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FIBERGLASS PULTRUSION SYSTEM FOR MANUFACTURING SPATIAL STRUCTURES

PULTRUSIOONI TEEL RUUMILISTE KLAASKIUDKONSTRUKTSIOONIDE TOOTMINE

MSc thesis

The author applies for
the academic degree
Master of Science in Engineering

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AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.
These materials have not been submitted for any academic degree.
All the works of other authors used in this thesis have been referenced.

The thesis was completed under Ahti Põlder's supervision

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Author

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Supervisor

.... signature

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TUT Department of Mechatronics
Chair of Mechatronics System

MSc THESIS TASK

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THESIS TOPIC:

Fiberglass pultrusion system for manufacturing spatial structures

Pultrusiooni teel ruumiliste klaaskiudkonstruktsioonide tootmine

Assignments to be completed and the schedule for their completion:

No.	Description of the assignment	Completion date
1.	Overview of different processes used for manufacturing composite materials, requirements for material, research on similar or alternative products, patents, published work	25.02.2016
2.	Pultruder prototype design (nozzle, die, drivers) with composite curing	04.04.2016
3.	Fiber feeding system	10.04.2016
4.	Implementing the prototype, testing, improvements	20.04.2016
5.	Analysis of the results, proposal of alternative structures, finalizing the work	13.05.2016

Engineering and economic problems to be solved: Developing a new solution that could manufacture spatial structures out of composite material, while being more time and cost efficient than existing solutions. Designing and prototyping a pultrusion system for use with an industrial robot.

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Confidentiality requirements and other corporate terms and conditions shall be set out on the reverse side.

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FOREWORD

The thesis was proposed by the Department of Mechatronics in cooperation with OÜ Kodasema, represented by Marek Strandberg. The thesis was written in the Department of Mechatronics in Tallinn University of Technology based on the requirements of OÜ Kodasema. Marek Strandberg provided the initial concept and the materials to start the project.

The author wishes to thank Marek Strandberg for the proposal of an interesting topic and the supervisor of this thesis, Ahti Põlder, for his great support and guidance.

EESSÕNA

Käesolev magistritöö on välja pakutud Mehhatroonikainstituudi poolt koostöös OÜ Kodasemaga, keda esindab Marek Strandberg. Töö teostati Tallinna Tehnikaülikooli Mehhatroonikainstituudis lähtuvalt OÜ Kodasema poolt esitatud nõuetele. Esialgne tööülesanne ja materjalid projekti alustamiseks olid põhiosas ette antud Marek Strandbergi poolt.

Autor soovib tänada Marek Strandbergi tema poolt esitatud huvitava teema ning abi eest. Erilised tänusõnad on autori poolt käesoleva magistritöö juhendajale Ahti Põlderile tema juhendamise ning toetuse eest.

1. INTRODUCTION

The aim of the work is to provide the company Kodasema [1] an alternative and more efficient way of producing fiberglass structural members for modular concrete walls.

The walls are used in constructing houses that can be used to form temporary housing areas and can be constructed quickly on-site and also moved when needed. The walls consist of a concrete panel with a high yield strength (70-90 MPa), a wooden panel that also acts already as an interior element and the glass fiber structural element separating them and creating room for insulation. A general depiction of said wall panel can be seen on figure 1.

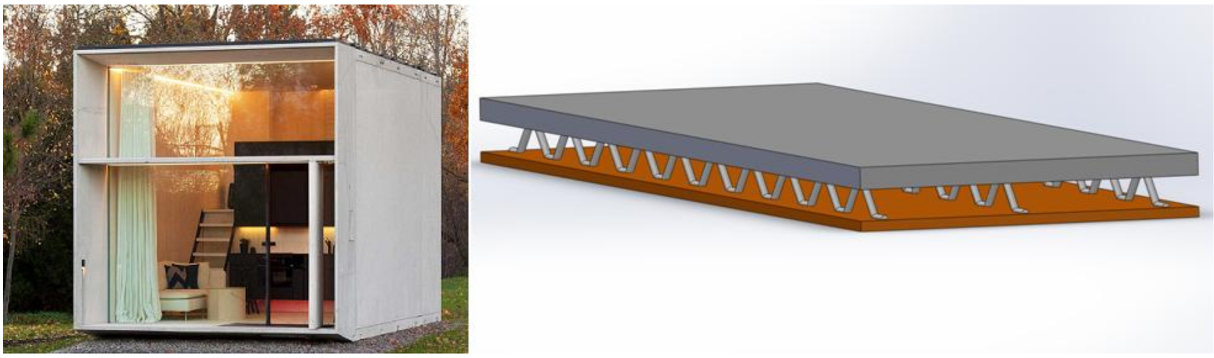

Figure 1. Modular house by Kodasema [1] and a representation of described modular wall

The main problem at hand is how to manufacture a spatial composite material structure with a constant cross-section onto a wooden panel without support elements, that could be a more efficient alternative to cutting or milling the structure from a piece of solid material, which is done at the moment, but taking into regard also the needed strength of the element.

The expected result would be that by using techniques of pultrusion and applying them to a version of freeform three-dimensional printing with the help of an industrial robot, a structural member made of composite material could have similar strength characteristics and reduce the amount of wasted material during processing, without a loss in production time. This would give the company a more efficient production process and would also show the potential use of such a solution in other fields of application and would create a good platform for future research and expansion.

2. THEORETICAL BASIS OF THE THESIS

2.1. Pultrusion

The main process for manufacturing a composite material with a constant cross-section is pultrusion. In the process fiber materials are impregnated with resin while being pulled through one or many dies which give the material its profile, before entering a heated die where the resin is cured (in the case of thermosetting polymers) as seen also on Figure 2. The solid profile must then cool before entering the gripping mechanism that does the pulling action, therefore a cooling process must be added between. After that the material can be cut to length. The line speed of the process is typically 1 m per minute, as is described in "Pultrusion for engineers" by T.Starr. [2]

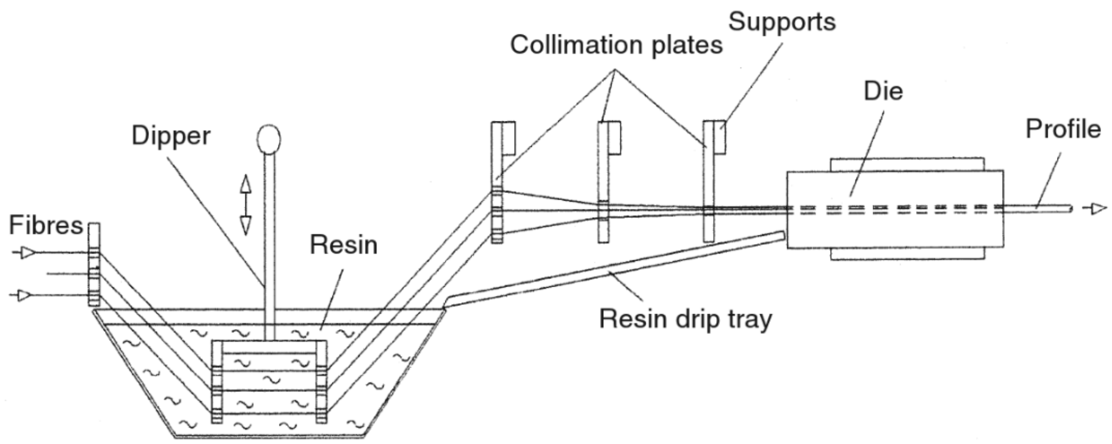

Figure 2. Resin impregnation in typical pultrusion system[2]

The pultrusion process is not limited to thermosetting polymers, it can be also used in the same way for ultraviolet radiation curing by using a UV transmitting die and a UV curing resin. Pultrusion speeds can also be higher, from 5 m per minute to 10 m per minute are reported in some cases, as is described in the patent "Pultrusion with cure by ultraviolet radiation" by T.Kanzaki . [3]

Pultrusion is therefore a effective process for manufacturing straight composite material elements with a constant cross-section but lacks in this form the ability to produce spatial structures.

2.2. Out of die ultraviolet cured pultrusion

To give the pultrusion process more flexibility and to reduce the needed pulling strength the curing process could also be done “out of die” as suggested also in the paper by Tena. I in 2015 [4].

In the article, the out of die ultraviolet (UV) cured pultrusion for manufacturing impact absorbing parts for the automotive industry was analysed. The composite used in the study was glass fibers with UV cured polyester resign. The thickness of the tested profile was 2 mm and the pulling speed for the pultrusion process was 0,65 m/min with the typical open bath resin impregnation system being used. Only one UV source was used, however, the experiments were done with a LED and an UV arc lamp.[4] A general diagram of the pultrusion system can be seen on Figure 3.

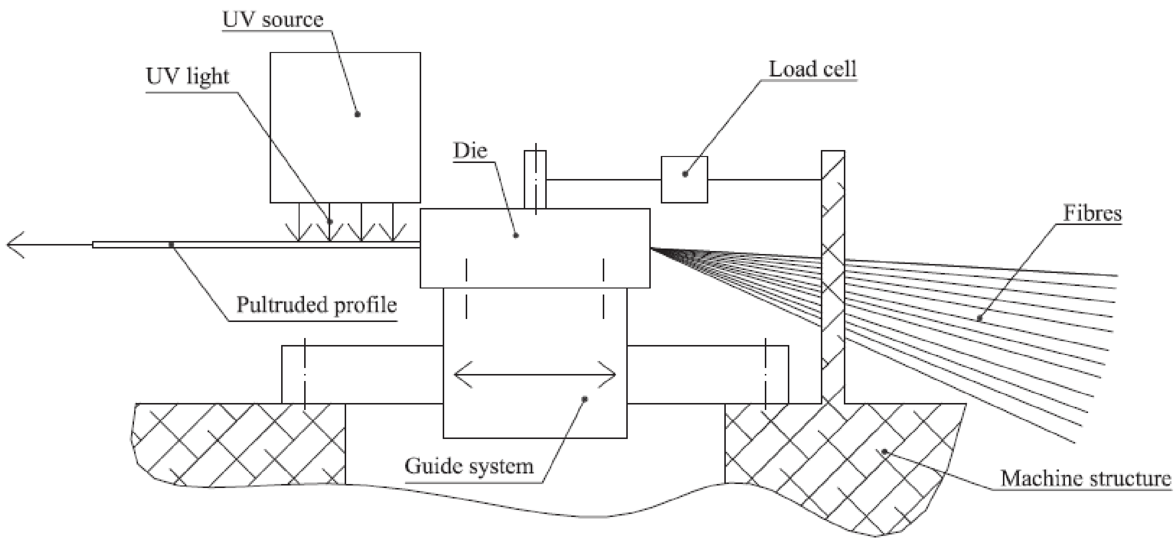

Figure 3. Pultrusion curing system with external UV light source [4]

The results of the study showed that using external curing is a feasible alternative to using an internal curing inside a die, in regard to that application. It was also concluded that the ultraviolet LED was more efficient than the arc lamp, due to the fact that the LED penetration capacity is higher and the expansion of the material during curing is lower [4]. This proves that the UV light source has to be designed in accordance with the material thickness to achieve maximum production speeds.

The required maximum force for the pulling action was registered at 80 N, while a typical pultrusion process requires a force in the range of kilonewtons.

2.3. Ultraviolet cured pultrusion for curved structures

A possible further development of the pultrusion system is described in the article by Britnell (2003), that uses an industrial 6-axis robot arm for performing the pulling action (Figure 4), and a curing system similar to the one described in the last chapter [5]. This gives the opportunity to produce structures with curvature and increases the beneficial aspects of the process. The materials used were again glass fibers with epoxy acrylate resins.

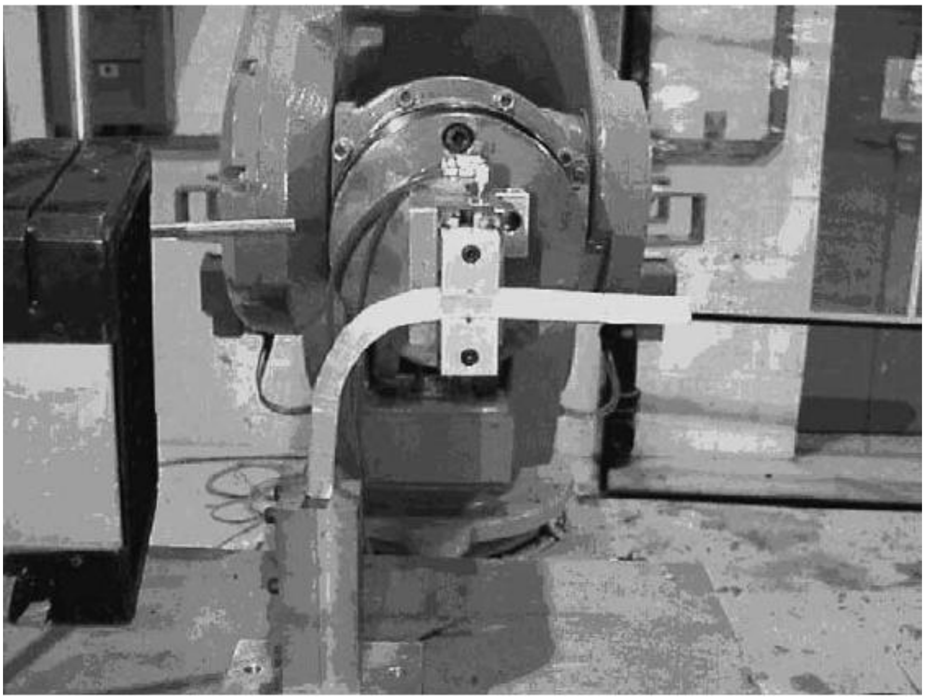

Figure 4. 6-axis robotic arm acting as the pultruder [5]

It is said that a pultrusion speed of 0,1 to 0,5 m/min was achieved while manufacturing curved structures, depending on the complexity of the shape. During the experiments a profile thickness of 6 mm was successfully cured while being illuminated from only one side. The authors suggest that using a 250 W UV light source with a 200–400 nm spectrum and illuminating the composite from both sides may result in a successful material thickness of up to 12 mm. The typical load for the pulling mechanism at 0,5 m/min is reported to be at 10 N. [5]

2.4. Similar or alternative products

3D printers are also capable of manufacturing composite materials (fiberglass, carbon fiber, kevlar), including complex shapes. An example of this would be the MarkForged Mark One [6] that uses filaments of composite materials to reinforce nylon and other printable polymers used in their printers. Its restriction is that it requires a special filament engineered especially for use with their equipment and its speed is still restricted by the layer-by-layer applying of material onto the workbed. [6]

An example of using UV curable resin is the stereolithography (SLA) technology in 3D printing. This technology is used in the Carbon3D [7] printer, which uses a projector underneath a pool of photopolymer resin to project a layer of the solid to a workbed and solidify the layer, which is then raised from the pool and "grown" with every layer. A similar printer is the Formlabs models Form 1 and Form 2 [8]. Several of these printers can be found in Estonian companies (3DPrinterOS, Shaperize, Kunstiakadeemia 3D labor). The process is quite fast but there are limits to the material that can be used and limits to the size, that restrict the commercial use of such a system at this time. Produced parts are generally strong enough to be machined but brittle. The larger Form 2 printer of Formlabs has a maximum workspace area of 35 × 33 × 52 cm and uses a resin specifically developed for their own use that cures with a 405 nm violet laser with an output power of 120 mW [8].

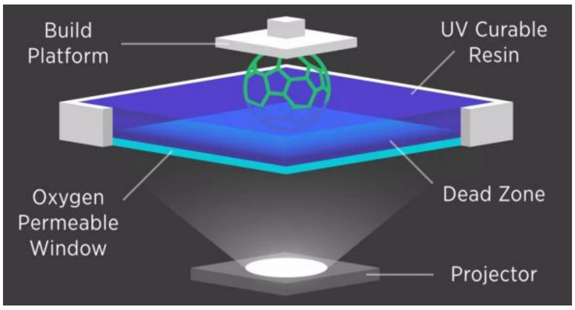

Figure 5. Continous liquid interface production [9]

A more similar product would be the project called Mataerial [10]. A 5-axis industrial robot that is fitted with a thermosetting resin extruder that is capable of making structures with a constant cross-section in mid-air without supporting structures. The resin is cured by two hot air blowers fitted on either side of the extruder and applied by thin layers or dots. The concept is intended to be used to created models or art and is by now evolved into freeform metal printing [10]. The use of such a composite "printer" for making structures with high yield strength is rather questionable.

The most similar product was unveiled by Festo in the beginning of April 2016. It is a novel 3D printer that uses glass fibres and UV-curing resin to build structures freely in space. The extruder is mounted on their EXPT-45 tripod and is referenced in their brochure as a “spinneret”, seen also on Figure 6. [11]

The 2400-tex glass-fibre roving (meaning the mass of fibers with a length of 1000 meters is 2400 grams [12]), is moved forward over rollers and at the same time covered with viscous resin. After exiting the nozzle, it is cured by UV light. The thread is cut off by a small cutting disc or bent to the next fixing point, when needed. The adjustment of UV light intensity gives the opportunity of keeping the resin in a liquid state in order to add a new thread to an existing structure. [11]

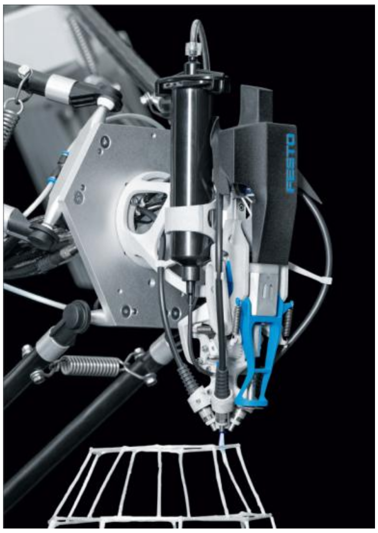

Figure 6. Festo 3D cocooner extruder [11]

General technical data of the 3D Cocooner [11]**:**

- Construction speed: 10 mm/s
- UV light: fibre-coupled LED; 365 nm; 9.3 mW
- Material: glass-fibre roving with 2400 tex for producing glass-fibre rods with 2 mm diameter and 60% fibre–volume ratio
- Weight of glass-fibre rod: 5–7 g/m
- UV plastic: 1-Vinylhexahydro-2H-azepin-2-on, acrylate mixture

The brochure of Festo is the only reliable information source on the project at this time and it seems that according to it the UV-curing resin is named as a light-curing plastic and no information is given about the after-curing of bended rods. No information is also given about the forming of the fibers and how they are moved forward inside the device.

2.5. Choice of pultrusion method

Taking into regard that the planned device should be compact and lightweight, the choice for using pultrusion with UV curing was confirmed. The supporting arguments can be summarized based on the previous chapters:

- Pultrusion using external UV curing has been used and is possible.
- The force needed for pultrusion is low enough to be done by a industrial robot or smaller electrical motors. Load for the pulling mechanism – 10 N [5].
- The speed of the pultrusion process could be at 0,5 m/min [5].
- UV LED is a sufficient light source (max intensity 8 W/cm^2 [4]).
- The most similar product is the Festo 3D Cocooner, unveiled after the start of this thesis (in April 2016) and it produces 2 mm glass fibre rods with UV-curing .

3. REQUIREMENTS AND MATERIALS USED

3.1. Requirements for the finished product

The initial requirements for the structure were based on the

- Diameter of pultruded profile: 3 – 4 mm
- 60 degree angle of the structure relative to the panel

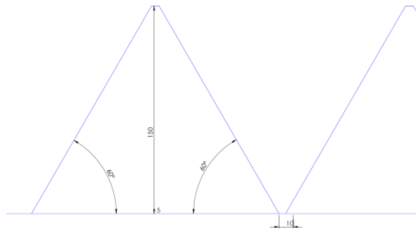

Figure 7. Schematical drawing of the structure

- Total weight of the mechanism under 5 kg, so that it could be implemented with the industrial robots in the Department of Mechatronics.[13, 14]

3.2. Materials and curing source

3.2.1. Fiberglass

The fiberglass used is a continuous roving glass fibre strands (2400 TEX)[15] already selected by Kodasema. This type of roving is originally intended to be used for production of fiberglass strand mats (Chopped strand mat or CSM). The chopped strand mat is used for moulding different shapes using the hand lay-up or spraying technique and then brushing the surface with resin. This means that the strands are very elastic and thin.

Figure 8. Fiberglass strands (2400 TEX)

The bundle of strands used are approximately 0,7 – 0,8 mm thick and a single strand is 0,04 mm thick respectively when measuring with a standard digital caliper. As defined by the units of TEX, the mass of fibers with a length of 1000 meters is 2400 grams

3.2.2. Adhesives and resin

The resin used for preliminary testing was 3M UV50 [16] ultraviolet curing adhesive intended for bonding glass to glass or metal to glass. That was already purchased by Kodasema. The fixture time is reported to be under 3 seconds at a wavelength of 365 nm and intensity 10 mW/cm^2. For achieving a dry to touch finish, the adhesive should be cured in the absence of oxygen or with the wavelength of 250 nm. Oxygen restricts the curing process, as with bearing adhesives and it should be noted that it is intended for assembling glass materials, not for structuring glass fibers [16]. Therefore, other possible adhesives from the same manufacturer were selected for possible testing and compared as seen in Table 1.

In addition to 3M, a secondary supplier was contacted for the purchase of Loctite UV fast curing adhesives to provide an alternative. It should be noted that the Loctite brand adhesives are generally more expensive. A comparison table of two possible candidates are shown in Table 2.

Table 1. Comparison of 3M UV adhesives

Product name	**3M UV50** [16]	**3M UV02**[17]	**3M UV75**[18]
Fixture Time (glass slide fixture 10mW/cm2 @365nm	< 3 s	< 2 s	< 3 s
Depth of Cure (cured for 30s at 10mW/cm2 @365nm)	1,5 - 3,5 mm	4 mm	5 mm
Viscosity	5500 – 7500 cps	2600 – 3800 cps	1700 – 1900 cps
Cures dry to touch	No	Yes	No
Tensile strength (steel to glass)	6 - 15 N/mm^2	N/A	N/A

Table 2. Comparison of Loctite UV adhesives

Product name	**Loctite AA3926** [19]	**Loctite 4304** [20]
Fixture Time (shear strength of 0.1 N/mm^2)	< 5 s	< 5 s
UV Depth of Cure, mm: Cured @ 100 mW/cm^2, measured @ 365 nm, for 10 seconds	> 2,2 mm	3 -6 mm
Viscosity	3000 - 8000 cps	10 - 35 cps
Tack free time 30 - 100 mW/cm^2	> 60 s	< 5 s
Tensile strength (steel to glass)	9,2 N/mm^2	18 N/mm^2

As an alternative to adhesives, the possible usage of resin that is used in 3D printers (described in chapter 2.4) was also considered. The most common of them being the Formlabs resin with different variations in colour and technical capabilities, which were selected based on their availability, as described in chapter 2.4, it was possible to acquire samples of the product from different companies based in Estonia.

The Formlabs photopolymer resins are designed for use in their printers which use a 405 nm violet laser with an output power of 120 mW. Generally UV light with a shorter wavelength produces a more rapid curing, so the use of a 365 nm wavelength would also be possible to use, in order to use the same light source on adhesives and resins. The main material properties of Formlabs resins, according to the datasheets, are given in table 3.

Table 3. Comparison of Formlabs resins.

Product name	**FLGPCL03 „Clear“** [21]	**FLTOTL02 „Tough“** [22]	**FLFLGR02 „Flexible“**[23]
Curing designed for 405 nm 120 mW laser	Yes	Yes	Yes
Viscosity	850 – 900 cps	1800 cps	4500 cps
Tensile strength at yield, curing done by printer @ 405 nm	38 MPa	N/A	N/A
Tensile strength at yield, post-curing 2 hours in 30 W UVA curing chamber	N/A	41,3 MPa	N/A
Tensile strength, curing done by printer @ 405 nm + post-cured with 365 nm light source	N/A	N/A	3,3 – 3,4 MPa

From this selection, the most suitable candidate for this application would be the FLGPCL03 „Clear“ resin. It achieves the highest tensile strength without any post-curing. With the resin “Tough” parts would be according to the datasheet less brittle and more impact-resistant, but require thorough post-curing to achieve final mechanical properties.

3.2.3. Curing (UV)

3.2.3.1. Selection of UV light source

The most compact solution for an ultraviolet light source is an UV LED. They are classed based on their wavelength range, as UV-A (400 – 315 nm), UV-B (315 – 280 nm) and UV-C (280 – 100 nm) [24]. Typically, lower wavelength LEDs cost is higher. Therefore the most available and low cost LEDs are from class A. After some market research it was concluded that LEDs with a wavelength below 365 nm are drastically more expensive and less available.

Based on their availability, price and suitability for project, two types of UV leds were selected and purchased for testing, compared in Table 4:

Table 4. Comparison of UV LEDs [25, 26]

Product name	**T5H36** [25]	**P8D136** [26]
LED type	standard dip-LED	COB type power LED (SMD)
Wavelength	365 nm	365 nm
Lens	Glass	Silicone resin
Optical power output	1 - 2 mW	40 - 70 mW
Forward current	25 mA	0,4 A
Forward voltage	3,9 - 4,2 V	3,9 - 4,5 V

The standard dip-LEDs optical power output is too low for this application as was also proven by initial testing, as described in chapter 4. P8D136 was proven to be sufficient for 3M UV50 resin and was selected also based on their availability.

3.2.3.2. UV LED P8D136

The curing is performed by UV leds (P8D136), with a peak wavelength of 365 nm with an optical power output of 40 – 70 mW. [26]

- Maximum rated current: 0,4 A
- Rated voltage: 3,9 – 4,5 V

While driving the LED at the maximum rated current it is important to provide proper cooling in the form of a heatsink, otherwise the LEDs lifespan is shortened. Use of thermal adhesive or thermal paste is recommended in the datasheet between the base plate of the LED and the heatsink. When assembling the LED to a component it is also important keep in mind that the base plate is connected to the anode and electrical conductivity between the heatsink should be avoided and tested after assembly. While soldering the leads the temperature should not go over 280 ℃ and should not be kept at this temperature for more than 3 seconds, otherwise it may melt the housing of the LED.

For selecting the parameters of a heatsink, the following data from the product data sheet is needed, shown in Table 5:

Table 5. Required data for heatsink calculations

Forward current	I_f = 0,4A
Forward voltage	Vf = 4,5 V
Power output	P = 1,8 W
Maximum case temperature	$T_{c=}$ 85 °C
Maximum junction temperature	Tj = 125 °C
Thermal resistance of the COB module	Rj-c = 14 °C/W

Thermal resistance of thermal adhesive between the COB module and the heat sink, and the thermal resistance from heat sink ($R_{heatsink}$) which has to make that the total design stay below the maximum required junction temperature Tj.

According to the datasheet the maximum required junction temperature is 110 °C

$$25\ °C \leq T_j \leq 110\ °C$$

If ambient temperature is 22 °C, then the maximum temperature increase is 88 °C. For safety reasons we could consider that all of the power is dissipated as heat. $P_{dissipated}$ = 1,8 W

Thermal resistance of the COB module is 14 °C/W, therefore[27]:

$$T_{COB} = T_{junction} - \left(Rjc \cdot P_{dissipated}\right) \quad (3.1)$$

$$T_{COB} = 110\ °C - (\ 14\ °C/W \cdot 1{,}8\ W) = 84{,}8\ °C$$

Finding the thermal resistance of the heatsink:

$$R_{heatsink} = \frac{T_{COB} - T_{ambient}}{P_{dissipated}} \quad (3.2)$$

$$R_{heatsink} = \frac{84{,}8\ °C\ - 25\ °C}{1{,}8\ W} = 33{,}2\ °C/W$$

The thermal resistance of the selected heatsink should be therefore smaller than 33,2 °C/W. Based on this value a suitable heatsink can be selected. Using also a general online heatsink calculator [28] it can be estimated that a piece of U-profile aluminium with the dimensions 25 x 20 x 3 mm with a length of 20 mm would be also suitable for one described LED. Nevertheless, the size of the heatsink should be confirmed by testing it at the devices rated current and application to ensure the proper cooling of the LED.

3.2.4. Safety requirements

During the operation, The UV LED radiates, which precaution must be taken to prevent looking directly at the UV light with unaided eyes. Do not look directly into the UV light or look through the optical system. If there is a possibility to receive the reflection of UV light, protect by using the UV light protective glasses so that UV light should not catch one's eye directly. Precautions must be taken to prevent looking directly at the UV light without protective glasses that are intended for UV-A class light and cover the eyes also from the sides. [26]

Based on the datasheets [17, 18, 16] of adhesives and resins main safety requirements are:

- Protective gloves – causes skin irritation
- Avoid contact to skin – wash thoroughly with soap and water when in contact
- Avoid contact to eyes – rinse cautiously with water when in contact
- Avoid inhalation of spray or and ingestion

Safety requirements regarding fiberglass [29]:

- Normal work clothing is recommended to avoid skin irritation
- Protective gloves
- Protective eyewear
- When in contact with material, wash with cold water (warm water opens the pores of the skin)

4. PRELIMINARY TESTING

To estimate the curing time, shape and structure of the pultruded fiberglass and the force needed for pultrusion, a simple test bench was constructed, seen on Figure 9. Tests were done with 5 bundles of strand resulting in a pultruded round profile with a diameter of approximately 3,5 mm, based on the the requirements given in chapter 3.1.

The fibers were wound on a spool and then guided to a die made of a spirally cut polymer tube with a length of 80 mm. The fibers were wound through the spiral into the tube, pressed together and placed between a vice.

Adhesive was applied by hand and the curing was performed using 2 UV LEDs described in chapter 3.2.3. For measuring the pulling force a digital spring scale was used (max load 10 kg/resolution 5 g).

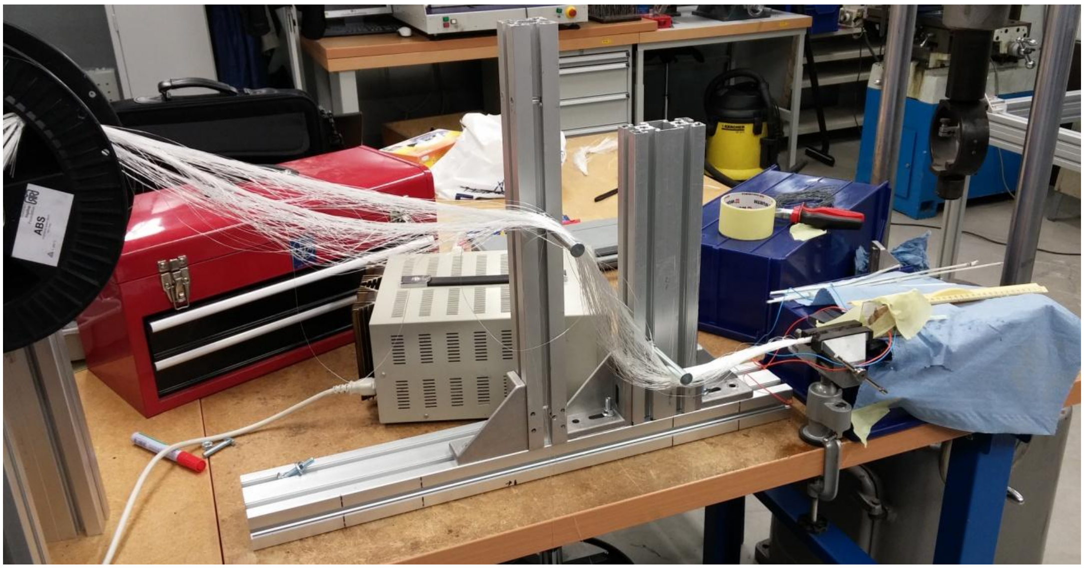

Figure 9. Pulling force test bench

Approximately 20 iterations were made combining different speeds. Tests showed results that a suitable pultrusion speed for this configuration was approximately 5 cm/min and the pulling force did not exceed 8 N. Depending on the saturation of resin and the feed of fibers the optimal value was 3 – 4 N. This is confirmed by the article discussed in chapter 2.3, where pultrusion load for pulling mechanism at a speed of 0,5 m/min was 10 N. Pultruded rods can be seen on Figure 10.


Figure 10. Manually pultruded rods

The bending of the structure was also tested which was done manually after exiting the material from the die. After curing the bent piece formed fibers well and was stabile. The characteristics of the pultruded structure were generally satisfactory. Due to the feature of the adhesive (3M UV50), the outside layer of the structure needs several hours to cure for a dry to touch finish.

5. SOLUTION CONCEPTS

For an automated, directly to the wall panel manufacturing of such a structure, conventional pultrusion solutions do not apply due to their pulling mechanisms and stationary resin tanks. The main complication in the general concept is the achieving of a suitable approach angle at which the device could approach the wall panel and form a connection to the anchoring place of the structure. Therefore, a system with separate driving, resin impregnation and guiding mechanisms is needed. For this, three main prospective ideas were developed for testing. It was decided that initially the pultruder body would stay vertical to eliminate a need for an additional drive to rotate the pultruder body and to simplify the design. A block diagram of the general pultrusion system concept is shown in Figure 11.

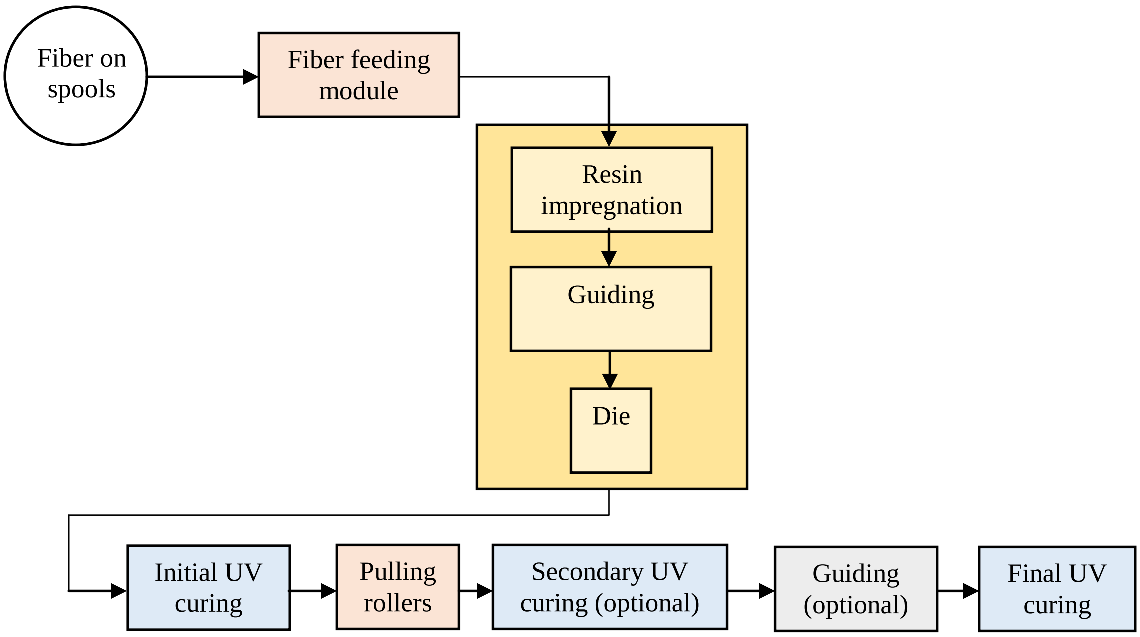

Figure 11. Block diagram of the pultrusion solution

5.1. Pultruder body with a hinge and flexible tubing for guidance

The pultruder body has a hinged piece containing a flexible hose for guiding the resin impregnated strands in the needed direction. The same piece also contains the LEDs for the final curing of the rods. Preliminary curing, if needed, is performed before the rollers that provide the pulling force to give the resin more viscosity, so that the pulling rollers would have more friction to the material. The main complication in producing the structure described is caused by not enough travel room when the pultruder is approaching the wall panel and the anchoring of the structure to the board should take place. As said, this concept would need pulling rollers that provide high traction for pulling the material through the die and forcing it into the guiding mechanism. An explaining diagram is given in Figure 12.

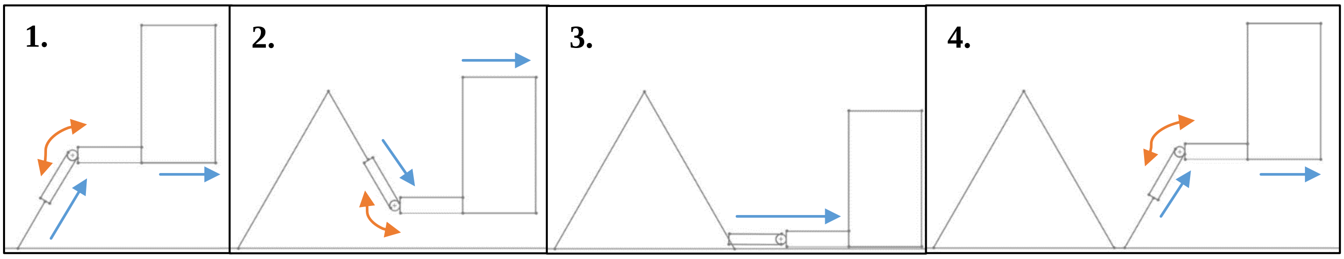

Figure 12. General motion diagram of the guided pultrusion

Motion steps:

1. The profile is fixed to the plate manually and starts moving upwards with the guiding tube at an angle of 60°.
2. After reaching the top of the structure the guiding tube is moved to an angle of 120° and starts its descent.
3. Reaching the bottom, the guide is made parallel to the plate and moved forward slightly, while producing a more flexible piece of structure. The structure is anchored in place by the elastic piece fed into the anchoring socket.
4. The guide is moved up along with the pultruder body and at the same time the guide tube is again turned to an angle of 60° while giving out a more elastic part of the rod. The process is repeated.

To achieve the needed approach angel, UV light source has to be regulated to provide a more elastic part of the rod that could be bent into the needed location and radius.

5.2. Pultruder body with a external guide

In order to achieve an approach angle that satisfies the requirements of the structure, a external guide could be used that is placed at a sufficient distance from the pultruder to give more clearance. The strands are guided to an external guide by tubing. Curing is performed similarly to the previous concept and the requirements for the pulling mechanism are similar. An explaining diagram is given in Figure 13.

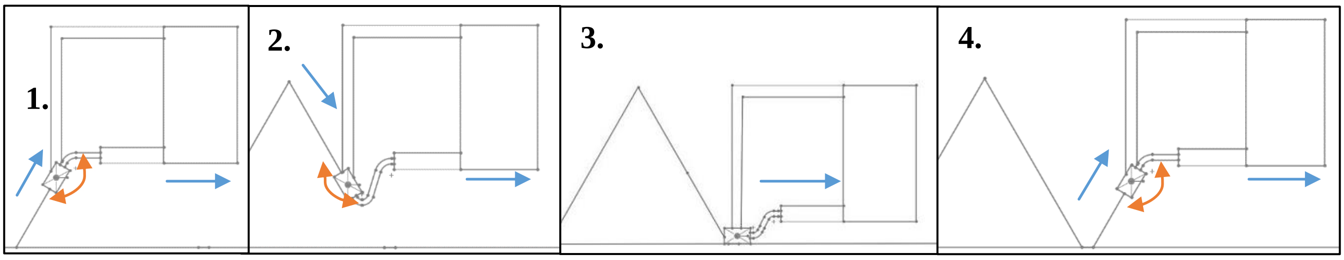

Figure 13. General motion diagram of the external guided pultrusion

Motion steps:

1. The profile is fixed to the plate manually and starts moving upwards with the external guiding piece at an angle of 60°.
2. After reaching the top of the structure the guiding piece is moved to an angle of 120° and starts its descent.
3. Reaching the bottom, the guide is made parallel to the plate and moved forward slightly, while producing a more flexible piece of structure. The structure is anchored in place by the elastic piece fed into the anchoring socket.
4. The guide is moved up along with the pultruder body and at the same time the guide piece is again turned to an angle of 60° while giving out a more elastic part of the rod. The process is repeated from step 2.

5.3. Folding the pultruded material by sections

The third concept would rely on folding the material to the needed specifications at a section of two straight pieces at a time. After fully curing the structure to the first bend, the device continues pultruding two straight rods while remaining horizontal and leaving a non-cured elastic piece of strand between them and finally moves back to fold the structure into the desired triangular shape. An explaining diagram is given in Figure 14.

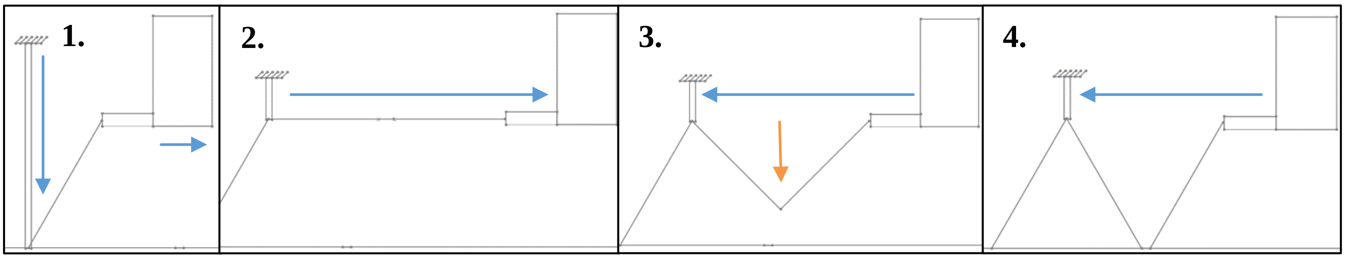

Figure 14. General motion diagram of the folding pultrusion process

This could be used with either existing linkage system described in previous chapters or without additional mechanisms, besides an additional mount to hold the tip of every linkage in place. The additional mount could be attached to the pultruder or to an additional robot manipulator that would the grip the structure and also provide additional resin and curing for anchoring the structure into the socket.

Motion steps:

1. The pultruder produces a cured rod in the desired length, leaving a flexible non-cured part in the end. The additional arm pushes the rod against the panel, injects resin into the socket and cures it.
2. The additional arm grips the end of the rod and the pultruder moves forward for two linkage lengths and leaves a flexible non cured part of the rod in the middle and also in the end.
3. The pultruder moves back and folds the linkages to the panel.
4. The additional arm equipped with resin injection and curing fixates the structure into the socket. Process starts again at step 2.

5.4. Comparison of concepts

Tabel 6. Comparison of pultrusion concepts.

Concept	**Flexible tubing**	**External guide**	**Folding by sections**
Pro	Does not need any additional gripping or supporting equipment	Does not need any additional gripping or supporting equipment	Gives a more thorough control over the forming of the structure
Con	Needs specific pre-curing and and high friction pulling rollers. Needs an additional motor to drive the guiding mechanism.	Needs specific pre-curing and and high friction pulling rollers. Needs an additional motor to drive the guiding mechanism.	Requires an additional manipulator with curing and resin injection

6. PROTOTYPE DESIGN

The prototype is designed to be fixed to the robot by an additional panel of aluminium or aluminium profile and therefore, for easier access, assembly and future modifications, the pultruder consists of different modules. The general measurements for the pultruder modules can be seen on appendix2.

All of the components were designed so that they can be made by CNC milling and lathing or with manual milling machines/lathes. The machining of most of the mechanical parts were ordered from Hecada OÜ, a company that specializes in manufacturing prototypes. For cost reduction, more simple components (e.g. cutting sheet material) were considered to be ordered from water jet cutting or laser cutting, but this would not have resulted in a sufficient saving. Therefore, most of the components were ordered from the aforementioned company and machined there by CNC milling and lathing according to the CAD models and drawings, except for some of the parts that were made by the author on a manual milling machine. Like the top motor mount, cover of the pultruder body, die plate, L-profile mounts, modified guide plates and all of the threaded holes for assembly were done manually to reduce the cost of the mechanical components.

6.1. Fiber feeding module

The fibers are fed to the pultruder using two rubber coated belt-driven rollers powered by a geared NEMA 14 stepper motor [30], described in chapter 6.4.

The module consists of two 10 mm aluminium sheets, milled to specification, and top and bottom sheets of 3 mm aluminium. The thickness of the materials is selected based on providing stability for the module and for simplifying the assembly with M4 bolts with a threading pitch of 1,0. This would reduce the chance of damaging the thread. One of the rollers is fixed to place, while the seconds acts an adjustable tensioner and is easily removable to assist in the initial placing of the fibers. For this, the sides of the module have milled in slots in them to hold in place and ease the assembly of the secondary roller. The dimensions of the module are selected based on that 10 bundles of strands, as they come from the spools can be fed through the system. The CAD-model is seen on Figure 15.

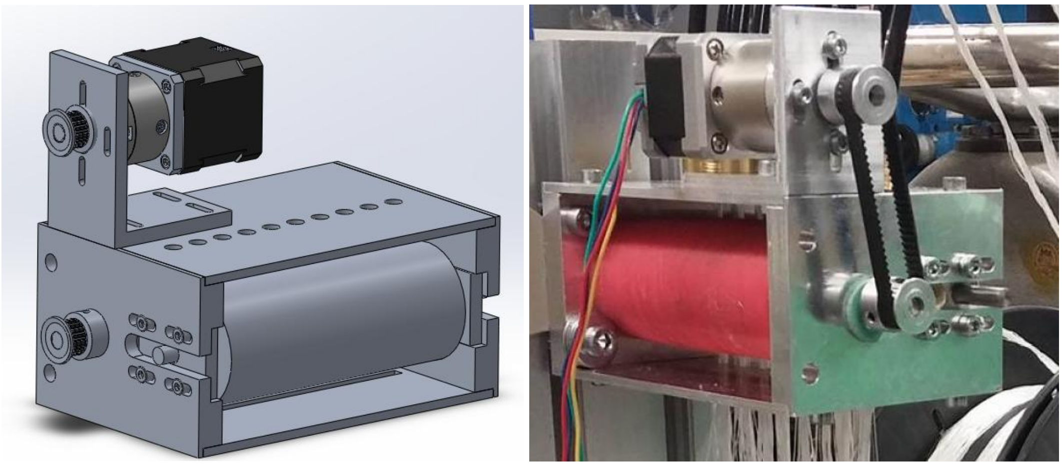

Figure 15. Fiber feeding module CAD model and implementation

A single stepper motor is mounted on top of the module with a 50x50x5 mm L-profile with adjustable distance to tighten the timing belt that transmits the rotational movement to the stationary roller, while the other is rotated by the friction between the contact area of the two.

The motor mount is designed for use with GT2 profile pulleys and a 158 mm timing belt for the same profile. This provides the option of tensioning the belt fully by moving the motor relative to the mount and the roller shaft and also removing the belt without any excess actions.

The rollers are assembled from a steel shaft (6 mm diameter), POM-C cylinder and rubber coating, with an overall diameter of 40 mm. The cylinders are fixed to the shaft with multiple M4 set screws. Rubber coating is placed over the cylinders with a press fit. Plastic washers are placed to control the axial thrust clearance.

The feeding of the strands to the module is designed by pneumatic tubing from spools of material, with a diameter of 6 mm, and are connected to the module by male M6 threaded push-to-connect type pneumatic connectors.

Roller bores and shafts are designed for iglidur J class [31] plastic plain bearings with the following dimensional specification:

- Shaft diameter – 6 mm
- Outside diameter – 8 mm
- Bearing width – 6 mm

Iglidur J class bearings have a low coefficient of friction when running dry and intended for low pressure, making it suitable for the discussed application. With a recommended maximum surface pressure of 35 MPa, iglidur J plain bearings are not suitable for higher loads.[31]

6.2. Resin impregnation and guiding module

In order to properly impregnate the fibers with the adhesive, the strands must be distributed evenly across the contact surface. For added flexibility the module has milled grooves to place different guide plates at different distances. The guide plates are made of two symmetrical pieces to able the initial placing and feeding of the fibers as can be seen on Figure 16.

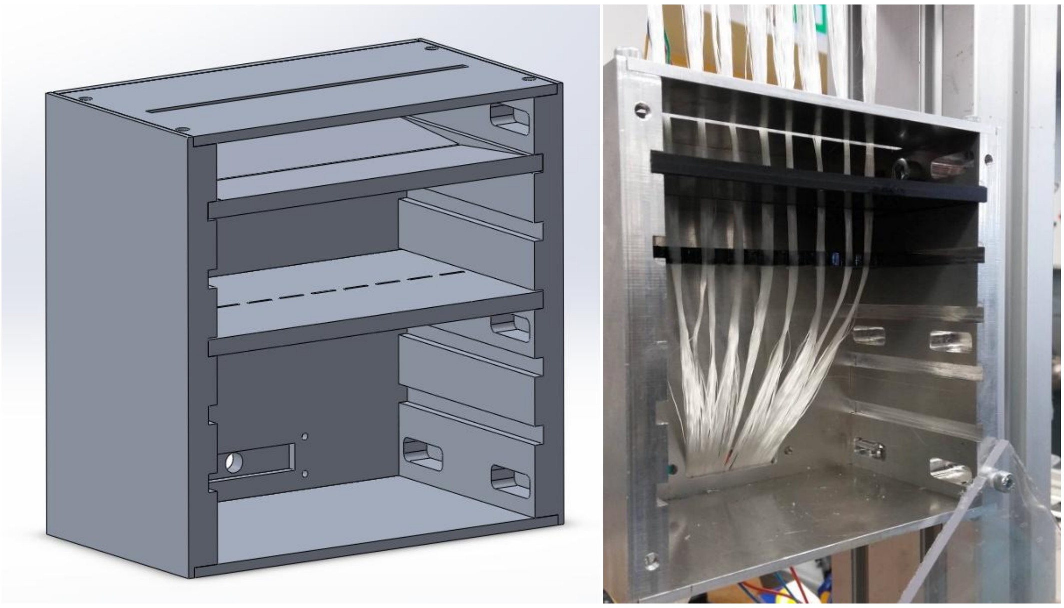

Figure 16. Resin impregnation and guiding module

Fibers need 2 to 3 guide plates at minimum for said design. First, an inclined piece to hold the resin while the strands are pushed together between the two sides of the plate and to hold in place the pool of resin that is guided by external tubing to the section. Secondly, a guide to hold the strands apart and, therefore, give the fibers maximal contact area with the first guide plate to achieve thorough impregnation. A third is needed to round the angle of the fibers before entering the die, that is mounted to the front side of the module. The die is made of a separate piece and interchangeable for different diameters, meaning different numbers of fibers. The die itself is drilled with a step (slightly conical hole) making it easier to push through the fibers, at the moment, a 4 mm hole is set for forming the fibers.

Additional slots are milled to the sides of the module to ease the threading and assembly of the module with M4 bolts. Slots help to remove the material cut by threading and provide a possibility to place nuts inside the slot when threads are damaged after extensive use.

Figure 17. Threading slots.

For the prototype, the cover of the module is designed to be made of polycarbonate (plexiglass) to give the opportunity to observe the formation of fiber while the device is working.

6.3. Puller module

Two NEMA 14 [32] stepper motors are mounted on two 3 mm bored aluminium sheets bolted together to give a stepped surface for motor mounting plates that can be adjusted for the initial placement of the fibers and the tensioning of the strand between the rollers. The selection of two 3 mm plates with corresponding slot sizes is made for cost reduction purposes. When bolted together they provide a slot for the motor plates to move perpendicular to the axis of the pultruded rods. The size of the module is considered to support either curing before the rollers or after, meaning, sufficient clearance is left for mounting the UV LEDs on either side. The CAD-model and the implementation is seen on Figure 18.

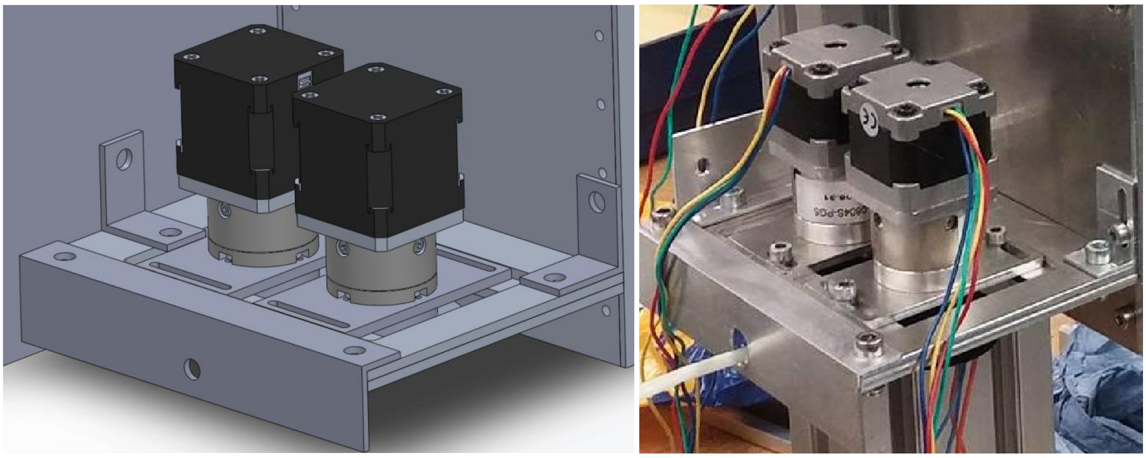

Figure 18. Puller module

The module is attached to the back plate of the pultruder body and to the impregnation and guiding module by pieces of L-profile aluminium (15 x 20 mm). For further attaching the components to the puller module an additional L-profile aluminium piece is bolted to the front.

Rollers for this module are designed with a U-profile shape to keep the shape of the pultruded profile and provide pulling force. Material selected for the rollers was POM polymer, for its availability and being easy to machine and modify. POM polymers are reported to be difficult to bond [33]. This makes the polymer more suitable for current application as adhesives do not bond with the material easily. Traction could be increased by coating the piece with rubber or cutting grooves into the contact area.

The selection of the diameter of the rollers was based on the size of the module and the dimensions of the motors that could be used, to provide sufficient clearance while tensioning the pultruder material between the rollers and keeping the overall dimensions of the module compact enough. On the other hand, the rollers should be with a maximum possible diameter to increase the theoretical contact surface with the pultruded material. An additional surface with a smaller diameter was designed for attaching the rollers to the motor shafts by M4 setscrews, as seen on the CAD model on Figure 19. The lathed pulling rollers were modified to provide more traction by adding perpendicular grooves to the contact area of the rollers as seen also on Figure 19.

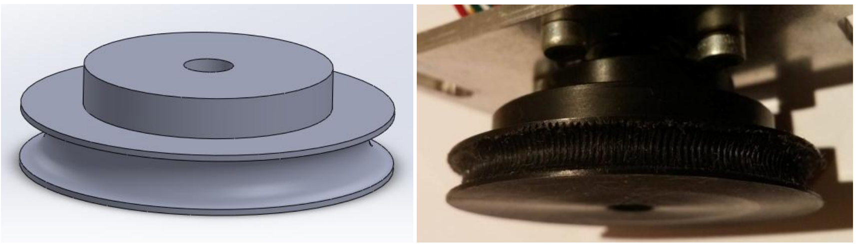

Figure 19. CAD-model of the pulling roller next to the grooved and already assembled one.

6.4. Stepper motors

Stepper motor selection was based on the criteria that the prototype needs a slow speed electrical motor with high torque capabilities within a wide range for further applications and improvements, while being compacts enough to fit in the requirements of the device.

For the final pulling of the material, two rollers with a diameter of 40 mm with a U-profiled groove were designed. Based on this and the results of preliminary testing, described in chapter 4.1., the approximate load torque of the motors can be calculated. For this the maximum value of the results are considered. $F_{pulling\ force} = 8N$, $r_{pulley} = 20\ mm = 2\ cm$

$$T_{load\ torque} = F \cdot r \quad (6.1)$$

$$T_{load\ torque} = 8\ N \cdot 2\ cm = 16\ Ncm$$

Assuming that the load is divided equally one motor should be able to handle a load torque of $8\ Ncm$.

Based on this, motors corresponding to the NEMA14 standard were selected, with two different gear ratios, 5:1 and 19:1, with holding torque of 84 Ncm and 280 Ncm, respectively [32][30]. This gives the opportunity for further development, varying and testing with different torque characteristics.

The corresponding safety factors are calculated as follows:

$$Safety\ factor\ 1\ (5{:}1\ Stepper) = \frac{84\ Ncm}{8\ Ncm} = 10{,}5$$

$$Safety\ factor\ 2\ (19{:}1\ Stepper) = \frac{280\ Ncm}{16\ Ncm} = 35$$

It should be noted, that the holding torque is the amount of torque that the motor produces when it is operating at maximum rated current but the motor itself is at rest. This means that this value shows the maximum torque capability of the motor to hold itself at a fixed position. Therefore the actual starting dynamic torque value is below that number, depending on the the type of motor and maker. A general torque/speed curve of a stepper motor is pictured on Figure 20. The torque/speed curve depends on the type of motor. Unfortunately, selected motors datasheet does not contain a precise torque/speed curve.

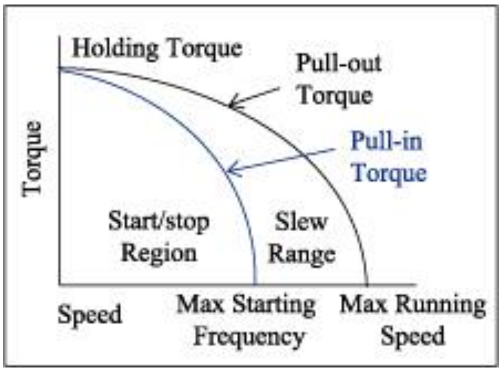

Figure 20. A general torque/speed curve of an stepper motor [34]

In Table 7, the calculated steps per revolution and step rate frequencies are calculated for different microstepping options, of selected stepper motors, at the speed of 0,8 rpm, which corresponds to a pultrusion speed of approximately 5 cm/min as also tested in chapter 4.

Table 7. Stepper motors step frequencies at different microstepping rate.

				Frequency of step pulse at microstepping rate for 0,8 revolutions per minute					
Motor:	**Torque N*cm**	**Steps per rev**	**0,8 rev**	**1**	**2**	**4**	**8**	**16**	**32**
Nema 14 5:1	83,9	1028,5	822,8	13,7	27,4	54,8	109,7	219,4	438,8
Nema 14 19:1	280	3829,7	3063,8	51,0	102,1	204,2	408,5	817,0	1634,0

It should also be noted that some sources say that while using microstepping, the torque characteristics of the stepper motor can change, giving out up to 30% less when microstepping[35][36]. Other tests show that there is no significant change in the torque characteristics while microstepping. This depends of course on the motor and driver used, but in this application, even a 30% drop of possible load torque is not an issue. Controlling the stepper motors is discussed in chapter 7.

6.5. Fiber spools

In addition to the components described in chapter 5, spools for storing the fiber strands were needed, as the material described in chapter 3.2.1. comes on one large spool of continuous bundle of fiber. The device requires up to 10 bundles of said fiber and therefore needs storing on separate spools that could be rotated by the pulling force of the fiber feeding module. In addition to storing the fibers, the fibers should also be separated to avoid knots in the fiber feed and any problems regarding the wrong alignment of fibers in the feed process.

For the implementation of this, three used 3D printer filament spools were used. Due to the fact that the spools are quite wide, temporary separators were used to divide the spool to sections to house three different fiber strands at a time. The spools were placed on a mount constructed of industrial aluminium profiles. A picture of the mounted spools can be seen on Figure 21.

Figure 21. Separated fibers wound on spools.

6.6. Solution for housing the UV LEDs

When attaching the light source to the device it is important to also take into consideration the heat conductivity and electrical conductivity between the LED base plate and the heatsink as described in chapter 3.2.3.2.

For testing the current application the LEDs were soldered onto pieces of PCB breadboard that had a corresponding hole cut into them for the placement of the LED so that the bottom plate of the LED would be thermally connected to the surrounding material through thermally conductive adhesive. Wires were soldered onto the PCB and the corresponding leads of the LED. The LEDs were placed in a 3 mm thick piece of U-profile aluminium by thermal adhesive to act as an initial heatsink and were tested for electrical conductivity between them to ensure that the anode would not be connected to the aluminium housing. A picture of this can be seen on Figure 22.

Figure 22. UV LEDs (P8D136) housed in U-profile aluminium

The U profile was attached to the part of the module with thermal adhesive to improve heat conductivity to the aluminium plates of the module.

7. CONTROL OF MOTORS AND UV LIGHT SOURCE

Controller selection for the management of the pultruder system was based on the need of availability and flexibility of the prototype, it was considered that the system has to be simple and expandable when needed, because a need for adding components may occur.

A cost efficient solution for controlling multiple stepper drivers and high power LEDs is a 3D printer controller that contains multiple stepper drivers (usually up to 5) and PWM controllable MOSFETs. A popular setup in the open-source 3D printing community is the combination of an Atmel Atmega 2560 [37] microcontroller on an Arduino with an extension board called RAMPS. This gives the opportunity to use the very common Arduino and an inexpensive extension board that is ready for application and eliminates the need to make a separate PCB for housing drivers and components separate of the microcontroller used. The use of such solutions also gives the opportunity to change components easily and quickly when problems occur, which is useful for a prototype or such a testing platform.

Technical specifications of the used controller are seen in Table 8.

Table 8. Technical specifications of the used microcontroller.[38]

Microcontroller	Atmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	128 KB of which 4 KB used by bootloader
Clock Speed	16 MHz

The Atmega2560 can be programmed by using the Atmel Studio, the Arduino IDE or MS Visual Studio with the Arduino extension.

7.1. RAMPS 1.4 extension board with DRV8825 drivers

The RAMPS 1.4 is an extension board designed for the Arduino Mega 2560, sometimes referred to as the Reprap Arduino Mega Pololu Shield [39]. A picture of the board used in this application, assembled with the necessary components, can be seen on figure 25.

Features important to this application [39] :

- Up to 5 stepper motor drivers
- 3 MOSFETs
- All the MOSFETs are hooked into PWM pins

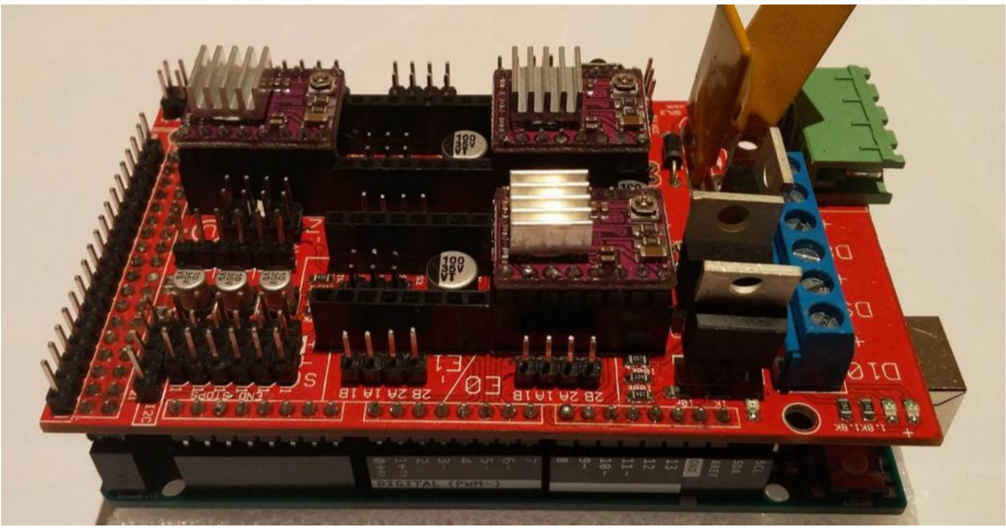

Figure 23. The assembled extension board with the Arduino Mega 2560 underneath

There are two common stepper drivers used with the RAMPS board, the DRV8825 and the A4988. Based on the RepRap Wiki and the DRV8825 datasheet the DRV8825 should provide better heat dissipation due to improved PCB layout [40]. The Texas Instruments DRV8825 is a newer model and in addition has the option of 1/32 microstepping, while the A4988 has an option of 1/16 microstepping at maximum. This gives the possibility of using a more smooth and quieter (less vibrations) motor control at low speeds with the DRV8825, that were selected for use in this project. Otherwise the drivers are quite similar, both have a rated output current of approximately 2 A and have adjustable current control that lets one set the maximum current output with a potentiometer. Also both have overcurrent protection and have a thermal shutdown function. [41][42]

When assembling the board, the heatsinks come usually with the driver and it is important to use heat conductive adhesives while applying the heatsinks to the drivers. Active cooling of the drivers is reccomended but depends on the output current to the stepper motors, normal conduction through the heatsinks provides sufficient cooling to a certain current limit. The thermal overload protection of the drivers activates when they reach the temperature of approximately 150 °C [40].

The output current was calculated according to the formula provided in the datasheet of DRV8825 [41], shown in formula 7.1

$$I = \frac{V_{ref}}{A_v \cdot R_{sense}} \quad (7.1)$$

Where

I - maximum current driven through winding

A_v- Gain of driver

R_{sense} - sense resistor value

$$I = \frac{0{,}2\ V}{5 \cdot 0{,}1} = 0{,}4\ A$$

The input voltage is set by adjusting the potentiometer on the driver and can be measured using voltmeter between the ground pin and the potentiometer screw. Initial values for this project were set to 0,2 V that gives according to the formula 7.1, an output current of 0,4 A, while the rated output current of the motors is 0,8 A. Motors were tested in application and the value was corrected when needed. Motors will stall when the load is too high and current too low and will overheat when the current is set too high.

Before assembling the board the wanted microstepping level has to be defined using jumpers on the pins beneath the drivers connecting them (marked MS1, MS2, MS3).

It should also be noted that it is possible to mount the drivers on the board in the opposite direction. This will short circuit the board and result in driver damage and/or in the extension board damage. The potentiometer should always be on the same side as the power input sockets on the board, see on Figure 23. The assembled extension board with the Arduino Mega 2560 underneath as green sockets on the right side of the board.

7.1.1. Controlling LEDs

The LEDs are controlled by the MOSFETs onboard the extension board used by pulse-width modulation (PWM).

Calculating the current limiting resistors is done accordingly to the formula:

$$R = \frac{V_{supply} - V_{Forward}}{I_{forward}} \quad (7.2)$$

Where

R – current limiting resistor value

V_{supply} - supply voltage

$V_{Forward}$ - LED forward voltage

$I_{forward}$ - forward current of the LED

$$P = I_{forward} \cdot V_{drop} \quad (7.3)$$

Where

P – power

V_{drop} – voltage drop of the resistor

Based on the data provided in chapter 3.2.3. , the high power LEDs would require a resistance with the closest value to a 20 Ω resistor capable of 3,5 W. And the corresponding values to the T5H36 LED would be a resistor with 330 Ω resistance and being capable of 0,5 W

7.2. Power Supply Unit

The power supply is selected based on the maximum require power consumption of the main used components, shown in table 8.

Table 9. Power consumption of components

Component	Quantity	Maximum current (at rated voltage)	Rated voltage	Estimated power output
Stepper motors	3	0,8 A	12 V	28,8 W
Controller	1	0,2 A	5 V	1 W
UV LEDs	2	0,4 A	4 V	3,2 W
Sum:		**3,4 A**		**33 W**

The power supply unit was also selected on the prerequisite that it should be low cost and highly available, therefore a standard PC power supply unit is used with an output power of 450 W.

DC outputs of the power supply used :

- +12 V_1 – 12 A
- +12 V_2 – 14 A
- +5 V – 30 A
- +3.3 V – 20 A

Selected power supply is sufficient for use with one 12 V line. Based on this the power is fed through the 5 A connector of the RAMPS board, (the secondary power input is intended for up to 11 A). The Arduino board is capable of running only off the 12 V power provided by the RAMPS board through the voltage regulator on the board, that provides 5 V to the microcontroller.

7.3. Controlling steppers

For controlling the stepper motors, pre-existing libraries for the Arduino microcontroller were used in programming the controller, to speed the process of developing suitable control. Because at the time, requirements for the library would only include running simultaneous stepper drivers at the same time with synchronised or different speeds, controlling the direction of the rotation and the speed of the steppers. This should be done easily by either predefining the characteristics of the drivers and motors and setting the appropriate rpm speed at once, or using the step frequency as an input.

An Arduino library named AccelStepper [43] was selected as it fulfils the aforementioned requirements and in addition also supports acceleration and deceleration.

As an input, the number of steps per second is used to set the speed of the motor. The value being either positive or negative sets the direction of rotation. The corresponding values for calculating the necessary can be seen in chapter 6.4. The code used itself can be seen in appendix 1.

7.3.1. Graphical user interface

As the prototype is only used for testing at the moment, a GUI was developed with MS Visual Studio using C# and a serial port connection to give the user a more convenient way of changing the pultrusion parameters. A screenshot of the interface can be seen on Figure 24.

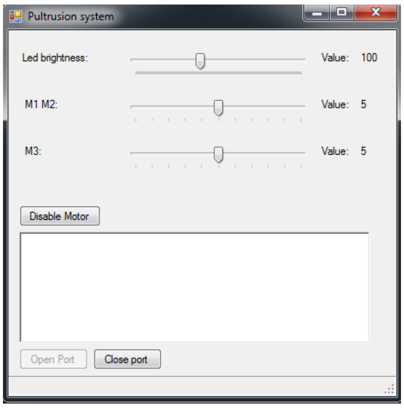

Figure 24. Screenshot of the GUI

The user has the opportunity to open and close the serial connection to the microcontroller and to see error messages in the text box above. Motor speeds are changeable by dragging the corresponding cursors to the specified revolutions per minute (RPM) value in a range of 0 – 10. Pulling module speeds are set with the same slider. The program calculates the necessary step pulse frequency to the corresponding RPM speed and sends the data to the microcontroller. The user also has the option to enable the motors and to set the LED light intensity in the range of 0 – 255 of PWM value, meaning 0 – 100 % intensity of the light source.

8. TESTING

8.1. Materials for testing

Due to supply problems regarding UV adhesives, all materials that are described in chapter 3.2.2. were not available for testing at the time of the completion of this thesis. Therefore testing was done mainly with Formlabs „Clear“ photopolymer resin and a small amount of 3M UV50 adhesive.

8.2. Setting up the device - feeding the fibers

During the first setup of the device, the most effective way of feeding the fibers was found out to be impregnating the fibers with the resin and curing parts of it to simplify the feeding of the strands from the spools to the fiber feeding module through the tubing and to the die. Any other high viscosity adhesive would also work as well but may result in premature curing in the tubing and therefore cause feeding failure afterwards. The “Clear” resin does not cure under visible light for a long period of time (hours) but forms the fibers to stick together even without curing and simplifying the process of initial feeding of the fibers.

For feeding the fibers through the feeding module they have to be first pulled through the tubing and the tubing connectors which can be then screwed onto the top plate of feeding module. Then by removing the tensioning roller the strands can be pulled through the module and guided through the bottom plate as seen on figure 26.

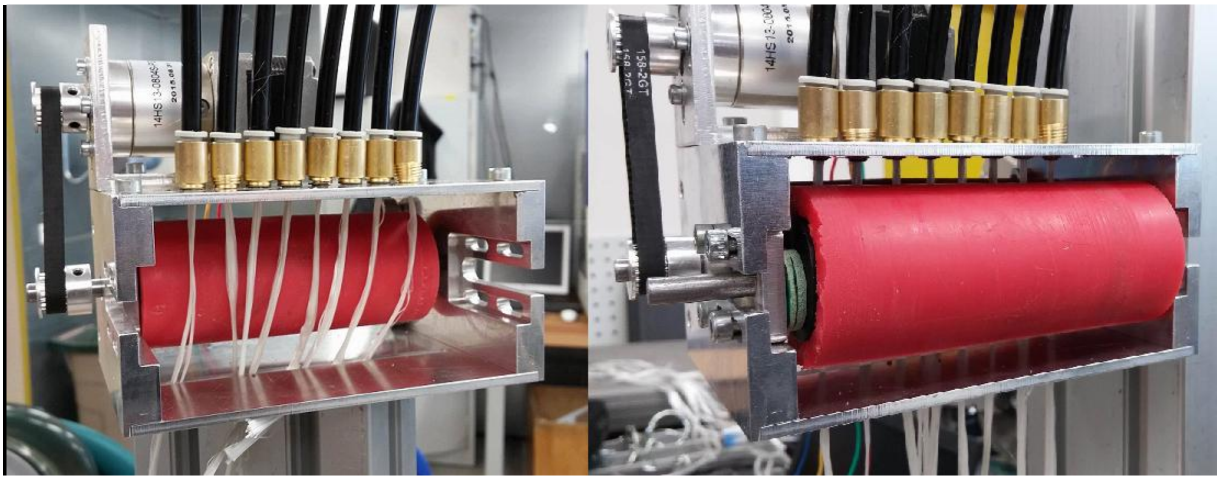

Figure 25. Guiding the fibers through the feeding module and after placing the tensioning roller.

The fibers can be then inserted to the impregnation and guiding module through the slot on top and pulled through the hole in the front of the module where the die is attached. The rear part of the guiding plates should be inserted beforehand. Seen on Figure 26.

Figure 26. Guiding the fibers through the guiding and resin impregnation module.

The fibers can then be pulled through the die. For this the tip of the fibers should be cut to length, formed with resin into a round shape, cured and cut to conical shape to simplify pushing through the fibers. The die is drilled with a step (slightly conical hole) making it easier to push through the fibers, pliers can be used to assist. Fibers pulled through the die plate can be seen on Figure 26.

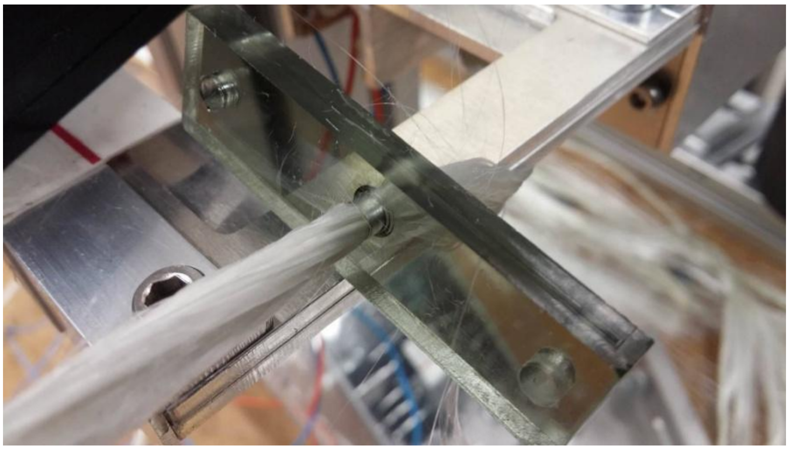

Figure 27. Fibers pulled through the die plate.

The die plate can be bolted on to the module, the feeding module tensioner roller can be tensioned firmly against the stationary roller and bolted together. The fibers should be then tensioned by hand and set into the slots of the guiding plates, front plates put into place to fixate them and the cover of the module bolted on. After this the first feeding of the system can be done with feeder motor and resin impregnated fibers can be placed between the pulling rollers.

8.3. Initial testing – pultruding straight rods

Initial testing was done with a stationary device attached to pieces of wide industrial aluminium profile. Resin impregnation was done manually by applying resin to the fibers with a syringe before their entering to the guiding and impregnation module, instead of filling the intended section above the first guide plate continuously full of resin, to save the amount of wasted resin. The assembled device for the initial testing can be seen on Figure 28.

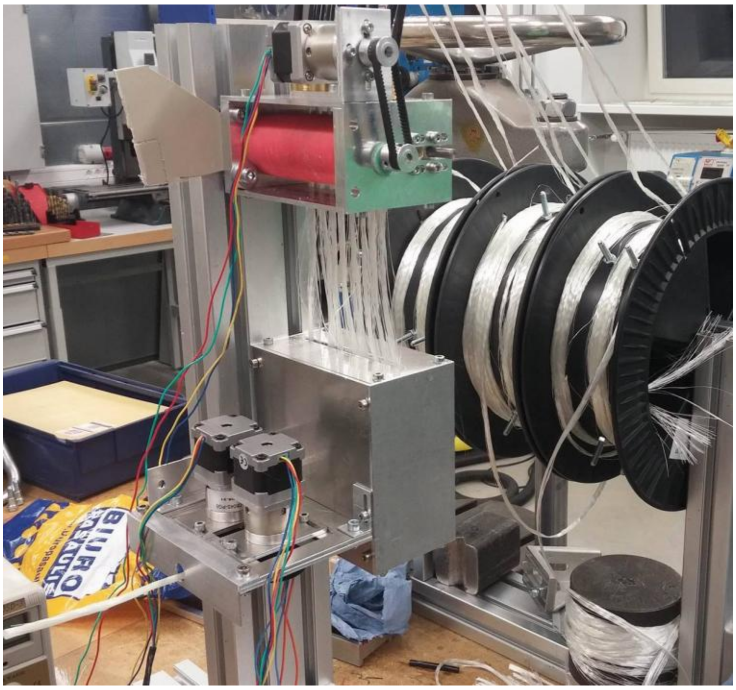

Figure 28. Device setup used for initial testing

Tests showed that the 3D printer resin is not suitable for the current roller design in the pulling module. The resin is with a lower viscosity (as described in chapter 3.2.2.) and does not provide enough friction between the contact area. When tensioning and adjusting the rollers to interlock the fibers with enough force to provide friction, then the structure of the rounded profile was lost. Tests were made with pre-curing the resin with two T5H36 LEDS but they did not provide enough curing even at low speeds. The selected high power LEDs were placed in the pre-curing position to provide sufficient pre-curing, but tests showed that the resin cured unstably, even with different intensity of the UV light. Meaning, that while some inner or middle parts of the fiber rods were cured fully, outer parts were left totally uncured. Bending the pre-cured rods meant that some of the inner fibers did not bend and the outer layer did still not provide enough friction for the contact area. The formation of fibers before the adding of pre-curing can be seen on figure 29. Light with longer wavelength should be tested for curing of said resin.

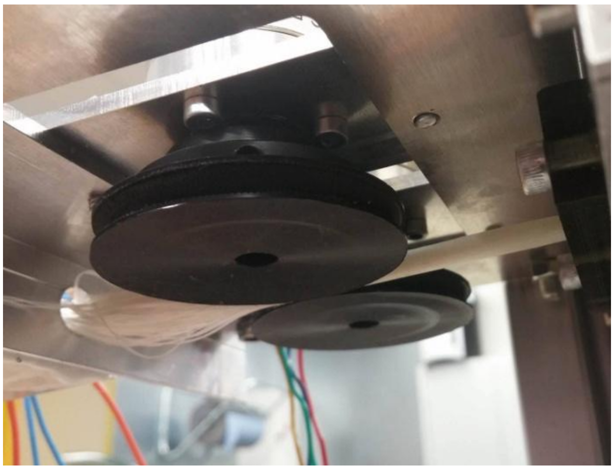

Figure 29. Fiber formation after die.

Therefore, it was decided that the most optimal concept to continue with, was the folding of the structure by sections as described in chapter Folding the pultruded material by sections as described in chapter 5.3. Fully pre-curing the material provided enough friction between the rollers for the pultrusion process to work and to test the work of other modules. That proved that feeding of the fibers works as intended and that the feeding module should be started before the pulling module to provide a sufficient reserve of fibers before the guiding module.

This gave a basis to presume that the concept of folding the structure by sections is implementable with leaving short sections of the material uncured.

8.4. Selection of optimal fiber density

To determine the number of optimal fiber bundles to be used with the corresponding 4 mm die, a series of tests were completed with three different quantities of fibers and both materials were used to determine any changes in the structure. To ensure proper curing and impregnation, so that the pultruded rods could also be used to test their tensile and yield strength the pultrusion speed was lowered to 20 mm/min. This gave the option of observing the pultrusion attentively to observe any problems with resin impregnation and curing. Curing power was set to maximum to fully form the fibers so that they would be suitable for further testing.

Based on the experience from initial testing the quantity of eight, nine and ten fibers were selected for testing. While pultruding the material with the resin at a fiber count of eight it was observed that at times the die did not provide necessary load to the rod while being cured and caused warping of the structure side-to-side, which lead to an oscillating effect when the deformed part reached the rollers. Parts made with the defect are shown on Figure 30. Attempts were made to correct the defect by realigning the pulling axis relative to the die, but after a short period of time the problem occurred again. It was therefore concluded that using eight fibers to form a 4 mm rod with said resin was not sufficient.

Figure 30. Deformities with 8 strands of fiber on top and a rod with minor deformities of the same kind shown below.

Similar tests were completed with nine and ten bundle of strands and no similar deformities occurred. Nevertheless, it was observed that at ten fibers per rod the 3D printer resin did not form the fibers as well as previously. The outside layer of the material was not fully impregnated, despite being in contact with resin for an adequate time, and lacked therefore in strength. Possible reason for this was the too narrow die for this number of fibers and as a result the resin was pulled off of the structure while being pulled through the die and was left in impregnation module. It should be also noted that the pulling load exceeded the friction between the pulling rollers at times and the pultrusion had to be assisted manually.

The optimal number of fibers concluded by the tests was nine. This resulted in a rod that was well impregnated with resin and did not have deformities. Also, no problems occurred with the pulling of the material. A picture of the rod consisting of nine bundles of fiber can be seen on Figure 31.

Figure 31. Nine bundles of fiber being pultruded. View from below the pulling module.

As the optimal fibre density was found, tests were done with the 3M UV50 adhesive and as said before, only a small amount was available for use, so only tests with the predefined optimal number of fibre density were conducted. The results were satisfactory, the formation of fibers seemed to be more effective compared to the resin used, as the surface of the rod was smoother and the impregnation of adhesive seemed to be more consistent at the same speed.

While cutting the rods to reveal the cross-section, it was also observed that the resin impregnated fibers did not cure fully, an area of approximately one third of the cross sectional area in the middle of the rod was not cured. On the other hand, the rods made with adhesive were fully cured at the same conditions.

9. ANALYSIS OF THE PULTRUDED MATERIAL

To evaluate the strength of the pultruded 4 mm rods, tensile and compression tests were conducted to give an initial overview of the suitability of the structure for the intended application.

Pultruded material described in chapter 8.4. was used for making test specimens suitable for compression and tensile strength tests. The shape of the specimens was based on TUT’s Laboratory of Mechanical Testing and Metrology regular test specimen size, as was consulted with them beforehand. Approximately 15 cm long pieces were cut from the rods of different density with a metal cutting saw and several additional pieces about 3 – 5 cm long of every corresponding density were cut to make reinforcements for the fixing points in the tensile/compression test machine to prevent breaking near the mounts and to move the point of highest stress to middle part of the pultruded rod. Reinforcements were added to the rod by using the resin used for pultrusion and curing it with the light source also used in the pultrusion process. As was described in chapter 8.4, the Formlabs “Clear” resin used for pultrusion does not cure fully even at low pultrusion speeds due to a possibly much lower depth of cure dimension and therefore, to give the materials more equal terms, the specimens were left to post-cure after adding reinforcements under visible daylight (placed on a windowsill) for approximately 6 hours to fully cure. This also aided in the curing of the reinforcements, but even after the aforementioned time, some of the resin used for reinforcement was not tack-free dry. Similarly to the 3M UV50, the Formlabs “Clear” resin does not fully cure the layer exposed to oxygen. A picture of the test specimens can be seen on Figure 32.

Figure 32. Test specimens for compression/tensile testing

As tensile strength of glass fiber is more well known and does not depend so extensively on the properties of the resin, therefore, emphasis of the tests was placed on compression testing to evaluate the strength properties of resin formation between strands. Two specimens on the right, shown on Figure 32, were used for tensile testing to give an comparison overview of a resin cured optimal (9 bundles of fiber) rod and the same rod with no resin applied for short section.

Tensile tests showed that even non impregnated fibers were capable of high tensile stress as can be seen on Figure 33. Ranging up to about 500 MPa at a maximum load of 7,4 kN. Same test was conducted with a fully cured rod, which showed a tensile stress maximum load of over 700 MPa at a maximum load of 8,82 kN, when a reinforcement from the bottom of the rod broke and slipped out of the mount. Therefore, it can be assumed that the tensile strength of such glass fiber rod is much higher.

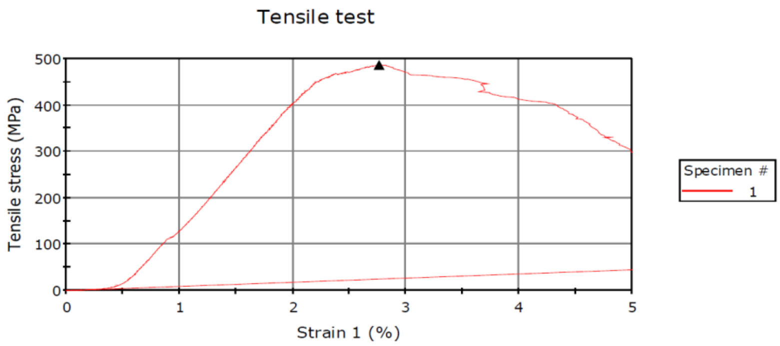

Figure 33. Tensile stress of non-cured fibers, tensile stress in MPa vs. Strain in %

Compression tests were conducted also at the Laboratory of Mechanical Testing and Metrology in TUT. The corresponding graph with all the test subjects is shown in Figure 34 and the results in Table 10. Compression test results for pultruder specimens

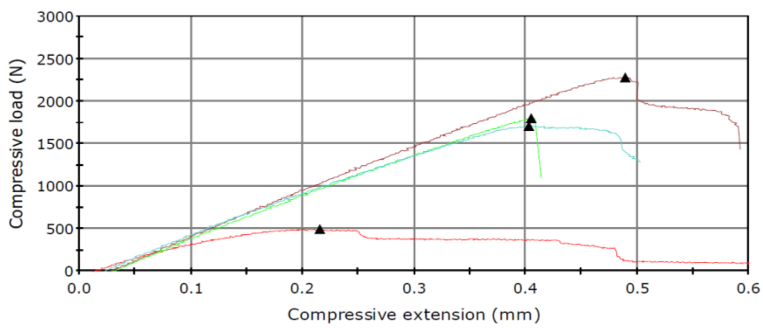

Figure 34. Compression test for 4 test specimens. Compressive load in N vs. compressive extension in mm. See also

Table 10

Table 10. Compression test results for pultruder specimens

Specimen	Rate (mm/min)	Maximum compressive ext (mm)	Maximum load (kN)	Colour on graph
10 bundles of fiber (resin)	1,0	0,22	0,50	Red
9 bundles of fiber (resin)	1,0	0,49	2,28	Brown
8 bundles of fiber (resin)	1,0	0,40	1,80	Green
9 bundles of fiber (adhesive)	1,0	0,40	1,71	Blue

The tests showed expected results that the weakest specimen under compression load was the specimen with 10 bundles of strand with insufficient resin impregnation and curing. It was estimated that the most durable under compression load would be the fibers that were cured with the adhesive, but instead the adhesive with a density of nine bundles of strand showed similar results to a resin cured eight bundle specimen and the most durable by a notable difference, was the specimen with nine bundles of fiber and cured with resin.

When deciding the optimal configuration for pultrusion density it should be taken into account that the resin does seem to be more durable to compression, but needs sufficient time for post-curing, when the adhesive reaches its final strength more quickly.

10. FUTURE WORK

10.1. Implementing with a robot

The next step for testing the selected concept would be implementing the solution with a cartesian robot provided by the Department of Mechatronics. To test the concept, the second manipulator or gripper described in chapter 5.3. has to be simulated, this would give an insight on the possible design of the secondary “arm” and whether there is a need for additional guiding mechanisms. The manual resin feeding, used at the time to save material, should also be replaced by filling the impregnation module with a sufficient amount of resin. In order to achieve this, the module has to be reassembled with sealant to prevent any leaking of the resin. Problems regarding friction in the pulling module would have to be assisted by the movement of the robot when flexible pieces of the structure are made. Depending on the gripper arm used and the specification of the robot, it may be possible that no additional pulling force would be needed by the stepper motors when implementing said concept.

10.2. Design improvements

The first major design improvement would be the development of more effective pulling rollers for better traction altogether and also with partly cured materials. One option would be to design custom rollers with slightly elastic rubber coating, on a steel or plastic centerpiece, that follows the cross-section of the pultruded profile similarly to the ones used at the moment. Secondary option would be to use some sort of tracked wheels option that would greatly increase the contact area between the pultruded material and the pulling units. These would also need to have a corresponding groove in their shape to keep the cross-section of the pultruded material.

Redesigning the die in an order that the it could be adjustable would also be useful for easier assembly and for changing the diameter. This could be achieved with changeable nozzles that correspond to a certain diameter with flexible protruding pieces in the direction of the movement and are tensioned by a conical nut placed on top, after the fibers are pulled through.

The use of capacitive sensors on the pultruder would be useful for measuring the resin level in the module and also the detection of the movement of fibers could be implemented to prevent any issues when there is a fiber jam.

The resin feeding system could be implemented by using pneumatics to either continuously or at a certain interval deliver resin to the module. Pressurised tanks are used to deliver UV lacquer to UV coating machines used in PCB production that could be also used for this solution at a lower pressure.

When the prototyping and testing phase of the product is finished, the controller for the system should also be replaced to give the product more reliability in industrial conditions. Alongside industrial durability this would also give the device some more added functionality.

CONCLUSION

It can be concluded from the thesis that a compact pultrusion system meant for use with a industrial robot can be used with ultraviolet light curing of adhesives and resin. Pultrusion itself can be done by stepper motors.

Comparison of 3M UV50 adhesive and Formlabs Clear resin was done based on the structures pultruded with the prototype, as a result it can be said that the optimal density fibers of such a pultrusion system is nine bundles of fibers at 4 mm pultruded round profile. The resin showed higher results when under compression, but did not form the fibers so well or cured as fast as the alternative adhesive.

Optimal speed for the pultrusion process using UV curing resin was between 20 – 50 mm / min.

SUMMARY

The aim of the thesis was to find an alternative and more efficient way of producing fiberglass structural members to increase the efficiency of modular concrete wall building by OÜ Kodasema.

The thesis was based on the research performed to ensure the success of the proposed solutions. Initial testing showed that the method of pultrusion was promising for use with a novel compact pultrusion device. Several concepts were developed to provide a prototyping platform that would prove the effectiveness of a compact pultrusion method using ultraviolet light for curing the structure. When designing the prototype, it was taken into account that the device should be implementable by a fully automated solution, compact and lightweight enough to be fitted to a smaller industrial robot.

The prototype was constructed so that future expansion and flexibility would be ensured. After the completion of the initial prototype, testing was performed to find the most suitable concept for further development. Due to the fact that UV-curing adhesive used for initial testing and designing of the prototype was not obtainable, a more available alternative was found to prove the concept in the form of UV-curing resin used in 3D printers. Test specimens were made to test the strength of the used materials and to provide comparison between two materials used for curing. Overall results showed that the material used for initial testing, the UV-adhesive was more suitable for the application. During testing the optimal density for the pultruded material was also found.

The prototype provided a platform for material testing and provided important information for the application of future improvements. The next step for testing the selected concept will be implementing the solution with a cartesian robot to develop a more flexible lightweight pultrusion technology.

KOKKUVÕTE

Käesoleva töö eesmärk oli leida alternatiivseid võimalusi OÜ Kodasema töö efektiivsemaks muutmiseks ruumiliste klaaskiudkonstruktsioonide tootmisel.

Magistritöö põhines tehtud uurimustööl, et tagada võimaliku lahenduse edu. Esialgsed katsetused näitasid, et pultrusiooni tehnoloogia on kasutatv uue kompaktsema kergekaalulise seadmega. Töö käigus arendati erinevaid kontseptsioone, et saada prototüübi platvorm, mis tõestaks kompaktse pultrusioonmeetodi kasutamise efektiivust UV-valgusega kõvenemisega uudseid võimalusi prototüüpseadme ehitamiseks eesmärgiga toota tulevikus klaaskiudkonstruktsioone pultrusiooni teel, selleks töötati välja erinevaid kontseptsioone. Prototüübi disainimisel sai määravaks seadme kompaktsus ja kerge kaal, et tööd oleks võimalik teha täisautomaatselt väiksema tööstusliku robotiga.

Prototüüpseade sai konstrueeritud võimalikult paindlikuna, et tulevikus oleks võimalik lahendust edasi arendada. Pärast esialgse prototüübi valmimist tehti katseid leidmaks kõige sobivam kontseptsioon edasiseks arenduseks. Kuna töö esimeses etapis katsetatud ja lubavaid tulemusi andnud UV-kõveneva liimi kättesaadavus ei olnud käesoleva töö teostamise perioodil hiljem enam võimalik, keskenduti kontseptsiooni tõestamiseks liimi alternatiivile nagu 3D printeri vaik. Katsekehad tehti, et määrata materjalide tugevust ja saada võrdlevaid tulemusi kasutatud materjalide kohta. Kokkuvõtvate tulemuste kohaselt osutus sobivamaks UV-kõvanev liim. Katsetuste tulemusel tehti kindlaks ka pultrudeeritud materjali optimaalne tihedus.

Prototüüpseadmel testitud platvorm võimaldab tulevikus lahenduse edasiarendamisel parandusi teha. Järgmise etapina on planeeritud kontseptsiooni testimine tööstusliku robotiga, et edasi arendada paindlik kergekaaluline pultrusioonitehnoloogia.

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APPENDICES

Appendix 1. Stepper motor control program used

```
#include <AccelStepper.h>
#define MOTOR_A_ENABLE_PIN 24
#define MOTOR_A_STEP_PIN 26
#define MOTOR_A_DIR_PIN 28
#define MOTOR_B_ENABLE_PIN 62
#define MOTOR_B_STEP_PIN 46
#define MOTOR_B_DIR_PIN 48
#define MOTOR_C_ENABLE_PIN 38
#define MOTOR_C_STEP_PIN 54
#define MOTOR_C_DIR_PIN 55
#define HEATER_0_PIN 10
AccelStepper motorA(1, MOTOR_A_STEP_PIN, MOTOR_A_DIR_PIN);
AccelStepper motorB(1, MOTOR_B_STEP_PIN, MOTOR_B_DIR_PIN);
AccelStepper motorC(1, MOTOR_C_STEP_PIN, MOTOR_C_DIR_PIN);

void setup()
{
  motorA.setEnablePin(MOTOR_A_ENABLE_PIN);
  motorA.setPinsInverted(false, false, true);
  motorB.setEnablePin(MOTOR_B_ENABLE_PIN);
  motorB.setPinsInverted(false, false, true);
  motorC.setEnablePin(MOTOR_C_ENABLE_PIN);
  motorC.setPinsInverted(false, false, true);

  motorA.setMaxSpeed(5000);
  motorA.setSpeed(90);


  motorB.setMaxSpeed(5000);
  motorB.setSpeed(450);

  motorC.setMaxSpeed(5000);
  motorC.setSpeed(-90);

  motorA.enableOutputs();
  motorB.enableOutputs();
  motorC.enableOutputs();
  analogWrite(HEATER_0_PIN, 255);
}
void loop()
{
  motorA.runSpeed();
  motorB.runSpeed();
  motorC.runSpeed();

}
```

Appendix 2. General measurements of pultruder modules