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Design and manufacturing of thin composite tape springs

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Abstract

A manufacturing method for tape springs in a deployment system for a nano satellite was developed. The system relies on composite tape springs for deployment force and post deployment structural integrity, and has been proposed and used in several previous nano satellites. The tape spring was made of preimpregnated glass fiber weave. Initial test verifying the tape springs functions have been made and proven successful. The tape springs have also been tested in an engineering model of the satellite and are able to perform an adequate deployment.

Further tests, especially long time storage are needed the tape spring solution for the deployment system looks promising.

Sammanfattning

En tillverkningsmetod för en komponent i utfällningsmekanismen till en nanosatellite har tagits fram. Systemet använder en bistabil kompositfjäder i form av ett fjädermåttband för att lagra utfällningsenergi samt som bärande struktur efter utfällningsförloppet. Komponenten tillverkas i förinpregnerad glasfiberväv. De inledande testerna visar att kompositfjädrarna uppfyller de ställda kraven. En prototyp av det utfällbara systemet togs fram och kompositfjädrarna testades i den. Även i de testerna presterade kompositfjädrarna enligt ställda krav.

Ytterligare prov, framförallt långtidslagring krävs för att verifiera kompositfjädrarnas funktion. Då alla test hittills varit lyckade verkar konstruktionslösningen lovande.

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1 Introduction

1.1 Nano-satellites

Nano-satellites are becoming more common and have been made possible by advances in technology allowing smaller satellite components. One type of nano-satellite is the CubeSat. It consists of standardized 1 liter units. A CubeSat can consist of one or several units. 1 to 3 units are the most common configuration[12]. The main benefit of nano-satellites is the reduction of cost and as there capabilities are increasing, they are becoming more interesting. Especially for academia, small companies or anyone with a limited budget.

1.2 SEAM

SEAM is a CubeSat project led by the Royal Institute of Technology in Stockholm (KTH). The project is a collaboration between KTH, ÅAC Microtec, ECM-Office, LEMI, BLE, GOMspace, SSC and Kayser Italia. The SEAM project is a FP7-project funded by the european union. The aim of the project is to *“develop and demonstrate in flight for the first time a concept of an electromagnetically clean nano-satellite with precision attitude determination, flexible autonomous data acquisition system, high-bandwidth telemetry and an integrated solution for ground control and data handling”*[6]. The purpose of the satellite is to collect information about the Earth’s magnetic field, hence electromagnetic cleanliness is of high importance.

The SEAM satellite will be a 3 unit satellite. The space in the satellite is very limited. To be able to make high quality measurements the sensors need to be at distance from other electronic equipment in the satellite. Since the satellite has to fit within a 3 liter box during launch, a deployment mechanism is needed. The satellite with its two booms deployed can be seen in Figure 1.

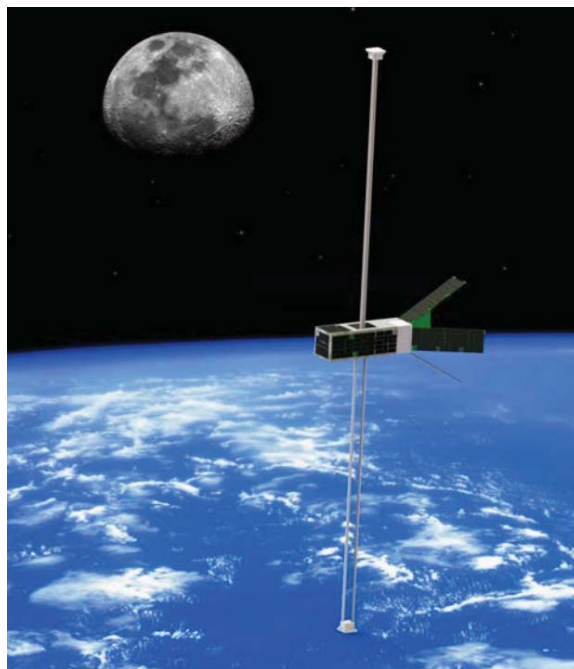


Figure 1: *Artistic rendering of the SEAM Satellite*[6]

The deployment mechanism selected is tape spring based. The tape spring is a thin shell structure. In its deployed state it has the shape of a beam with a semi-circular cross section as seen in Figure 2. It can be rolled in the same way as a steel tape measure. The tape spring is stable in these two states. Only composite tape springs are stable in these two states, steel tape springs are not. When the tape spring is rolled it stores energy which is released when it deploys. If the spring is completely rolled up it is stable, but if just a small part of it is left un-rolled it will start to deploy[5]. The tape spring and this energy rolled up state can be seen in Figure 3.

Tape springs have previously been used in satellites in different configurations. One example is the CubeSat Diffraction Telescope which can be seen in Figures 4 and 5. Another previous usage of tape springs is the CubeSat SIMPLE boom designed by Jeon and Murphy [7] which can be seen in Figures 6 and 7. The SEAM is based on the design of the SIMPLE boom. Bi-stable laminates are not only used in the shape of coiled tape springs, there are other ways to utilize the bi-stable laminate to both provide structural integrity and deployment force. One example is the Non-Planar Deployable structure designed by Footdale and Murphy [2]. It uses a tape spring based hinges. The tape spring hinges provide deployment energy and once deployed become stiff thus acting as stiff structural elements. The Daser Boom Concept uses a truss made of tape springs enabling it to be stowed and later deployed [10] it can be seen in Figure 9.

Previously in the SEAM project manufacturing of tape springs and simulations of tape spring deployment have been made by Herlem[4]. The results showed that the tape spring solution is viable but in need of an improved production method. It was also noted that relaxation in the material is a critical issue. When being in a coiled state for a period of the time the tape springs loose their deployment ability. This relaxation effect has also been observed in other composite tape spring applications[8][9][11].

In a typical single layer plain weave tape spring the deployment energy decreases during storage in the tape springs coiled state. After a sufficiently long time e.g. a few hours in the coiled state the tape spring will not deploy. This is due to relaxation in the matrix. When the tape spring has lost all deployment energy it is neutrally stable. It now requires an external force to be uncoiled and coiled. In Figure 10 a neutrally stable tape spring can be seen. If it had not been neutrally stable it would have continued deploying until fully uncoiled. This effect poses a problem since the satellite has to be



Figure 2: *Uncoiled tape spring*



Figure 3: *Coiled tape spring*

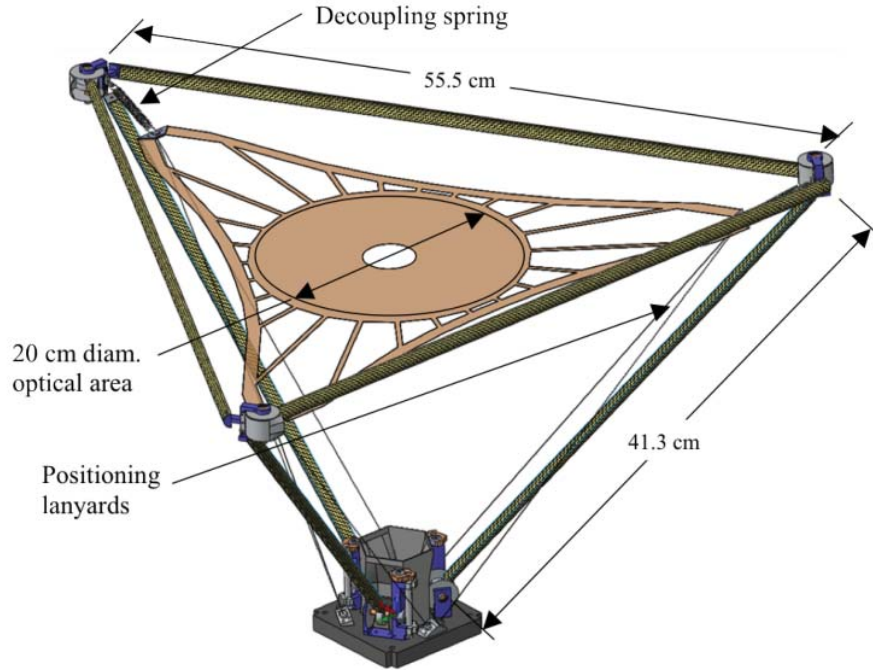


Figure 4: *Rendering of the CubeSat Diffraction Telescope [3]*

able to be stored for periods of weeks or even several months. To increase deployment energy the layup can be changed. If more fibers are placed in the $0^\circ/90^\circ$ direction more deployment energy is acquired. The main drawback is when the deployment energy is so large that the tape spring is no longer bi-stable. This can be counteracted by forcing the tape spring into a coiled state and storing it until enough energy has been lost through relaxation and it becomes bi-stable. Another solution is to use special low-relaxation polymers as matrix material. This has been tested by Thomas Murphy at United States Air Force Research Laboratory but the effect is not significant enough to enable storage in the time scale of months.

1.3 Requirements for boom

The SEAM satellite will deploy two arms each consisting of two tape springs, thus requiring a total of four tape springs. Each arm is to deploy 1 meter outward from the satellite and the arms need to fit inside the satellite when stowed.

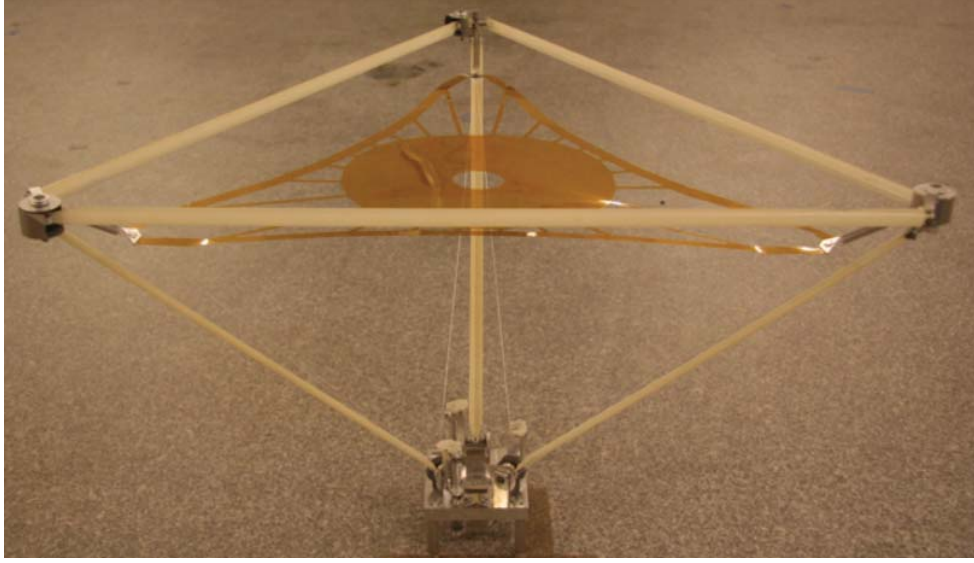


Figure 5: *Photograph of the CubeSat Diffraction Telescope [3]*

These requirements give a boom length of 1 meter for deployment. To fit when stowed the width is not to exceed 22 mm and the thickness not to exceed 0.3 mm. The tape spring cross section is a circular sector. To achieve maximum bending stiffness and strength the tape springs are made to be a full 180° semi circle. When designing the tape spring several conflicting requirements have to be taken into account. There are several benefits and drawbacks of increasing the tape springs stiffness. High stiffness leads to a high deployment speed. This is not beneficial since it exerts high forces on the tape springs and other satellite components. When the boom is deployed high stiffness is beneficial since it minimizes deflection of the structure. The different design parameters' drawbacks and benefits can be seen in Table 1.

Table 1: *Boom requirements overview*

Parameter	Consequence	Comment
Stiffness		
Large stiffness	Low deflection	Good
Small stiffness	Low deployment speed	Good
Thickness		
Small thickness	Small volume	Good
Small thickness	Low stiffness	Good and bad
Small thickness	Low strength	Bad
Large thickness	Large volume	Bad
Large thickness	High stiffness	Good and bad
Large thickness	High strength	Good
Width		
Small width	Small volume	Good
Small width	Low stiffness	Good and bad
Small width	Low strength	Bad
Large width	Large volume	Bad
Large width	High stiffness	Good and bad
Large width	High strength	Good

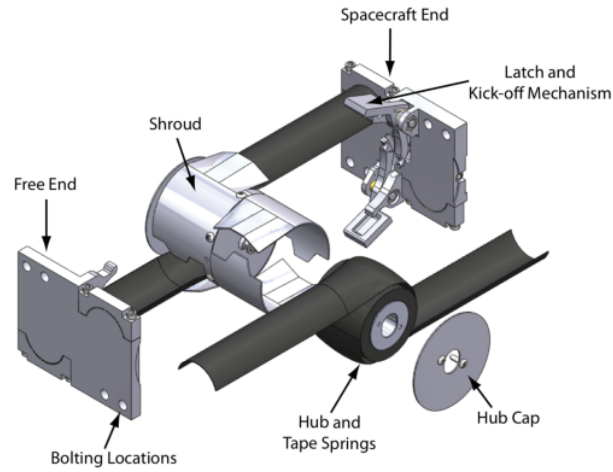


Figure 6: *Rendering of the SIMPLE boom*[7]

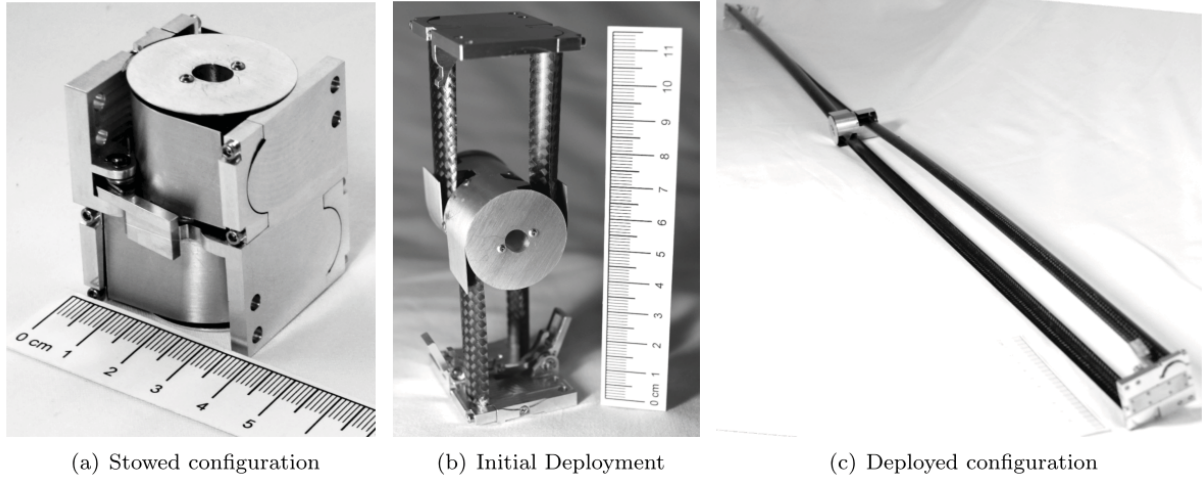


Figure 7: *Photograph of the SIMPLE boom[7]*

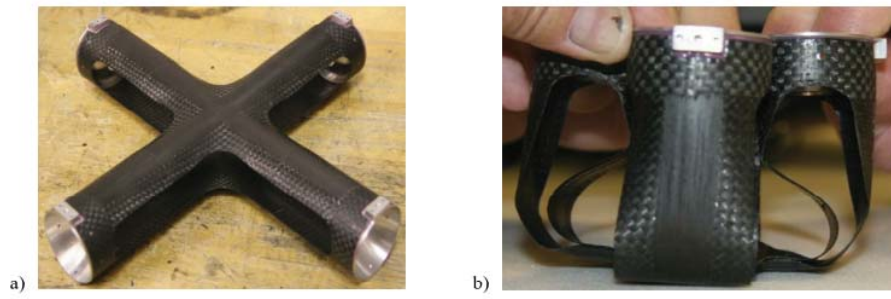


Figure 8: *Hinge used in the Non-Planar Deployable structure[2].*

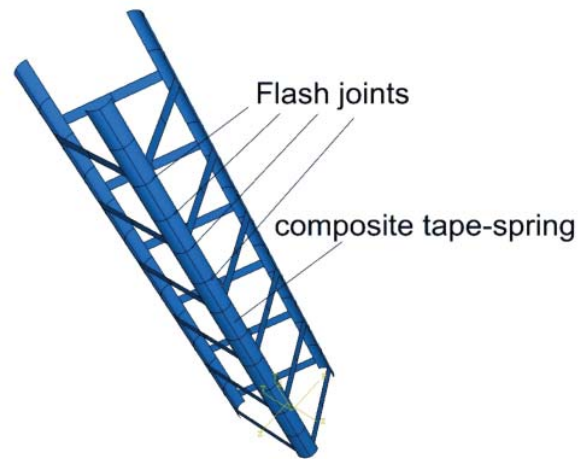


Figure 9: *Daser Boom Concept - A truss made of tape springs*[10]



Figure 10: *A partially coiled neutrally stable tape spring*

2 Material

2.1 Material selection

To reduce interference with the satellites magnetic measurements a non magnetic material is required. It is also important that the material can be manufactured in the shape of a tape spring. The cured has be to sufficiently stiff to provide deployment force and structural stiffness in the deployed state.

Fiber composites can fulfill all of these requirements. The most common and easily acquired types of fiber are glass, carbon and aramid fiber. All non magnetic and non metallic but carbon fiber is conductive. The main difficulty when searching for an appropriate material was thickness. The tape springs must be to thin enough to be stowable in the satellite. Many fibers commercially available are too thick to be used. Two types glass fiber weaves were found to be suitable candidates for the boom and used for further testing. Carbon fiber provides more stiffness per thickness unit compared to glass fiber. Carbon fiber weaves of suitable thickness proved more difficult to acquire and were therefore not tested.

2.2 Glass fiber

The first fiber material used was the fiber glass weave HexForce 1080 1100 TF970 from Hexcel. It is an unbalanced plain weave and has a nominal weight of 48 g/m^2 . The weave is thin compared to commonly used weaves. This makes it difficult to handle because it easily shears and changes shape. The difficulty during handling and the many layers required because of the thickness lead to a search for a replacement weave.

2.3 Preimpregnated Glass fiber

To increase ease of handling a pre-impregnated weave was selected. The weave selected was Hexply M77/38%/107P/G also manufactured by Hexcel and has a nominal weight of 107 g/m^2 . The pre-impregnation makes the weave stiffer which leads to easier handling since the weave is not as easily sheared. The increased thickness leads to fewer layers in the tape springs which gives a quicker and simpler layup process.

2.4 Handling Epoxy

An issue with preimpregnated fibers is that the matrix often is epoxy based. To be allowed to handle epoxy in Sweden you need to complete a course in handling of thermoplastics and undergo a medical examination[1]. This is because incorrect handling of epoxy can lead to skin allergy. The allergy usually occurs due to repeated exposure to epoxy but can emerge quickly. To reduce the risk of acquiring epoxy allergy protective gloves and clothing has to be worn. It is also important to keep track of what equipment and working areas which are contaminated by epoxy since they cannot be used without protective equipment. To be able to work with preimpregnated fibers I made sure a course in handling of thermoplastics was held by the company FeelGood for myself and the colleagues of the department.

3 Fiber layup

Bi-stability is given by layers with angles other than 0° and $\pm 90^\circ$. Layers with fibers angles equal or close to 0° and $\pm 90^\circ$ are only stable in the uncoiled deployed state. Layers with 45° angles give the smallest deployment force.

To achieve a balanced laminate, weaves are used because weaves make it possible to get a $+45^\circ$ and a -45° at the same distance from the laminate neutral layer. If two unidirectional layers would be used instead, the layers would be located at different distances from the laminate neutral layer. This is very important because a difference in distance will lead to the laminate being unbalanced, which makes it want coil in a helix shape. When using weaves only $\pm 45^\circ$ and $0^\circ/90^\circ$ layers are possible to achieve. Therefore $\pm 45^\circ$ layers are used as outer layers in the laminate.

When a laminate consisting of $\pm 45^\circ$ layers is stored in its coiled state for more than a couple of hours its properties change. It is no longer able to deploy. This is due to relaxation in the matrix. Changing to a low relaxation matrix and using different post curing methods does not improve this behavior significantly¹. To solve this problem more fibers in the $0^\circ/90^\circ$ are added. This increases deployment energy and force. If many layers are added it can make the coiled state unstable. It is thus possible to create a laminate that is unstable in its coiled state when newly manufactured but after being forced to be coiled for some time it becomes stable due to relaxation.

¹Through personal communication with Thomas W. Murphey

Table 2: *Layup overview*

Layup stacking	Effect	Result
$[\pm 45^\circ / \pm 45^\circ]$	High Relaxation	No deployment
$[\pm 45^\circ / 0^\circ / \pm 45^\circ]$		
Thick 0°	Low-relaxation	Loss of bi-stability
Thin 0°	High Relaxation	No deployment

3.1 Layups tested

The first layup tested was a three layer laminate with $\pm 45^\circ$ layers in the top and bottom and a $0^\circ/90^\circ$ as the middle layer. This layup did not prove to have enough deployment energy to overcome the matrix relaxation after one full day in coiled state in room temperature.

To overcome the relaxation problem a $0^\circ/90^\circ$ or 0° layer can be added. If the added layer is too thin it will not provide enough deployment energy to overcome the relaxation problem. If the added layer is too thick it will provide too much deployment energy making the tape spring loose its bi-stability. Therefore a tuning of the thickness of the added layer is required. In these tests only one type of weave was available. The thickness could therefore only be changed in discrete steps with adding and removing a layer of weave. This makes it difficult to optimize the thickness of the laminate since there is no room for fine adjustments. In Table 2 the behavior of different layups is shown.

The second layup tested was a four layer laminate. A second $0^\circ/90^\circ$ layer was added in to the layup. Now the layup has two $0^\circ/90^\circ$ layers in the middle and one $\pm 45^\circ$ layer at the top and a second one at the bottom. This layup gives a laminate that is close to stable when it is newly manufactured and creeps into a stable form after being coiled for one day in room temperature. A concern with the four layer laminate is that its thickness is too large and the tape spring will not fit in the satellite. There is also a concern that its deployment force will be too large resulting in a fast deployment speed. One solution to achieve performance somewhere in between a four layer and a three layer laminate is to let the fourth layer only be present during a certain length of the laminate.

A laminate was manufactured with three full length layers and a fourth $0^\circ/90^\circ$ layer that only went from one edge to the middle of the laminate. The laminate was coiled so the four layer section is deployed first. This lets the four layer section build up deployment speed that later is used to deploy the three layer part. After one week of storage the laminate is able to deploy. The last 50-100 mm of the laminate does not deploy. This could be helped by the added deployment mass that will be present in the final satellite, this has however not been tested. This type of mixed layer layup poses another problem: in the booms deployed state the three layer part is closest to the boom root. It is detrimental to the performance the deployed boom to have the least stiff part of the tape spring located close the root where the largest bending moment is located.

4 Production methods

4.1 Pipe mold

The first production method tested was using a copper pipe as a mold. Fibers where cut and placed on the pipe and secured with tape. The fibers were then soaked in resin and packed in a vacuum bag with peel ply and breather. The laminate was then left to cure for 12 hours at room temperatures and then post cured in an oven at 80°C for 2 hours. The laminate was de-molded and excessive material was cut off using a diamond band saw.

This method gives a tape spring of adequate quality. Since peel ply is placed on both top and bottom both sides of the laminate are rough. The method is time consuming since much of time is needed to align the fiber properly along the pipe mold.

4.2 Half-pipe mold

To improve the quality of the tape spring and reduce manufacturing time, two new molds where created. One male mold as seen in Figure 11 and one female as seen in Figure 12. The molds where manufactured for testing purposes out of parts that where immediately available and are shorter and wider than the final tape spring will be.

The layup technique was changed from wet layup to prepreg layup. A thicker weave was chosen to decrease the number of layers needed.

Strips of the weave were cut and placed in the molds. The molds were then vacuum-bagged without a peel-ply. Vacuum was then introduced and the molds were placed in an oven at 95°C for 2 hours. The laminates were de-molded and excess material was cut off using a diamond band saw.

Placing fibers in the female mold was more difficult than placing them on the male mold. Both methods were easier to work with than the pipe-mold. The change to pre-preg also made the manufacturing process easier. The pre-preg is less sensitive during handling, it does not shear as easily. This method yields smooth surfaces on both sides of the laminate.



Figure 11: *Male half-pipe mold*

4.3 Aluminum mold

The male half-pipe mold gave the best results. Therefore a new mold was manufactured from milled aluminum blocks and a steel rod. This mold was manufactured to the correct length and width to be able to manufacture tape springs of the correct dimensions.



Figure 12: *Female half-pipe mold*

At first the mold was covered with a piece of vacuum bag so the laminate would not bond to the aluminum. Air trapped between the mold and the vacuum film caused wrinkles in the laminate during curing. The vacuum bag between the laminate and mold was therefore removed and the mold was instead treated with release agent. This reduced wrinkling.

On top of the release agent pre-preg plies were laid up to from the laminate. At first, this was done with mold and fibers at room temperature. To keep the ply in place on the mold it was taped at the edges with “office tape”. With this method it was difficult to get the plies to fit tightly to the mold. Instead of doing layup with a room temperature mold the molds was preheated to 70°C. When the plies where laid up on the mold the viscosity of the matrix was lowered as the temperature increased, making the plies stick to the mold better and no “office tape” was needed. The lowered viscosity also made the laminate consolidate better during layup. This improvement also reduced wrinkles leading to a better end result.

With the aluminum mold it is possible to cure at higher temperatures than with the wooden mold. The laminate was cured at 125°C for 1 hours. The matrix cures in 7 minutes at 120°C, but the mold takes 90 minutes to reach that temperature.

With this method and this mold it is possible to produce a tape spring of correct dimensions and of adequate quality.

5 Mounting Hub

The hubs where the laminate tape springs are mounted and coiled around were constructed. They were designed in a CAD-program and then 3D printed by the company Kayser-Italia. The hubs were designed to meet the size requirements set by the space available in the satellite. The hubs must also be designed so the natural coiling radius of the tape springs is achieved. The hub can be seen in Figure 13. The hub is to be mounted on a axle with 5 mm diameter with two plastic bearings to reduce friction. The final hub will be made from aluminum. A prototype hub was 3D printed in plastic and used for testing. A 1 meter tape spring with 0.3 mm thickness can easily be rolled up on the hub, which can be seen in Figure 14. The hubs can be seen mounted on a part of the satellite frame in Figure 15.

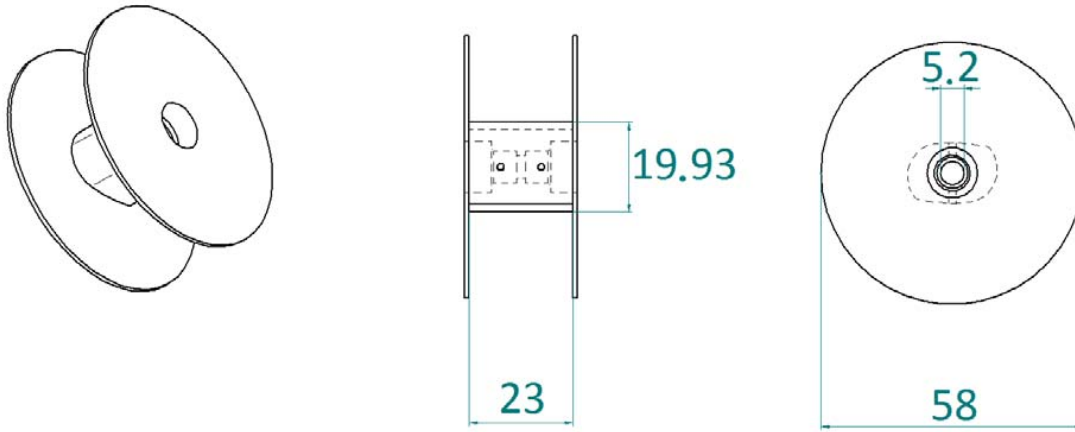


Figure 13: *Mounting hub*



Figure 14: *Hubs the lower one with two 1m tape springs coiled*

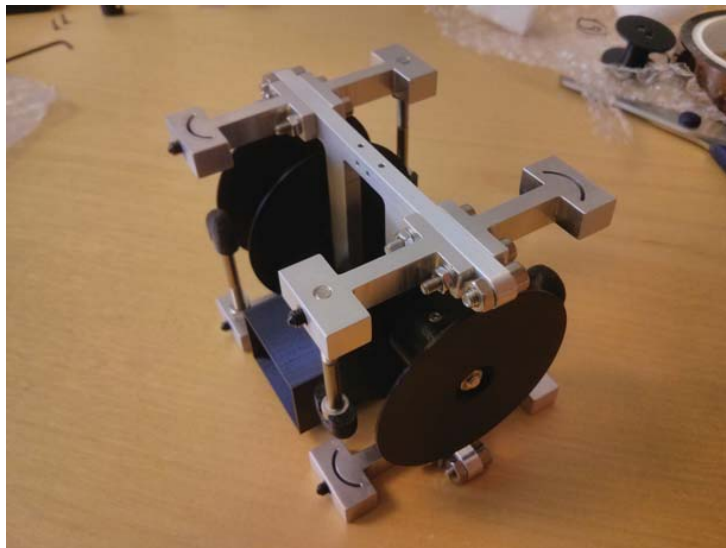


Figure 15: *Hubs attached to aluminum frame*

6 Final production method description

The purpose of this section is to provide detailed instructions of the manufacturing process. This section can be used as a manufacturing instruction for later research or for the manufacturing of the final tape springs.

6.1 Mold preparation

Make sure the mold is clean from any leftover resin, glue or tacky-tape. Coat the part of the mold that will be in contact with the laminate with release agent (Acmosan 82-7001). Spray the agent on the mold and polish with a piece of paper, let dry for 20 minutes. Repeat 3 times. In figure 16 the mold is being coated with release agent.

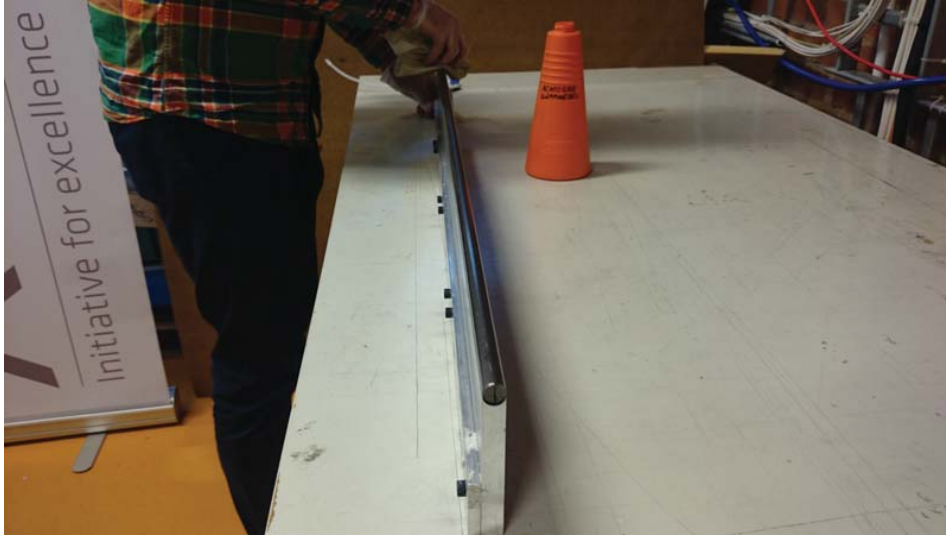


Figure 16: *Mold being coated with orange release agent bottle*

The mold is now ready for preheating. Place the mold in the oven set at 65° celsius for one hour.

6.2 Fiber preparation

The pre-preg is taken out of the freezer and put on the work table. On the work table there is a hardboard plate where lines are drawn for cutting $\pm 45^\circ$ and $0^\circ/90^\circ$ layers. Align the fibers and cut along the lines as many as needed for your layup. An image from the cutting process can be seen in Figure 17.



Figure 17: *Weave being cut*

Mark the center of each short side of the plies. This will be used for alignment during layup.

6.3 Laminate layup

Make sure the mold has been preheated at 65°C for at least one hour. After preheating the mold is hot enough to do fiber layup for at least 40 minutes. When handling the hot mold protective gloves are generally needed.

Start fiber layup by placing the first ply flat on top of the mold. Make sure the alignment markers align.

When the ply is placed correctly on top of the mold, start to fold the sides down. Start in the middle and make sure to pull the ply down, so no air is trapped between the mold and the ply. The $\pm 45^{\circ}$ layers deforms easily if you pull to hard. A schematic view can be seen in Figure 18 and in Figures 19, 20 and 21 photographs of the process can be seen. Repeat this procedure for every layer.

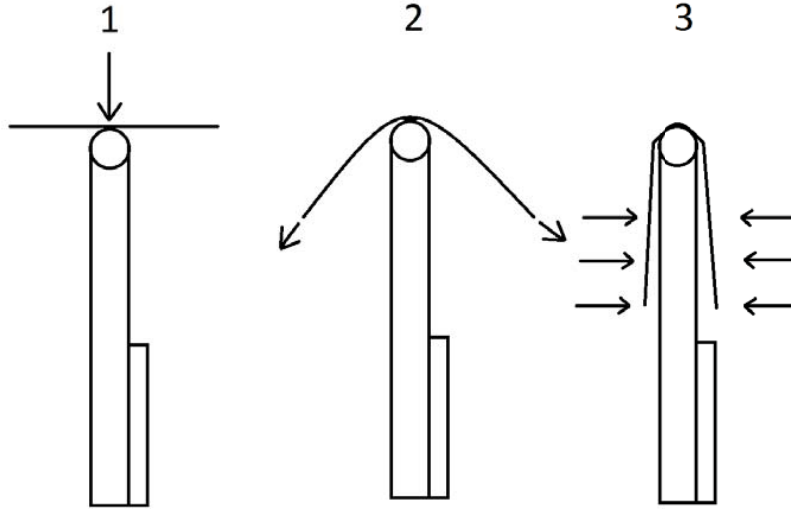


Figure 18: *Fiber layup on mold*

6.4 Vacuum bagging

Cut a piece of vacuum film with the size $1 \times 2.5 \text{ m}^2$. Place the mold according to Figure 22. Place breather on the mold according to the Figure 22 to protect the vacuum bag from the mold's sharp corners. Place tacky tape and attach vacuum tube according to the Figure 22. A drawing of the vacuum bagging can be seen in Figure 22 and a photograph in Figure 23.

Start expelling air slowly and make sure no kinks form over the laminate. This can be done by pulling excessive vacuum film.

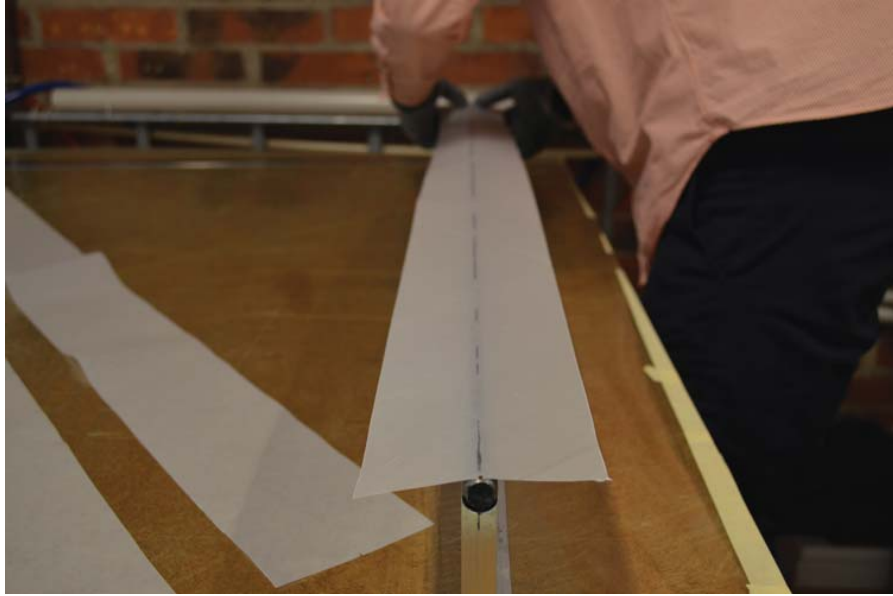


Figure 19: *Weave being layed up onto mold*



Figure 20: *Weave being layed up onto mold*



Figure 21: *Weave being layed up onto mold*

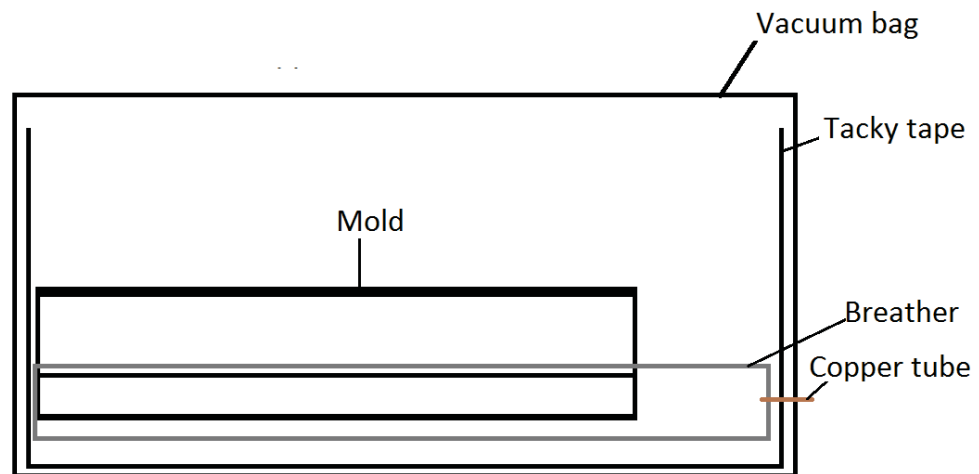


Figure 22: *Vacuum Bagging*

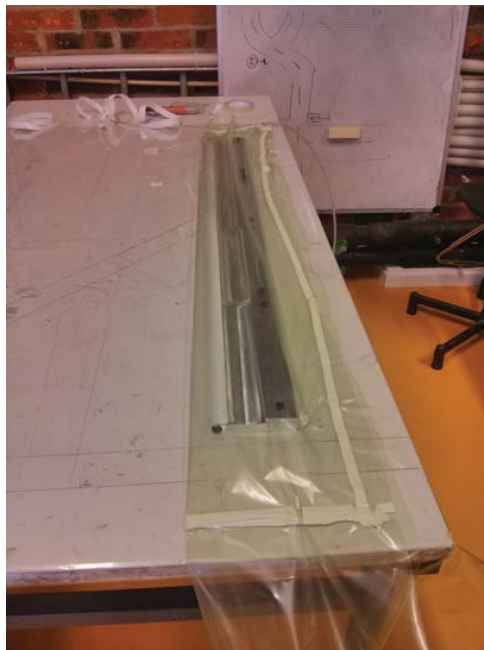


Figure 23: *Fold in vacuum bag*

6.5 Curing

When full vacuum (-1 bar) has been reached place the mold in the oven set to 125°C . Let it cure for 2 hours. Keep the vacuum pump on during the curing process to make sure that vacuum is maintained.

After 2 hours of curing remove the mold from the oven, disconnect the vacuum tubing and leave it to cool.

6.6 Demolding

In room temperature the mold is cold enough for demolding after about 1 to 2 hours. If demolded too early, the vacuum film easily sticks to the laminate. Start demolding by pulling the vacuum film. Try to do this without removing the laminate from the mold. If the laminate comes off the mold it is more difficult getting the vacuum film off.

When all vacuum film is off, the laminate can be taken off the mold. If it does not come off easily a razor can be used to start peeling it off from one edge.

A picture of the demolded tape spring can be seen in Figure 24, note the excess material that needs to be removed.

6.7 Post cure-treatment

When the laminate is demolded the excess material has to be cut off. This is done with the diamond blade band saw.

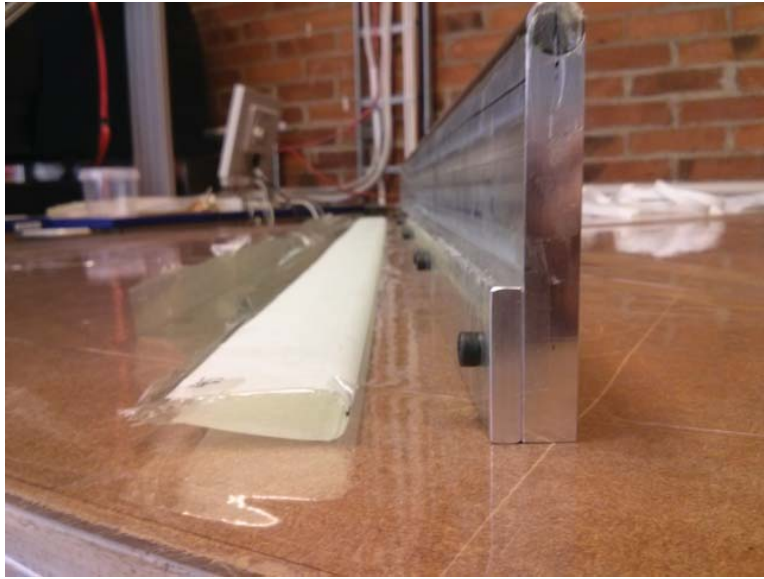


Figure 24: *Demolded tape spring*

7 Discussion

Further work needs to be done to investigate what happen when the tape springs are left coiled for a long time, several months.

A deployment test with the springs mounted in a engineering model of the boom has been made. Even though the springs had been stored in their coiled state for several weeks the deployment energy was sufficient to deploy the boom despite frictional losses. Photographs from the deployment can be seen in Figures 25 and 26.

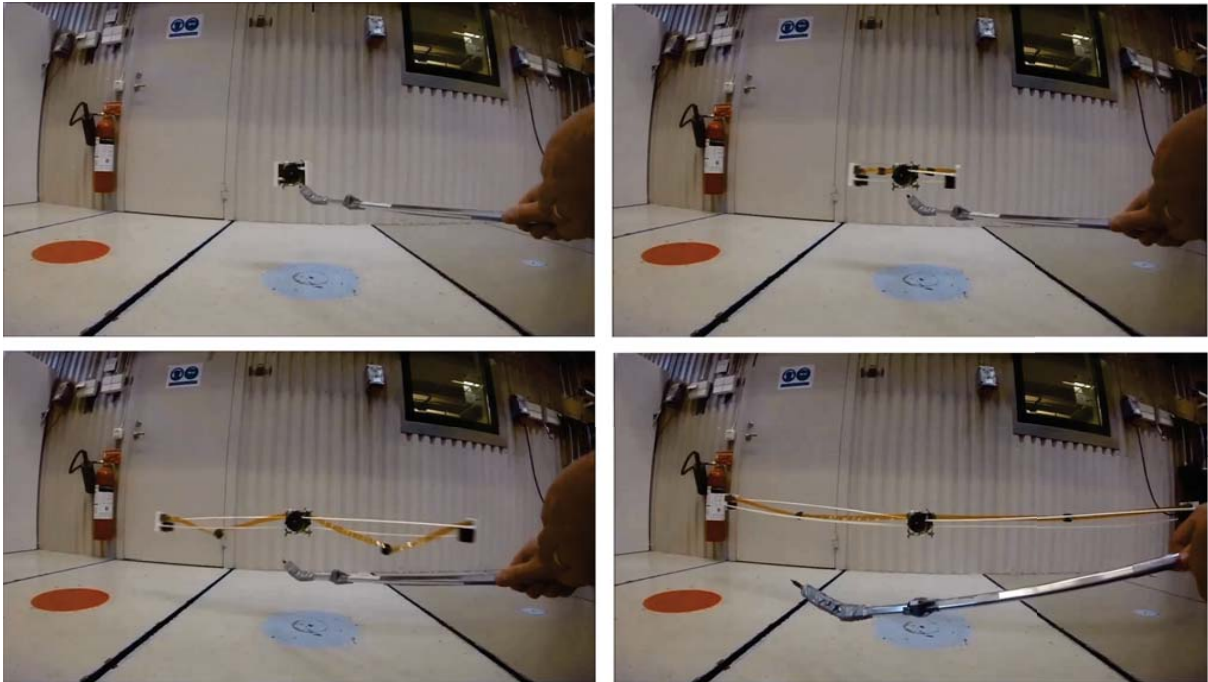


Figure 25: *Side view photograph of boom deployment*

8 Conclusion

A production method for the tape springs has been developed. It gives consistent results and tape springs of adequate quality. With the method it is possible to fabricate a tape spring that is capable of deploying after being stored for weeks.

9 Acknowledgments

I would like to thank my supervisor Dr. Gunnar Tibert for giving me the opportunity to be a part of the SEAM project and for all help and support during this project. I would also like to thank Monica Norrby and Anders Beckman for help and guidance in the KTH Lightweight Structures Lab.

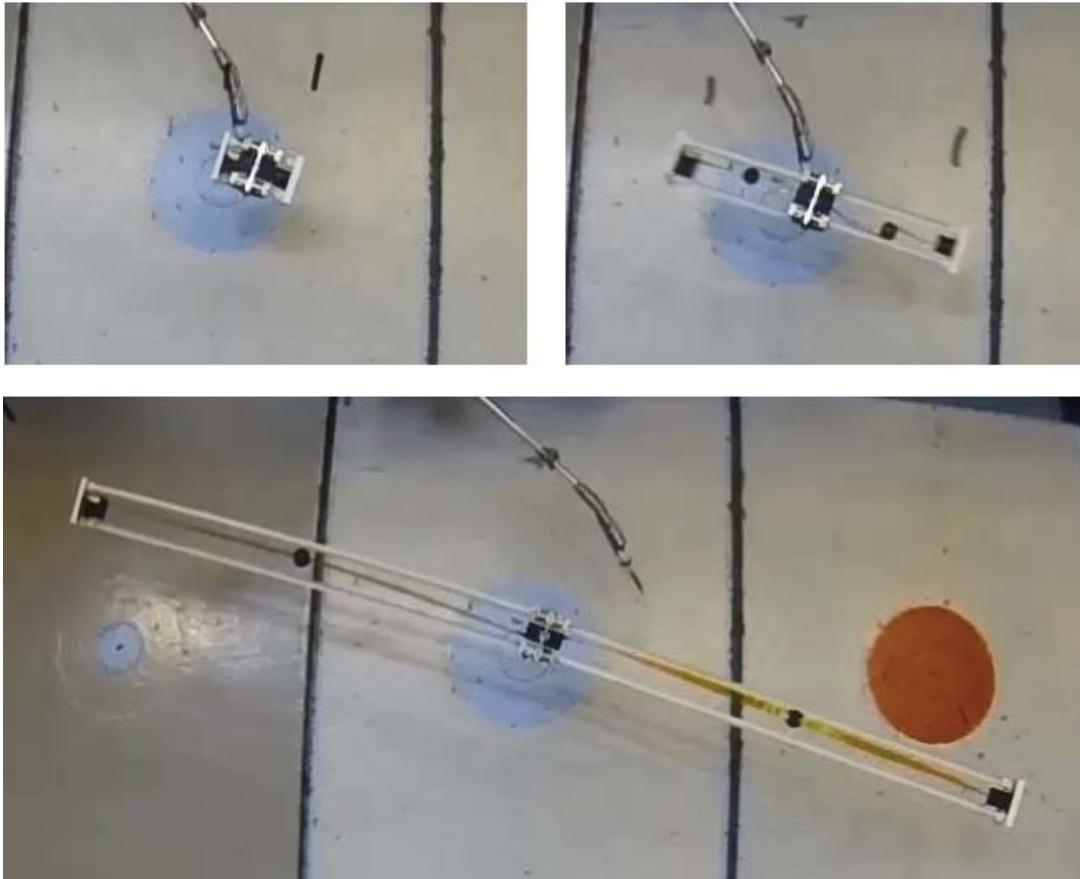


Figure 26: *Top view of boom deployment*

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