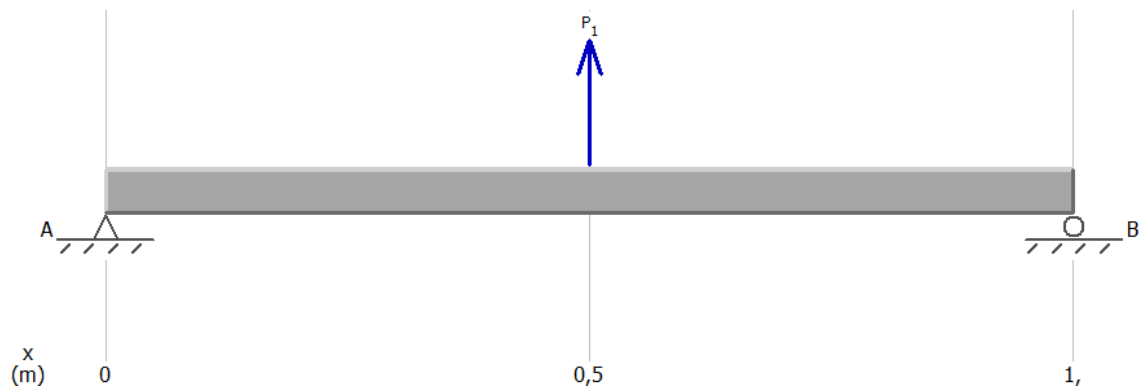


Figure 50 – Load diagram

Using

$$P_1 = (F_t * SF) / 4 \quad (4.15)$$

Where:

P_1 , is the concentrated load;

F_t , is the total force (32 347,015 N);

SF, is the safety factor (1,5)

Resulting in $P_1 = 12130,13$ N

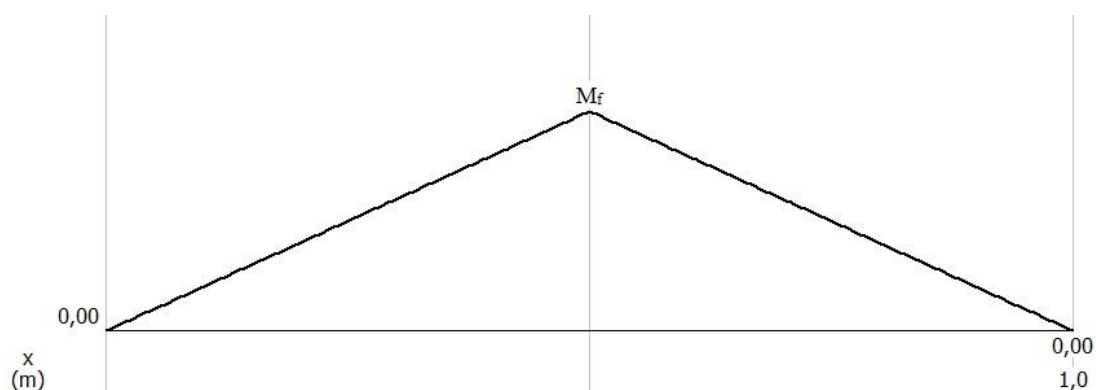


Figure 51 – Moment diagram

$$M_f = (P_1/2) * (l/2) = (P_1 * l)/4 \quad (4.16)$$

Where:

M_f , is the bending moment;

l , is the length (1m).

Which totals, $M_f = 3032,533 \text{ Nm}$

Applying:

$$\sigma_{ys} = M_f / \omega \quad (4.17)$$

Where:

σ_{ys} , is the yield strength of the material, in this case S355 Steel (355 MPa);

M_f , is the bending moment (3032,533 Nm);

ω , is the elastic section modulus.

$$\omega = M_f / \sigma_{ys} \quad (4.18)$$

Resulting in, $\omega = 8642.345 \text{ mm}^3$

The selection of steel profile is done by consulting the SZC catalogue and finding a profile with an elastic section modulus superior to the one calculated. The chosen profile VKT square steel tubing, presented in Figure 52, has an elastic section modulus of $\omega = 10700 \text{ mm}^3$ with a width of $b = 40 \text{ mm}$.

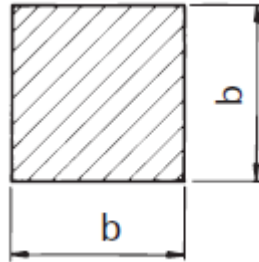


Figure 52 – Square section tube dimensions

The profile can also be RRK hollow square steel tube, seen in Figure 53, which has an elastic section modulus of $\omega = 9490 \text{ mm}^3$, and its dimensions are $b = h = 50 \text{ mm}$ and $t = 4 \text{ mm}$.

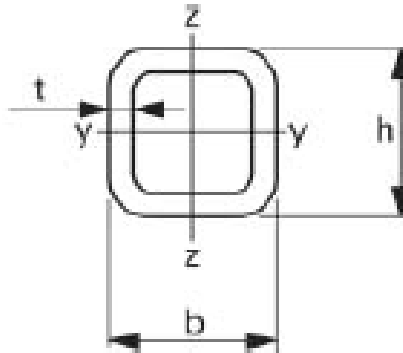


Figure 53 – Hollow square section tube dimensions

Beam 3 – tension

For the vertical beams an approximation can be made to a fixed beam on one side and free on the other, shown in the following Figure 54.

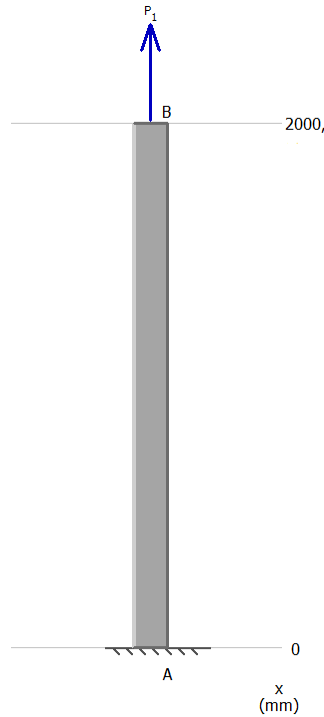


Figure 54 – Load diagram

Once again

$$P_1 = (F_t * SF) / 4 \quad (4.19)$$

Where:

P_1 , is the concentrated load;

F_t , is the total force (32 347,015 N);

SF, is the safety factor (1,5)

Resulting in $P_1 = 12130,13$ N

$$\sigma_{ys} = P_1 / A_t \quad (4.20)$$

Where:

σ_{ys} , is the yield strength of the material, in this case S355 Steel (355 MPa);

A_t , is the area of the tube.

$$A_t = P_1 / \sigma_{ys} \quad (4.21)$$

Which totals, $A_t = 34.169 \text{ mm}^2$

Once more, the selection of steel profile is done by consulting the SZC catalogue. This time, finding a profile with an area superior to the one calculated. The chosen profile VKT square steel tubing, presented in Figure 55, has an area of $A_t = 100 \text{ mm}^2$ with a width of $b = 10\text{mm}$.

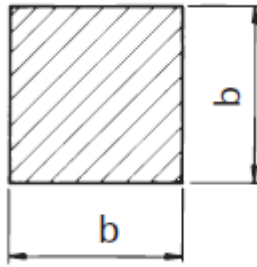


Figure 55 – Square section tube dimensions

Description of the operating procedure

As already mentioned, a collaborative robot alone fails to meet all requirements to the stages of the process.

The action of withdrawing the protective films and placement of the final vacuum bag are very particular and require dexterity, thus would have to be performed by a worker. It is also intended that the placement of the intermediate vacuum bags ceases to be performed, since it would be replaced by a stage of compaction performed by the robot with support from a support frame.

The process would be performed as followed:

- The carbon fibre prepreg would be positioned without the upper protective film;
- The worker would place the robot over the ply, using an interface to monitor positioning;
- Once the correct position of the robot is ensured, using the interface, the worker would select only vertical movement and, once the gripper contacts the ply, select the vacuum option to allow the gripper to pick up the ply. The vacuum valves would have sensors to allow only the ones that detect a vacuum to be activated;
- Then the worker would move the robot to a position that would allow for the withdrawal of the inferior protective film;
- The worker would then position the gripper over the mould, checking the interface to ensure correct positioning;
- After moving until contact with the mould, the worker would use the insufflation function on the interface, this would be fulfilled based on the CATIA model, to ensure that the insufflation is executed in the optimal controlled way to avoid the formation of creases. To allow for the compaction pressure, hydraulic cylinders would fix the gripper.

In the following Figure 56 and Figure 57, a representative layout is shown, to ease the comprehension of the operating procedure.

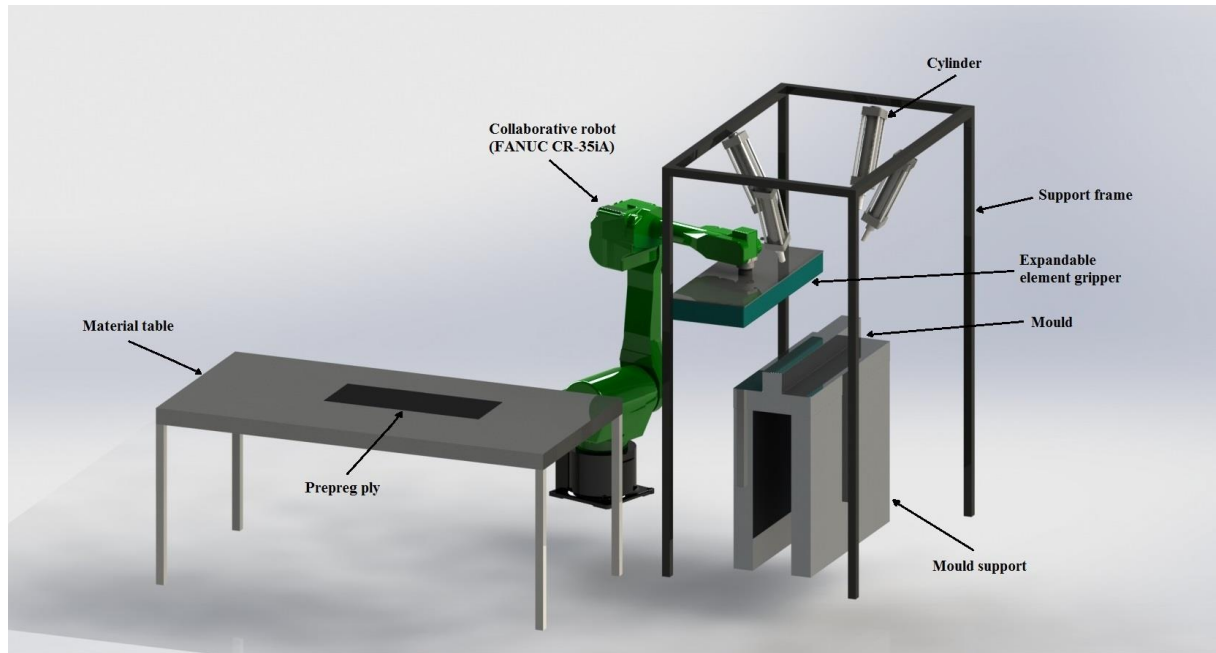


Figure 56 – Envisioned layout

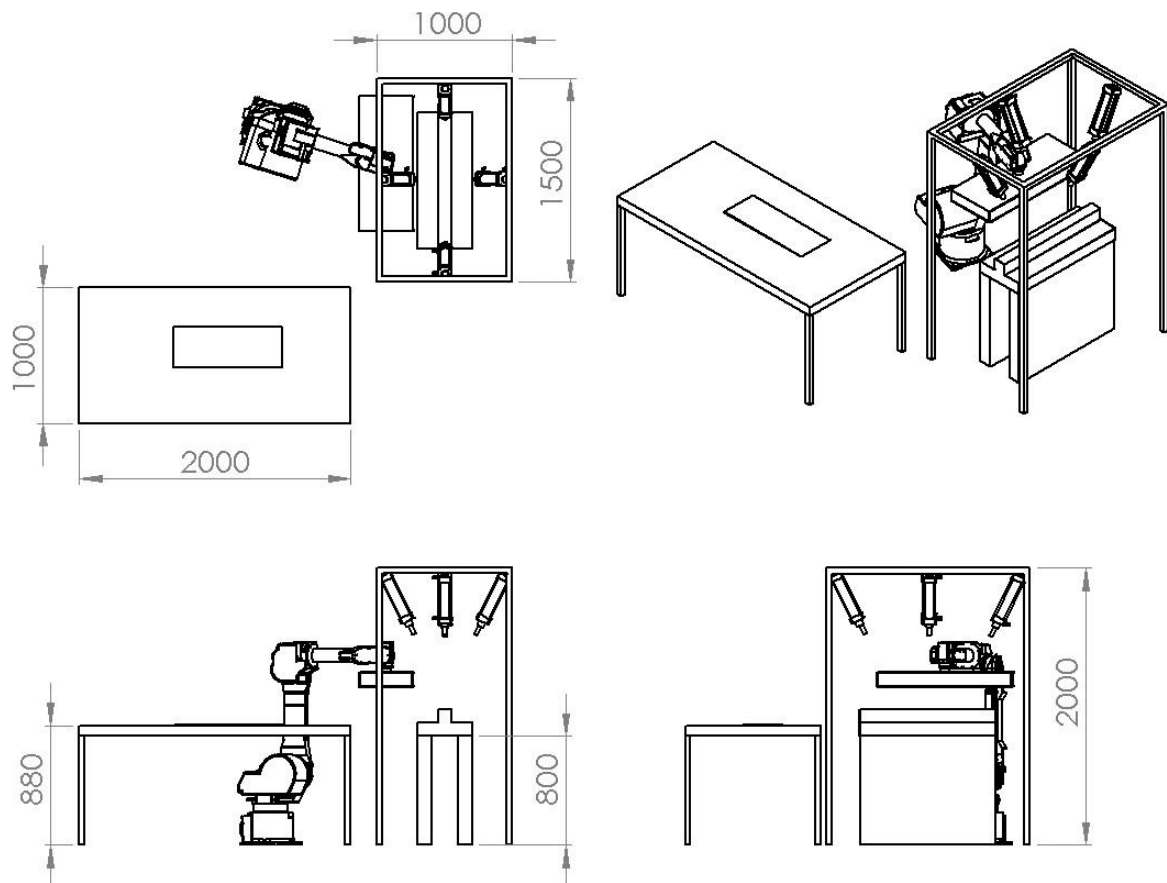


Figure 57 – Envisioned layout technical drawing

5 Conclusion and future work

5.1 Conclusion

The objective of this thesis was to study the current manufacturing system consisting in prepreg hand lay-up, and develop a new manufacturing system implementing a collaborative robot cell to obtain CFRP stiffeners. Early on, two components were identified as essential to satisfy this objective: the collaborative robot and the gripper.

Considering all the particularities of the process and the technological gap between manual lay-up and automated production, it quickly became apparent that a new approach to satisfy the problem was needed, thus began the conceptualization of a new gripper capable of performing multiple actions.

The dimensioning of the gripper performed is only an introduction to the concept, allowing for an understanding of the additional requirements needed in a development stage, such as the plate, cylinders and support frame, which are essential for its function.

To function with the expandable element gripper of variable geometry theorised a collaborative robot was chosen, the FANUC CR-35iA, which would be supported by a frame so that no damage would occur to the robot during the compaction stage of the process.

The main objective of the theorised model is to be able to adapt to moulds of different geometry, making it capable of producing a wide variety of parts without the need of changing gripper, unlike anything seen in current industrial robots which have a dedicated gripper for each task.

An attempt on simulating the insufflation of the expanding element was also made, however due to the extreme deformation of the material, the program used (Abaqus) was unable to return any logical results.

5.2 Future work

This thesis only described a first approach to an idea with still much to be worked upon.

There are many aspects to further develop the expandable element gripper of variable geometry. On a first stage:

- Optimal material for expandable element, a further study into the materials capable of high deformation as long as pressure resistance;
- Better knowledge of material behaviour, simulate with multiple materials and mould geometries the adaptability and rupture points of the expandable element;
- Optimal internal geometry, determine which geometry would allow for better pressure distribution as well as mould adaptability;

- Insufflation process, develop a program to perform an ideal insufflation based on a CATIA design of the mould.

On a second stage:

- Development of a working prototype, to allow for a real world evaluation of the performance;
- Integration of a force sensing system, in order to relay information about the compaction stage, permitting further improvements of the insufflation;
- Energetic and cost evaluation, so that a study of implementation viability can be done, when compared to the current hand lay-up.

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