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Integration Tools for Design and Process Control of Filament Winding

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Abstract

Filament winding is a fabrication method for composite material structures, in which fibres are wound around a rotating mandrel. It is a versatile and dexterous process especially well-suited for creating and optimizing parts with a linear rotational axis. Products like pressure tanks, golf clubs or violin bows are commonly created using this technique. The winding itself is done through software solutions that generate a CNC program for the part in question. There are several such software solutions commercially available, all with different modes of operation and functionalities. However, they are also proprietary and offer little to no access into their inner logic.

To optimise a part before production Finite Element Analysis software is often used. The part in question is modelled; material, forces and constraints are applied; and an analysis is run. Currently (June 2012), there are few options available for analysing filament wound products. Modelling a part with accurate filament winding layup generally has to be done manually, in a very time-consuming process.

In this thesis, the author has performed a pilot study into the development of filament winding software. Software has been developed, capable of integrating both with a filament winding machine and with Finite Element Analysis software, and operating as a link between the two. The software has functionalities to extract geometrical variables from an Abaqus mandrel model; to write G codes and create a CNC program file; simulate a filament winding process in the Abaqus viewport; and, using a CNC program file, add accurate and corresponding layup to an Abaqus part.

The main goal of this thesis, however, has been to create something that will serve as a basis from which others can continue development. The intention being that the software will be open source, so that anyone and everyone using it may change, improve and add on to it.

Sammendrag

Fibervikling er en produksjonsprosess for kompositttstrukturer, der fibre vikles rundt en roterende mandrel. Det er en allsidig og fleksibel prosess som egnes spesielt godt til å optimere og fremstille produkter med en lineær rotasjonsakse. Produkter som trykktanker, golfklubber og fiolinbuer produseres ofte ved hjelp av denne teknikken. Viklingen i seg selv gjøres ved hjelp av programmvare, som genererer et CNC program for den aktuelle delen. Det finnes flere typer slik programvare tilgjengelig, alle med forskjellige virkemåter og funksjonaliteter. Imidlertid er de også patentbeskyttet og tillater lite eller intet innsyn i hvordan de virker.

For å optimere et produkt før vikling anvendes programvare for Finite Element Analysis. Produktet modelleres; materiale, krefter og grensebetingelser legges til; og en analyse blir utført. Per i dag (juni 2012) finnes det få muligheter for analyse av fiberviklede produkter. For å modellere en del med en realistisk vikle-layup, må det vanligvis gjøres manuelt i en svært tidkrevende prosess.

I denne oppgaven, har forfatteren gjennomført en pilotstudie om utvikling av programvare for fibervikling. Programvare har blitt utviklet, som er i stand til å integrere med både en fiberviklemaskin og Finite Element Analysis programvare, og som kan fungere som en link mellom de to. Programvaren har funksjonaliteter for å trekke ut geometrivariabler fra en Abaqus mandrel-modell; skrive G koder og generere en CNC programfil; simulere en vikleprosess i et Abaqus-vindu; og, ved hjelp av en CNC programfil, legge til korrekt og tilsvarende layup i en Abaqus mandrel modell.

Hovedmålet i denne oppgaven har, imidlertid, vært å skape noe som kan tjene som et grunnlag som andre kan fortsette på. Hensikten er at programvaren skal ha åpen kildekode, slik at alle og enhver som bruker det kan endre, forbedre og tilføye til programvaren.

THE NORWEGIAN UNIVERSITY
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DEPARTMENT OF ENGINEERING DESIGN
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MASTER THESIS SPRING 2012
FOR
STUD.TECHN. INGER SKJÆRHOLT

INTEGRATION TOOLS FOR DESIGN AND PROCESS CONTROL OF FILAMENT WINDING

Integrering av designverktøy og maskinstyring av vikleprosesser

Filament winding is a fabrication method for creating composite material structures. The process is usually fully automated and involves winding fibers on a mould or mandrel. The mandrels rotates while a carriage moves horizontally, laying down fibers in the desired pattern. Filament winding is well suited to automation and the orientation of the filaments can be carefully controlled. Products being produced by this technique range from golf clubs, pipes, oars, bicycle forks, power and transmission poles, pressure vessels to missile casings, aircraft fuselages and lamp posts and yacht masts. During the spring 2011 a new modern filament winding machine was installed at the department and will be available for the project. The machine control utilizes a standard PC based control system with interfaces to various 3D model files and machine control files.

One major challenge is the automatic integration between data and parameters from an optimum solution obtained by finite element analysis, and the parameters for the control system of the winding machine. Ideally, an integration tool shall be able to utilize the database of a FEA system to generate the machine control files, and vice versa: from a machine control file or database a finite element model should be automatically generated.

The objectives of the current project is:

- Review, systemize and report relevant state-of-art, fundamental theory and possible solutions
- Develop modules of the integration tools, benchmark the system by theoretical and experimental examples, and make documentation

In this context, a module is any part of the system that provides exchange of data, conversion, numerical computations, user interaction, etc.

As being a software development task, comprehensive and continuous documentation should be emphasized.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

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Nomenclature

a	-	Linear equation slope variable
b	-	Linear equation constant
c	-	Constant
cylinderLength	-	Length of cylinder model (half of mandrel cylinder length)
H	-	Horizontal axis
legH	-	Coordinate value of P2 on horizontal axis
legV	-	Coordinate value of P2 on vertical axis
mandrelLength	-	Total length of mandrel
$P1_H$	-	Coordinate value of P1 on the horizontal axis
$P1_V$	-	Coordinate value of P1 on the vertical axis
R	-	Cylindrical radius
r	-	Dome opening radius
s	-	Circle section
signH	-	Sign of P2 horizontal coordinate value
signV	-	Sign of P2 vertical coordinate value
t	-	Parametric variable
U	-	Angle between P1 and horizontal axis
V	-	Vertical axis
W	-	Angle between P2 and horizontal axis
X	-	Rotation of mandrel
	-	Angle between two points on a cylinder
x(t), y(t), z(t)	-	Points on geodesic curve
x(y)	-	Point on straight line between P1 and P2
x_2	-	Coordinate value of P2 on second axis
x_2	-	Coordinate value of P1 on second axis
Y	-	Lateral movement along the mandrel
x, y, z	-	Coordinates of point on spherical surface
y(x)	-	Point on straight line between P1 and P2
y_1	-	Coordinate value of P1 on axis of rotation
y_2	-	Coordinate value of P2 on axis of rotation
α	-	Filament winding angle

Abbreviations

CNC – Computerised Numerical Control

NC – Numerical Control

FEA – Finite Element Analysis

GUI – Graphical User Interface

CLI – Command Line Interface

PDE – Python Development Environment

AWI – Abaqus Winding Integration

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Chapter 1. Introduction

Filament winding is a fabrication method for creating composite material structures. Fibres, which have been either pre-impregnated or are dipped in a resin bath immediately before winding, are wound around a rotating mandrel. The shape of the mandrel corresponds to the inner geometry of the part to be produced. Depending on the choice of fibre, resin, fibre tension and the angle with which the fibres are wound around the mandrel the mechanical characteristics of the finished product will change. Filament winding is therefore a quite flexible and dexterous production process. The filament winding procedure is especially well suited for making parts with a linear rotational axis like pressure tanks, tubes, golf clubs, missile castings and the likes. These are all articles which have been produced using this process for quite some time. Filament winding is, however, not limited to parts with a linear rotational axis, but can also be used to make things like t-joints, bends or other non-symmetrical shapes.

To produce a part using filament winding, a CNC program is generated by one of the available filament winding software and exported to the filament winding machine. There are several such software solutions commercially available today. They all have the same basic features, and varying degrees of additional functionalities. As with most commercialised software these are proprietary and offer few or no options for control beyond the Graphical User Interface (GUI). In some cases this poses a problem for the industrial companies using the software, amongst others if the part to be wound does not fit the standard shapes and profiles embedded in the software solution exactly. It is a common approach to use the software only as a basis for the winding program, then hard code to fit a specific part for mass production.

Another challenge of filament winding is 3D modelling and analysis. Modelling an accurate part with a filament winding layup is very difficult and time consuming. Without specialised software some of the assumptions necessary to make the modelling process manageable also lead to the result being a poor approximation. As a result, in such cases when it is acceptable to use an approximation of a filament wound part it is very impractical to do manually.

These issues formed the basis for the motivation behind this thesis and its objectives. It was decided to do a pilot study developing software able to integrate with the finite element analysis (FEA) software “Abaqus” and a filament winding machine. Such software would not only make it possible to model an acceptable approximation of a filament wound part, but also to create a model that is a close replica of the physical part. The main goal, however, has been to create something open source. Software to serve as a basis from which other scientist can continue development; hopefully resulting in open source software that is more flexible than what is available today.

1.1 Outline

In chapter 2, a presentation of the necessary background information is given. A short introduction to filament winding, filament winding software and CNC programming has been compiled. Also, the subjects of the FEA software Abaqus and its scripting interface have been covered.

In chapter 3, the motivation behind the thesis has been covered along with the initial plans of an overall approach. The search for the kinematic equations of a filament winding machine has been described and discussed, and the strategy for software development detailed.

In chapter 4, the development of the Abaqus Winding Integration software package, the design choices discussed, and the mode of operation documented.

In chapter 5, the Abaqus Winding Integration Tools have been evaluated. Fields with improvement potential have been remarked, and suggestions on further development and expansion given.

Finally, in chapter 6, the conclusions and a summary of suggestions for further work have been presented.

Chapter 2. Background

The following chapter will give the necessary theoretical background for the main subjects of this thesis. The basics of filament winding (mandrel properties, fibre types and winding patterns) have been covered. Different choices for winding software have been discussed. A summary of Abaqus FEA compiled, and an introduction into scripting and CNC programming given.

2.1 Filament Winding

Filament winding is a manufacturing method used for creating composite material structures. Following is a brief introduction into the key concepts in filament winding extracted from [5-9] .

Filament winding is a fully automated process that involves winding continuous fibres onto a rotating mandrel. During the winding process the fibres are placed on the mandrel in a repeating pattern, forming several layers. As a fully automated process filament winding is very well suited to high-precision work. By controlling the choice of fibre and resin, fibre tension and the fibre path on the mandrel the mechanical properties of a finished part can be influenced, controlled and produced with high accuracy.

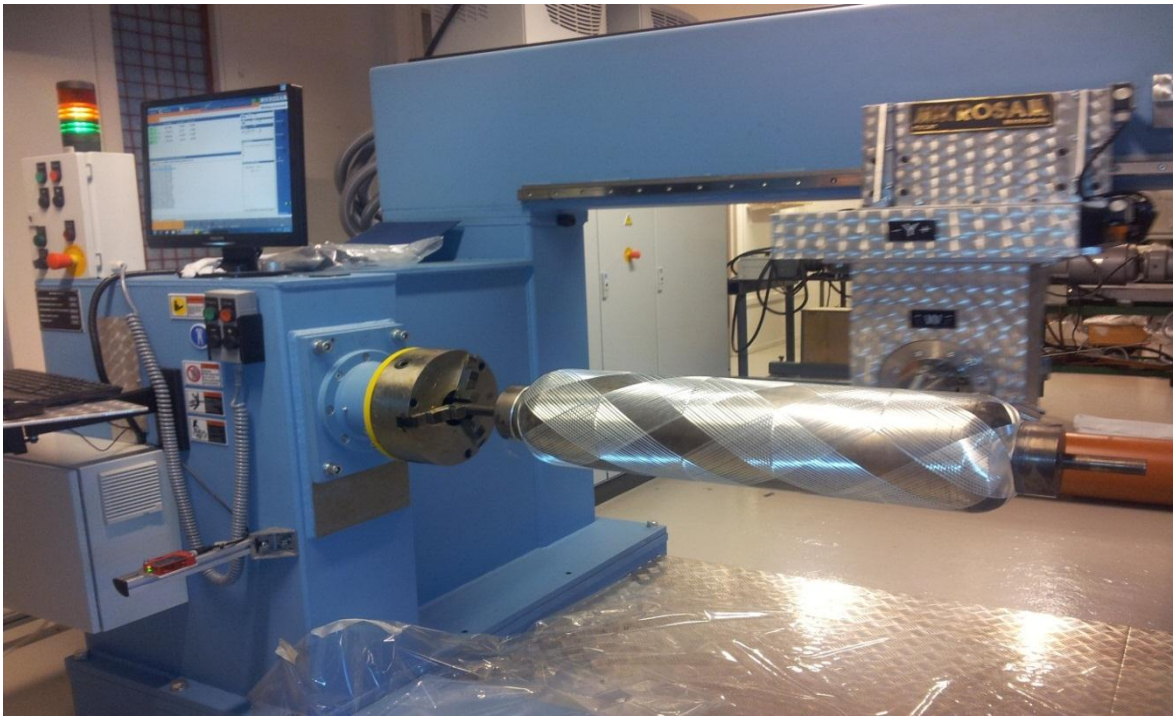


Figure 1 - Filament winding of cylindrical mandrel with domes

2.1.1 Mandrel

The mandrel is a mould that corresponds to the inner geometry of the part. Changing the mandrel parameters will affect the inner properties of the part accordingly. This is true for parameters like inner surface roughness, as well as the geometrical values. If it is necessary to alter the outer parameters of a part it has to be done by additional machining after the winding process is completed. Post-machining is performed, for example, on aero dynamical parts like airplane components.

After the winding process has been completed the mandrel must, in most cases, be removed from the finished composite; unless it is meant to be a part of the end product. Depending on the situation, geometry of the part, heat tolerances and similar factors, the of mandrel is chosen. Some options for the mandrel composition include water soluble or fusible salts and plasters or by using collapsible metal designs. It can be inflatable, made from alloys with a low melting point, or any of several other existing designs. The best type of mandrel for any given part depends on the different characteristics and requirements of the winding process and the part itself.

The most straightforward parts to wind are those with a linear rotational axis and a smooth surface, like pressure tanks and other cylinder formed parts like the one in Figure 1. It is, however, also possible to wind non-axisymmetric shapes like elbows or t-joints, as the part in Figure 2 and Figure 3. Although filament winding is very flexible the production technique also has limitations. For example it is generally not possible to wind a surface which has concave geometry features (with the exception of saddle shapes). One way to achieve such curvature on a filament wound part it would be to wind fibres bridging the concave area. Then, apply external pressure to push the fibres into place during curing.

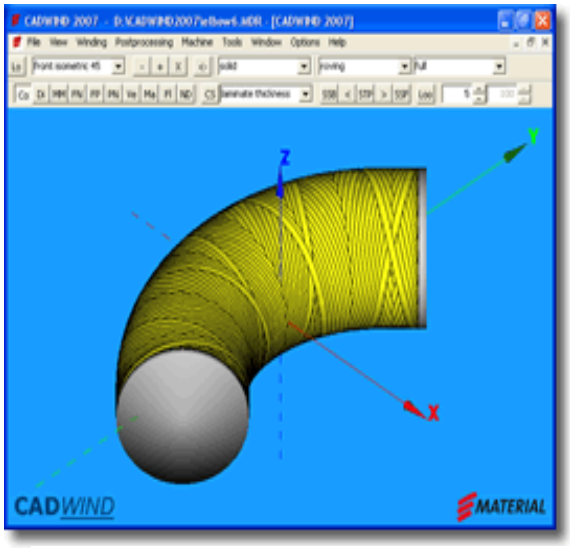


Figure 2 - Simulated elbow winding pattern [1]

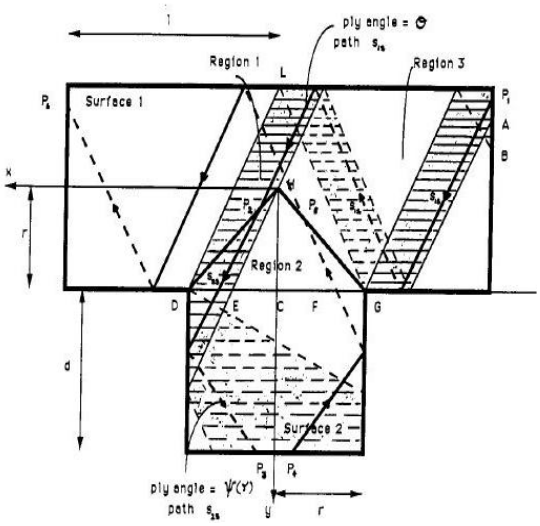


Figure 3 - Geodesic t-shape winding pattern [6]

2.1.2 Fibres

The fibres wound onto the mandrel are continuous, except for the very rare occasion when it is necessary to change a spool during winding. This is not a frequent occurrence, and therefore does not affect the mechanical properties of the part in any adverse way. The most common filament winding materials are carbon or glass fibres that have been either pre-impregnated, wet rolled or are wet wound.

Pre-impregnated fibres (also known as prepregs) have very good characteristics in the areas of quality control and reproducibility of resin content, uniformity and band width control. As some resins require special equipment to impregnate the fibres, they can be rendered too impractical or too expensive to produce locally. Alternatively they can be bought as a finished product from a distributor. Most of these prepregs, not produced locally, have solvents or preservatives added in the resin mixture to extend shelf life, These additives also affect the tack of the fibres, which, in turn, can lead to problems during winding.

Wet rolled fibres are impregnated locally and then re-rolled and tested before they are used for winding. This technique allows for the opportunity to perform quality control of the fibres before they are wound around the mandrel. After testing the fibres can be stored in a freezer, or used almost immediately after impregnation. Consequently the need for solvents or preservatives in the resin is eliminated. However, the negative effects of prepregs do not always warrant the investment of a freezer unit.

Wet winding is when the fibres are impregnated with resin immediately before winding. This is done by either pulling the fibres through a resin bath or over a resin covered roller directly before they are wound around the mandrel. This system is very cost effective, but is less reliable in terms of quality than both prepregs and wet rolled fibres. The resin content in the fibres is affected by parameters such as the viscosity of the resin, interface pressure at the mandrel surface, winding tension, numbers of layers per inch and the mandrel diameter. These are all parameters that are likely to change during the winding process, thereby increasing the inaccuracies and tolerances of the finished product.

A table comparing the positives and negatives of the three forms of impregnation can be found in [6] , page (3-26).

2.1.3 Winding Patterns

There are three basic winding patterns in filament winding; helical, hoop and polar winding Figure 4. The most important element in all of these patterns is the winding angle, α, which is the equivalent of the ply angle in other composite structures.

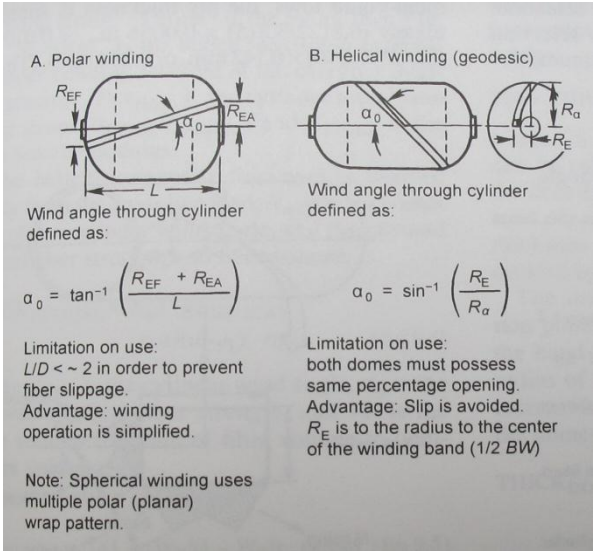


Figure 4 – Polar and helical winding patterns [5]

In helical winding the winding pattern is a multi-circuit pattern consisting of fibres with a winding angle approximately between 5° and 80°. Depending on this angle the mandrel might rotate several times before the fibres have traversed the whole circumference of the mandrel, and start laying adjacent to the previous windings. The resulting pattern is one of alternating positive and negative winding angles, each layer forming a two-ply layup of [α/-α].

The polar winding pattern is characterised by the fibres passing tangentially to the polar opening at the opposite end of the mandrel. The resulting layup has fibres angled from approximately 0° to 5°. As one pattern traverses the whole circumference of the mandrel the fibres will advance one band width for each pattern.

A hoop pattern consists of circumferential winding, and is also commonly referred to as a radial winding pattern. It is a term for winding where the winding angle approaches 90°. For each rotation of the mandrel the fibres advance one bandwidth, lying directly adjacent to one another along the mandrel axis of rotation. This winding pattern is most commonly used to produce a balanced-stress structure in combination with other types of winding. It should be noted that hoop winding can only be applied to the cylindrical part of a mandrel.

2.1.4 Winding Parameters

The geodesic path is one of the main principles in filament winding. In a dictionary it is defined as “designating the shortest surface line between two points on a surface” [5]. In filament winding it means that the fibres follow the shortest path on the mandrel surface between the two points. Logically, the geodesic path is also a stable path, as the fibres would have to stretch to deviate from the set pathway.

The geodesic path on a cylinder is a helical path with a constant winding angle, α. This means that to wind the end points of a cylinder the geodesic path cannot be followed completely. In so doing it is possible to change the winding direction and generate a complete layer. In deviating from the geodesic part the friction between the fibres and the mandrel surface is utilised, ensuring that the fibres stay in place. On a completely spherical part, on the other hand, every pathway is geodesic. Therefore, to wind on a spherical mandrel, additional parameters would have to be in place (starting point, winding vector, etc.) to determine the appropriate winding path.

It is known that for any point on the geodesic part on an axisymmetric mandrel the following equation holds.

$$r\sin(\alpha) = constant \tag{1}$$

Equation (1) is called Clairaut’s relation. It is a key concept of filament winding in determining winding path and winding angles. On a cylinder, as mentioned, the geodesic path follows a constant winding angle. Across a dome shape, however, the angle of the geodesic curve increases as the dome radius decreases. At the dome opening the winding angle will have increased to 90°. Consequently for a cylindrical mandrel with domes the complete path can be determined by Clairaut’s equation.

2.1.5 Winding Software

Filament winding has been used as a production process for more than 50 years [10]. As such there are several types of software for filament winding commercially available. A selection of these is presented in the following section.

Software	Distributor	Key Functionalities
CADWIND	MATERIAL	Integration with FEA software, pre-winding simulation options
Winding Expert	Mikrosam	Possibilities for extra module to integrate with FEA software
ComposicaD	Seifert & Skinner & Associates	Graph winding path before winding, take thickness build-up into account

CADWIND is considered one of the leading software solutions available on the market today. According to the developers it has been the standard program used in filament winding for more than 20 years [11]. It is developed and distributed by a company called MATERIAL based in Aachen, Germany.

The CADWIND software is capable of calculating a winding path for any kind of shape, be it an axisymmetric or a non-axisymmetric part, based on a specific set of mandrel and machine variables. It is also capable of handling variations in the winding angle, both along the length of the part and in different layers, consequently adding several degrees of freedom to the software. A part may consist of one long part with different winding angles along its length, a part with different kinds of winding layered on top of each other, or both. There are also several possibilities as to which kind of machine is to be used. Whether it has two degrees of freedom, six degrees of freedom or is a specialised machine, CADWIND is able to integrate with any machine capable of interpreting common G-codes.

The CADWIND user interface allows for several types of pre-winding interaction. A winding process can be simulated, complete with machine parameters (carriage position, winding angle, time, cycle etc.) displayed on the computer screen during the process. Post-simulation the software can be used to generate graphs depicting machine dynamics like speed-time or acceleration-time.

CADWIND is also said to be able to integrate with any FEA program. The necessary data can be exported from CADWIND to the FEA program in question so that the part can be analysed [1, 12].

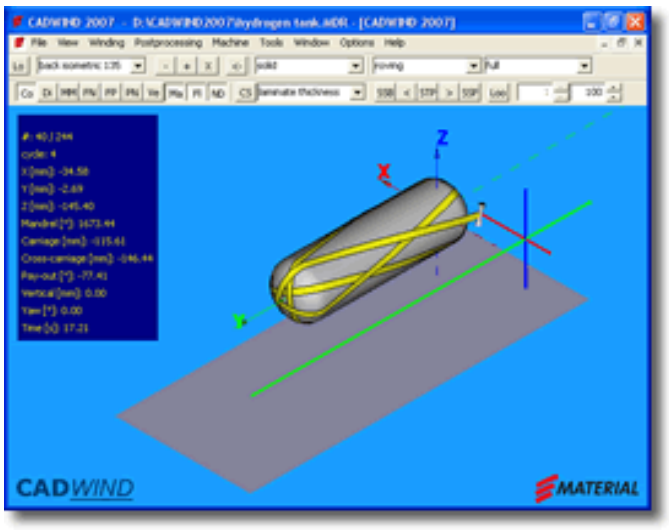


Figure 5 – Cadwind [1]

Winding Expert is the filament winding software from Mikrosam, a company based in Prilep, Macedonia, that makes modern machines for the composite industry. According to the information on their web pages “Winding Expert is a user friendly program which allows the composite designer flexibility to create winding programs that will completely fulfil the product requirements” [13].

Winding Expert is capable of generating machine code for both radial and helical winding. It handles the transitions between different types of winding, and custom winding patterns. In the case of a non-symmetric mandrel with a more complicated geometry, a part can be imported from one of the more commonly used CAD software and used as a mandrel. With an extra module the software also has the possibility of exporting data to an FEA program and perform an analysis of the finished part [2].

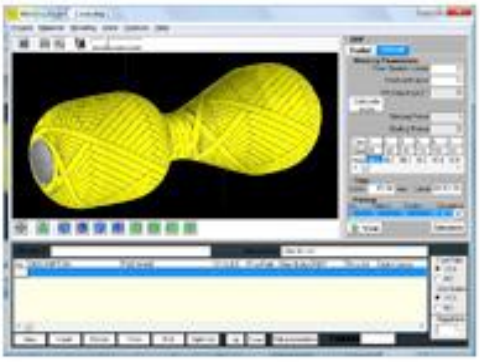


Figure 6 - Winding Expert [2]

ComposicaD is filament winding software created by ComposicaD and distributed by Seifert & Skinner & Associates, a consulting firm based in Belgium and the United States. According to their webpages ComposicaD is “the ultimate software for filament winding pattern generation”.

The software has a structure with several different levels of access to different ranges of functions. The levels range from the most advanced, which can make winding patterns for several different shapes, to the lowest level for companies who only have need of winding pipes. ComposicaD also has a special series available which allows for generation of patters for non-symmetric parts like elbows and t-shapes as well [14].

As with most winding software ComposicaD is capable of calculating both radial and helical winding paths using either geodesic or non-geodesic path algorithms. It can be used to generate CNC codes for machines with up to six degrees of freedom, and includes the option of graphing winding parameters prior to winding. In addition it has a functionality of generating helical winding patterns for symmetrical parts by re-making the mandrel for each layer, thereby taking the thickness build-up into account. Lastly the software has two different ways of creating the layup, from pre-defined mandrel geometry or with a

composite layup table. With the latter option it is possible to make winding patterns for several parts of varying lengths and diameters much quicker than with similar software where it is required to re-make the layup structure for every single part [3, 15].

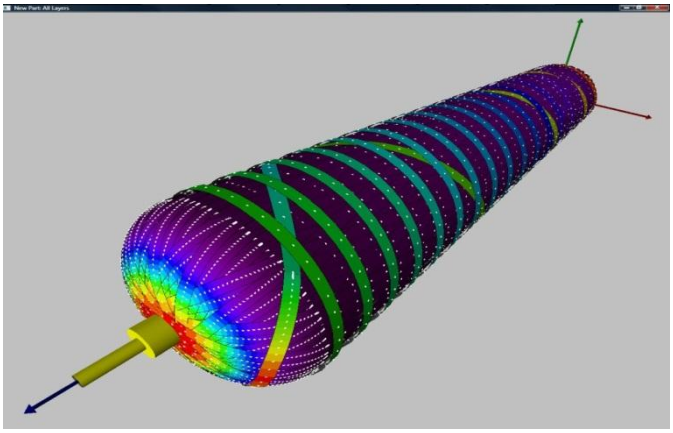


Figure 7 – ComposicaD [3]

2.2 Abaqus FEA

Abaqus is a suite of software applications for Finite Element Analysis (FEA) and is a branch of Dessault Systèmes [16]. With Abaqus it is possible to model complex assemblies and refine them, use custom designed materials and to model discrete manufacturing processes. It is a versatile modelling program that enables the user to perform complex analyses of parts and systems.

The Abaqus FEA Suite consists of several different analysis environments, and is continually expanding. There are environments for modelling, meshing and visualizing mechanical parts, for performing drop tests, crushing and manufacturing processes, as well as for heat transfer, and turbulence modelling. There are also several different add-on tools for more specialised applications [17].

2.2.1 Abaqus/CAE

Abaqus/CAE is the environment for finite element modelling, visualisation and process automation. It is the part of the Abaqus FEA suite that has been used in this thesis. With this environment it is possible to both create 3D-models from scratch by sketching, or import a model from other modelling programs like Catia or NX. Once the part is finished a mesh is applied, dividing the part into a series of elements. Lastly forces and constraints are added to the model so that it can be analysed and refined to fit the specific needs of a case [18].

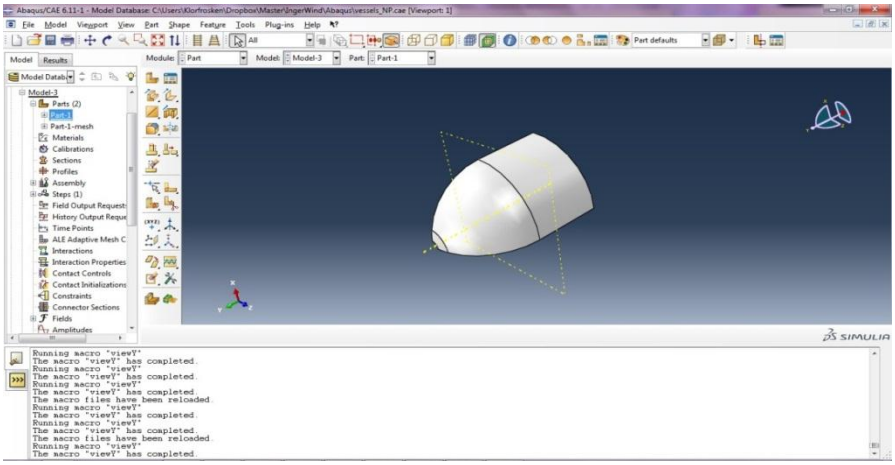


Figure 8 - Abaqus user interface

The process of modelling a part with layup properties resembling the layup formed by a winding process is extremely time-consuming. The applied layup would have to be an approximation, and a separate composite layup added to each element of an orphan mesh part (see chapter 4.2.2). As every single layer, and combination of layers, is unique there would be a lot of work involved. Not only in the modelling process itself, but with the extensive preparations necessary the task of calculating the winding angle for each ply of every layup. In addition the calculations would have to be related to a specific element and its placement and rotation on the model.

2.2.2 Wound Composite Modeler for Abaqus

One of the extensions for Abaqus FEA enables the creation, running and post processing of a finite element model with a filament winding layup [19]. As described in the previous section is performing this task without the plug-in is very time-consuming, and not really a viable option. The Wound Composite Modeler has tools to generate a winding layup, enabling the software to create the part geometry and mesh. The winding layup can be generated with an existing part as mandrel or by choosing the appropriate elliptical, spherical or geodesic shapes available. When necessary it is also possible to add a table of individual points from which Abaqus can create a shape to act as a mandrel.

Although the Wound Composite Modeler seems to include all thinkable options for creation and analysis of a part, it does not have any way of generating a corresponding CNC program. This means that, regardless of its intentions, the use of the plug-in is limited. Except for the case of simple winding patterns it is highly unlikely that the winding pattern generated by a different software will be identical to the layup generated by the Wound Composite Modeler [4].

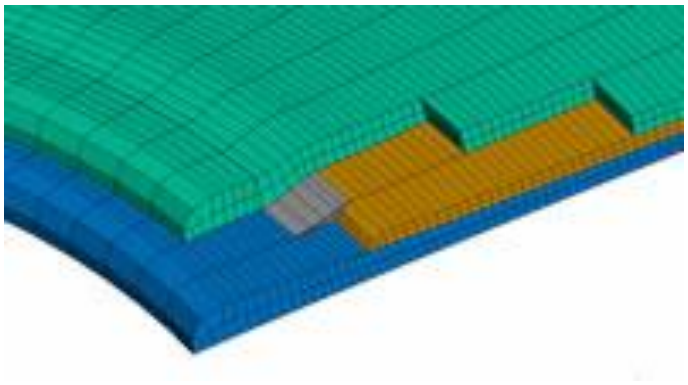


Figure 9 - Wound Composite Modeler [4]

2.3 Scripting and Integration

One of the main foci of this thesis has been integration with Abaqus, therefore scripting in the Abaqus environment is important. The following section provides a short introduction to the Python programming language, and an extensive explanation of Abaqus and its scripting interfaces.

2.3.1 The Python Programming Language

According to the Python web pages Python is a programming language that lets you work more quickly and integrate your systems more effectively. Learning to use Python will result in almost immediate gains in productivity and lower maintenance costs [20].

Python is created with an open source license, meaning that it is free to use even in proprietary software solutions. As a programming language it is often compared to TCL, Perl, Ruby, Scheme or Java. There are several advantages to using Python; amongst others the syntax is very clear and readable, the object orientation intuitive and it includes extensive standard libraries and third party modules for virtually every task. Also, importantly, it includes an extensive newsgroup with tutorials (both for beginners and more advanced users) and a wiki-page. It is a flexible and fast language that can integrate with several types of objects, and can easily be expanded should the need arise.

More information about Python and its functionalities can be found in [21].

2.3.2 Abaqus Scripting Interfaces

Abaqus is a complete FEA solution which includes a scripting interface, allowing for the creation of one's own features and routines. This is a supplement to the Graphical User Interface (GUI), and provides added flexibility for more advanced users. The Abaqus Scripting Interface can be considered an extension of the Python object-oriented programming language [22], meaning it uses the Python structure in conjunction with additional Abaqus-specific classes. Using scripts it is possible to perform any task without the use of the GUI as long as the appropriate commands are known. An overview of all the Abaqus commands can be found in the "Abaqus Scripter's Reference Manual" [22]

The Abaqus GUI serves as an interface for the Abaqus kernel. Clicking a button in the GUI sends a Python command to the kernel, which executes the command. Scripting is a way of maintaining control of exactly which tasks are performed by the Abaqus kernel. For the more experienced user some tasks are easier to perform by scripting, than with the GUI. Scripting can be done by recording a macro through the Abaqus GUI or by creating a script file. Short commands can be executed using the embedded Command Line Interface (CLI) is used. A flowchart depicting the command structure in Abaqus is given in Figure 10.

There are several reasons, besides increased control, to use the Abaqus Scripting Interface. Macros are a powerful tool while performing repetitive tasks; either if there is an operation that is performed often (opening a specific model database, adding a certain material or a standard part that is created frequently), or for performing parametric studies without having to manually change each parameter between analyses. Scripting is also used to create and modify model databases or access data in an output database. If necessary or practical a script can communicate with the Abaqus kernel, completely circumventing the GUI. This, however, has not been investigated further in this thesis and more on the subject can be read on page (2-3) – (2-4) in [22].

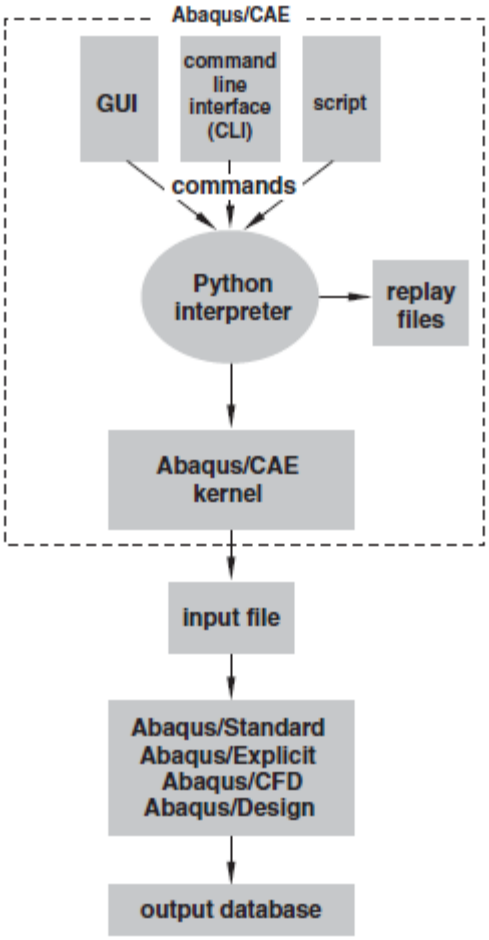


Figure 10 - Abaqus scripting interface commands and Abaqus /CAE

2.3.2.1 Recording a Macro

The 'Record Macro' button in the GUI registers and records a sequence of commands actions are performed. When the 'Stop Recording' button is pushed the commands are automatically converted to a macro that performs the exact same actions as recorded. Using this function to create a macro requires no previous programming knowledge of the user, but is also limited by the GUI. It is important to know exactly what to do and how it is done.

Depending on what tasks are performed, using this function might result in a macro that includes unnecessary steps; for example creating a macro to move a part into a certain perspective. Adjusting the view manually one would normally have to rotate the model several times before being completely satisfied. If the 'Record Macro' function is active every step of the way is recorded, not just the end result, as can be seen below. Thus every time the macro is run the perspective is not moved to the end position immediately, but will go through all the same adjustments as when the macro was created.

```
session.viewports['Viewport: 1'].view.setValues(
   nearPlane=265.212, farPlane=448.192, width=118.596,
   height=51.4552, viewOffsetX=26.5073,
   viewOffsetY=-22.0573)

session.viewports['Viewport: 1'].view.setValues(
  nearPlane=243.599, farPlane=437.46, width=108.931,
  height=47.262,
  cameraPosition=(-19.4574, 301.964, 183.445),
   cameraUpVector=(0.458362, 0.217248, -0.861805),
   cameraTarget=(6.46227, -18.0045, -33.2302),
    viewOffsetX=24.3471, viewOffsetY=-20.2598)

session.viewports['Viewport: 1'].view.setValues(
  nearPlane=244.522,farPlane=436.538, width=109.344,
    height=47.4411, viewOffsetX=27.4739,
  viewOffsetY=-36.6223)

session.viewports['Viewport: 1'].view.setValues(
  nearPlane=233.493, farPlane=391.867, width=104.412,
    height=45.3012,
   cameraPosition=(23.5205, 317.481, -54.5409),
   cameraUpVector=(0.465033, -0.442465,-0.766791),
   cameraTarget=(4.46965, -67.064, -12.5626),
    viewOffsetX=26.2347, viewOffsetY=-34.9704)
```

2.3.2.2 Command Line Interface (CLI)

The Abaqus CLI is located in a section of the Abaqus window beneath the Abaqus Viewport and is easily accessed. The CLI can be compared to the windows command prompt as it works the same way. Abaqus commands are entered in the command line and executed by pushing 'enter'. The only prerequisites to use the CLI are a basic knowledge of Python syntax and the relevant Abaqus commands for the tasks to be performed. It is, however, easiest to perform simple single line commands in this fashion. Most programmers will agree that it is very limiting being unable to use, for example, for-loops and if-statements. The CLI is therefore best suited for quick commands performed while creating or analysing a part, and not for repetitive tasks or more complex code.

2.3.2.3 Creating a Script

Creating a script can be done using a standard text editor, like TextPad, or using the embedded Abaqus Python Development Environment (PDE). The Abaqus PDE is an application made for creating, editing, testing and debugging of Python scripts. It is a matter of opinion whether it is preferable to use the PDE or code in TextPad using Python syntax highlighting.

Although the Abaqus Python interpreter can be used to execute pure Python scripts if desired, one would normally not use Abaqus for this purpose. Therefore it is assumed all scripts are created to interact with Abaqus objects. A script should include the import statements 'from abaqus import * ' and 'from abaqusConstants import * ' to gain access to the Abaqus modules. These enable the use of Abaqus-specific commands within the script. It should be noted that Python supports inheritance, meaning that if a script imports functions from a secondary file, this primary file does not necessarily have to include these to import statements.

The Abaqus structure is comprehensive. Although complete documentation is available it can be challenging to find the appropriate commands within. As such, it can be a useful tool to use a generated macro as a basis for a script, or to discover the proper commands for performing certain actions. All Abaqus macros are stored in an easily accessible file called 'abaqusMacros' in the Abaqus work directory. With access to this file and a basic understanding of programming it is possible to take advantage of the 'Record Macro'-function more extensively.

2.3.3 Abaqus Structure

Abaqus extends Python with approximately 500 additional objects, and can therefore not be illustrated with a single figure. It is, however, quite helpful to view some relevant parts of the Abaqus structure symbolically. This eases the understanding of the program structure, and simplifies the scripting process. Figure 11 shows the model and element structure in Abaqus.

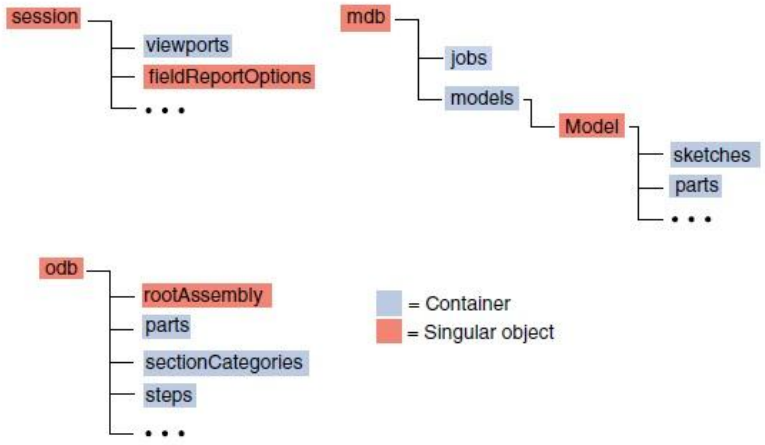


Figure 11 - Abaqus structure

2.3.3.1 Containers and Objects

In Figure 11 containers are marked in pink and singular objects are marked in blue. A container is an object that contains objects of a similar type, either as a repository or a sequence. An example of a container is the 'elements' container that contains all the elements on a model. The singular objects contain no other objects of a similar type; they are unique to the specific session. As an example of a singular object an Abaqus session only contains one model database and every model and part within has a unique part name. For simplicity the rest of this section refers to the structure depicted in Figure 12.

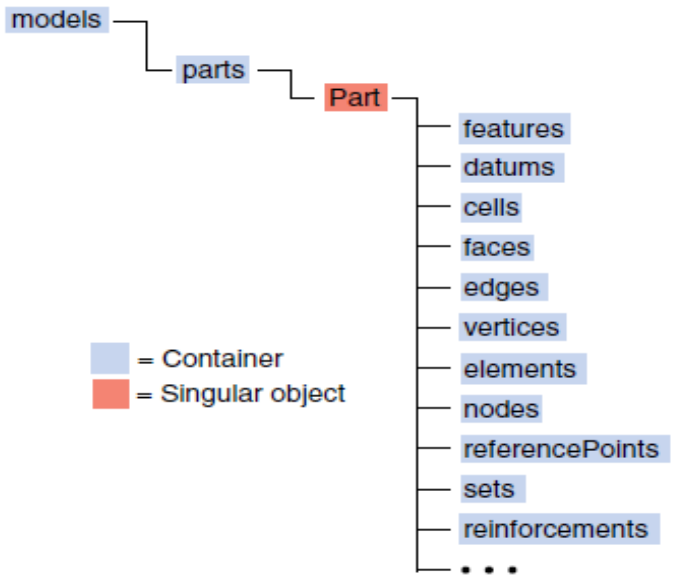


Figure 12 - 'models' object

Each separate element in the 'elements' container is also in and of itself a container. It is created with a 'connectivity' container, an 'instanceName', a 'label' and a 'type'. Each element corner is a node container and is initiated with a 'coordinates' container, an 'instanceName' and a 'label'. As with the 'elements' container, there is a 'nodes' container with all the nodes of a part. The element 'connectivity' list contains the indexes of each node on the element, and the nodal 'coordinates' container contains a list of the global coordinate values for the node. Figure 13 shows an element marked in red, with four blue nodes on a part.

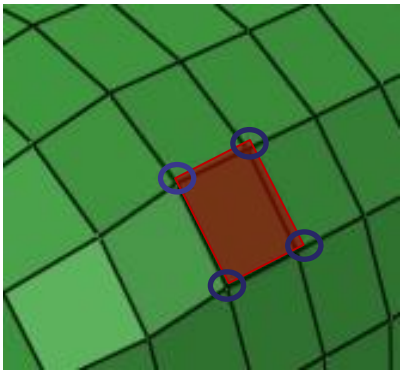


Figure 13 - Elements and nodes

To access a specific container or object in the Abaqus interface, either using the CLI or a script, the following command structure is used. The example accesses the 'nodes' container of a part.

```
mdb.models['modelName'].parts['partName'].nodes
```

The correspondence between Figure 12 and the command can easily be seen. 'Mdb' is an abbreviation of 'model data base', 'models' is the keyword for the model container, 'parts' for the part container and 'nodes' accesses the nodes container. To discover what a container or object contains one can consult the Abaqus Scripter's Reference Manual [23], or use the Python print function as shown in Figure 14.

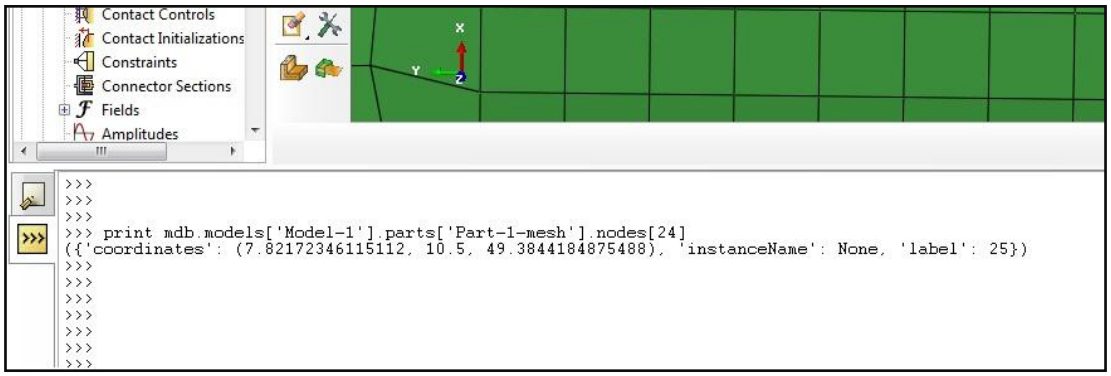


Figure 14 - Python print function

Another fact worth mentioning about the Abaqus structure is that the containers are stored as lists. For example the nodes container consists of a list of 'node' objects. A 'node' object consists of a list of several objects; amongst others the coordinates-object which contains a list of the node coordinates [X, Y, Z]. As an example the appropriate command to access the x-coordinate of a specific node (in this case node 24) would be:

```
mdb.models['modelName'].parts['partName'].nodes[23].coordinates[0]
```

Note that using Python all list indexes begin with 0, hence the index for node number 24 is 23.

2.3.4 Scripting in Practice

Scripting is quite straightforward with Abaqus. Except for the two aforementioned import statements there are no restrictions or requirements of a script. However, there are some practical advice that comes from experience.

To execute a script in Abaqus one can use the 'run script' button in the file menu, or create a macro. During a development process most programmers prefer a written macro as this requires less key strokes in the long run; they add up over time. Technically the script file can be located anywhere on the disk, but for simplicity it is strongly recommended to have all script files located in the Abaqus work directory. This is due to Abaqus' way of searching for

the files. Unless all the necessary files (scripts and models) are located in the work directory the scripts will not work directly.

Lastly, when developing scripts it is important to note that when Abaqus imports a script it is temporarily stored somewhere for easy access until Abaqus is closed. Consequently the changes made to a script will not be registered unless reloaded first. The two main ways to reload a script is by using the 'reload(...)' in the Abaqus CLI, or at the top of the primary script file, as shown below.

```
# necessary lines to use the abaqus functions
from abaqus import *
from abaqusConstants import *
import __main__

# import and reload the tools
import mandrelProperties
reload (mandrelProperties)
```

2.4 CNC Programming

CNC is an abbreviation of Computerised Numerical Control, a term often used in automation. Numerical Control (NC) is an expression that can be traced back at least as far as 1952, the U.S. Air Force, John Parsons and MIT in Cambridge. In the early 1960's it was slowly starting to be used in production manufacturing, and with the arrival of CNC in 1972 it really began taking off. The real boost, however, came with the arrival of affordable microchips ten years later.

According to [24], where this theory has been extracted from, "Numerical Control can be defined as an operation of machine tools by the means of specifically coded instruction to the machine control system". This is a good definition for both NC and CNC, the difference between the two being the computer. A production line with NC has automation, but little room for change. The programs are hardwired into the machines making it quite difficult to change after manufacturing of the system. With CNC the programs are stored in a computer, which in turn controls the machines. This enables one machine to execute several different programs, and for a programmer to change the program after implementation along with changes to the part or the production line.

```
(Example Code)
N10 G01 G21 G91 G94 F50000
N20 X20 Y10 Z30
N30 X30 Y50 Z35
N40 X-35 Y5 Z4
```

Figure 15 - CNC example

2.4.1 The CNC Programming Language

The CNC programming language is a language built from sequential blocks following a certain set of rules. A complete CNC program is defined as a collection of all the blocks giving a machine the necessary instructions for its production process. The program block consists of one or more programming words, which are a combination of characters. A character can be a letter, a symbol or a number, and is the smallest unit of a CNC program. Creating a programming word is done by combining a letter with one, or more, digits and symbols. The programming words in the CNC programming language are equivalents to mathematical or programming functions. The letter (also called the word address) is the function call and the digit(s) the function argument. All the letters of the English alphabet defines a function category with its own set of functions. A description of all the categories can be found in [24], p. 43-45. The most commonly used programming words are N (block number or sequence number), G (preparatory commands), X, Y, Z (coordinate value designations) and F (feedrate function). With the exception of the preparatory commands there can only be one

function per word in a sequence block; for example there can only be one M addressed word or one word with an X coordinate command. Figure 15 shows an example of some CNC code. Note that the first line is enclosed in parenthesis, which is the proper way to add comments in CNC programming.

2.4.2 The Most Common Addresses

2.4.2.1 Sequence Number (N)

In a CNC program the order of the programming words within a sequence block is almost inconsequential. There are some exceptions, but they will not be discussed further in this thesis. This fact is, however, dependent on the sequence number being the first word of a program block. The N address designates the beginning of a block and is the programmers' way of orienting inside the program.

When numbering a block there are some rules that have to be followed. One cannot use the sequence number '0', insert negative sequence numbers or use decimal points. As to the spacing of the numbers there are no set rules, it is a matter of preference. Generally there is a set increment, of for example 10, between the blocks in a new program. This increment facilitates the adding of lines in case of revision.

2.4.2.2 Preparatory Commands (G)

The preparatory commands are most commonly referred to as G codes. It is a command meant to prepare the control system for the desired action. The G codes are usually the beginning of a program, and at the beginning of the block directly following the sequence number.

As can be seen in Figure 15 there is nothing preventing a program block from containing more than one G code; as long as they are not conflicting commands. In other words it is, for example, not possible to use both 'G00', rapid positioning, and 'G01', linear interpolation, in the same block. This would be telling the machine to use two different modes of displacement at the same time. Using 'G91' and 'G01' (incremental dimensioning and linear interpolation respectively) in the same block presents no problem however. Incremental dimensioning is illustrated in Figure 17, linear interpolation means that the machine moves in a straight line when moving from point A to point B. Should a mistake be made such that a program block contains two conflicting G codes the one furthest to the right in the program block will be used.

The majority of the G codes are modal functions, meaning that they remain active after first appearing in the program. This renders it unnecessary to repeat most G codes more than once per program, the exception being if they have been cancelled by a conflicting command and need to be re-activated. A list of groups of G codes can be found in [24], p. 52. Except for group 00 (unmodal G codes) the G codes will stay active until cancelled out by another G code from the same group. Although G codes are mostly standard this is not always the case, there are different types of control systems with some differing commands.

To ensure that the program will be universal one should therefore use the most common groups of G codes. A list of these G codes can be found on page 49 in [24].

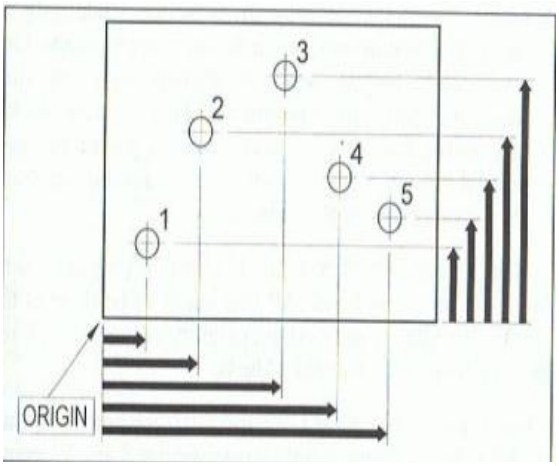


Figure 16 – Absolute dimensioning

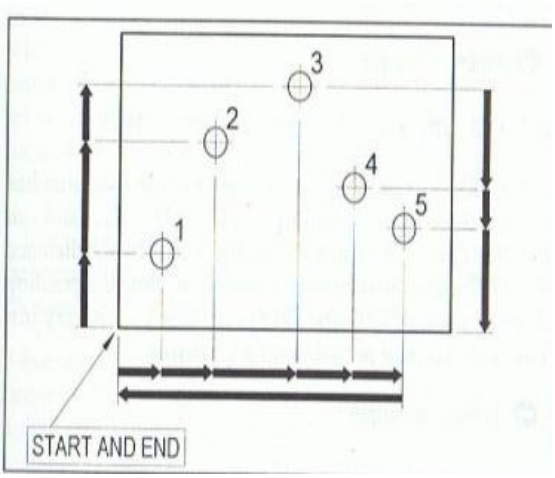


Figure 17 - Incremental dimensioning

2.4.2.3 Coordinate Functions (X, Y, Z)

The coordinate functions are the commands for motion along the axes. It should be noted that the coordinate functions are not limited to X, Y, Z, and can vary between different machines. It depends on the number of degrees for freedom of the machine and the designations of the axes.

A coordinate command can be interpreted in several different ways, depending on the G code(s) preceding it. A 'G90' code indicates absolute dimensioning, meaning all measurements (X, Y, Z, or whichever coordinates apply to the machine for which the program is made) are measured from a pre-defined reference point. This reference point might be a point on the part, the point of origin for the machine or anywhere in between. Using the 'G91' code in the program means incremental dimensioning. An incremental command uses the previous position of the machine as a reference point, moving from there. The concepts of absolute and incremental positioning are illustrated in Figure 16 and Figure 17.

Two other important preparatory commands related to coordinate functions are 'G20' and 'G21'. These are the commands for English and metric units respectively. Depending on where the machine is manufactured and the control system the standard will vary. To ensure the code works in the intended fashion it should always be specified at the beginning of a program what type of units are used.

2.4.2.4 Feedrate Function (F)

This function controls the speed of the machine and can have a great influence on the machined part, but also be of little consequence. In filament winding the speed refers to both the rotational speed of the mandrel and the speed of the feed carriage, which means it is relative.

As with the coordinate commands the feedrate can be measured in two different kinds of units, one of which is usually pre-defined within the control system automatically. To make a program as versatile as possible, or if the standard machine setting is unknown, it should also be specified within the program itself. To have the feedrate in inches/minute the modal preparatory command ‘G98’ is used, or to use millimetres/minute ‘G94’ is added.

Chapter 3. Foundation

As discussed briefly in chapter 1 this thesis has been a pilot study into the development of filament winding software. This chapter discusses the motivation behind the study and details some of the key difficulties encountered and the decisions made.

3.1 Motivation

Filament winding is a very complex process. There are numerous different ways to wind each shape, and an almost infinite number of windable shapes. A seemingly insignificant adjustment in the part geometry can cause the entire machine routine to change considerably, and even small numerical errors in the input parameters of software might result in complete failure of the winding process. This means that good filament winding software needs to be flexible and comprehensive, both in analysis and generation of CNC program, as well as intuitive and easy to understand. Logically a simple user interface able to handle complex cases is fairly difficult to achieve. Accounting for every possible shape and form, generating accurate layup, and still creating something that is intuitive and easy to understand is a big challenge.

3.1.1.1 Commercial Software

Although the commercial winding software currently available works, it is proprietary and offers little to no control outside of the GUI. This results in a certain lack of flexibility, which has turned out to be a challenge in the filament winding industry. To create accurate composites it is important that the CNC program is tailored to fit the part in question every step of the way. There should be as few approximations as possible, and a minimum of accumulated numerical errors. Control over all the various minute details that affect the material properties of the finished product, like crossover points, winding speed, mandrel shape, etc., is highly useful. Currently it has become common among companies working in mass production to use the software-output only as a basis for the winding program. After the CNC-program has been generated by the software it is manually tweaked and changed to fit the specific part. Although hard coding is unnecessary in theory, it is considered the best approach by some.

For the companies creating and distributing the software it is important to keep their patents and ensure that their software remains unique. The companies utilizing the software, on the other hand, would prefer access to the mode of operation enabling them to optimise the software to fit their specific needs. There is no way to satisfy both parties, and the software distributors have the power to suit their own needs.

From a user point of view, this is a problem. Although hard coding with a software-generated CNC-program as a basis is more efficient than creating something from scratch, it is far from ideal. The optimal solution would be to have access to software so flexible that it could be used by anyone, to wind anything. As long as the software remains closed source this is very difficult to achieve. However, if software existed that was completely open source it is conceivable that those using it could contribute by improving and adding functionalities as the need arises. This is an approach that has proven successful in other cases with similar software challenges; for example resulting in the popular computer operating system Linux.

Open source software has the advantage that it can be tweaked to fit every unique case. It is not limited by a single generalised user interface, but can be moulded to capture and process nuances as well. Such software also has the advantage of the user being able to trace the logic and the programming. If any errors or faulty logic is discovered it can easily be repaired, which will not only benefit the current user, but improve the software permanently and benefit others as well.

3.1.1.2 Integration with FEA Software

There are numerous variables affecting the material properties of a filament wound composite, which means that there are no simple ways of determining its behaviour. To be able to perform an accurate analysis of the mechanical properties of such a component would therefore be very valuable in an optimisation process. Currently the only option for this process known to the author is the 'Wound Composite Modeler' extension for Abaqus discussed in 2.2.2 . The extension does enable analysis of a part with a filament winding layup, but it does in no way ensure that the analysed part corresponds to a physical part. In other words: the actual wound composite part might have completely different mechanical properties than the analysed part. Software capable of taking all of the different variables of a filament winding (crossover points, thickness build-up, continuation of fibres, etc.) into account would be an achievement. Although it is not expected that this goal is reached with this thesis, it is hoped that it will form the basis of what is to be such software.

3.2 The Overall Approach

During the initial phase of the thesis work some fundamental principles were laid down to guide the development.

The first decision made was that of using Python as the development language. It was predetermined to integrate with Abaqus FEA software, which limited the choice of programming languages to either Python or C++. Although the author was more familiar with C++ than with Python the choice fell on Python. This was due to the fact that the Abaqus documentation was much more extensive for Python than for C++. As the two languages are fairly similar it was determined that more time would be wasted by searching for the C++ Abaqus commands than by learning the Python syntax.

Secondly, it was decided that thorough documentation should be a key factor of the finished product. As a pilot project intended for others to continue on, focus on the importance of thorough documentation ensures ease of understanding and future reference. It benefits the continued development of the software if the groundwork has been meticulously done and well documented.

Finally, it was decided to begin development with the simple shape of a pressure tank with cylindrical domes and equal dome openings. Although spherical domes are not very common on real parts, the geometry is simple, which aids the initial development process. The logic being that it is better to begin with simple shapes focusing on sound logic throughout the process, than to immediately start with a complex case. With the latter chances are that the end result will only work for that specific case and include faulty and hard-to-follow logic. This in turn would lead to someone else having to start the work anew sometime in the future.

3.3 The Kinematics of Filament Winding

The generation of a CNC program for a part is done by investigating the kinematics of a filament winding machine. Consequently the mathematical equations expressing the movement along the axes are a key part of the winding process.

Although filament winding as a production process has been used for many years, and there is a lot of existing literature, some of the fundamentals are not as well documented as one would expect. There are plenty of books and papers documenting both geodesic and non-geodesic winding, determination of mandrel shape and optimal design of filament wound parts, but documentation of the automation process is surprisingly scarce. The reason for the lack of articles on the subject is difficult to determine. One theory is that all the research has resulted in proprietary software, and therefore has not been published.

By the means described in Appendix B five articles were found on the subject of kinematics of filament winding. These articles have been investigated and evaluated in the sections below.

Filament Winding of Revolution Structures, [25], by Faissal Abdel-Hady, was published in the "Journal of Reinforced Plastics and Composites" in May 2005. The article gives a short and concise introduction to filament winding and the kinematics of a filament winding machine, before going on to show examples of implementation with simple software.

At first glance the article seems to include all the necessary elements to understand the automation process behind a filament winding machine. Equations (2) through (5) are the final equations describing the machine path during winding, as they are given in the paper.

$$\tan(\theta) = \frac{\lambda \sin(\psi)}{\left[R_0 - \left(\frac{\lambda R_0' \cos(\psi)}{\sqrt{1 + R_0'^2}} \right) \right]} \tag{2}$$

$$x_0 = R_0 - \frac{\lambda R_0' \cos(\theta)\cos(\psi)}{\sqrt{1 - R_0'^2}} + \lambda \sin(\theta)\sin(\psi) \tag{3}$$

$$z_0 = \frac{\lambda \cos(\psi)}{\sqrt{1 + R_0'^2}} + z \tag{4}$$

$$\tan(\phi) = \frac{\cos(\psi)}{R_0' \sin(\theta)\sin(\psi) + \sqrt{1 + R_0'^2 \cos(\theta)\sin(\psi)}} \tag{5}$$

However, upon closer inspection of the derivation of the equations themselves inconsistencies become apparent. While equation (2) seems sound, equations (3), (4) and (5) contain more or less obvious mathematical errors and, what is assumed to be, typing errors.

This has been detailed further in Appendix C. Unfortunately efforts to contact the author regarding this issue have been unsuccessful, and the article was deemed unreliable.

Kinematic Analysis of Trajectory Generation Algorithms for Filament Winding Machines, [26], written by Dejan Trajkovski, was presented on the 11th World Congress in Mechanism and Machine Science in August 2003. It gives a brief introduction into filament winding and then proceeds to derive equations for the movements of a filament winding machine using a conical cylinder as a basis. In conclusion, the results of the winding equations used for a cylinder with elliptical domes and un-equal dome openings are shown graphically.

$$\gamma = \arctan\left(\frac{R + r_f \sin(\beta)\cos(\alpha)}{r_f \sin(\alpha)}\right) \tag{6}$$

$$Y_E = -\sqrt{\left(r_f \sin(\alpha)^2 + \left[R + r_f \sin(\beta)\cos(\alpha)\right]^2\right)} \tag{7}$$

$$Z_E = z_E \tag{8}$$

Although the mathematics behind the kinematic trajectory equations (6), (7) and (8) appear sound, the rotation of the feed-eye is not taken into account. The rotation of the feed-eye during winding ensures that the fibres are placed flatly on the mandrel and do not twist or bundle during the winding process. This is not something that would make the equations unusable, but neither is it ideal. Winding great composites require control of every aspect of the winding process, something which this paper does not offer.

In addition, the article assumes the lateral feed-eye position to be directly across from the locus on which the winding occurs, as shown in Figure 18. Once again, this fact does not render the equations useless, but neither is it conducive to optimal winding. Logic dictates that if the feed-eye is directly across from the locus, the fibres will slide in place along the geodesic curve in the course of the winding process. Such an approach might cause bunching of the fibres, and unintentional deviations from the geodesic path caused by the friction between the fibres and the mandrel. As the intention of this thesis has been to do sound and thorough ground work, this article was also dismissed.

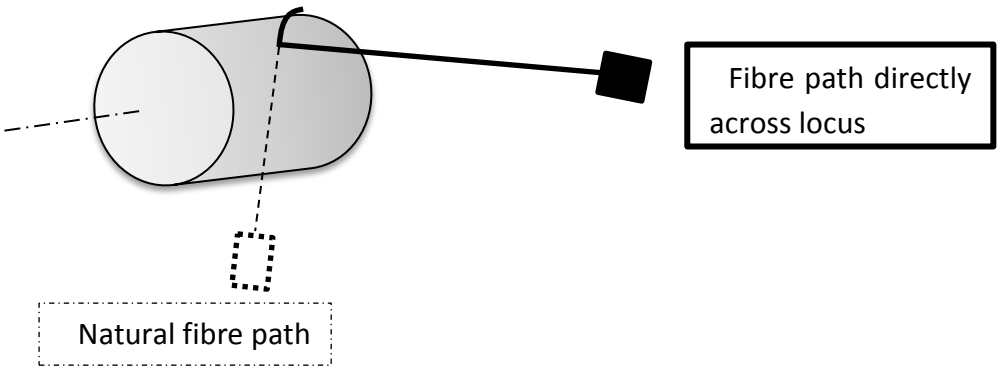


Figure 18 - Fibre paths

"Filament Winding, Part 1 & 2" and "Filament Winding: A Unified Approach" [27-29] are all titles written by Sotiris Koussios from TU Delft. "Filament Winding. Part 1: determination of the wound body related parameters" and "Filament Winding. Part 2: generic kinematic model and its solutions" are both articles that were published in "Composites. Part A: applied science and manufacturing" in October 2003. "Filament Winding: A Unified Approach" is a book of approximately 350 pages published in January 2004, based on the doctorate of Sotiris Koussios. These three titles all detail the same approach to the kinematics of filament winding. The physics and mathematics behind the approach appear sound and sufficiently comprehensive, and being based on analytical geometry, one would assume sufficiently versatile.

In short, equations (9) through (12) describe the movements of a filament winding machine.

$$C = -\phi \pm \left(\frac{\lambda \sin(\alpha)}{\sqrt{\lambda^2 \sin^2(\alpha) + \left(\rho + \lambda \cos(\alpha)\sin(\beta)\right)^2}} \right) \tag{9}$$

$$X = \sqrt{\lambda^2 \sin^2(\alpha) + \left(\rho + \lambda \cos(\alpha)\sin(\beta)\right)^2} \tag{10}$$

$$Y = \rho + \lambda \cos(\alpha)\cos(\beta) \tag{11}$$

(12)

$$A = \arctan\left(\frac{\cos(\alpha)}{\eta} \right)$$

$$\textit{where } \eta = \left[\sin(\alpha)\cos(\omega) + \cos(\alpha)\sin(\beta)\sin(\omega) \right]$$

$$\textit{and} \quad \omega = C + \phi$$

To solve these equations it is necessary to solve a set of equations for the variables ϕ and β, which in turn lead to the necessity of solving equation (13).

$$L(i) = \int_{\theta_{up}}^{\theta_i} \frac{\sqrt{G(t)}}{\cos(\alpha(t))} dt \qquad 1 \le i \le p \tag{13}$$

At this point, however, ambiguities preventing the continuation of this approach were discovered. It proved possible to solve the integral for 'L' using the trapezoidal rule in an Excel spread sheet, but solving the same integral using Maple (a powerful mathematical computation engine with an intuitive, "clickable" user interface [30]) provided contradictory results. The Maple solution had one imaginary and one real part, which for a real length along a cylinder does not hold. It was decided to abandon this approach as well.

3.3.1.1 In conclusion

After the evaluation of the found articles the author, in agreement with her advisor, determined that further work into the problem would be useless in the remaining time frame of the thesis work. A broader understanding and knowledge of automation, as well as the kinematics of filament winding would be necessary. It was decided that the focus for the rest of the thesis should be kept on the development of the software.

3.4 Software Development

One of the key factors of the developed software is its functionality of integrating with Abaqus. As such the first thing done was to get familiar with the Abaqus interfaces, both GUI and the scripting interface, to provide a solid basis for the development process. The development process itself was done as a stepwise process towards the goal of fully functional software; Software capable of integrating with both a filament winding machine and FEA software.

The first step was to develop a module with the ability to determine mandrel properties of an Abaqus model automatically. This is a principal function for both the generation of a CNC program and addition of a composite layup to the part. With this functionality in place it was possible to progress to more filament winding specific modules.

As it was determined to temporarily exclude the kinematics of filament winding from the software development a set of functions on which to focus were thought of. These were:

1. A visual crash test where an assembly is created with a feed-eye. The feed-eye should be moved in accordance with a CNC program; in such a way that it is possible to visually verify that there will be no collision during the winding process.
2. The addition of a filament winding composite layup to an Abaqus mandrel part. The main concern should be basic assumptions and approximations, so as to ensure an accurate result.
3. Creation of a class based structure for ease of further development and functionalities.

Throughout the development process emphasis was made on structure, readability, flexibility and simplicity of the software.

3.4.1.1 In Conclusion

The goal of this development process has been to create the basis for open source filament winding software capable of integrating with FEA software.

The concept of filament winding software is not new, there are several such software solutions in existence already; but none of them are considered ideal. They are proprietary and offer little to no control outside of the GUI. In addition, a certain lack in the market has been discovered. There is, as far as the author knows, no software available that is capable of modelling a filament wound part with layup that corresponds to that of a physical part.

With these principal facts in mind the thesis work was started. Initially it was focused on generating a CNC program based on an Abaqus model and integration with Abaqus/CAE. Then, the focus was switched to include specific functionalities of the software. The end result was the “Abaqus Winding Integration Tools”, the documentation for which can be found in the following chapter.

Chapter 4. Abaqus Winding Integration Tools

This chapter contains a description of the Abaqus Winding Integration Tools and discussions of the choices that have been made throughout the development process.

4.1 Introduction

The Abaqus Winding Integration (AWI) software package is an open source solution intended to bridge the gap between the FEA software Abaqus and a filament winding machine. It contains a set of scripts, or modules, executable through the Abaqus interface. The tool-set is intended for use in the filament winding process. Ultimately it should result in software including functionalities like creating a CNC program based on an Abaqus model, and adding the corresponding winding layup to an existing model.

The AWI software package is meant to serve as a basis for further expansion and development of a more complete and dexterous set of tools. In time, it is the intention that the software shall be capable of handling any windable shape or form. When the package is put in use, as it is open source, others will be able to implement their own functionalities, correct mistakes and in general improve the software according to their own specific needs. Hopefully, the effect over will be an improved and continually expanding software solution more versatile and comprehensive than proprietary software available today.

The AWI software package has been developed at the Norwegian University of Science and Technology (NTNU) in Trondheim and can be viewed in its entirety in Appendix E. The software has been created with a class based structure, as this facilitates understanding, readability and future expansion. Classes enable variables to be changed and used in several different functions without them having to be stored in an outside script or sent into and returned from functions repeatedly. This makes for a clearer structure where additions can easily be built in without drastically changing anything. As an added effort to make reading of the tools intuitive the variable names have been carefully chosen to, as accurately as possible, describe the information they contain.

In using the tools it is important to note that all measurements should be in millimetres. This is the standard unit for most filament winding machines and therefore the standard unit for AWI.

4.2 General Notes

The following section includes some generalities for the AWI tools. Topics discussed include choice of variable names, model specifications, general approach based on nodes and elements and the overall software structure. For reference there is an alphabetical list of all the AWI variables in Appendix F.

4.2.1 Variables

All of the AWI tools contain a header including the title of the tool, a short description of what it does, import statements for the necessary files and Python and Abaqus libraries and three global constants.

```
### global constants. Do. NOT. Change. These!
X_AXIS = 0
Y_AXIS = 1
Z_AXIS = 2
```

These constants could easily have been avoided, but it was decide that the code becomes much more intuitive with them in place. The following piece of code is an abbreviated version of what is used to determine the rotational axis of a part. It is clear that the first version, with the global constants, is easier to follow than the second one utilising the '0', '1', and '2' terms.

```
### code with global constants
    if round(currentNode.Radii[Y_AXIS], 5) ==
                                    round(nextNode.Radii[Y_AXIS], 5):
        mandrel.rotationalAxis = Y_AXIS
        mandrel.H = X_AXIS
        mandrel.V = Z_AXIS

### code using numerical values
    if round(currentNode.Radii[1], 5)==round(nextNode.Radii[1], 5):
        mandrel.rotationalAxis = 1
        mandrel.H = 0
        mandrel.V = 2
```

It is the intention that several different people, not necessarily in contact with one another, should be able to understand and continue development of the software. In an effort to achieve this the choice was made to rather use longer, more descriptive, variable names such as 'rotationalAxis'. The fewer 'temp', 'var' and 'foo' variables there are the simpler and more intuitive the tools will be. However, long variable names have not been used indiscriminately. A balance was found between longer and more descriptive variable names and those that were too long, making the code more difficult to read. Examples of the latter type of variable are the 'CylindricalMandrel' variables 'H' and 'V', which represent the horizontal and vertical axes of a coordinate system. These variables could easily have been called 'horizontalAxis' and 'verticalAxis' instead, but given that they are often used to call list variables it was determined that the longer versions would render the code less legible. As

the ‘rotationalAxis’ variable, although technically the same type of variable as ‘H’ and ‘V’, is a key variable it was determined that it should retain its descriptive name.

4.2.2 Model Specifications

Currently there are several restrictions as to what type of Abaqus model can be used as a mandrel. The most important of these, which is also not likely to change during development, is that the model must be an ‘Orphan Mesh Part’. An ‘Orphan Mesh Part’ is a part that has been created from the mesh of another part and consists of a shell of elements identical to the mesh. Figure 19 shows a modelled mandrel part and its ‘Orphan Mesh Part’. To create a mesh part one simply uses ‘Mesh’-menu on the menu bar in the mesh environment and clicks the ‘Create Mesh Part…’-button. A second option is to use the following command in the CLI or a script:

```
mdb.models['modelName'].parts['partName']
                                .partFromMesh(name='meshedPartName')
```

For the time being there are also some geometrical limitations of the mandrel model. The mandrel must be a cylindrical mandrel with spherical domes (a ‘pressure tank’ – shape), and the dome openings in each end must be of equal size. The mandrel should be modelled as a generic shell of revolution, with the rotational axis along one of the global coordinate axes. As the mandrel is axisymmetric it is not necessary to model the complete mandrel. For example ¼ of a cylinder is sufficient, the degrees of revolution are unimportant. However, for the function calculating the cylinder length to function correctly the length of the modelled cylinder must be half of the actual cylinder length.

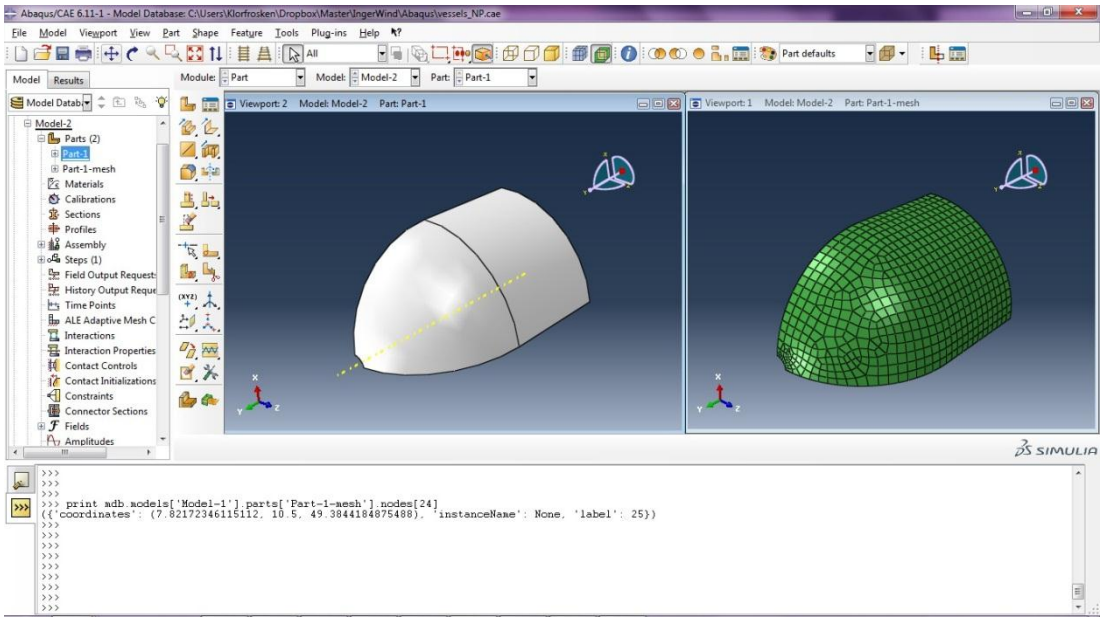


Figure 19 - Mandrel and 'Orphan Mesh Part'

4.2.3 Elements and Nodes

Several of the tool procedures are based on the nodes and elements of the 'Orphan Mesh Part'. On such a part the elements and nodes are created with no obvious logical correlation between the node/element id and placement on the model. There is a definite logic behind this process, but not one that can easily be used in a script. For a part with an unstructured mesh there is also the added challenge that the elements do not have the same amount of nodes. However, it is still considered a good method for integration. The method enables the discovery of all of the model parameters without any additional information about the model, like orientation and size. The only required information is the model name of the relevant Abaqus mandrel model, and its associated 'Orphan Mesh Part'.

4.2.4 Miscellaneous

All the AWI tools have been tested on a set of models and part with different types of mesh and spatial orientation. It has been verified that they work for models with any axis of rotation and both structured and unstructured meshes. Two examples of test models are shown in Figure 20 and Figure 21. The test models can be downloaded along with the master thesis.

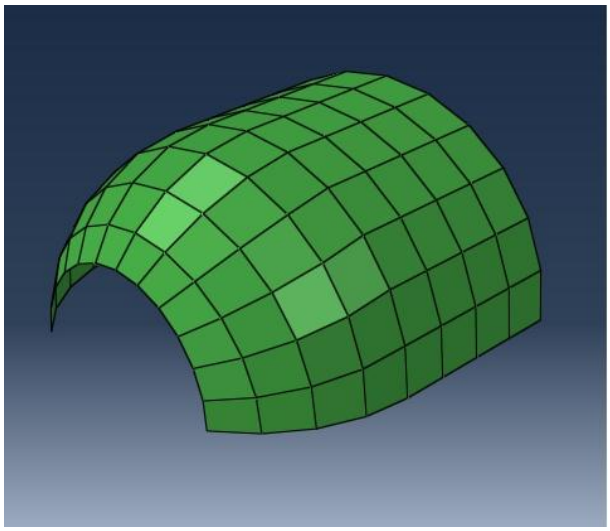


Figure 20 - Structured mesh

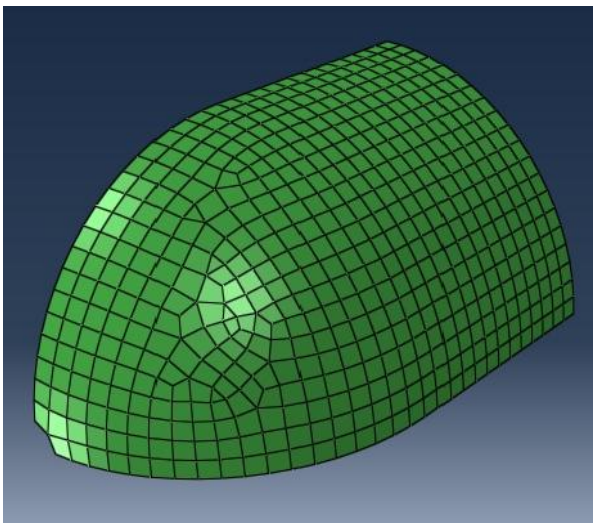


Figure 21 - Unstructured mesh

The AWI software package has been created with a class based, module based structure. All the functions belonging together are placed together in a single module for clarity. At the bottom of each module there is an execution function that utilises the modular function to perform the specified task for which the module is intended.

4.3 Classes.py

This module contains all the AWI class definitions. Classes are a practical tool when programming that helps create more readable and manageable code.

4.3.1 MachineParameters

The 'MachineParameters' class includes variables containing all the physical limitations of a specific filament winding machine; such as maximum mandrel radius and length. These are used to verify that the mandrel does not exceed the limitations of the filament winding machine, and that a generated CNC-program does not dictate movement outside any of the axis-ranges. The class contains only the '__init__(…)' function, which sets all the relevant parameters. It is important to ensure that the parameters sent into the function are the correct ones in accordance with the winding machine that is to be used, and that they are in the right order.

As the class has no class functions, but only stores the values for each variable which are accessed by other tools, it is technically unit-neutral. However, as the rest of the tools assume millimetres, the input for this class presumes millimetres as well.

4.3.2 CylindricalMandrel

This class includes all the mandrel properties for a cylindrical mandrel with spherical end domes and equal dome openings.

4.3.2.1 Model Variables

This first section of variables contains information about the Abaqus model that describes the mandrel, like the model name and part name, and some of its containers that are accessed often. Examples of containers are the 'nodes'- and 'elements'- variables which point to the model containers with the same name as shown below.

```
self.nodes = mdb.models[modelName].parts[partName].nodes
self.elements = mdb.models[modelName].parts[partName].elements
```

4.3.2.2 Geometrical Variables

The second variable section of the class contains all the geometrical mandrel properties, like radii and lengths. Upon initiation all of these, with the exception of 'rotational axis', are set to 'None'.

The 'rotational axis' variable is set to 'undetermined' and not 'None' because of how axes are assigned. Even though the global variables ensures the readability by allowing the axes to be set to and called by 'X_AXIS', 'Y_AXIS' and 'Z_AXIS' they are still read by Python as '0', '1' and '2' respectively. A consequence of this is that if 'rotational axis' is set to '0' a logical test will return a false negative. For example, the following segment of pseudo code would result in an infinite loop even if the if-statement should be true and the 'rotational axis' set to '0'.

```
mandrel.rotationalAxis == None

while not mandrel.rotationalAxis:
  if radius(YZ_coordinates) == radius2(YZ_coordinates):
        mandrel.rotationalAxis = 0
```

To take advantage of the numerical assignment of the axes the two remaining axes are also determined, 'V' represents the vertical axis and 'H' the horizontal axis. It was determined to use a coordinate system with the current rotational axis pointing inwards in the plane and the two remaining axes pointing to the right and upwards as shown in Figure 22. Having a consistent assignment of the axes allows for practical use of lists instead of if-statements in the code.

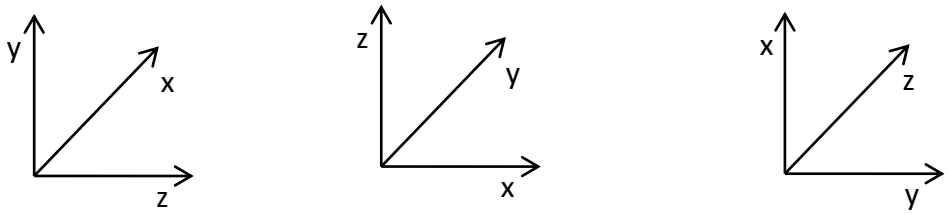


Figure 22 - Axis configurations

Most of the following variables are quite self-explanatory, 'radius' being the cylinder radius and 'domeOpening' the radius of the dome opening. The 'minLength' and 'maxLength' variables represent the smallest and greatest value on the rotational axis of the cylinder and are used, amongst others, to calculate the length of the cylinder. There are two separate length variables; the 'mandrelLength', which is the calculated total length of the cylinder including the domes, and the 'cylinderLength' variable which is the cylinder length of the Abaqus model.

The last geometrical variable, 'pointOfOrigin' is set as the coordinate on the axis of rotation of the dome opening as indicated in Figure 23. This serves to determine the starting point for winding and determining the dome variable.

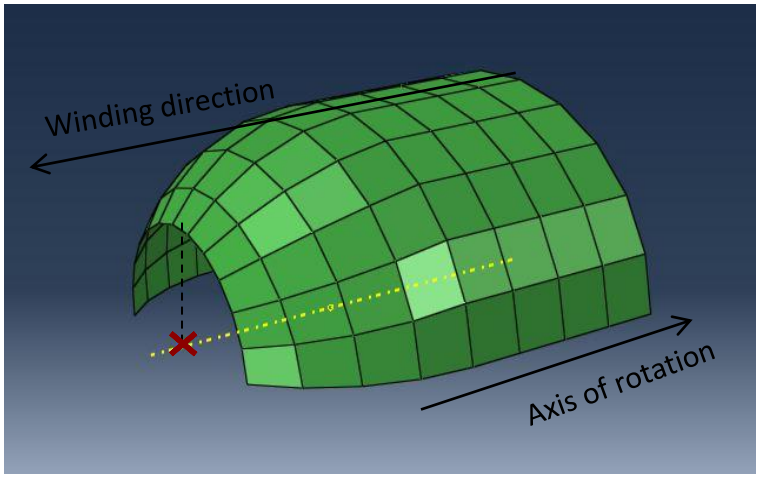


Figure 23 – Mandrel properties

4.3.2.3 G Code Variables

The G code variables are used when writing or reading G codes.

One of the G code variables is a list of lines called 'lines'. Lines of CNC code are added to it as they are created for the current Abaqus model. 'domeVariable' is a variable set to either '-1' or '1', depending on the placement of the dome on the model. If the maximum value of the model on the rotational axis is on the dome it is set to '1', if the minimum value is on the dome it is set to '-1'. The dome variable of the mandrel in Figure 23 is equal to '1'. 'windingDirection' is a variable that changes depending on the direction of the winding. It is equal to '-1' if the winding is happening in the negative direction on the rotational axis of the Abaqus model, as shown in Figure 23.

4.3.2.4 Class Functions

The class functions of the cylindrical mandrel class are 'setLength', 'calculateTotalLength', 'setDomeVariable', 'verifyMandrel' and 'printProperties'.

'**setLength**' is a function that sets the three length variables appertaining to the Abaqus mandrel model ('minLength', 'maxLength' and 'cylinderLength') and calls the functions 'calculateTotalLength' and 'setDomeVariable'.

The '**setDomeVariable**' function simply compares the 'pointOfOrigin' variable to the 'minLength' variable and determines the placement of the dome in reference to the cylinder and the global coordinate axes.

'**calculateTotalLength**' is a function that determines the length of the mandrel. There were two choices of how to calculate the mandrel length; to calculate an approximation of the length or to derive an equation for the true length of the mandrel.

An approximation of the mandrel length would have been calculated assuming that the spherical domes are complete. Or, in other words, that the length of the dome along the mandrel axis of rotation would equal the dome radius as in equation (14).

$$\text{mandrelLength} = 2 * \left(\text{R} + \text{cylinderLength} \right) \tag{14}$$

This approximation would, in most cases, be sufficient as it is only used to determine whether the mandrel is within the machine parameters or not. However, it was decided that an equation for the true mandrel length was to be derived. Although not a frequent occurrence, the instances when the mandrel does just fit within the machine parameters it would be very frustrating if one would have to "fool" the software into thinking that the mandrel fits by inserting a greater value for the appropriate machine parameter. Also, if the use of the parameter were to change in the future it would cause errors if it is not exact.

The true cylinder length is calculated using equation (15), the derivation of which can be found in appendix D.1

$$\text{mandrelLength} = 2 * \left(\sqrt{R^2 - r^2} + \text{cylinderLength} \right) \quad (15)$$

'**printProperties**' prints a summary of all the relevant mandrel properties in the Abaqus Message Area, while simultaneously calling the 'verifyMandrel' function to determine whether the mandrel is within the mandrel properties.

The '**verifyMandrel**' function checks the mandrel properties against the machine parameters to ascertain whether the mandrel is within the machine parameters. If the mandrel exceeds any of the parameters a statement is printed, including what part of the mandrel that does not meet the requirements of the filament winding machine. As shown below the name of the filament winding machine whose parameters are not met is also printed. This is a precaution to ensure that the mandrel is tested against the right requirements, in case the machine parameters have not been set properly.

```
if (self.radius > settings.maxMandrelRadius):
    print "The mandrel radius is too great for the ",
                                        settings.Name, " machine"
```

4.3.3 Material

The 'material' class is created to contain several materials commonly used in filament winding. Each material should include all the relevant material properties and a string specifying the name of the material. Currently it only contains the 'carbon_epoxy' material with approximate values for the material properties.

4.3.4 CustomNode

A 'CustomNode' object is initiated using a mandrel object, an element on the Abaqus model and a numerical value 'node'. It contains a list of nodal coordinates ('XYZ') and a list of radii ('radii') calculated using different coordinate combinations.

4.3.4.1 Class Variables

The 'XYZ' list is first created containing only zeroes and then filled with the appropriate coordinate values. An introduction to scripting with Abaqus and explanation of the nodes and elements structure can be found in section 2.3.2 2.3.3 . Node coordinates are accessed and set using the following command structure, which extracts the x-coordinate value for the relevant node:

```
self.XYZ[X_AXIS] = mandrel.nodes[element.connectivity[node]]
                                                .coordinates[X_AXIS]
```

To easier understand the command it can be shortened thusly:

```
nodeID = element.connectivity[node]
self.XYZ[X_AXIS] = mandrel.nodes[nodeID].coordinates[X_AXIS]
```

'element' is an element from the model elements list and 'node' is a numerical value for the node's position in the connectivity list.

As with the 'XYZ' list the 'radii' list is created containing only zeroes and then filled with the appropriate values. Technically they could both have been tuples, as they are not to be changed after the values are set, but that would have resulted in long and unnecessarily complicated commands.

The values in the 'radii' list are the three radii calculated on the assumption that the x-axis, y-axis and z-axis respectively are the axis of rotation. This method is possible as one of the model requirements is that it is created with its rotational axis as one of the global axes, meaning that the nodal coordinates also can be interpreted as the legs of a right triangle as shown in Figure 24. The picture shows the node, marked in red, and its three corresponding radii.

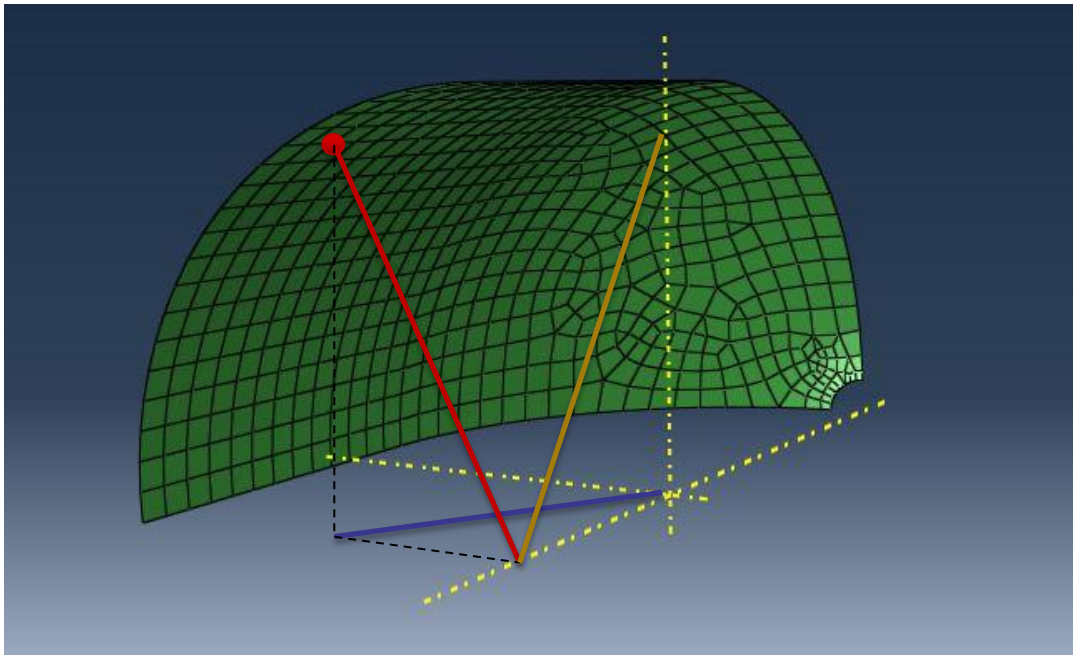


Figure 24 - Different radii for a node

Using lists to store these values instead of separate variables is a very deliberate move to take advantage of the numerical assignment of the axes. Logically the rotational axis determines what values are relevant for calculations. As several of the AWI tools use iteration through elements and nodes as a tool failure to take advantage of this could result in a lot of over-complex code filled with if-statements.

4.3.4.2 Class Functions

The '**calculateRadius**' function employs the Pythagorean Theorem to determine the hypotenuse of a triangle, and is used to determine the node values in the 'radii' list.

'**returnRadius**' and '**returnAxisCoordinate**' are functions that return the node radius and coordinate on the axis of rotation, respectively. They are both functions that are greatly simplified by the use of lists and numerical axis coordinate values. Both of the functions take the rotational axis for the mandrel as input and use it to determine which of the coordinate

values or radii to return. If the values had not been set in lists these functions would have had to consist of several if-statements testing for the rotational axis, as shown below:

```
def returnAxisCoordinate(self, rotationalAxis):
    if mandrel.rotationalAxis == X_AXIS:
        return self.X

    if mandrel.rotationalAxis == Y_AXIS:
        return self.Y

    if mandrel.rotationalAxis == Z_AXIS:
        return self.Z
```

Instead the function looks much simpler:

```
def returnAxisCoordinate(self, rotationalAxis):
    return self.XYZ[rotationalAxis]
```

The last 'customNode' function is '**printProperties**', which prints the values in the two class variables. This function serves no purpose in the use of the tools, but is quite practical when debugging or adding to the software.

4.3.5 CNCLine

'CNCLine' is a class for tool generated G code lines.

A 'CNCLine' object is initiated with all the relevant line variables, rounds them down to five digits, and formats them into a string, 'string', which is then entered into the text file for the CNC program. Each 'CNCLine' object is added to the mandrel variable 'lines' where it can be easily extracted later. The object also has variables for each of the line variables 'N', 'X', 'Y', 'Z' and 'W'. These separate line variables serve two purposes. They ensure easy access without having to search through the string, and they store the accurate value, not the rounded one.

Rounding the variables is not ideal, but practical all the same. Numerical errors will forever be an issue, whether it is a computational error or a human error. To avoid the issue of accumulated numerical errors as much as possible it is preferable to round any and all numerical values at the last possible moment. For this reason the rounding of the machine variables is done at this step, and only in the 'string' variable.

4.3.6 GCode

This class includes all the relevant G Code variables, like the sequence number, the sequence incremental value and variables for the total movement in each axis direction.

Upon initiation the 'GCode' class opens or creates the appropriate text file and adds several opening lines and comments to the top of the file. Lastly the first program line, containing the proper preparatory commands, is inserted with the sequence number '10'. The result is shown in Figure 25.

The class also contains a function that adds a program block to the text file while simultaneously checking whether the movement along any of the axes exceeds the machine limits. If the physical machine boundaries are overstepped the function will print statements of in which direction the error occurred. In the common case, when the boundaries are not exceeded, the function adds the program block to the list of program blocks and the writes the block into the text file.

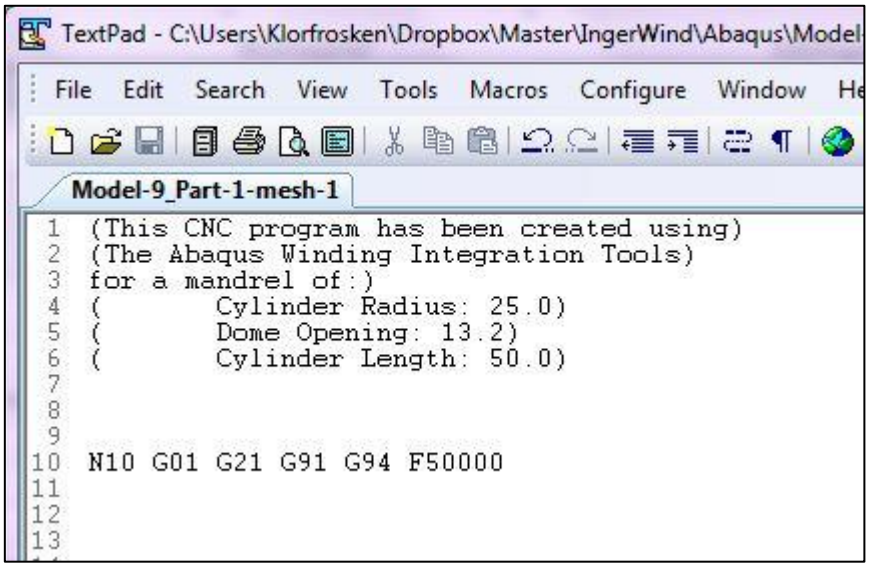


Figure 25 - GCode opening lines

4.3.7 LayupConstruction

'LayupConstruction' is a class used while adding layup to an Abaqus model.

4.3.7.1 General variables

Currently the only general variable is the 'material' variables, which stores the material used for the winding layup.

4.3.7.2 Movement Variables

These variables track the movement of the mandrel during the winding process.

'P1' stores the coordinate value of the current position on the mandrel. Before winding has begun it is assumed to begin at the dome tip on the rotational axis and '0' on the two remaining axes. The variable 'P2' is the next position on the mandrel determined by the rotation of the mandrel and the movement along the rotational axis.

Considering the plane created by the horizontal and vertical mandrel axes 'P1' and 'P2' becomes points on a circle. The 'crossesHorizontal' and 'crossesVertical' variables (initially set as 'False') describe whether the two points are located in the same quadrant or if 'P2' is on the other side of one of one of the axes. Figure 26 shows the two different possibilities for placement of 'P2'. For the red instance of 'P2', located in quadrant II, the vertical axis, 'V' has been crossed and 'crossesVertical' set to 'True'.

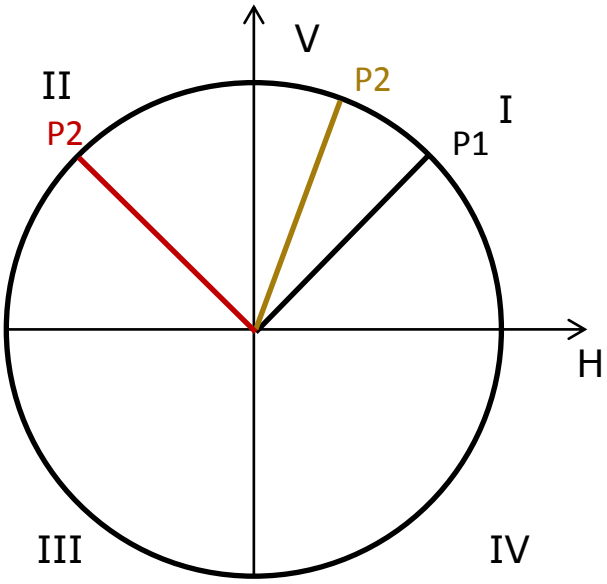


Figure 26 - Placement of P2

4.3.8 Assembly

The 'assembly' class is used to perform a visual crash test for a CNC program. It includes a function that creates a part called 'feedEye', which is to be placed in an assembly together with the mandrel part. In the assembly the 'move' function is used to move the feed-eye in relation to the mandrel according to the CNC codes. The 'move' function translates the feed-eye incrementally using the Abaqus 'translate' command, then immediately redraws the feed-eye in the new position, as shown below:

```
self.assemblyDir.translate((self.feedEye, ), newCoords)
session.viewports['Viewport: 1']
                        .view.setValues(drawImmediately = True)
```

4.4 MandrelProperties.py

This module contains functions that determine the mandrel properties for the relevant Abaqus model and adds them to the 'CylindricalMandrel' object 'mandrel'.

Determining the geometrical properties of a part is, in most cases, quite easy by visual inspection. It is, however, not as simple to accomplish by scripting, especially when the goal is to create a versatile script. Consequently some of the functions might appear inefficient, but the procedures have been specifically chosen to promote flexibility.

4.4.1 determineRotationalAxis

The 'determineRotationalAxis' function discerns the rotational axis of an axisymmetric mandrel by comparing the different nodal radii.

4.4.1.1 Approach

The mandrel is axisymmetric, and it was resolved that the best way to determine its axis of rotation would be to somehow compare radii in different directions for a locus on the mandrel. As the element nodes are already pre-defined loci with global coordinate values, the logical step was to use these in this function. To calculate the radii in different directions the best approach would be using the Pythagorean Theorem for each global coordinate plane, which resulted in the 'CustomNode' class, its 'radii' variable and its 'calculateRadius' function.

The choice was made to design a function that iterates through the 'elements' list of a 'CylindricalMandrel' object comparing nodal variables until the rotational axis of the model has been found.

4.4.1.2 Design Choices

To iterate through the 'elements' list of a 'CylindricalMandrel' object there were two choices considered; a while loop or a for loop. Normally, when iterating through a list, a for loop is the obvious choice. However, in this instance, it is not necessary to iterate through the complete list and a while loop was considered as well. There are no great differences between the two choices, except that in a for loop it would be necessary to utilise the break statement and in a while loop utilise a counter to iterate through the list. Ultimately the choice fell on the while loop, simply because it makes the code more intuitive to read.

```
while mandrel.rotationalAxis == 'undetermined':
```

For the choice of what nodes to compare, it was decided that, to avoid a for loop within the while loop, the first node in the 'connectivity' list of two elements should be compared. Alternatively one could iterate through the nodes on an element instead, but as there is no real difference between the two in terms of result the idea of a for loop was rejected to keep the code as structured as possible. A consequence of this choice, combined with the desire to make flexible software capable of handling any type of mesh, is that the two nodes compared might actually be the same node. If the mesh is unstructured, or a triangular

mesh, the elements do not necessarily have the same amount of nodes and are not oriented identically. In some cases the first node in the 'connectivity' list of two elements will be the same node; therefore a test comparing the coordinates of the two nodes was implemented.

As a precaution, both during development and later, it was decided to insert an option for manual input of the rotational axis. If ever the function should fail to determine the rotational axis of the relevant mandrel model it does not necessarily cause the software to crash.

During the testing of the function on different types of meshes it was discovered that in some, very rare, cases it was impossible to determine the rotational axis of the model because of very small differences in the calculated radii (for example: 125,00001468 != 124,999998575). An educated guess is that this is caused by slight inaccuracies in the nodal placement, a phenomenon the author has also observed in other 3D modelling software. With such high accuracy in the calculation of the radii the small inaccuracies in nodal placement cause false negatives. To compensate for this it was decided to round the values down to five decimals as they are compared.

Normally rounding variables is frowned upon as it causes numerical errors that stack. However, in this instance it has no effect on any actual values and does therefore not pose a problem. As the variables are only rounded when they are compared, but keep their original exact value in the node object, and the rounded value is not used for any form of calculation this approach has no negative effect on the rest of the tools.

In comparing the radii there is a slight chance of the test returning a false positive. This happens if the nodal coordinates are both too close to the point of origin for the model, the global (0, 0, 0). In such a case the 'radii' value for the nodes could be zero (and thereby equal) in a different direction than the one indicating the correct rotational axis. To avoid this issue it was determined that a fail-safe variable should be used to check that the rotational axis determined is indeed the right one. Before finally setting the axis of rotation this fail-safe variable should be set to equal an axis for which the nodal 'radii' value has been determined equal and then compared to the relevant axis when the nodal values are again equal. This means that the function must register the same axis as the rotational axis twice before it sets the 'rotationalAxis' variable of a 'cylindricalMandrel' object and exits the loop. In other words two sets of elements must to have the same 'radii' value for the rotational axis to be set and the function completed.

4.4.1.3 Mode of Operation

A while loop is utilised to iterate through all the elements in the model 'elements' list until the rotational axis has been found. Moving through the list, nodal 'radii' values for the first node ('currentNode') in the connectivity list of each element is compared to those of the next element in the list ('nextNode').

At the top of the function a variable ‘counter’ is set equal to zero, and for each run through the loop incremented by one. ‘counter’ is used to move through the ‘elements’ list so that in turn a ‘customNode’ object can be initiated.

```
element = mandrel.elements[counter]
currentNode = classes.CustomNode(mandrel, element, 0)
```

If ‘counter’ has reached the end of the ‘elements’ list without being able to determine the rotational axis, the function prompts for manual input through the Abaqus GUI.

```
if counter >= len(mandrel.elements):
    print "it was not possible to determine the rotational
          axis"

    #ask for manual input through GUI
    rotationalAxis = getInput(
        'Enter the numerical value for the rotational Axis:
        \n(X-Axis = 0, Y-Axis = 1, Z-Axis = 2)')
    mandrel.rotationalAxis = int(rotationalAxis)
```

Whenever the ‘counter’ has still not reached the end of the ‘elements’ list the ‘nextNode’ object is created and the two nodes ‘currentNode’ and ‘nextNode’ compared.

To ensure that the two nodes compared are not in reality the same node, the function compares their coordinate values. If they are equal, they are the same node and the loop is continued.

For each of the axes (X, Y, Z) the nodal ‘radii’ values are rounded down to five decimals and compared; are the nodal values identical in any direction a variable, ‘test’, is checked. If ‘test’ is not equal to the axis in question it is either the first instance of nodal equality, or a previous comparison has returned a different axis. Regardless, the ‘test’ variable is set to the current axis and the loop continued. If ‘test’ is equal to the rotational axis in question, the rotational axis of the mandrel is set, and the loop is exited.

```
if round(currentNode.Radii[X_AXIS],5) ==
                                round(nextNode.Radii[X_AXIS], 5):
    # if the fail-safe variable is 'None' or another axis
    if test != X_AXIS:
        test = X_AXIS

    # if the previous comparison also returned this axis, the
      rotational axis is set
    elif test == X_AXIS:
        mandrel.rotationalAxis = X_AXIS
        mandrel.H = Z_AXIS
        mandrel.V = Y_AXIS
```

As can be seen from the code segment above, the ‘determineRotationalAxis’ function simultaneously sets the horizontal and vertical axis for the mandrel when the rotational axis of the mandrel has been found.

4.4.2 determineRadii

The 'determineRadii' function determines the radius of the cylinder and the dome opening radius of an Abaqus mandrel model.

4.4.2.1 Approach

The cylindrical radius and the radius of the dome opening are the greatest and smallest radii respectively on the Abaqus mandrel model.

It was determined that the best way to discover the two radii would be to iterate through all the elements of a model and compare the different radii. Normally it is not considered ideal to iterate through a list such as this, especially as it is likely to be quite large as the elements on a model is shrunk for accuracy of analysis. Nevertheless, it was deemed the best solution.

4.4.2.2 Design Choices

One of the solutions considered to avoid an iteration loop was to somehow sort the elements into two separate lists; one containing all the cylindrical elements, and one containing the elements of the dome. This would have required iteration through all of the elements to first determine the cylindrical radius, and then another iteration to sort the elements. As such sorting of the elements would only be useful for this specific task, and it would require more iterations than simply comparing all the radii it was rejected. It was concluded that, as the only known variable is the rotational axis of the model, an iteration loop would be the best choice.

As the orientation of the elements is unknown it was deemed necessary to iterate through all of the nodes of an element and not just pick one at random as is done in 'determineRotationalAxis'. For the cylindrical part of the model it would most likely not have posed a problem, but for the dome opening it is imperative that each node is inspected to ensure that the correct value for the minimum radius is found. Figure 27 illustrates a case where a random node would not return the correct radial value.

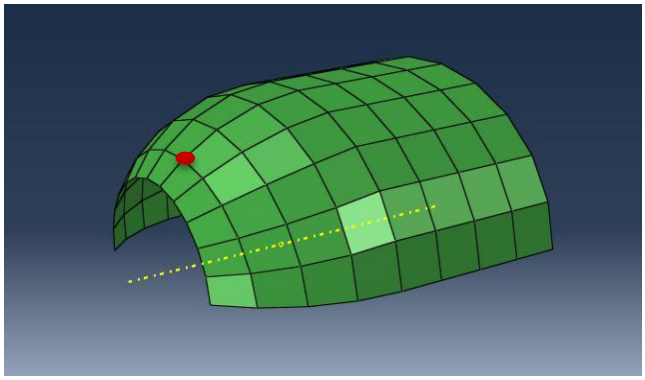


Figure 27 - Node returning wrong radius

To iterate through all of the element nodes a variable ‘nodesOnElemen’ is utilised. This was done to compensate for the fact that the function is intended to work for any type of mesh; unstructured as well as structured.

There is no knowledge of the size of the model, and therefore it is impossible to set arbitrary values for comparison. The ‘maxRadius’ could have been set to equal zero, but for the ‘minRadius’ variable there is no value that will always be bigger than the minimum radius of an actual Abaqus model. One solution would be to assume a value of, for example, 100 000, but it is still not completely certain that the minimum radius will always be smaller than this value. It could happen that the units are set in micro metres, or that the mandrel to be wound is humongous.

The simple, and obvious, solution that was decided upon is that of initiating ‘maxRadius’ and ‘minRadius’ as ‘None’ and then set them to equal the radius of the first node of the first elements to serve as points of comparison. This way the initial values for ‘maxRadius’ and ‘minRadius’ will always be lesser than, greater than or equal to the following nodal radii.

During the development process of the AWI Tools the ‘pointOfOrigin’ value of the ‘CylindricalMandrel’ class was created. As this value, by definition, is located at the tip of the mandrel (or in other words at the same locus as the minimum radius) it was decided that the logical way to set this variable would be along with the minimum radius. In most cases an effort has been made to keep functions separate and simple, not performing too many tasks at once. However, it was determined that such a simple task as setting this variable did not warrant an additional function with an iteration loop.

4.4.2.3 Mode of Operation

A double for loop is utilised to iterate through all the nodes on all the elements in the ‘elements’ list of an Abaqus model comparing the radii. For each node the local radius is compared to the function variables ‘minRadius’ and ‘maxRadius’.

For each element the number of nodes is determined (‘nodesOnElement’), and the nodal properties for each node investigated.

```
for element in mandrel.elements:
        nodesOnElement = len(element.connectivity)

        # iterate through the nodes
        for i in range(nodesOnElement):
            currentNode = classes.CustomNode(mandrel, element, i)
            tempRadius =
                    currentNode.returnRadius(mandrel.rotationalAxis)
```

For the first node on the first element the ‘minRadius’ and ‘maxRadius’ variables are set to equal the nodal ‘tempRadius’. This then serves as the point of comparison for the rest of the nodes. The ‘tempRadius’ value of each following node is compared to the function variables

'minRadius' and 'maxRadius'. If the local radius is less than 'minRadius' or greater than 'maxRadius' the appropriate value is replaced by the local 'tempRadius'.

```
        # set point of comparison on the first iteration
        if minRadius == None:
            minRadius = tempRadius
            maxRadius = tempRadius

            # in case the first node is on the dome opening
            mandrel.pointOfOrigin =

currentNode.returnAxisCoordinate(mandrel.rotationalAxis)

        elif tempRadius < minRadius:
            minRadius = tempRadius
            mandrel.pointOfOrigin =
               currentNode.returnAxisCoordinate(mandrel.rotationalAxis)

        elif tempRadius > maxRadius:
            maxRadius = tempRadius
```

Simultaneously as the nodal radii are compared, the 'pointOfOrigin' value of the 'mandrel' object is set whenever the 'minRadius' value is replaced.

4.4.3 determineLength

The 'determineLength' function calculates the length of the cylindrical part of an Abaqus mandrel model.

4.4.3.1 Approach

To determine the length of the cylindrical part of a mandrel it is necessary to determine the extreme points of the cylinder along the axis of rotation.

The choice was made to accomplish this in the same way as with the model radii. By means of iterating through all of the elements comparing nodal attributes. The difference being that in this case it is the nodal coordinate on the axis of rotation that is compared, and not radii.

4.4.3.2 Design Choices

As with the 'determineRadii' function a double for loop was deemed necessary, including the 'nodesOnElement' set to the number of nodes for each element. See section 4.4.2.2 for a closer explanation of the reasons behind this decision.

To distinguish between the elements on the cylindrical part of the mandrel and the elements on the dome the nodal radius was compared to the radius of the 'CylindricalMandrel' object 'mandrel'. It was considered whether this task would be simpler, and require fewer actions, if the elements were sorted as explained in section 4.4.2.2 . However, it was determined that it would most likely not result in more efficient code and was therefore not worthwhile.

4.4.3.3 Mode of Operation

A double for loop iterated through the elements in a 'CylindricalMandrel' object 'elements' list. When appropriate the nodal coordinate on the rotational axis for all the element nodes are compared to the function variables 'minLength' and 'maxLength' to determine the extreme points of a cylinder.

For each element the number of nodes is determined ('nodesOnElement'), and the nodal properties for each node investigated. If the local node radius is not equal to the radius of the 'mandrel' object, the current element is not located on the cylinder and the for loop is continued.

```
if round(tempRadius, 5) != round(mandrel.radius, 5):
    break
```

For the first node on the first element on the cylindrical part of the mandrel the 'minLength' and 'maxLength' variables are set to equal the nodal position on the rotational axis of the 'mandrel' object. This then serves as the point of comparison for the rest of the nodes. A variable, 'rotAxCoordinate', is compared to the function variables 'minLength' and 'maxLength' for each of the following nodes on the cylinder. If the local 'rotAxCoordinate' is less than 'minLength' or greater than 'maxLength', the appropriate value is replaced.

```
if minLength == None:
    minLength = rotAxCoordinate
    maxLength = rotAxCoordinate

elif rotAxCoordinate < minLength:
    minLength = rotAxCoordinate

elif rotAxCoordinate > maxLength:
    maxLength = rotAxCoordinate
```

Once the for loop has finished iterating through the elements the 'CylindricalMandrel' class function 'setLength' is called and the 'minLength' and 'maxLength' variables are used to calculate the length of the cylindrical part of the model.

```
mandrel.setLength(minLength, maxLength)
```

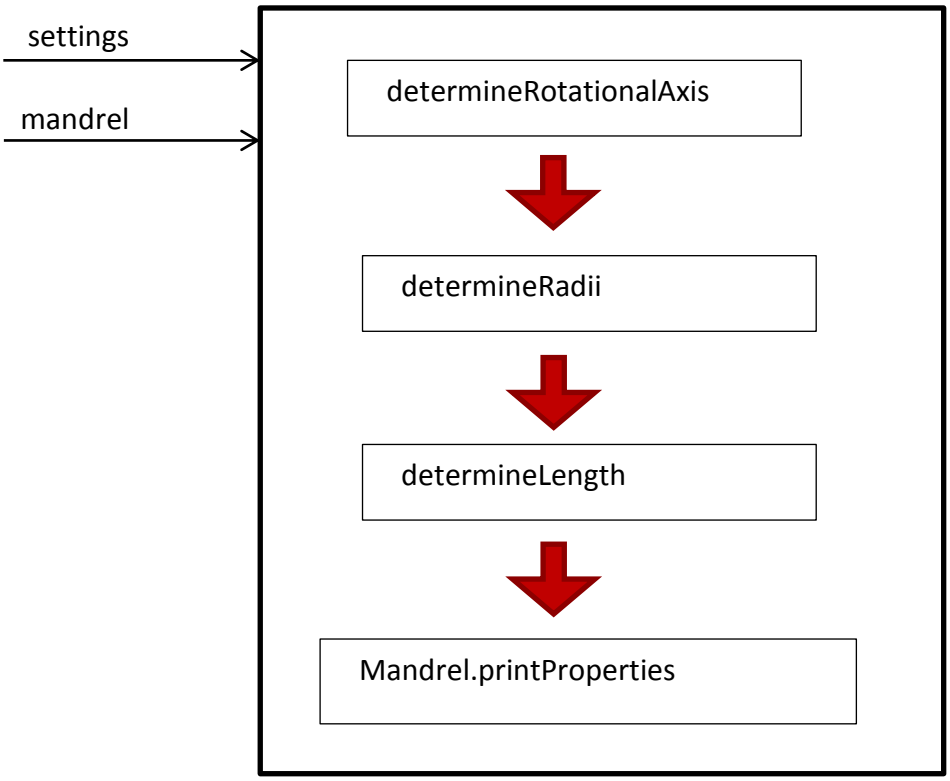
4.4.4 setProperties

'setProperties' is the execution function of the 'mandrelProperties' module. The function executes the 'determineRotationalAxis' function, 'determineRadii' function and the 'determineLength' function, one after the other, to determine and calculate the mandrel properties.

Lastly, the 'printProperties' function of the 'CylindricalMandrel' object 'mandrel' is executed and the properties of the Abaqus mandrel model printed.

```
print 'Mandrel Properties: '
print '-----------------------------------'
mandrel.printProperties(settings)
```

4.4.4.1 *Flowchart of Execution Function*



4.5 GCode.py

The 'GCode.py' module is intended to include all the functions necessary to generate a CNC program based on the mandrel properties of an Abaqus model.

Initially it was the intention that this module should include functions for the kinematic equations for a filament winding machine, but due to the unforeseen circumstances described in chapter 3.3 the module is currently incomplete.

4.5.1 createCNCprogram

The 'createCNCprogram' function generates a CNC program for the relevant Abaqus mandrel model.

4.5.1.1 Approach

This function will most likely be the execution file of the 'GCode' module. It is created as a means of collecting the variables for blocks of CNC code and writing it to a file and the 'mandrel' object 'lines' variable.

4.5.1.2 Design Choices

It was determined that the filename of the CNC program should be unique and descriptive to make it easily identifiable. Consequently it was decided that the filename should include the Abaqus model name and the model part name.

Also, for clarity, it was decided to include a print statement after the completion of the CNC program to inform that the program has been generated, and for which Abaqus mandrel model.

4.5.1.3 Mode of Operation

First, the filename of the CNC program is set.

```
fileName= "{0}_{1}".format(mandrel.modelName, mandrel.partName)
```

Secondly, a 'GCode' class object is initiated with the filename, creating the CNC program file and writing the topmost comment lines. Then the lines (currently a set of lines with random values for the variables) are added to both the CNC program file and the 'lines' variable of the 'CylindricalMandrel' object 'mandrel'.

Once the CNC program has been generated a statement is printed in the Abaqus Message Area, including the 'printProperties' function of the 'mandrel' object.

```
print "a CNC-program has been created for: "
mandrel.printProperties(settings)
```

As the function is run through Abaqus, the text file will be located in the Abaqus work directory.

4.6 layup.py

The 'layup.py' module contains the functions necessary to add the approximation of a filament winding layup to an Abaqus mandrel model based on blocks of CNC code.

Adding layup to an Abaqus mandrel model is a challenge, and its solution involves approximations and assumptions. Two different solutions were considered to solve the problem, and the decision of which to choose was done based on its determined accuracy.

Solution 1:

As long as the geodesic winding technique used the winding angle for a point on the mandrel can easily be calculated by means of Clairaut's equation (1). If one assumes a known number of complete layers of winding on the mandrel a layup of [α/-α] can be added to the elements for each layer. It should be noted that this assumption disregards the crossover points of a winding layup. Also, depending on the shape and size of the elements further assumptions and approximations would have had to be made in regards to, for example, the winding angle across the dome. On the cylindrical part of the mandrel the winding angle would remain constant, but crossing the dome it changes rapidly to the required angle of 90° at the dome opening. Accounting for this fact could, amongst others, be done by calculating the mean winding value for each element or by choosing the middle point of the element to calculate the winding angle.

In addition to the approximation being a poor one, this solution lacks flexibility. There is no accounting for the different layers that form in the winding process, and having been modelled as a uniform layer it does not actually correspond to any actual physical part. It does, however, suit a preliminary model where no CNC program has been created yet. It is, most likely, possible to analyse a model with such a layup and use the results as a rough draft of the capabilities of the finished part. This should, however, be investigated more fully before a hypothetical implementation.

Solution 2:

In geodesic winding the fibres are placed on the shortest possible path between two points on the mandrel, a fact that can be taken advantage of when creating an approximate winding layup on an Abaqus model. If the path between the two points 'P1' and 'P2' is projected into a two-dimensional plane it can be approximated to a straight linear line under certain conditions. This approach has been detailed in appendix D.3

Under the conditions that $P1_x$ or $P2_x$ cannot be too close to the radial value, and that they must be located in the same or adjoining quadrants, the path can be considered linear between two points. The linear equation for this straight line can easily be derived from the coordinates of those two points. With this line in place the elements can be projected into the same plane and it can be determined whether each element lies on the winding path or not.

Using this approach with ‘P1’ and ‘P2’ as the starting and ending points of a CNC program block each element will end up with a unique combination of plies as a layup. Although an approximation, this results in a layup whose plies will correspond directly to a part wound with the relevant CNC program. As far as this author knows there are no other software solutions that include this functionality of using FEA software to create a model that directly corresponds to a real part. It was decided, therefore, to start developing this solution, as it is more advanced.

4.6.1 addMaterial

The ‘addMaterial’ function adds a carbon/epoxy material to the ‘LayupConstruction’ object ‘layup’ and adds the material to the relevant Abaqus mandrel model.

4.6.1.1 Approach

The choice to create this function was made for structure. The material needed to be added to the Abaqus mandrel model, and the name of the material accessed for each layup to be added.

4.6.1.2 Design Choices

It was decided to keep the Abaqus commands that add a material to an Abaqus model separate as they are long and appear unstructured at first glance. Having them collected in a function has the added bonus of adding readability to the code as well.

To avoid having to send the ‘Name’ variable of the ‘material’ object back and forth between functions it was decided to connect the material to the ‘layup’.

4.6.1.3 Mode of Operation

The ‘carbon_epoxy’ material is set as the layup material.

```
layup.material.carbon_epoxy()
```

A material with the same name as the layup material is added to the Abaqus part.

```
mdb.models[mandrel.modelName]
                            .Material(name = layup.material.Name)
```

Then the material properties are set using the Abaqus material commands (the complete commands can be viewed in E.4

```
mdb.models[mandrel.modelName]
                        .materials[layup.material.Name].Elastic(…)

mdb.models[mandrel.modelName]
                        .materials[layup.material.Name].Density(…)
```

4.6.2 readGCodes

The 'readGCodes' function reads a CNC program block and extracts from it the rotation of the mandrel and the lateral movement of the carriage along the rotational axis of the mandrel.

4.6.2.1 Approach

A CNC program block read from a file is read as a string. It was decided that the most practical approach to search through a string for matches of the relevant parameters would be to use the built-in Python regular expressions. An introduction to these can be found in[31] or [32].

4.6.2.2 Design Choices

During the development, it was determined to start by assuming the same axis notations for the filament winding machine as the "MAW 20 LS 4/1" from Mikrosam. The relevant axes for this function would then be the rotation of the mandrel, 'X', and the lateral movement of the carriage, 'Y'.

To account for the comment lines and the first line of modal commands in the CNC program the Python exception handling interface is used. If the 'X' and 'Y' values are not found in the string, the 'AttributeError' is raised. In this case the lack of the 'X' and 'Y' values in the string only means that the line is one of the top lines of comments or modal commands.

It was observed that a CNC program can be written with either points or commas. As Abaqus only accepts floats using points it was determined to utilise the Python 'replace' function to ensure that the float values will be in the correct format.

4.6.2.3 Mode of Operation

A variable, 'line', from a CNC program is sent to the function, and matches for the 'X' and 'Y' values searched for.

```
matches = re.search(
    r'\A N(\d+) \s+ X(\d+(,\d+)?) \s+ Y(\d+(,\d+)?)',
   line, flags=re.M | re.S | re.X)
```

If matches are found, a tuple '(X, Y)' is retuned, but if an exception is raised the function simply returns nothing.

4.6.3 Sign

'Sign' is a simple function that determines the sign of a numerical variable. It was implemented to increase readability of the code as it negates the need for several identical if statements.

If the value is negative it returns '-1' and if it is positive it returns '1'.

4.6.4 calculateP2

'calculateP2' is a function that, based on the rotation of the mandrel, calculates the end point of a CNC program block, 'P2'.

4.6.4.1 Approach

As the lateral movement along the axis of rotation can be extracted directly from the CNC program block, the position of 'P2' on the axis of rotation can easily be calculated. Determining the two remaining coordinate values of 'P2', however, is not as simple.

The rotation of the mandrel, 'X', translates as an angle in the plane formed by the horizontal and vertical axes of the mandrel. Therefore it was decided that the best way to determine the coordinates of 'P2' would be to use basic trigonometry. The mathematics behind the approach have been detailed in appendix D.2

4.6.4.2 Design Choices

The choice of using trigonometry was made because the lateral movement along the axis of rotation is so easily calculable. With this coordinate determined the two others can be considered independently of the third one, and the problem is somewhat simplified. With only two axes to consider the problem is transformed into a unit circle of radius 'R' passing through the two points 'P1' and 'P2', as shown in Figure 28. As the coordinates of 'P1' and the angle, 'X', between the two points is known the coordinates of 'P2' can be calculated.

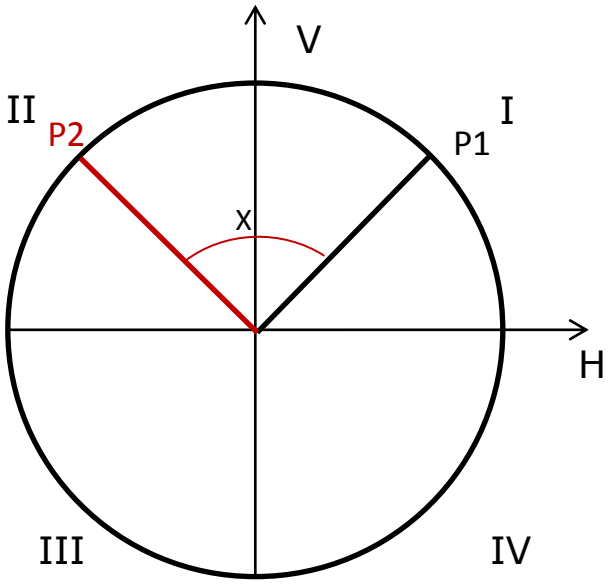


Figure 28 – Simplified problem

To simplify the problem further an assumption was made that the rotation of the mandrel will be small enough that 'P1' and 'P2' will always be located in either the same quadrant or adjoining quadrants of the unit circle. This decision limits the problem to eight different permutations of placement. This approach, and pictures of all placements of 'P2', has been further detailed in D.2

Due to the fact that the coordinate values will vary in sign the mode of calculating the coordinates of ‘P2’ will vary depending on the quadrantic placement of the two points. An effort was made to find an approach that was as uniform as possible. The result was a method based on the rotation of the mandrel, ‘X’, the angle between ‘P1’ and the horizontal axis, ‘U’, and the angle between ‘P2’ and the horizontal axis, ‘W’. Using this method the approach to calculating ‘W’ is the same for quadrants I and III and quadrants II and IV.

The angle ‘U’ is calculated using equation (16), where ‘$P1_V$‘ is the coordinate value of ‘P1’ on the vertical axis, and ‘$P1_H$‘ the coordinate value on the horizontal axis.

$$U = \tan^{-1}\left(\frac{|P1_V|}{|P1_H|}\right) \tag{16}$$

For quadrants I and III the calculation of ‘W’ is as follows:

If the added value of the angles ‘U’ and ‘X’ is less than 90° the two points are located in the same quadrant (I and III respectively), and the angle ‘W’ is calculated using equation (17).

$$W = U + X \tag{17}$$

Are ‘P1’ and ‘P2’ located in adjoining quadrants (II and IV respectively) the angle, ‘W’, is calculated using equation (18).

$$W = \pi - (U + X) \tag{18}$$

For quadrants II and IV the calculation of ‘W’ is as follows:

If the added value of the angles ‘U’ and ‘X’ are less than 90° the two points are located in the same quadrant (II and IV respectively) the angle, ‘W’, is calculated using equation (19).

$$W = U - X \tag{19}$$

Are ‘P1’ and ‘P2’ located in adjoining quadrants (III and I respectively) the angle, ‘W’, is calculated using equation (20).

$$W = X - U \tag{20}$$

To account for the change of sign between ‘P1’ and ‘P2’ the ‘sign’ variable for the appropriate axis is changed whenever the two points are not located in the same quadrant. In addition one of the variables of the ‘layupConstruction’ object ‘layup’ is changed. If ‘P1’ is located in quadrant I and ‘P2’ in quadrant II ‘crossesVertical’ is set to ‘True’ and if ‘P1’ is located in quadrant II and ‘P2’ in quadrant III ‘crossesHorizontal’ is set to ‘True’ and so forth.

Once the angle ‘W’ has been determined the leg lengths of a triangle formed by ‘P2’ and the horizontal axis is calculated using equations (21) and (22).

$$legH = signH * \left[R * \cos(W) \right] \tag{21}$$

$$legV = signV * \left[R * \sin(W) \right] \tag{22}$$

Without the 'sign' variable these calculations would have resulted in the absolute leg lengths of 'P2', meaning its coordinates had it been located in quadrant I. With the use of the 'sign' variables this problem is avoided.

It should be noted that these calculations assume 'X' to be set in radians. This might not be the case and should be checked to ensure that the function works, but a hypothetical conversion from radians to degrees will not pose a problem.

To calculate the lateral movement along the axis of rotation it was decided to implement a 'cylindricalMandrel' class variable 'windingDirection'. The coordinate system assumed when deriving the equations was set with the rotational axis in the opposite direction of that of the filament winding machine coordinate system. This means that it is necessary to reverse the sign of the 'Y' movement variable before it is employed.

4.6.4.3 Mode of Operation

'P1', the rotation of the mandrel, 'X', and the lateral feed-eye movement, 'Y' are used to calculate the coordinate values of the end point of a CNC program block, 'P2'.

A variable for the point 'P1' is created and the signs for its horizontal and vertical coordinate values, 'signH' and 'signV', are determined. Then the angle, 'U' between 'P1' and the horizontal axis is calculated.

```
P1 = layup.P1
# determine what quadrant P1 is located in
signH = sign(P1[mandrel.H])
signV = sign(P1[mandrel.V])

# calculate the angle between P1 and the horizontal axis
U = math.atan2(abs(P1[mandrel.V]),abs(P1[mandrel.H]))
```

These values are then used to determine the quadrantic placements of 'P1' and 'P2'. If the two 'sign' values are equal (both either positive or negative) 'P1' is located in quadrant I or quadrant III.

```
# if the coordinates of P1 are in quadrant I or III
    if (signH == signV):
        # if P1 and P2 are in the same quadrant
        if (U+X) < (math.pi/2):
            W = U+X

        else:
            W = math.pi - (U+X)
            signH *= -1
            layup.crossesVertical = True
```

If the ‘sign’ values are not equal, ‘P1’ is located in quadrant II or IV.

```
    # if the coordinates of P1 are in quadrant II or IV
    else:
        # if P1 and P2 are in the same quadrant
        if (X < U):
            W = U-X

        else:
            W = X-U
            signV *= -1
            layup.crossesHorizontal = True
```

For each case the angle between ‘P2’ and the horizontal axis, ‘W’, is calculated. When the two points ‘P1’ and ‘P2’ are not located in the same quadrant two additional variables are changed. Depending on which axis has been crossed the ‘signH’ and ‘crossesHorizontal’ or the ‘signV’ and ‘crossesVertical’ are altered. The ‘sign’ value is multiplied by ‘-1’ to change its sign, and the second variable is set to ‘True’.

Lastly, the coordinates of ‘P2’ are calculated using the cosine and sine of the angle ‘W’.

```
    legH = signH * (mandrel.radius * math.cos(W))      #horizontal
leg
    legV = signV * (mandrel.radius * math.sin(W))    #vertical leg
    legLateral = P1[mandrel.rotationalAxis] +
                                        mandrel.windingDirection * Y
```

The ‘P2’ list of the ‘layupConstruction’ object ‘layup’ is filled.

```
    ### set values for P2
    layup.P2[mandrel.rotationalAxis] = legLateral
    layup.P2[mandrel.V] = legV
    layup.P2[mandrel.H] = legH
```

4.6.5 collectBoxElements

The ‘collectBoxElements’ function collects a set of elements between the points ‘P1’ and ‘P2’ in a list using the Abaqus ‘getByBoundingBox(…)’ command.

4.6.5.1 Approach

With the point of origin and the end point of a CNC program block in place, it is possible to iterate through all of the elements on a model to determine which ones cross the winding path. However, to avoid iteration through the complete model it was decided to take advantage of the Abaqus ‘getByBoundingBox(…)’ command. As the coordinates of the two points, ‘P1’ and ‘P2’, are known this function is ideally suited for this purpose.

4.6.5.2 Design Choices

The ‘getByBoundingBox(…)’ requires the maximum and minimum coordinate values of the bounding box as arguments. Consequently the coordinate values of ‘P1’ and ‘P2’ need to be

sorted for each axis. As the two points are not necessarily located in the same quadrant, it is impossible to know which one of the points has the smaller or greater coordinate value in a specific direction. To circumvent this problem it was decided to sort the coordinate positions of 'P1' and 'P2' into two lists, 'minCoords' and 'maxCoords', independently of which point the value originates from. These lists will then be used as arguments for the 'getByBoundingbox(…)' command.

In the cases where the points are not located in the same quadrant it is not sufficient to use only the coordinate values of the points as arguments for 'getByBoundingBox(…)'. It is clear from Figure 29 that if the points are in separate quadrants, using only the maximum and minimum coordinate values will result in a bounding box that does not encompass all the relevant elements. The red box illustrates the correct bounding box, whereas the brown stippled line illustrated where the topmost boundary of the box would have been with only the coordinate values as boundary conditions. Therefore the 'crossesHorizontal' and 'crossesVertical' variables of the 'layupConstruction' class were created. If any of these variables are 'True', an axis has been crossed and the minimum/maximum value in the appropriate direction must be set to equal the mandrel radius, or the negative mandrel radius, depending on the quadrants in question.

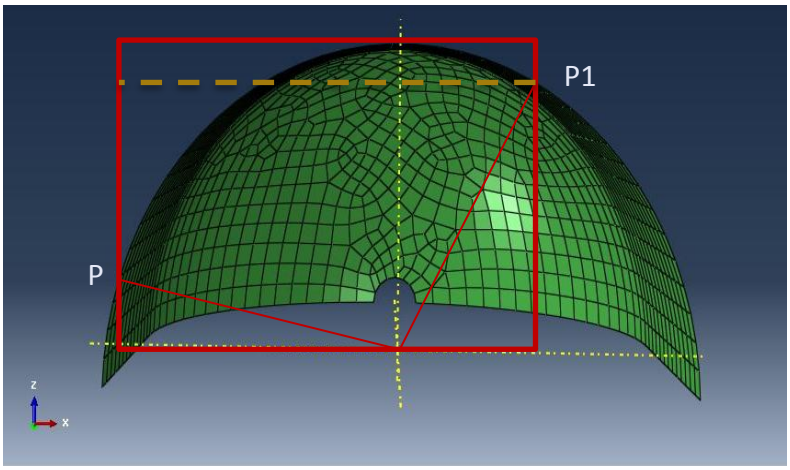


Figure 29 - Bounding box between P1 and P2

4.6.5.3 Mode of Operation

The Abaqus 'getByBoundingBox(…)' command is utilised to collect the elements between two points, 'P1' and 'P2'. Based on the coordinate values of 'P1' and 'P2' and their quadrant on the unit circle, the maximum and minimum coordinates of the bounding box are determined.

Two lists, 'minCoords' and 'maxCoords', are created and initially filled with zeroes, before the 'P1' and 'P2' variables of the 'layupConstruction' object 'layup' are copied to the function variables 'P1' and 'P2'.

The coordinate values for each list index in the 'P1' and 'P2' lists are compared and sorted. The greater of the two values is placed in the 'maxCoords' list, and the smaller of the two in the 'minCoords' list.

```
for i in range(3):
    if (P1[i] < P2[i]):
        minCoords[i] = P1[i]
        maxCoords[i] = P2[i]
    else:
        minCoords[i] = P2[i]
        maxCoords[i] = P1[i]
```

A test is run to check whether the 'crossesHorizontal' or 'crossesVertical' variables of the 'layup' object are set to 'True'. If either one is 'True', depending on the quadrant placement of 'P1', the 'minCoords' or 'maxCoords' list is changed in the appropriate direction to encompass all the relevant elements.

```
# if an axis has been crossed the max/min variable
# must be mandrel radius to collect all elements
if layup.crossesHorizontal:
    if sign(P1[mandrel.V]) >  0:
        minCoords[mandrel.H] = -1* mandrel.radius
    else:
        maxCoords[mandrel.H] = mandrel.radius

if layup.crossesVertical:
    if sign(P1[mandrel.H]) > 0:
        maxCoords[mandrel.V] = mandrel.radius
    else:
        minCoords[mandrel.V] = -1*mandrel.radius
```

The Abaqus 'getByBoundingBox(…)' command is used, with the values of 'minCoords' and 'maxCoords' as arguments, to collect all the elements between 'P1' and 'P2' in a list.

4.6.6 collectLayupElements

The 'collectLayupElements' function iterates through the elements collected in the 'collectBoxElements' function and determines whether each element is located in the winding fibre path or not.

4.6.6.1 Approach

To determine which elements are located in the winding path, the pathway is projected into the plane formed by the rotational axis and either the horizontal or vertical mandrel axis. For each element, its nodal coordinates are projected into the same plane and a check is performed to ascertain whether the winding path crosses the element or not.

4.6.6.2 Design Choices

It was determined to use basic math to determine the linear equation, (23) and (24), for the line between 'P1' and 'P2'. The derivation of equations (25) and (26) can be found in D.3

$$y(x) = ax + b \tag{23}$$

$$x(y) = \frac{y - b}{a} \tag{24}$$

$$a = \frac{y_2 - y_1}{x_2 - x_1} \tag{25}$$

$$b = y_1 - ax_1 \tag{26}$$

To cope with the restriction of the points not being too close to the mandrel radius in the plane, it was determined to use the location of 'P1' and 'P2' in the unit circle to define the projection plane. As shown in Figure 30, if 'P1' is located in quadrant I or III the logical projection plane is the plane formed by the rotational axis and the horizontal axis (shown by the vertical stippled lines). Is P1 located in quadrant II or IV the logical projection plane will be the plane formed by the rotational axis and the vertical axis (shown by the red stippled vertical lines being very close together, whereas the black horizontal ones are further apart).

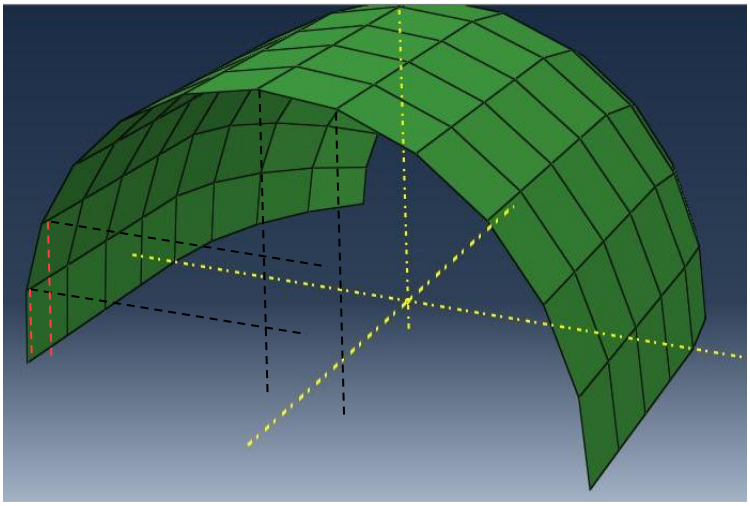


Figure 30 - Projection of elements

To ascertain whether an element is located on the fibre path, its nodal coordinate values in the projection plane are gathered and sorted. Subsequently the value of the linear equation for each of these values is calculated using equations (23) and (24). It is then determined whether the line passes through the element or outside of it. This approach has been detailed in D.3

4.6.6.3 Mode of Operation

The variables 'P1' and 'P2' of the 'layupConstruction' object 'layup' are copied to the function variables, 'P1' and 'P2'.

Based on the quadrant placements of 'P1' and 'P2' and their coordinate values, the constants 'a' and 'b' of a linear equation between the two points are determined.

```
if sign(P1[mandrel.H]) == sign(P1[mandrel.V]):
    a = ((P2[mandrel.rotationalAxis]-P1[mandrel.rotationalAxis])
                /(P2[mandrel.H] - P1[mandrel.H]))
    b = P1[mandrel.rotationalAxis] - P1[mandrel.H]*a

# if P1 is in quadrant II or IV
else:
    a = ((P2[mandrel.rotationalAxis]-P1[mandrel.rotationalAxis])
                /(P2[mandrel.V] - P1[mandrel.V]))
    b = P1[mandrel.rotationalAxis] - P1[mandrel.V]*a
```

A for loop is utilised to iterate through all of the elements. For each element the maximum and minimum nodal coordinate values in the appropriate directions are determined. For the first node the 'minY', 'maxY', 'minX' and 'maxX' values are all set to the coordinate values of the current node, to serve as points of comparison for the following element nodes.

When the minimum and maximum values for the element have been determined, the corresponding points on the line between 'P1' and 'P2' are calculated.

```
Y_min = a*minX + b
Y_max = a*maxX + b
X_min = (minY - b)/a
X_max = (maxY - b)/a
```

If one or more of the points on the line are between the minimum and maximum variables in the appropriate direction, the element is in the winding path and is appended to the 'sectionElements' variables; unless it has already been appended.

Element in winding path:

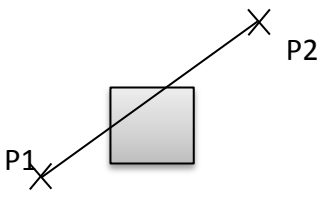


Figure 31 - Straight line crossing element

When the linear equation has been established, the maximum and minimum values in the appropriate plane for the elements are found by iterating through the nodes on the element. If a point on the line is located between the maximum and minimum value as

shown in Figure 31, the element is appended into a list of elements called 'sectionElements' where all the elements in the fibre path are collected.

```
appended = False     #variable ensures an element is only
                     appended once
if (((minY < Y_min) and (Y_min < maxY)) or
                          ((minY < Y_max) and (Y_max < maxY))):
    appended = True
    sectionElements.append(element)

if (((minX < X_min) and (X_min < maxX)) or
                          ((minX < X_max) and (X_max < maxX))):
    if appended == False:
        sectionElements.append(element)
```

After iterating through all the elements in the 'boxElements' variable the function returns the 'sectionElements' list containing all the elements in the fibre winding path.

4.6.7 addPly

The 'addPly' function adds a single ply to the layup of each of the elements in the 'sectionElements' list.

4.6.7.1 Approach

The function calculates the winding angle based on the rotation of the mandrel, 'X', and the movement along the axis of rotation, 'Y'. A for loop then iterates through all the elements of the 'sectionElements' list and adds an additional ply with the calculated angle to its composite layup.

4.6.7.2 Design Choices

It was decided that instead of calculating the winding angle of each element based on the elements relative location on the model, an approximation based on 'X' and 'Y' would be used. This decision was made to avoid having to calculate the placement of the element on the model, which is not necessarily equal to its coordinate values.

Based on the movement of the mandrel the winding angle for the element is calculated using equation (27). This equation, whose derivation can be found in D.4 assumes a cylindrical shape, which across the dome is only an approximation assuming small movements along the axis of rotation. It is unknown to what degree this will affect the analysis of the part, and this should be investigated further.

$$\alpha = \tan^{-1}\left(\frac{Y}{RX}\right) \tag{27}$$

Each composite layup is given a unique name, 'layupName', based on the element label, which makes it easy to determine whether there is a 'compositeLayup' object already connected to the element.

4.6.7.3 Mode of Operation

Based on the rotation of the mandrel, 'X', the lateral movement along the axis of rotation, 'Y', and the radius of the mandrel the winding angle for the layup is calculated.

```
alpha = math.degrees(math.atan(Y/mandrel.radius/X))
```

A for loop iterates through all the elements in the 'sectionElements' list adding a ply with the winding angle to the composite layup of the element.

For each element the variable 'layupName' is set based on the element label.

```
layupName = 'layup e[%r]' %element.label
```

The function then tries to access the composite layup of the current element. If it fails, an exception is raised and a composite layup created for the element. A pointer to the composite layup, 'compositeLayup' is set and the rotation of the layup set to follow the global coordinate system of the model. Simultaneously the 'plyName' variable is set to 'Ply 1'.

```
# if not: create composite layup for the element
except KeyError:
    # create composite layup
    compositeLayup = mandrel.part.CompositeLayup(
        name = layupName,
        offsetType = TOP_SURFACE,
        symmetric = False,
        thicknessAssignment = FROM_SECTION)

    plyName = 'Ply 1'

  # set rotation to be relative to the global coordinate system
    compositeLayup.orientation.setValues(
        orientationType = GLOBAL,
        localCsys = None,
        additionalRotationType = ROTATION_NONE,
        angle = 0.0)
```

If a composite layup already exists for the element 'compositeLayup' is set to point to the existing composite layup for the element. The appropriate 'plyName' is found and set based on the existing number of plies in the composite layup.

```
#check if the current element already has a composite layup
try:
    compositeLayup = mandrel.part.compositeLayups[layupName]

    numPlies = len(compositeLayup.plies)+1
    plyName = 'Ply %r' %numPlies
```

When the ‘compositeLayup’ variable and the ‘plyName’ have been set, the ply is added to the element using the Abaqus ‘CompositePly(…)’ command. The thickness is specified according to the material of the ‘layupConstruction’ object ‘layup’ and the orientation set to the winding angle in relation to the rotational axis of the mandrel.

```
# add ply to element
compositeLayup.CompositePly(
    suppressed = False,
    plyName = plyName,
    thicknessType = SPECIFY_THICKNESS,
    thickness = layup.material.thickness,
    region = region1,
    material = layup.material.Name,
    orientationType = SPECIFY_ORIENT,
    orientationValue = alpha,
    axis = rotAxes[mandrel.rotationalAxis])
```

4.6.8 addLayup

‘addLayup’ is the execution function of the ‘layup’ module. Depending on the mode with which it is initiated, it adds layup to the model. The function creates a ‘layupConstruction’ object ‘layup’ and adds the material to the model using the ‘addMaterial’ function. The ‘calculateP2’, ‘boxElements’, ‘sectionElements’ and ‘addPly’ functions are then, in turn, used to add plies.

There are three different modes for the function:

- Input from File, ‘f’
- Generated CNC Program, ‘g’
- Manual Input, ‘m’

4.6.8.1 Input from File, ‘f’

This method, initiated with an ‘f’, reads the lines of a CNC program from a specified file and adds a layup accordingly.

A window prompting for input is opened in the Abaqus GUI. The input needed is the file name of the file containing the CNC program on which the layup will be based. For the software to find the file and open it for reading it has to be located in the Abaqus work directory. For each program block in the file the ‘X’ and ‘Y’ values are extracted. If they are not present, the loop continues to the next program block, and a section of layup is added to the model. To continue the movement along the model the ‘P1’ variable is set to equal the calculated ‘P2’. The finished layup will be continuous, and a very close approximation of a real part wound with the same CNC program.

4.6.8.2 Generated CNC Program, ‘g’

To add a winding layup based on a CNC program generated for the specific model this method, ‘g’, is used.

Technically this method could have been omitted and the ‘f’ method could have been used instead. When a CNC program is generated for an Abaqus model it is written in a file that can be used as input. However, using this method is simpler as it negates the need to search through each program block for the ‘X’ and ‘Y’ values. To add layup to the model the mandrel variable ‘lines’ is iterated through and the ‘X’ and ‘Y’ values for each ‘CNCLine’ object used to determine the section of layup.

4.6.8.3 Manual Input, ‘m’

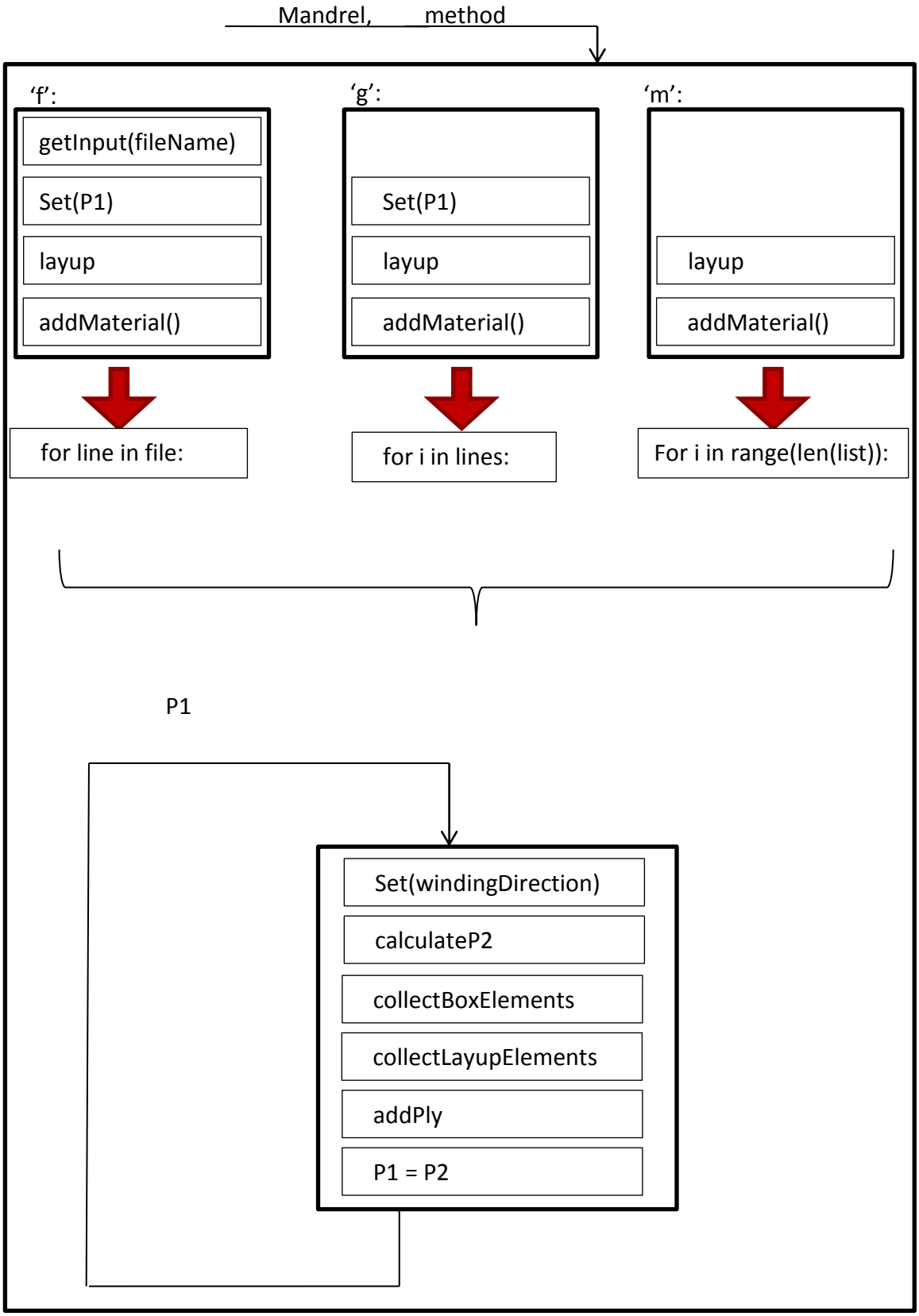
This method, initiated with an ‘m’, is used for debugging. Normally it is not necessary to run a complete program to see if the code works, it is more convenient to just add layup for a few points.

Currently the method contains four points, one in each quadrant of the unit circle, corresponding to the test part ‘part-1-mesh-1’ of ‘Model-9’.

4.6.8.4 Remarks

When all of the CNC program blocks have been added to the layup the Abaqus model will have a layup directly corresponding to the real part wound with the same CNC program, including cross-over points. The accuracy of the layup will depend upon how fine the mesh is. For a fine mesh the approximations done will cause smaller errors and the ‘sectionElements’ list for each program block will correspond more closely to the actual winding path.

4.6.8.5 Flowchart Execution Function



4.7 visualCrashTest.py

The 'VisualCrashTest' module is designed to perform a visual crash test of a CNC program in the Abaqus GUI.

4.7.1 createTestSetUp

'createTestSetUp' creates an assembly with a constructed feed-eye and the relevant Abaqus mandrel model.

4.7.1.1 Approach

To create a test set up it is necessary to create a part to serve as the feed-eye of the filament winding machine. The feed-eye part and the mandrel part is the put together in an assembly and oriented correctly in relation to each other.

4.7.1.2 Design Choices

It was decided that the feed-eye part should be rotated to have its flat surface facing the mandrel part as shown in Figure 32. Also, for the starting point of the crash test it was assumed that the CNC program originate at the tip of the mandrel dome. This is not true for all CNC winding programs, but was used to have a basis from which to operate.

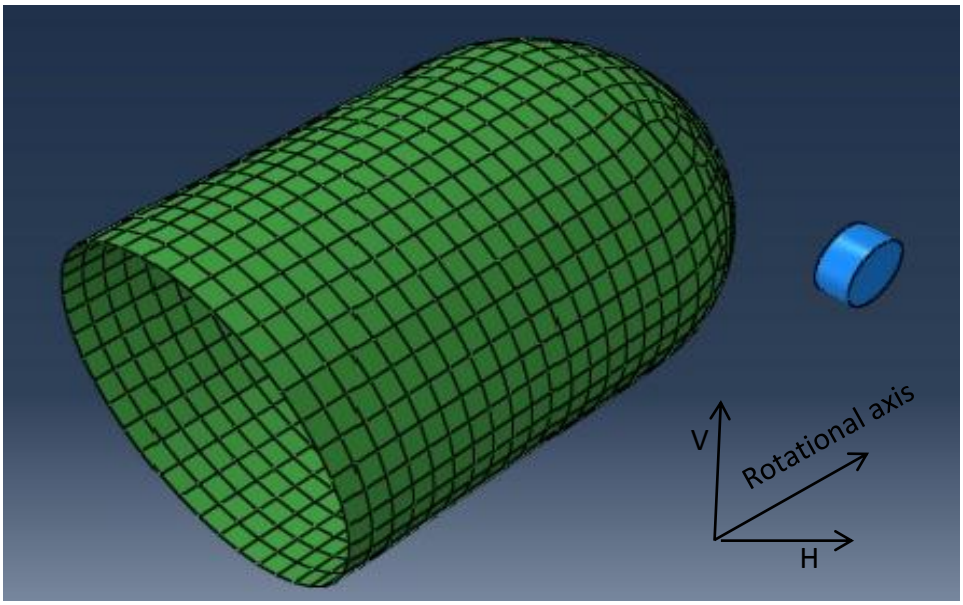


Figure 32 - Mandrel and feed-eye assembly

For convenience, the view in the viewport is set as shown in Figure 32 and fit to the screen. This makes it easier for the observer to see what is happening during the simulation.

4.7.1.3 Mode of Operation

First, the 'assemblyDir' variable of an 'Assembly' object 'assembly' is set to the 'rootAssembly' of the relevant Abaqus mandrel model. The viewport is changed to display the assembly and the 'feedEye' part of 'assembly' and the mandrel part are added to the assembly.

```
#adding the two parts to the assembly
assembly.assemblyDir.Instance (
    assembly.feedEye, part = feedEyePart, dependent = ON)
assembly.assemblyDir.Instance (
    'Mandrel', part = mandrelPart, dependent = ON)
```

Based on the axis of rotation for the mandrel part, the 'feedEye' part is rotated, and the 'setView' variable created.

```
# define practical view based on rotational axis
# and rotate feed-eye according to model
if mandrel.rotationalAxis == X_AXIS:
    assembly.assemblyDir
           .rotate((assembly.feedEye, ), (0,0,0), (0,0,-5), 90)
    setView = (45, 45, 0)

if mandrel.rotationalAxis == Y_AXIS:
    assembly.assemblyDir
           .rotate((assembly.feedEye, ), (0,0,0), (0,-5,0), 90)
    setView = (-45, 0, -45)

if mandrel.rotationalAxis == Z_AXIS:
    assembly.assemblyDir
           .rotate((assembly.feedEye, ), (0,0,0), (-5,0,0), 90)
    setView = (45, 135, 90)
```

The feed-eye is moved a distance away from the mandrel and to the tip of the mandrel dome, which is assumed to be the starting position of the CNC program.

```
### move the feed-eye to an initial position
offset = [0, 0, 0]
offset[mandrel.H] = mandrel.radius + mandrel.radius/4
assembly.assemblyDir.translate((assembly.feedEye, ), offset)
```

Lastly, the view in the viewport is set and fit to screen.

```
# set appropriate view and fit to screen
session.viewports['Viewport: 1'].view.rotate(
    xAngle=setView[0], yAngle=setView[1],
    zAngle=setView[2], mode=TOTAL)
session.viewports['Viewport: 1'].view.fitView()
```

4.7.2 runTest

'runTest' is the execution function of the 'visualCrashTest' module. It initialises the 'Assembly' object 'assembly and runs the 'createTestSetUp' function.

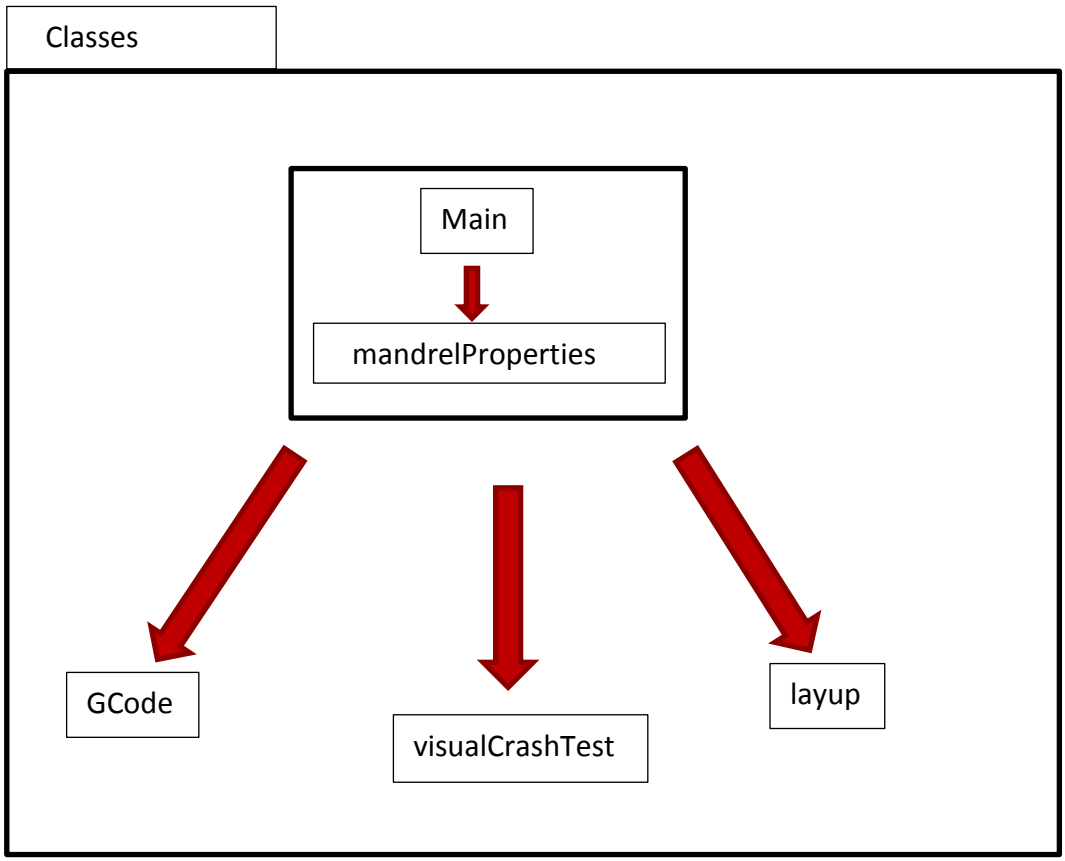
Running the visual crash test is done by way of the 'lines' variable of the 'CylindricalMandrel' object 'mandrel'. For each CNC program block the feed-eye is moved within the assembly and then paused there for one second with the Python 'sleep' function.

```
for i in range(len(mandrel.lines)):
    assembly.move(
         mandrel, mandrel.lines[i].Y, mandrel.lines[i].Z)
    time.sleep(1)
```

4.8 main.py

The ‘main’ module utilises all the other modules in turn. It can be said to be the “key” module. It has no functions of its own, but is the only one connecting all of the other AWI modules. Many of the modules interconnect (for example by class objects being utilised in several modules) resulting in the necessity of this module.

In ‘main.py’ all of the other modules are imported and reloaded, a ‘modelName’ and ‘partName’ set for the Abaqus mandrel model to be analysed and all of the functions run.



Chapter 5. Evaluation

This thesis has been a pilot study and the modules developed are intended to serve as a basis for further development. The contents of this chapter are intended to aid whoever will continue the work in the future. It poses questions regarding the current modules and suggests opportunities for further work that might be beneficial in a start-up process.

5.1 General Notes

The modules have all been tested on Abaqus mandrel models with different types of mesh and spatial orientations. However, all of these models are quite small and, with one exception, have fairly large elements. As a precaution a test model should be created with a large cylinder radius and very small elements. This will ensure that there are no problems with the functions when the elements grow smaller.

It should also be investigated whether it is possible to have the module files located in a different directory than the Abaqus work directory. As the AWI software grows it will become impractical to have all the files in the Abaqus work directory instead of in a separate AWI directory.

5.2 Remarks on Existing Functions

This section discusses possibilities of improvement and expansion of the current AWI modules.

5.2.1 Classes.py

5.2.1.1 MachineParameters

This class currently only allows for the parameter composition of the filament winding machine at NTNU, which is a five-axis machine. It might be beneficial to expand the class, to create functions for other types of machines as well, with different number of axes.

Another practical functionality, would be the possibility to store a set of machine parameters or a 'machineParameters' object. Such a function would negate the need to insert the same machine parameters every time the software is used. This functionality would be especially beneficial if the software is used to generate CNC programs for more than one filament winding machine.

Lastly, a function for converting units from inches to millimetres would increase the flexibility of the software even more. This is no difficult task to do by hand, but it is an added luxury for whoever is using the software if the manual conversion is rendered unnecessary.

5.2.1.2 CylindricalMandrel

The mandrel is currently one of the most restricting factors of the AWI software, and one of the key variables in filament winding. It is, therefore, an aspect of the software that should be made more flexible.

There are numerous possibilities for how additional mandrel shapes could be implemented. Additional mandrel classes could be created, or the current mandrel class could be changed to allow for different types of mandrels. Possibly, the mandrel class could be changed to contain shapes that can be combined (cylinder, cone, elliptical dome, spherical dome etc.), instead of predefined mandrel compositions. No matter the mode, there should be options for any type of mandrels; Both cylindrical and conical mandrel, with elliptical, spherical or parabolic dome shapes should be possible.

Furthermore, it could be beneficial to implement a function that can create a standard Abaqus mandrel model based on manual input parameters from the GUI. With such a function the user would be given the opportunity to choose between a custom mandrel created in Abaqus or one of several standard mandrels already stored in the software. A simple GUI could be created for input of geometrical variables, with several standard profiles available. Depending on the needs of the user, the appropriate combination of cylinder shapes, dome shapes and radii would be chosen.

Currently the 'verifyMandrel' function only prints a statement in the Abaqus Message Area if the mandrel exceeds the limitations of the filament winding machine. It does not in any way disrupt the running of the modules. A possible way to deal with this would be to create an exception class for mandrel values that are too great, and then interrupt the modules.

5.2.1.3 Material

The material class could easily be expanded by adding further standard materials. In addition it should contain a function to create a custom material with unique material properties in case this should be needed.

5.2.1.4 CNCLine

In this class the rounding of the CNC block variables is performed. To minimise the numerical errors caused by this procedure an additional variable for the machine tolerance could be added. This way there would be no additional numerical errors caused by the function, outside of those already present.

The class could also be made to include additional types of CNC blocks; like modal command lines or comments. This would create added flexibility to the software, making it able to, for example, choose the modal commands to be included.

5.2.1.5 GCode

This function adds the topmost lines to a generated CNC program, but does not include any kind of calculation of the point of origin for the winding in relation to the filament winding machine. In other words: it assumes the feed-eye of the filament winding machine to be located at the tip of the mandrel. There should be an additional parameter (for example in this class or the 'machineParameters' class), that includes the distance from the winding machine point of origin to a point on the mandrel. This distance should then be taken into account when generating the CNC program.

Aside from these small facts, the main thing that needs to be done about this function is to implement the kinematic equations for a filament winding machine. This is one of the key concepts of the software, and should be prioritised. One possible approach to the problem could be to form a collaborative group, including someone with a deeper understanding of automation in the filament winding process.

5.2.2 MandrelProperties.py

5.2.2.1 determineRotationalAxis

In this function it was deemed necessary to round the radii variables to make the function work. Although, as previously mentioned, this has no adverse effects on any calculations, the necessity of the 'round(…)' function should be investigated. If the hypothesis posed in chapter 4.4.2.2 is correct, it should not pose a problem. However, as the issue could be caused by other factors, it might affect the software in unknown ways. This is especially true as so many of the modules rely heavily on nodes and nodal coordinates.

With a fail-safe in place it is highly unlikely that this 'round' function will cause a false positive. This has, however, not been tested for extremely small meshes. A test model should be created, and the effects of a small mesh size investigated. It might be that this, combined with the 'round' function, will result in false positives despite the fail-safe.

The 'determineRotationalAxis' function should also be expanded to include functionalities for different types of mandrel shapes. Currently, it is based on a cylindrical mandrel with spherical domes, and requires that a part of the mandrel is cylindrical to work. If the mandrel shape is conical, the two elements compared must be located next to each other around the circumference of the mandrel for the function to work. The mesh elements might be placed randomly, and there is therefore no guarantee that this function will work for such a mandrel. There is, of course, a small chance that it will work, but leaving it up to chance whether a function works or not is far from ideal.

As the software is developed and expanded to include different types of mandrels (not only conical, but also elliptical or square are possibilities) it should be investigated whether this approach is the best one, or if an alternative approach ought to be found. It might be that the best way to determine the rotational axis is to tailor functions to each mandrel type, or some other way as of yet conceived.

5.2.2.2 determineRadii

The efficiency of this approach should be investigated. There are grounds for debating whether the 'determineRadii' function is as efficient as it could be. The function iterates through all of the nodes of every element. This means that in reality, depending on mesh type, each node is investigated three or four times. If one wishes to keep the tools functional for every type of mesh, this might prove a challenge. With no way to predict the element and node placements it is not possible to, for example, exclude a certain set of nodes off hand. One possible solution could be to register the investigated nodes in a list or a class and then check whether the current node has already been used. It is, however, unlikely that this will actually be more efficient than the current solution.

One viable solution would be to use the 'getByBoundingBox(…)' command to collect a selection of elements along the axis of rotation. The command has no required arguments, which means that if no boundaries are given in any one direction the bounding box will be infinite in that direction. Knowing the rotational axis, this can be utilised by creating a box that is infinite along the axis of rotation. The rest of the variables need to be determined somehow, as the spatial orientation, except for the rotational axis, is unknown. It is important that they are chosen in such a way that elements on all parts of the mandrel are included. Figure 33 shows black bounding boxes encompassing elements of all radii, while the red bounding box does not.

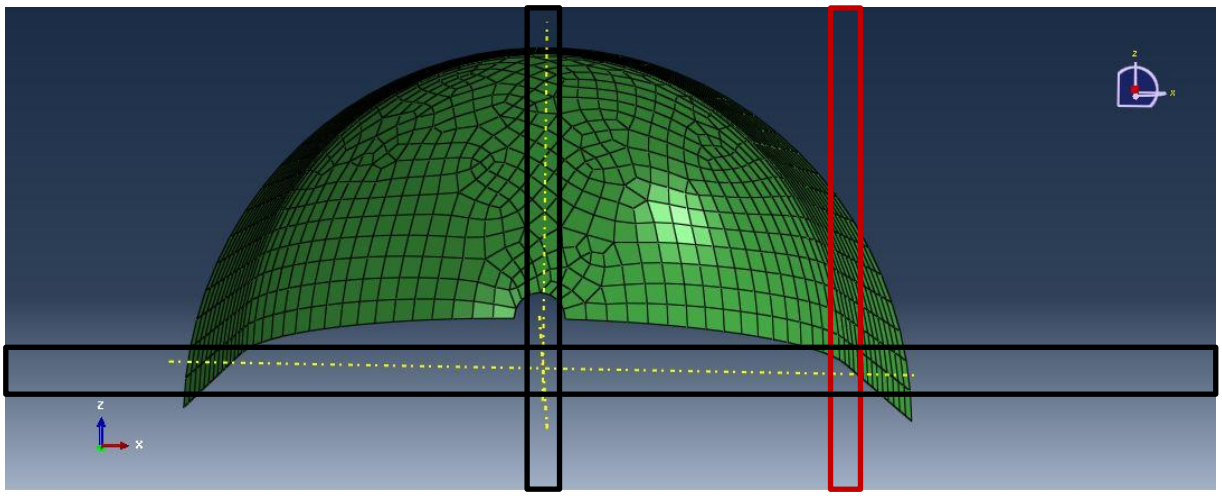


Figure 33 - Bounding box on mandrel

One suggestion on how to do this is written using pseudo code below.

```
#choosing the proper limits for the boundingBox
if (mandrel.rotationalAxis == X_AXIS):
    boxY = boxZ = maxBox = None
    numVar = 0

    while not maxBox:
        numVar += 10
        boxY = mandrel.elements.getByBoundingBox(
            yMin = -1*numVar
            yMax = numVar)

        boxZ = mandrel.elements.getByBoundingBox(
            zMin = -1*numVar
            zMax = numVar)

        if (len(boxZ) > len(boxY)):
            maxBox = boxZ
        else:
           maxBox = boxY
```

After the elements have been properly chosen, the current 'determineRadii' function can be used. There will still be unnecessary iterations, but not nearly as many as in the present version. the number of elements will have been greatly reduced, thereby greatly increasing the efficiency of the function.

This method is based on the premise that the part sketch is done in a plane of the global coordinate system. Seeing as how the rotational axis has to correspond to one of the global axes it is considered implausible that this is the case. Should it be a cause for worry a solution should not prove too challenging to implement. Using trigonometry it should prove simple to write a function incrementally rotates the bounding box until elements have been gathered. In addition, the current function, iterating through all of the elements, could be used as a fail-safe.

5.2.2.3 determineLength

This function works in the exact same way as the 'determineRadii' function, and, as such, has the same weaknesses. Most of the nodes are investigated several times, but the problem can be solved in the same way as for the above-mentioned function.

For a cylindrical mandrel it will not always be considered necessary to model the entire length of the mandrel. The dome and its shape are more important factors, and the proper cylinder length can easily be simulated for analysis. For such cases it might be convenient to implement an option for manual input of the true cylinder length.

5.2.3 GCode.py

5.2.3.1 createCNCProgram

The initial lines of the CNC program are set upon initiation of the 'GCode' class. It should be considered, however, whether to include an additional line that moves the feed-eye to the start position, and then stops, so that the fibres can be attached to the mandrel. If there is no such function in the CNC program the fibres must be attached before the program is run. As the feed-eye might have to move far before the winding can start it might cause problems during wet winding. Fibres, already impregnated, are likely to cause a mess in such situations.

It has been observed that at least some CNC programs are written with ',' as the decimal point, in Abaqus floats use '.' as their decimal points. It should be investigated what the standard is and how it can be determined, then a function written accordingly.

5.2.4 layup.py

5.2.4.1 collectLayupElements

The assumption for this function is that the geodesic curve on a cylinder projected onto a plane can be approximated to a straight line. As shown in D.3 this is only true under certain conditions. It should therefore be investigated whether it is possible to use the parametric functions of a helix more directly to determine the winding path in the plane. This would, most likely, result in a more flexible function capable of handling several different shapes.

In addition, there are currently conditions for the points, 'P1' and 'P2', of the CNC program block. They should located in the same quadrant or adjoining quadrants, and the two points cannot be too close to the relevant axes (horizontal axis for 'P1' in quadrants I and III, and vertical axis for 'P1' in quadrants II and IV). These conditions are, however, not enforced. There is no test verifying that the conditions are actually fulfilled. Such a test should be implemented, including measures to take if the test fails. For example, the movement could be split into two smaller portions if the angle between the points is too great, or if one or both are located too close to the horizontal or vertical axis.

Lastly, it should be investigated whether this approach is sound across the mandrel dome. Currently, the assumption is that the movements along the axis of rotation across the dome are small. With small movements it is possible to approximate the dome segment to a cylinder with a certain numerical error. It is unlikely that this holds, especially towards the tip of the dome, and an alternative solution should be found.

5.2.4.2 addLayup

For the 'input from file' mode of operation for this function it is most likely possible to insert the complete file path for the CNC program file. This would negate the need of copying the file into the Abaqus work directory. This has, as of yet, not been tested, but should not prove too challenging to determine and implement.

An interesting extension for this module would be to include the fibre bandwidth in the calculations. It should be investigated whether it is possible to include this parameter into the mathematical method determining the elements on which to add layup. Instead of just investigating whether the line between 'P1' and 'P2' crosses an element, one could include a distance +/- half the bandwidth as well.

Another possibility for creating an accurate winding layup would be to section the actual part instead of an 'Orphan Mesh Part'. This would be more accurate in terms of shape and path, but also more complex in its approach. Amongst others, the location of the pathway on the model would need to be determined and a generic way of sectioning the part according to the pathway, winding angle and bandwidth created to use in a script.

Challenges with this module include some of the assumptions made about the filament winding machine. It assumes that any and all winding programs originate at the tip of the mandrel dome. This is something that must be investigated further. There is no set standard for this variable, and it might change depending on the software used to generate the winding program. It should be determined whether there is any kind of set standard or norm, what is the most typical starting point for winding software and if there is any way to know this by checking the code or some kind of software manual.

Also, the axis designations are assumed to correspond to the filament winding machine at NTNU, which might not always be the case. As the AWI software is expanded, a way needs to be found to account for possible differences in axis designations of the winding machine and the CNC program. A verification script needs to be written, ensuring that the values extracted and set are indeed the values they are assumed to be; for example that the 'X' value does in fact describe the rotation of the mandrel.

Currently the tool assumes incremental movement of the filament winding machine. This is the most common setting, but there is no guarantee that a CNC program is not written using absolute dimensioning. It would be fairly simple to check this variable using Python regular expressions on the program block containing modal commands.

This module relies heavily on the Abaqus 'getByBoundingBox' command. In using this command it is important to note that the bounding box must envelop complete elements for them to be collected. Figure 34 shows a mandrel part with a bounding box in red, and four shaded elements that are collected in the box. If the mandrel elements are too great, or the steps of the CNC block too small, no elements will be collected. This has the potential to greatly affect the accuracy of the resulting winding layup.

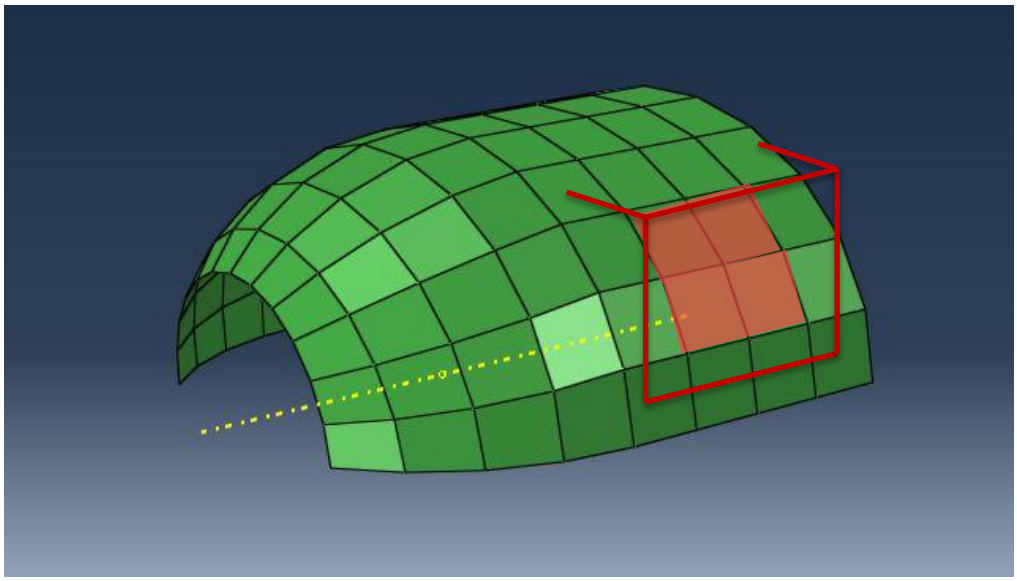


Figure 34 - collecting elements by bounding box

Some kind of functionality should be implemented to handle such cases, when the 'collectBoxElements' function returns an empty list. One possibility, would be to store the 'minCoords' and 'maxCoords' lists in-between steps, for example in the 'ConstructionLayup' object. 'minCoords' and 'maxCoords' for the two steps could then be compared and a bigger bounding box generated. Should the 'collectBoxElements', once again, return an empty list, the process can be repeated and the second set of 'minCoords' and 'maxCoords' overwritten.

This module adds a unique composite layup, with a unique set of plies, to each element. Due to the way the function collects the layup elements, and the approximations, there is currently no guaranteeing that the elements have the same number of plies. Also, the angle on each ply might not correspond the way they are supposed to, for example if there is a "missing" ply. It has not been investigated how Abaqus calculates stresses in a composite layup during analysis. Therefore, documentation should be found on this subject, and the function changed, to ensure that it will truly render the desired result of an accurate filament winding layup. The fibres used in filament winding are continuous, and the finished Abaqus mandrel model should reflect that fact before it is analysed.

Although the approximation is a very good one it has not been investigated whether it does actually correspond to the physical attributes of a real part. It should be checked whether only a part of the mandrel being model has any bearing on the results. As the winding layups are unique for each element the part cannot be said to be symmetrical, but it might prove to

be close enough to symmetrical to be acceptable. If this turns out not to be the case one solution would be to automatically model a part with the same parameters as the partial model, or to complete the partial model by revolving and mirroring the existing part.

Currently, the module has only been tested for arbitrary P1 values on different mandrel models, and not for a complete CNC program. It is possible that using a proper CNC program will result in unforeseen problems that need to be dealt with.

5.2.5 visualCrashTest.py

At the moment this module only supports movement extracted from the 'lines' variable of a 'CylindricalMandrel' object. Using the same approach as the 'layup' module this script could probably be updated to include functionality to run a visual crash test based on a CNC program file, as well as the generated CNC program.

5.3 Further Expansions

In this section suggestions are made for some additional modules and their hypothetical properties.

5.3.1 Graphical User Interface (GUI)

As the software grows it will also become more complex and unmanageable. It will be difficult to keep track of all of the functionalities, variations and permutations embedded in the software. The code structure is likely to become less structured and more confusing for those not intimately familiar with it. The simple solution is to create a software GUI from which operations and functionalities are run. A GUI helps section functions into a more apparent structure. It will make it easier to get started for new users, as well as eliminate the need to be familiar with Python and programming to use the software.

Lastly, a GUI might also help spreading the software. As the intention is for the modules to be universal, flexible and that those using them should continue the development, it is imperative that they are considered worthwhile to learn and improve. With a GUI it is more likely that new users, unfamiliar with the software, will take the time to familiarise themselves with it.

5.3.2 Winding Parameters

As briefly mentioned in chapter 2.1 there are numerous parameters that affect the mechanical properties of a filament wound part. Cross-over points, feed-rate, thickness build-up and fibre tension are just some of these. An investigative study should be done, defining and sorting these parameters, and determining how they can be implemented in the software. This should be done, not only in terms of generating a CNC program, but also in terms of modelling in Abaqus. Studying how Abaqus models and analyses composite layup should be an important part of optimising the AWI software.

5.3.3 Circumventing the Abaqus GUI

Currently this software works though the Abaqus GUI. However, for some of the modules this is not technically necessary. For example, there is no need for the GUI when determining the mandrel properties. As long as the model name and part name are known, the module can be run without the need for a viewport. As mentioned in chapter 2.3.2 there is a way of communicating with the Abaqus kernel, without the use of the GUI. It might be beneficial to investigate how this is done, and whether it would be practical to implement such functionality. Most likely, as the software expands, there will be more modules not dependent on the Abaqus GUI, and as an AWI GUI is created it might be considered impractical to have both GUIs running at once.

Chapter 6. Conclusion

This thesis has been a pilot study into the development of filament winding software capable of integrating with FEA software. The goal was to create the basis for highly flexible, open source software from which development might be continued. Key functionalities of the software were to be generation of a CNC program for a part modelled in Abaqus, and the addition of a corresponding, accurate composite layup to the modelled part.

Much to the surprise of this author and her supervisor both, the documentation of the kinematics of filament winding were not as thorough and easily accessible as initially presumed. After an extensive literature study only five papers were found on the subject, all of which, for various reasons, were dismissed. What was to be a big part of the thesis groundwork was therefore determined to be outside of the thesis scope. Instead, focus was shifted entirely to the software development.

To produce software adequately flexible and comprehensive it was decided that attention must be paid to the structure, readability, and simplicity of the code, and to generally sound and thorough reasoning when creating the framework. The intention being that others can continue the development process independently of the author, without aid. As the software is completely open source, the aim is that anyone and everyone using the software solution can add on to, change and optimise the functionalities according to their specific needs. Such continuous expansion and bettering of the software would ensure it being up to date, always improving.

The primary result of this thesis is the “Abaqus Winding Integration” (AWI) software solution. It is a set of modules with several different functionalities related to filament winding. Those functionalities include extracting mandrel properties from an Abaqus mandrel model of a cylindrical part with spherical domes, and a framework for the generation of a CNC program for that same model. The AWI software includes functionalities for performing a visual simulation of the winding process in the Abaqus GUI based on a generated CNC program. Finally, it also includes a module for adding a composite layup to an Abaqus mandrel model. The layup will correspond directly to a CNC program generated using the AWI software, or to a CNC program imported from an external file; it generates an accurate model for the filament wound part on which analysis can be performed.

6.1 Further Work

The following is a summary of the discussion in chapter 0 – Evaluation. Recommendations are made for those who are to continue the development to investigate the following areas:

- The kinematics of filament winding need to be investigated and understood.
- The AWI software should be expanded to include several additional types of mandrel and dome combinations.
- A GUI should be developed and implemented.
- The layup module should be expanded and the mathematical method perfected.
- The winding parameters influencing filament winding should be mapped and a plan of implementation made

In addition to the abovementioned main areas sever smaller suggestions were made (function converting from millimetres to inches, additional choices for type of filament winding machine, reading and adding modular G codes, a more effective 'determineRadii' and 'determineLength' functions, etc.)

Bibliography

1. *Cadwind Features*. Material; Available from: http://www.material.be/cadwind/features/index.html.
2. *Winding Expert*. Mikrosam; Available from: http://www.mikrosam.com/new/article/en/winding-expert/.
3. *Press Release from Seifert & Skinner*. ComposicaD; Available from: http://www.seifert-skinner.com/Other/PressReleaseJuly2010.pdf.
4. *Abaqus Extension for Filament Wound Composite Structures, Capability Brief*. Simulia; Available from: http://www.simulia.com/products/extensions/AppBrief_COPV.pdf.
5. Peters, S.T., *Composite filament winding*2011, Materials Park, Ohio: ASM International. VI, 167 s.
6. Seereeram, S. and J.T.Y. Wen, *An all-geodesic algorithm for filament winding of a T-shaped form.* Industrial Electronics, IEEE Transactions on, 1991. **38**(6): p. 484-490.
7. Peters, S.T., W.D. Humphrey, and R.F. Foral, *Filament winding composite structure fabrication*1999, Covina, Calif.: SAMPE International Business Office. Div. pag.
8. Lubin, G., *Handbook of fiberglass and advanced plastics composites*1969, New York: Van Nostrand Reinhold. XVIII, 894 s.
9. Eckold, G., *Design and manufacture of composite structures*1994, Cambridge: Woodhead. VIII, 397 s.
10. Shen, F.C., *A filament-wound structure technology overview.* Materials Chemistry and Physics, 1995. **42**(2): p. 96-100.
11. Green, J.E., *Overview of filament winding.* SAMPE Journal, 2001. **37**(1): p. 7-11.
12. *Company*. Material; Available from: http://www.material.be/company/index.html.
13. *Cadwind Demo and tutorial downloads*. Material; Available from: http://www.material.be/cadwind/download/index.html.
14. *Mikrosam history*. Mikrosam; Available from: http://www.mikrosam.com/new/article/en/history/.
15. *About ComposicaD*. ComposicaD; Available from: http://www.composicad.com/about.php.
16. *ComposicaD flyer*. ComposicaD; Available from: http://www.composicad.com/ComposiCAD_Flyer1.pdf.
17. *About SIMULIA*. Simulia; Available from: http://www.abacom.de/about/about.html.
18. *Abaqus FEA*. Simulia; Available from: http://www.abacom.de/products/abaqus_fea.html.
19. *Abaqus/CAE*. Simulia; Available from: http://www.abacom.de/products/abaqus_cae.html.
20. *Composite Filament Winding, Abaqus*. Simulia; Available from: http://www.simulia.com/products/wound_composites.html.
21. *Python*. Available from: www.python.org.
22. *Python Standard Libraries*
23. Simulia, *Abaqus Scripting User's Manual.* Abaqus Documentation, 2010.
24. Simulia, *Abaqus Scripting Reference Manual*, 2010.
25. Smid, P., *CNC programming handbook: a comprehensive guide to practical CNC programming*2003, New York: Industrial Press. XX, 508 s.
26. Abdel-Hady, F., *Filament winding of revolution structures.* Journal of Reinforced Plastics and Composites, 2005. **24**(8): p. 855-868.

27. Trajkovski, D., *Kinematic Analysis of Trajectory Generation Algorithms for Filament Winding Machines.* Proceedings of the 11th World Congress in Mechanism and Machine Science, 2003.
28. Koussios, S., *Filament Winding a Unified Approach*, 2004, Delft University of Technology.
29. Koussios, S., O.K. Bergsma, and A. Beukers, *Filament winding. Part 2: generic kinematic model and its solutions.* Composites Part A: Applied Science and Manufacturing, 2004. **35**(2): p. 197-212.
30. Koussios, S., O.K. Bergsma, and A. Beukers, *Filament winding. Part 1: determination of the wound body related parameters.* Composites Part A: Applied Science and Manufacturing, 2004. **35**(2): p. 181-195.
31. *Maple webpages*. MapleSoft; Available from: http://www.maplesoft.com/products/maple/index.aspx.
32. *Python Regular Expressions1*. Python; Available from: http://docs.python.org/library/re.html.
33. *Python Regular Expressions2*. Python; Available from: http://docs.python.org/howto/regex.html.
34. *Helix*. Wolfram Alpha; Available from: http://www.wolframalpha.com/input/?i=helix.
35. *Cutting Helix*. Wolfram Alpha; Available from: http://mathworld.wolfram.com/Helix.html.

Appendix A – List of Figures

Appendix B – Research History

During the literature study the scientific article databases Scopus, Elsevier, EI Village and google scholar were used.

As a point of origin for the literature study the paper “Filament Winding of Revolution Structures” by Faissal Abdel-Hady was used [25]. This paper was used as a main source in a previous project, but was shown to contain several mistakes and therefore considered unreliable. With one exception it proved almost impossible to find the sources cited in the abovementioned article. Instead it was decided to use the articles citing this one instead, a functionality which can be found in most of the article databases. There were five such articles. From this point of origin a thorough investigation of these articles, their sources, their sources’ sources and so on was done.

In addition a search using the following search words was conducted.

- “Filament Winding” automation
- Geodesic path algorithm
- Determination of Feed-eye Position
- Algorithm “filament winding”
- Machine Control “filament Winding”
- (feed-eye pay-out eye) (movement algorithm)

At one point there were no new articles, books or related books. The decision was made that, although scarce, the documentation found should suffice.

Appendix C – Evaluation of Equations

This appendix details the mathematical inconsistencies of "Filament Winding of Revolution Structures", by Faissal Abdel-Hady [25].

The equations given in the paper are as follows:

$$\tan(\theta) = \frac{\lambda \sin(\psi)}{\left[R_0 - \left(\frac{\lambda R_0^{'} \cos(\psi)}{\sqrt{1 + R_0^{'2}}} \right) \right]} \tag{2}$$

$$x_0 = R_0 - \frac{\lambda R_0^{'} \cos(\theta)\cos(\psi)}{\sqrt{1 - R_0^{'2}}} + \lambda \sin(\theta)\sin(\psi) \tag{3}$$

$$z_0 = \frac{\lambda \cos(\psi)}{\sqrt{1 + R_0^{'2}}} + z \tag{4}$$

$$\tan(\phi) = \frac{\cos(\psi)}{R_0^{'} \sin(\theta)\sin(\psi) + \sqrt{1 + R_0^{'2} \cos(\theta)\sin(\psi)}} \tag{5}$$

In the derivation of equations (2) through (4) the two following equations are utilised:

$$T_\alpha = \begin{bmatrix} \frac{R_0^{'} \cos(\theta)\cos(\psi)}{\sqrt{1 + R_0^{'2}}} - \sin(\theta)\sin(\psi) \\ \frac{R_0^{'} \sin(\theta)\sin(\psi)}{\sqrt{1 + R_0^{'2}}} + \cos(\theta)\sin(\psi) \\ \frac{\cos(\psi)}{\sqrt{1 + R_0^{'2}}} \end{bmatrix} \tag{28}$$

$$\lambda T_\alpha = \begin{bmatrix} R_0 \cos(\theta) - x_0 \\ R_0 \sin(\theta) \\ z_0 + z \end{bmatrix} \tag{29}$$

Following the logical steps in combining equations (28) and (29) equation (2) remains the same, but equations (3) and (4) suffer minor changes. In equation (3) the first term of the equation r should be $r\cos(\theta)$, and the sign of the last term of equation (4) should be the opposite.

In the derivation of equation (5) three equations are utilised:

$$\mathrm{n}_f = \mathrm{T}_\alpha \times \mathrm{x}_x \tag{30}$$

$$\mathrm{x}_x = \vec{i} \tag{31}$$

$$\mathrm{T}_\alpha = \begin{bmatrix} \dfrac{\mathrm{R}_0^{'}\cos(\theta)\cos(\psi)}{\sqrt{1+\mathrm{R}_0^{'2}}} - \sin(\theta)\sin(\psi) \\ \dfrac{\mathrm{R}_0^{'}\sin(\theta)\sin(\psi)}{\sqrt{1+\mathrm{R}_0^{'2}}} + \cos(\theta)\cos(\psi) \\ \dfrac{\cos(\psi)}{\sqrt{1+\mathrm{R}_0^{'2}}} \end{bmatrix} \tag{32}$$

Combining equations (30), (31) and (32), supposedly result in equation (33)

$$\mathrm{n}_\mathrm{f} = \begin{bmatrix} 0 \\ \dfrac{\cos(\psi)}{\sqrt{1+\mathrm{R}_0^{'2}}} \\ \dfrac{\mathrm{R}_0^{'}\sin(\theta)\sin(\psi)}{\sqrt{1+\mathrm{R}_0^{'2}}} + \cos(\theta)\cos(\psi) \end{bmatrix} \tag{33}$$

Upon close inspection, however, it can be seen that the two equations (28) and (32), although expressions for the same variable, are not identical. Regardless of which of the two are used to derive equation (33), it is not correct. Looking at equation (5) it is assumed that equation (28) is the correct one. Accurately making use of the vector product of (28) and (31) equation (33) should be:

$$\mathrm{n}_\mathrm{f} = \begin{bmatrix} 0 \\ \dfrac{\cos(\psi)}{\sqrt{1+\mathrm{R}_0^{'2}}} \\ -\left(\dfrac{\mathrm{R}_0^{'}\sin(\theta)\sin(\psi)}{\sqrt{1+\mathrm{R}_0^{'2}}} + \cos(\theta)\sin(\psi)\right) \end{bmatrix} \tag{34}$$

Accordingly equation (5) should read:

$$\tan(\phi) = \frac{n_{f\vec{j}}}{n_{f\vec{k}}} = \frac{\dfrac{\cos(\psi)}{\sqrt{1+R_0^{'2}}}}{-\left(\dfrac{R_0^{'}\sin(\theta)\sin(\psi)}{\sqrt{1+R_0^{'2}}}+\cos(\theta)\sin(\psi)\right)}$$

$$= \frac{-\cos(\psi)}{R_0^{'}\sin(\theta)\sin(\psi)+\sqrt{1+R_0^{'2}}\cos(\theta)\sin(\psi)} \qquad (35)$$

Appendix D – Derivation of Equations

This appendix contains derivation of formulae used in the Abaqus Winding Integration tools.

D.1 Mandrel Length

Equation (36) describes any point on the surface of a sphere in Cartesian coordinates.

$$R^2 = x^2 + y^2 + z^2 \tag{36}$$

Any cross-section in the xz-plane (marked in red on Figure 35) will be a circle for which the following holds:

$$r_d^{\,2} = x^2 + z^2 \tag{37}$$

Combining equations (36) and (37) yields equation for the y coordinate of the point 'P' in terms of the radius of the sphere, 'R', and the radius at point 'P', 'r'.

$$y = \sqrt{R^2 - r^2} \tag{38}$$

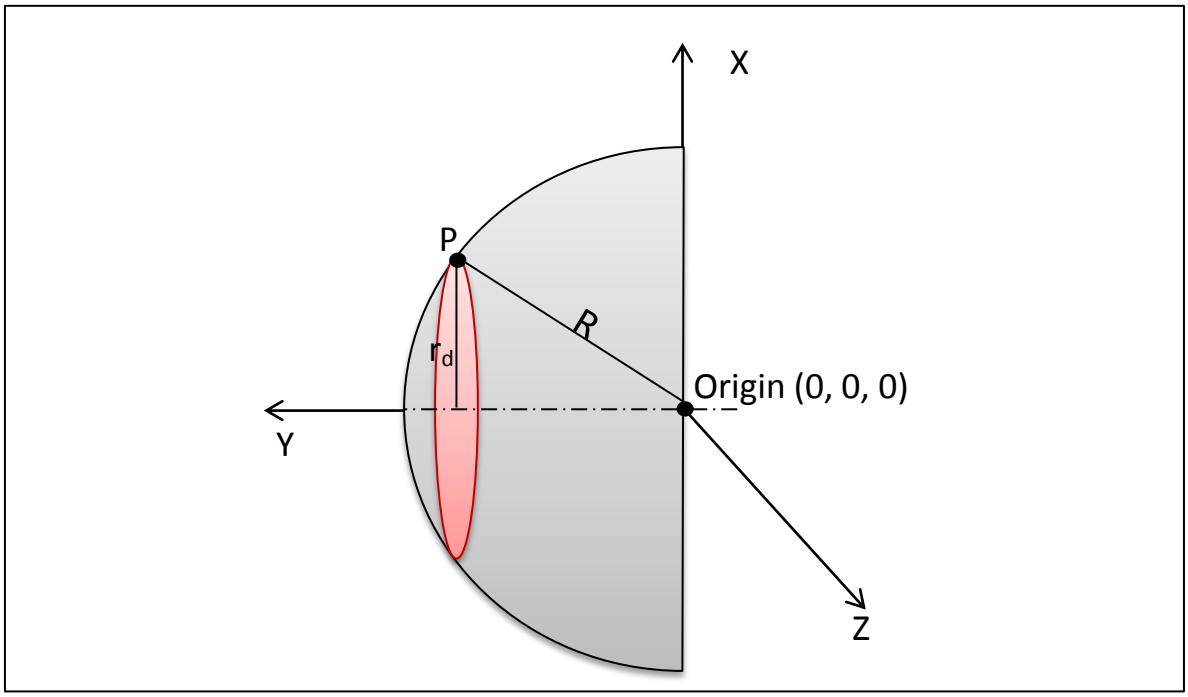


Figure 35 - Sphere

Equation (38) describes the length of a mandrel dome in terms of the dome radius, 'r', and the cylinder radius, 'R'. Adding up with the length of half a cylinder this yields the equation for the true length of a cylindrical mandrel with spherical domes:

$$\text{mandrelLength} = 2 * \left(\sqrt{R^2 - r^2} + \text{cylinderLength} \right) \tag{15}$$

D.2 Coordinates of P2

This approach is based on 'P1' being located in one of the quadrants of the unit circle, and 'P2' being located in the same, or adjoining, quadrant. Figure 36 through Figure 39 show 'P1' in different quadrants and the respective possible locations of 'P2'.

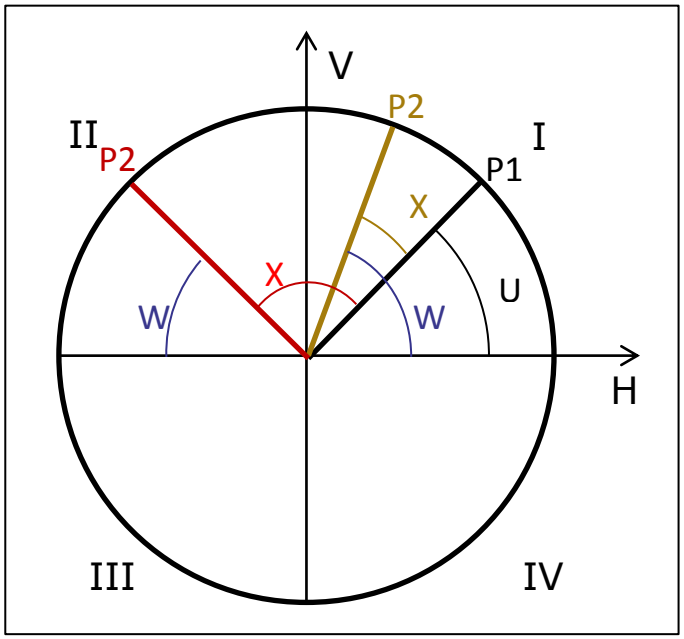


Figure 36 - P1 in quadrant I

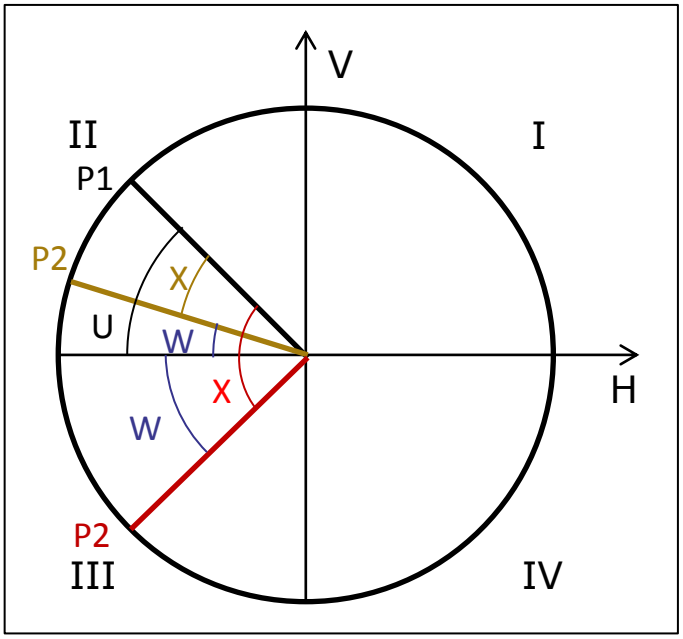


Figure 37 - P1 in quadrant II

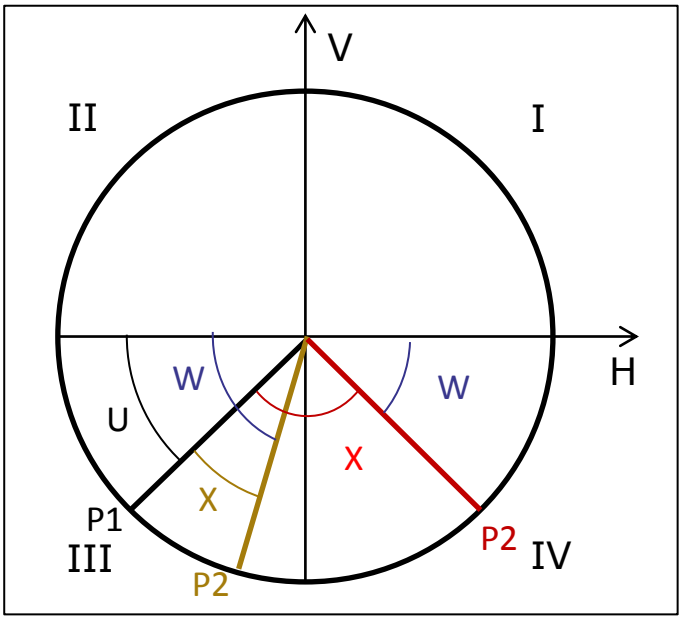


Figure 38 - P1 in quadrant III

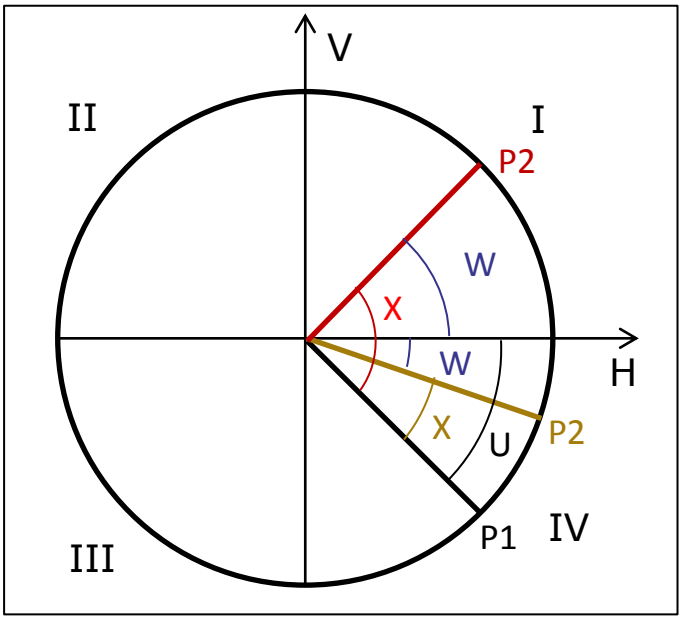


Figure 39 - P1 in quadrant IV

From the figures above the needed equations to determine the leg lengths of the triangle formed by ‘P2’ can be determined.

Equation (16) holds for P1 in all quadrants.

$$U = \tan^{-1}\left(\frac{|P1_V|}{|P1_H|}\right) \tag{16}$$

To calculate the angle ‘W’ it is necessary to determine the location of ‘P2’ this is achieved using the rotation of the mandrel, ‘X’. Equation (39) applies to ‘P1’ in quadrant I or III, and equation (40) for ‘P1’ in quadrant II or IV.

$$V + X \leq \pi \tag{39}$$
$$X \leq V \tag{40}$$

Once the location of ‘P2’ has been determined the following table can be utilised to determine the angle ‘W’.

P1	P2	Equation	
I [III]	I [III]	$W = U + X$	(17)
I [III]	II [IV]	$W = \pi - (U + X)$	(18)
II [IV]	II [IV]	$W = U - X$	(19)
II [IV]	III [I]	$W = X - U$	(20)

Equations (21) and (22) are then used to determine the coordinates of the point ‘P2’, yielding the coordinate value on the horizontal axis, and vertical axis respectively.

$$legH = signH * R\cos(W) \tag{21}$$
$$legV = signV * R\sin(W) \tag{22}$$

D.3 Linear Equations

The parametric equations for a geodesic curve around a cylinder are as follows [33].

$$z(t) = R\cos(t) \tag{41}$$

$$x(t) = R\sin(t) \tag{42}$$

$$y(t) = ct \tag{43}$$

Projecting the curve into the plane yields the curve depicted in Figure 40 for R = 20 and c = 1. Plotting in the yz-plane would result in the cosine curve.

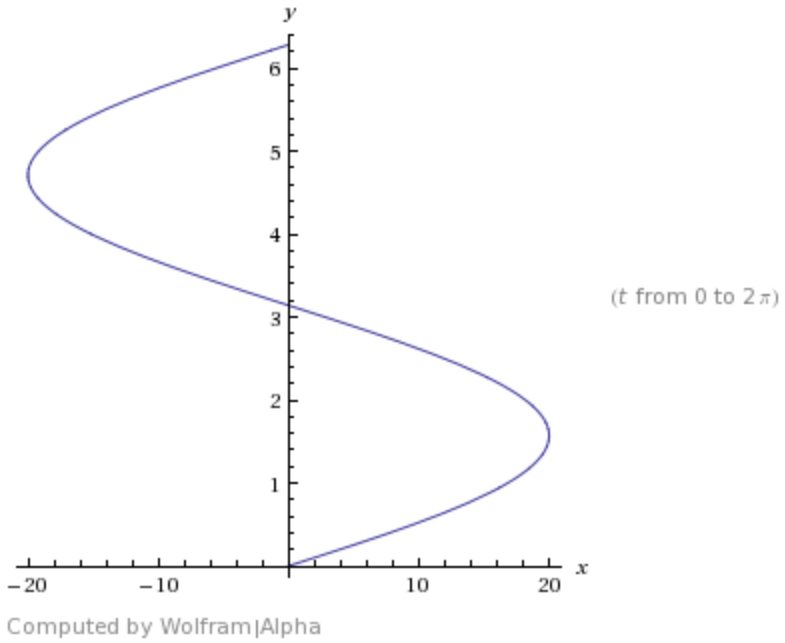


Figure 40 - plot of x(t), z(t) for R = 20, c = 1

From Figure 40 it is clear that as long as $P1_x$ and $P2_x$ are not too close to the radial value, and they are located in adjoining quadrants, the path can be considered linear between two points. The linear equation for such a line can easily be derived from the coordinates of those two points. With this line in place the elements can be projected into the same plane and it can be determined whether each element lies in the winding path or not.

Equations (23) and (24) are expressions for the straight line between two points.

$$y(x) = ax + b \tag{23}$$

$$x(y) = \frac{y - b}{a} \tag{24}$$

With two known points P1(x1, y1) and P2(x2, y2) the slope variable, ‘a’, and constant, ‘b’, can be calculated using equations (25) and (26).

$$a = \frac{y_2 - y_1}{x_2 - x_1} \tag{25}$$

$$b = y_1 - a x_1 \tag{26}$$

Knowing the nodal coordinates of an element it can easily be projected onto the same plane as the line between ‘P1’ and ‘P2’. To ascertain whether the element is in the winding path it must be determined if a point of the line lies between the boundary values of the element. This has been illustrated in Figure 41.

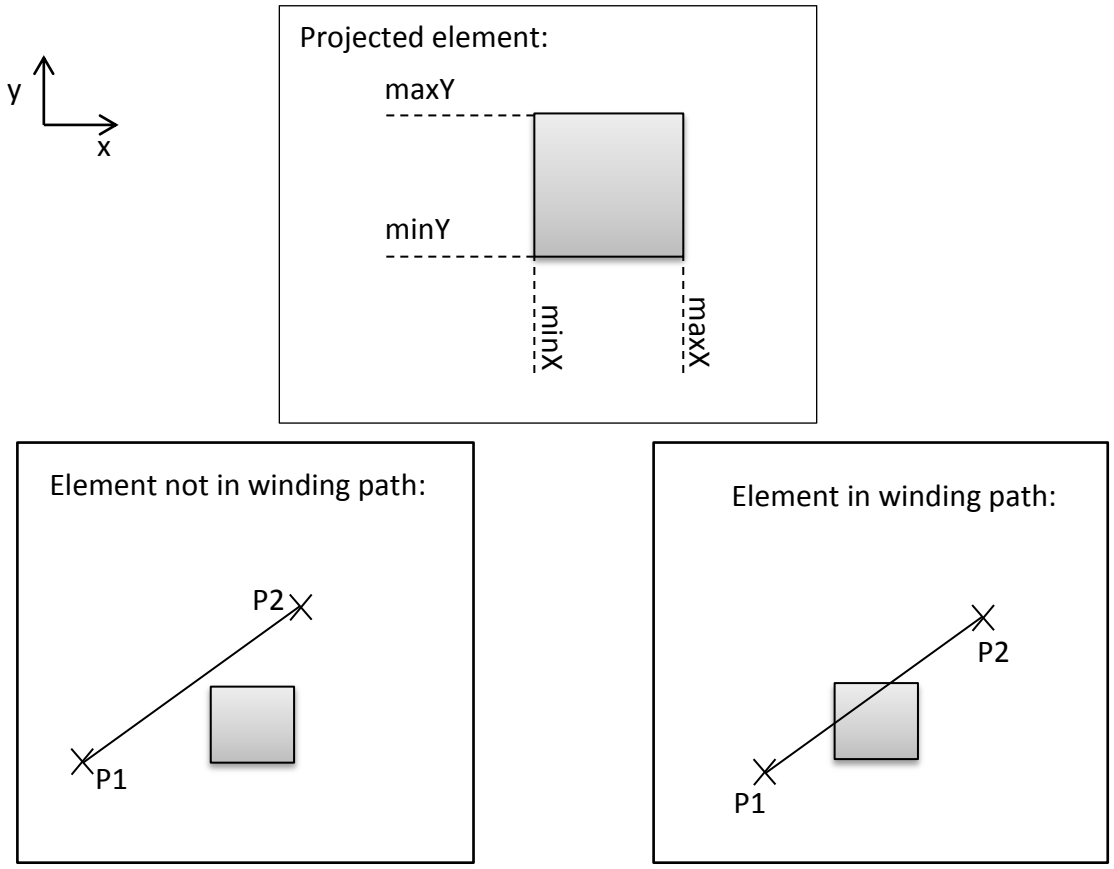


Figure 41 - Projected element and winding path

The right square in Figure 41 shows an element in the winding path. Inserting the element ‘minX’ value in equation (23) yields the cross-over point between the winding path and the left hand vertical element boundary. The element ‘maxY’ value in equation (24) yields the cross-over point between the winding path and the topmost horizontal element boundary. The cross-over values will be between the minimum and maximum values of their respective axes. If the values are not between the minimum and maximum values the element is not in the winding path.

D.4 Winding Angle, α

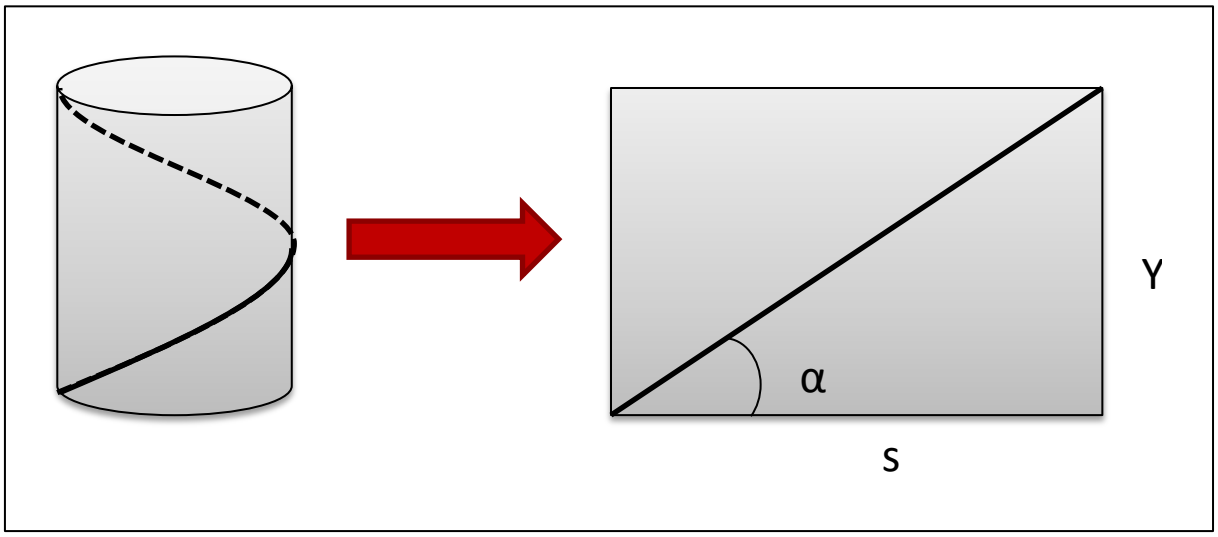


Figure 42 - Helical path on cylinder

If a cylinder with a helical pattern is cut and unfolded the resulting path on the resulting rectangle is a straight line [34]. From Figure 42 it is clear that equation (44) must be true.

$$\tan(\alpha) = \frac{Y}{s} \tag{44}$$

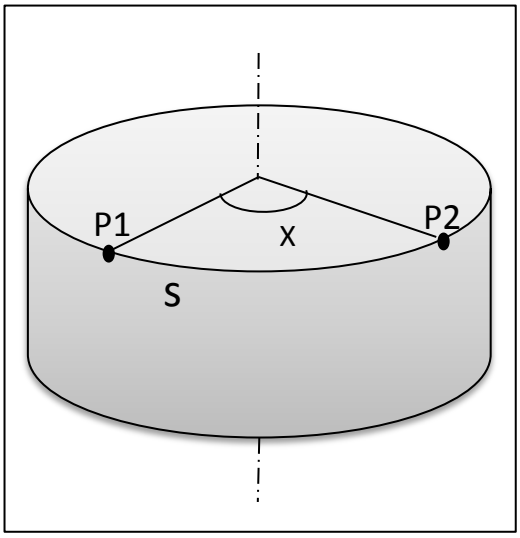


Figure 43 - Circle segment on cylinder

From Figure 43, and using the rules of ratio, equation (45) is derived.

$$\frac{X}{s} = \frac{2\pi}{2\pi * R} = \frac{1}{R} \tag{45}$$

Combining equations (44) and (45) results in equation (27); an expression for the winding angle on a cylindrical mandrel in terms of the rotation of the mandrel, 'X', the lateral movement along the axis of rotation, 'Y', and the radius of the cylinder, 'R'.

$$\tan(\alpha) = \frac{Y}{RX} \tag{27}$$

Appendix E – Integration Tools

Following are the Abaqus Winding Integration Tools in their entirety.

Note that the line numbers will not be identical to those in the *.py files as they have been formatted slightly for this appendix.

E.1 classes.py

```
1  ######################################################################
2  #                                                                    #
3  #                           CLASSSES                                 #
4  #                                                                    #
5  ######################################################################
6
7  '''
8  This file contains all the classes used in
9  the Abaqus Winding Integration Tools
10
11 For more information about the functions, how they work and why
12 the procedures have been chosen see
13 "Integration Tools for Design and Process Control of Filament
14 Winding"
15 by Inger Skjaerholt
16 '''
17
18 # necessary Python and Abaqus libraries and files
19 from abaqus import *
20 from abaqusConstants import *
21
22 import math
23
24 ### global constants. Do. NOT. Change. These!
25 X_AXIS = 0
26 Y_AXIS = 1
27 Z_AXIS = 2
28
29 ### BODY ###
30 ### Filament winding machine limits
31 class MachineParameters:
32     def __init__(self, string, maxMandrelRadius, maxWindingLength,
33                  maxMandrelLength, maxZStroke, maxWStroke):
34         self.Name = string
35         ### machine parameters in mm
36         # parameters on X-axis
37         self.maxMandrelRadius = maxMandrelRadius
38         self.maxWindingLength = maxWindingLength #max length to wind
39
40         # parameters on Y-axis
41         self.maxMandrelLength = maxMandrelLength
42                                         #max length including shafts
43
44         self.maxZStroke = maxZStroke
45         self.maxWStroke = maxWStroke
46
47
```

```
### cylindrical mandrel with spherical end domes and with identical
dome openings
class CylindricalMandrel:
    def __init__(self, modelName, partName):
        # Model variables
        self.modelName = modelName
        self.partName = partName
        self.model = mdb.models[modelName]
        self.part = mdb.models[modelName].parts[partName]
        self.nodes = mdb.models[modelName].parts[partName].nodes
        self.elements = mdb.models[modelName]
                                            .parts[partName].elements

        # Geometrical variables
        self.rotationalAxis = 'undetermined'
        self.H = None   #horizontal axis
        self.V = None   #vertical axis
        self.radius = None
        self.domeOpening = None
        self.minLength = None
        self.maxLength = None
        self.mandrelLength = None   #total length including domes
        self.cylinderLength = None
        self.pointOfOrigin = None

        # G Code variables
        self.lines = list()
        self.domeVariable = 1
        self.windingDirection = -1

    ### Class functions
    def setLength (self, minLength, maxLength):
        self.minLength = minLength
        self.maxLength = maxLength
        self.cylinderLength = (maxLength - minLength)

        self.calculateTotalLength()
        self.setDomeVariable()

    def calculateTotalLength(self):
        self.mandrelLength = 2* (
            math.sqrt(self.radius**2 - self.domeOpening**2)
            + 2*self.cylinderLength)

    def setDomeVariable(self):
        if (self.pointOfOrigin < self.minLength):
            self.domeVariable = -1

    # verifying that the mandrel does not exceed the capabilities of
      the winding machine
    def verifyMandrel (self, settings):

        if (self.radius > settings.maxMandrelRadius):
            print "The mandrel radius is too great for the ",
                                            settings.Name, " machine"

```

```
104             if (self.mandrelLength > settings.maxWindingLength):
105                 print "The mandrel length is too great for the ",
106                                                 settings.Name, " machine"
107 
108             else:
109                 print "The mandrel is within the parameters of the ",
110                                                 settings.Name, " machine"
111 
112         def printProperties (self, settings):
113             self.verifyMandrel(settings)
114             print "Model: ", self.modelName, ", Part: ", self.partName
115             print "Rotational Axis: ", self.rotationalAxis
116             print "Radius: ", self.radius
117             print "Dome Opening: ", self.domeOpening
118             print "Length: ", self.cylinderLength
119 
120 
121     ### common winding materials
122     class Material:
123         def __init__(self):
124             self.Name = None
125             self.E_1 = None
126             self.E_2 = None
127             self.E_3 = None
128             self.nu_12 = None
129             self.nu_13 = None
130             self.nu_23 = None
131             self.G_12 = None
132             self.G_13 = None
133             self.G_23 = None
134             self.rho = None
135             self.thickness = None
136 
137         def carbon_epoxy(self):
138             self.Name = 'Carbon_Epoxy'
139             self.E_1 = 14000
140             self.E_2 = 8000
141             self.E_3 = 8000
142             self.nu_12 = 0.3
143             self.nu_13 = 0.3
144             self.nu_23 = 0.55
145             self.G_12 = 4000
146             self.G_13 = 4000
147             self.G_23 = 2581
148             self.rho = 1600
149             self.thickness = 0.15
150 
151 
152 
```

```
153  ### often used node variables
154  class CustomNode:
155      def __init__(self, mandrel, element, node):
156          # nodal coordinate values
157          self.XYZ = [0, 0, 0]
158          self.XYZ[X_AXIS] = mandrel
159                .nodes[element.connectivity[node]].coordinates[X_AXIS]
160          self.XYZ[Y_AXIS] = mandrel
161                .nodes[element.connectivity[node]].coordinates[Y_AXIS]
162          self.XYZ[Z_AXIS] = mandrel
163                .nodes[element.connectivity[node]].coordinates[Z_AXIS]
164
165          # Radii calculated using different coordinate combinations
166          self.radii = [0, 0, 0]
167          self.radii[X_AXIS] = self.calculateRadius(
168              self.XYZ[Y_AXIS], self.XYZ[Z_AXIS])
169          self.radii[Y_AXIS] = self.calculateRadius(
170              self.XYZ[X_AXIS], self.XYZ[Z_AXIS])
171          self.radii[Z_AXIS] = self.calculateRadius(
172              self.XYZ[X_AXIS], self.XYZ[Y_AXIS])
173
174      # calculate a radius using pythagoras
175      def calculateRadius (self, leg1, leg2):
176          return math.sqrt(leg1**2 + leg2**2)
177
178      # get the node radius
179      def returnRadius (self, rotationalAxis):
180          return self.radii[rotationalAxis]
181
182      # get the node coordinate ON the rotational axis
183      def returnAxisCoordinate(self, rotationalAxis):
184          return self.XYZ[rotationalAxis]
185
186      def printProperties (self, nodeName):
187          print nodeName, ':'
188          print 'XYZ = (',
189               self.XYZ[0], ' , ', self.XYZ[1], ', ', self.XYZ[2], ')'
190          print 'Radii = (',
191         self.radii[0], ' , ', self.radii[1], ', ', self.radii[2], ')'
192
193  ### CNC code line to be put in the mandrel variable 'lines'
194  class CNCLine:
195      def __init__(self, N, X, Y, Z, W):
196          self.N = N
197          self.X = X
198          self.Y = Y
199          self.Z = Z
200          self.W = W
201
202          self.string = "N{0} X{1} Y{2} Z{3} W{4}\n".format(
203              str(round(N,  5)),  str(round(X,  5)),  str(round(Y,  5)),
204  str(round(Z, 5)), str(round(W, 5)))
205
206
207
```

```
208  ### G code variables
209  class GCode:
210      def __init__(self, filename, mandrel):
211
212          # increment variables
213          self.N = 10         #variable for the sequence number
214          self.increment = 10 #sequence number incremental value
215
216          # movement variables
217          self.totalX = 0
218          self.totalY = 0
219          self.totalZ = 0
220          self.totalW = 0
221
222          self.writeOpeningLines(filename, mandrel)
223
224      def writeOpeningLines(self, filename, mandrel):
225          self.GCodeFile = open(filename, 'w')
226
227          ### as the G-code file is created the topmost lines in the
228              program are written
229          # comment lines to explain for what type of mandrel the
230            program has been written
231          self.GCodeFile.write (
232              '(This CNC program has been created using)\n')
233          self.GCodeFile.write (
234              '(The Abaqus Winding Integration Tools)\n')
235          self.GCodeFile.write ('for a mandrel of:)\n')
236          self.GCodeFile.write (
237              '(\tCylinder Radius: ' +
238                str(round(mandrel.radius, 2)) + ')\n')
239          self.GCodeFile.write (
240              '(\tDome Opening: ' +
241                str(round(mandrel.domeOpening, 2)) + ')\n')
242          self.GCodeFile.write (
243              '(\tCylinder Length: ' +
244                str(round(mandrel.cylinderLength, 2)) + ')\n')
245          self.GCodeFile.write ('\n\n\n')
246
247          # first block of the program with preparatory commands etc.
248          self.GCodeFile.write ('N10 G01 G21 G91 G94 F50000\n')
249
250
```

```
251         def addLine (self, settings, mandrel, X, Y, Z, W):
252 
253             ### adding the movement to the total movement along the axes
254             self.totalX += X
255             self.totalY += Y
256             self.totalZ += Z
257             self.totalW += W
258 
259             ### ensuring that the limits of the machine
260                 have not been exceeded
261             if (self.totalY > settings.maxMandrelLength):
262                 print "error! The maximum movement along the X-axis
263                     has been exceeded"
264 
265             if (self.totalZ > settings.maxZStroke):
266                 print "error! The maximum movement along the Z-axis
267                     has been exceeded"
268 
269             if (self.totalW > settings.maxWStroke):
270                 print "error! The maximum rotation around the W-axis
271                     has been exceeded"
272 
273             else:
274                 # constructing the next line
275                 self.N += self.increment
276                 line = CNCLine (self.N, X, Y, Z, W)
277 
278                 # adding the line to the list of program lines
279                 mandrel.lines.append(line)
280 
281                 # writing the line into the program file
282                 self.GCodeFile.write(line.string)
283                 return
284 
285             # the limits of the machine have been exceeded
286             # the process is stopped
287             return "something to stop the loop"
288 
289 
290 
```

```
### variables used while adding layup to a model
class LayupConstruction:
    def __init__(self, P1):
        # general variables
        self.material = Material()

        # movement variables
        self.P1 = P1            #starting point for CNC block
        self.P2 = [0, 0, 0]     #ending point for CNC block
        self.crossesHorizontal = False
        self.crossesVertical = False

    def printPoints(self):
        print 'P1: (',
                 self.P1[0], ', ', self.P1[1], ', ', self.P1[2], ')'
        print 'P2: (',
                 self.P2[0], ', ', self.P2[1], ', ', self.P2[2], ')'


### Assembly with feed-eye
class Assembly:
    def __init__(self, mandrel):
        self.feedEye = 'Feed-Eye'
        self.mandrelName = mandrel.modelName
        self.assemblyDir = None

        self.createFeedEye(mandrel)

    def createFeedEye(self, mandrel):
        # base sketch
        sketch = mandrel.model.ConstrainedSketch (
            name = 'Section Sketch', sheetSize = 200.0)

        sketch.CircleByCenterPerimeter((0.0, 0.0), (0.0, 5.0))

        # creating the part
        part = mandrel.model.Part(name = self.feedEye)
        part.BaseSolidExtrude (sketch = sketch, depth = 5.0)

    def move (self, mandrel, Y, Z):
        #using the axes of the FW machine at NTNU as a standard
        # X = rotation of mandrel
        # Y = movement along the rotational axis
        # Z = movement perpendicular to the mandrel
        # W = rotation of the feed-eye

        # currently W and X are not relevant,
        # but they will probably be in the future

        newCoords = [0, 0, 0]
        newCoords[mandrel.rotationalAxis] = Y
        newCoords[mandrel.V] = -1*Z

        self.assemblyDir.translate((self.feedEye, ), newCoords)
        session.viewports['Viewport: 1']
                               .view.setValues(drawImmediately = True)
```

E.2 mandrelProperties.py

```
1  ##################################################################
2  #                                                                #
3  #          FUNCTIONS TO DETERMINE MANDREL PROPERTIES             #
4  #                                                                #
5  ##################################################################
6
7  '''
8  This file contains functions to gather and set mandrel properties
9  based on a model from Abaqus/CAE
10
11 For more information about the functions, how they work and why
12 the procedures have been chosen see
13 "Integration Tools for Design and Process Control of Filament
14 Winding"
15 by Inger Skjaerholt
16
17 '''
18
19 # necessary Python, Abaqus libraries and files
20 from abaqus import *
21
22 import classes
23 reload (classes)
24
25 ### global constants. Do. NOT. Change. These!
26 X_AXIS = 0
27 Y_AXIS = 1
28 Z_AXIS = 2
29
30 ### BODY ###
31 '''
32 This function iterates through the list of mandrel elements
33 comparing radii in different directions to determine Rotational Axis
34 '''
35 def determineRotationalAxis (mandrel):
36     counter = 0
37     element = mandrel.elements[counter]          #first element in
38                                                   the elements list
39     test = None      #fail-safe test variable
40
41     currentNode = classes.CustomNode(mandrel, element, 0)
42
43     while mandrel.rotationalAxis == 'undetermined':
44         counter += 1
45
46         # if the counter has moved to the end of the elements list
47         # it was not possible to determine the rotational axis
48         if counter >= len(mandrel.elements):
49             print "it was not possible
50                                     to determine the rotational axis"
51
52
```

```
            #ask for manual input through GUI
            rotationalAxis = getInput(
                'Enter the numerical value for the rotational Axis:
                \n(X-Axis = 0, Y-Axis = 1, Z-Axis = 2)')
            mandrel.rotationalAxis = int(rotationalAxis)
            break

        element = mandrel.elements[counter]     #next element
        nextNode = classes.CustomNode(mandrel, element, 0)

        # if the coordinates are identical it is unnecessary to
          compare them
        if (currentNode.XYZ == nextNode.XYZ):
            currentNode = nextNode
            continue

        ### comparing to see if the different radii are equal,
            determining the rotational axis
        if round(currentNode.radii[X_AXIS],5) ==
                                    round(nextNode.radii[X_AXIS], 5):
            # if the fail-safe variable is 'None' or another axis
            if test != X_AXIS:
                test = X_AXIS

            # if the previous comparison also returned this axis,
              the rotational axis is set
            elif test == X_AXIS:
                mandrel.rotationalAxis = X_AXIS
                mandrel.H = Z_AXIS
                mandrel.V = Y_AXIS

        if round(currentNode.radii[Y_AXIS], 5) ==
                                    round(nextNode.radii[Y_AXIS], 5):
            if test != Y_AXIS:
                test = Y_AXIS

            elif test == Y_AXIS:
                mandrel.rotationalAxis = Y_AXIS
                mandrel.H = X_AXIS
                mandrel.V = Z_AXIS

        if round(currentNode.radii[Z_AXIS], 5) ==
                                    round(nextNode.radii[Z_AXIS], 5):
            if test != Z_AXIS:
                test = Z_AXIS

            elif test == Z_AXIS:
                mandrel.rotationalAxis = Z_AXIS
                mandrel.H = Y_AXIS
                mandrel.V = X_AXIS


        # if the rotational axis has not been determined
          move one element further
        currentNode = nextNode

```

```
109
110 '''
111 This function iterates through all the nodes on all the elements in
112 the elements list
113 determining the smallest and greatest radius along the axis of
114 rotation.
115 '''
116 def determineRadii (mandrel):
117     minRadius = None
118     maxRadius = None
119
120     for element in mandrel.elements:
121         #number of nodes on an element.
122          Will vary depending on element type
123         nodesOnElement = len(element.connectivity)
124
125         # iterate through the nodes
126         for i in range(nodesOnElement):
127             currentNode = classes.CustomNode(mandrel, element, i)
128
129             # radius given by node j on element i
130             tempRadius = currentNode
131                                 .returnRadius(mandrel.rotationalAxis)
132
133             # set point of comparison on the first iteration
134             if minRadius == None:
135                 minRadius = tempRadius
136                 maxRadius = tempRadius
137
138                 # in case the first node is on the dome opening
139                 mandrel.pointOfOrigin = currentNode
140                        .returnAxisCoordinate(mandrel.rotationalAxis)
141
142             elif tempRadius < minRadius:
143                 minRadius = tempRadius
144                 mandrel.pointOfOrigin = currentNode
145                        .returnAxisCoordinate(mandrel.rotationalAxis)
146
147
148             elif tempRadius > maxRadius:
149                 maxRadius = tempRadius
150
151     mandrel.radius = maxRadius
152     mandrel.domeOpening = minRadius
153
154
155
```

```
'''
This function iterates through all the elements in the elements list
determining the outer extreme coordinates on the rotational axis for
the cylinder
'''
def determineLength (mandrel):
    minLength = None#minimum coordinate value on the rotational axis
    maxLength = None#maximum coordinate value on the rotational axis

    for element in mandrel.elements:
        # variable for the number of nodes on an element.
          Will vary depending on element type
        nodesOnElement = len(element.connectivity)

        # iterate through the nodes
        for i in range(nodesOnElement):
            currentNode = classes.CustomNode(mandrel, element, i)
            rotAxCoordinate = currentNode
                        .returnAxisCoordinate(mandrel.rotationalAxis)
            tempRadius = currentNode
                                .returnRadius(mandrel.rotationalAxis)

            # tempRadius is not equal to the cylinder radius
              and therefore on the dome
            if round(tempRadius, 5) != round(mandrel.radius, 5):
                break

            # set points of comparison on the first iteration
            if minLength == None:
                minLength = rotAxCoordinate
                maxLength = rotAxCoordinate

            elif rotAxCoordinate < minLength:
                minLength = rotAxCoordinate

            elif rotAxCoordinate > maxLength:
                maxLength = rotAxCoordinate

    mandrel.setLength(minLength, maxLength)


'''
This function gathers and determines the mandrel properties
based on a specific model in Abaqus/CAE
'''
def setProperties(settings, mandrel):
    determineRotationalAxis(mandrel)
    determineRadii(mandrel)
    determineLength(mandrel)

    print 'Mandrel Properties: '
    print '-----------------------------------------'
    mandrel.printProperties(settings)
```

E.3 GCode.py

```
1  ######################################################################
2  #                                                                    #
3  #                    FUNCTIONS TO WRITE G CODE                       #
4  #                                                                    #
5  ######################################################################
6
7  '''
8  This file contains all the custom made functions necessary to create
9  G codes based on an Abaqus model
10
11 For more information about the functions, how they work and why
12 the procedures have been chosen see
13 "Integration Tools for Design and Process Control of Filament
14 Winding"
15 by Inger Skjaerholt
16 '''
17
18 # necessary Python, Abaqus libraries and files
19 from abaqus import *
20
21 import classes
22 reload (classes)
23
24 ### global constants. Do. NOT. Change. These!
25 # (global constants added for readability)
26 X_AXIS = 0
27 Y_AXIS = 1
28 Z_AXIS = 2
29
30 ### BODY ###
31 '''
32 This function creates a CNC program based on an Abaqus model
33 '''
34 def createCNCprogram (settings, mandrel):
35     #set file name for the CNC program
36     fileName = "{0}_{1}".format(mandrel.modelName, mandrel.partName)
37
38     code = classes.GCode(fileName, mandrel)
39
40     '''
41     mathematics of winding
42     code.addLine(settings, X, Y, Z, W)
43
44     '''
45     ### random points for testing
46     code.addLine(settings, mandrel, 10, 20, -5, 20)
47     code.addLine(settings, mandrel, 15, -8, 13, 5)
48     code.addLine(settings, mandrel, 30, 50, 9, 30)
49
50
51     print "a CNC-program has been created for: "
52     mandrel.printProperties(settings)
```

E.4 layup.py

```
1  ######################################################################
2  #                                                                    #
3  #                    FUNCTIONS TO ADD LAYUP                          #
4  #                                                                    #
5  ######################################################################
6
7  '''
8  This file contains all the custom made functions necessary to
9  add layup on an Abaqus model
10
11 For more information about the functions, how they work and why
12 the procedures have been chosen see
13 "Integration Tools for Design and Process Control of Filament
14 Winding"
15 by Inger Skjaerholt
16
17 '''
18
19 # necessary Python, Abaqus libraries and files
20 from abaqus import *
21 from abaqusConstants import *
22 import __main__
23 import regionToolset
24
25 import re       #necessary library to search through a string
26 import math
27
28 import classes
29 reload (classes)
30
31 ### global constants. Do. NOT. Change. These!
32 # (global constants added for readability)
33 X_AXIS = 0
34 Y_AXIS = 1
35 Z_AXIS = 2
36
37 ### BODY ###
38 '''
39 This function adds the carbon_epoxy material to the model
40 '''
41 def addMaterial(mandrel, layup):
42     layup.material.carbon_epoxy()
43
44     # add material to the Abaqus model
45     mdb.models[mandrel.modelName].Material(
46         name = layup.material.Name)
47
48
49
```

```
50        # set material properties
51        mdb.models[mandrel.modelName]
52                                  .materials[layup.material.Name].Elastic(
53            type = ENGINEERING_CONSTANTS,
54            table = ((layup.material.E_1, layup.material.E_2,
55                layup.material.E_3, layup.material.nu_12,
56                layup.material.nu_13, layup.material.nu_23,
57                layup.material.G_12, layup.material.G_13,
58                layup.material.G_23), ))
59
60        # set material density
61       mdb.models[mandrel.modelName]
62                  .materials[layup.material.Name]
63                              .Density(table=((layup.material.rho, ), ))
64
65
66    '''
67    This function extracts the relevant values from a line of G code
68    '''
69    def readGCodes(line):
70        try:
71            matches = re.search(
72                r'\A N(\d+) \s+ X(\d+(,\d+)?) \s+ Y(\d+(,\d+)?)',
73                line, flags=re.M | re.S | re.X)
74
75            X = float(matches.group(2).replace(",", "."))
76            Y = float(matches.group(4).replace(",", "."))
77
78            return (X, Y)
79
80        except AttributeError:
81            return
82
83
84    '''
85    This function to determine if a variable is positive or negative
86    '''
87    def sign(var):
88        if var < 0:
89            return -1
90        return 1
91
92
93
```

```
94  '''
95  This function determines the coordinate values for P2
96  based on P1, rotation of mandrel and movement along the Y-axis
97  '''
98  def calculateP2(mandrel, layup, X, Y):
99      P1 = layup.P1
100
101     # determine what quadrant P1 is located in
102     signH = sign(P1[mandrel.H])
103     signV = sign(P1[mandrel.V])
104
105     # calculate the angle between P1 and the horizontal axis
106     U = math.atan2(abs(P1[mandrel.V]),abs(P1[mandrel.H]))
107
108     # if the coordinates of P1 are in quadrant I or III
109     if (signH == signV):
110         # if P1 and P2 are in the same quadrant
111         if (U+X) < (math.pi/2):
112             W = U+X
113
114         else:
115             W = math.pi - (U+X)
116             signH *= -1
117             layup.crossesVertical = True
118
119     # if the coordinates of P1 are in quadrant II or IV
120     else:
121         # if P1 and P2 are in the same quadrant
122         if (X < U):
123             W = U-X
124
125         else:
126             W = X-U
127             signV *= -1
128             layup.crossesHorizontal = True
129
130     legH = signH * (mandrel.radius * math.cos(W))     #horizontal leg
131     legV = signV * (mandrel.radius * math.sin(W))     #vertical leg
132     legLateral = P1[mandrel.rotationalAxis] +
133                                         mandrel.windingDirection * Y
134
135     ### set values for P2
136     layup.P2[mandrel.rotationalAxis] = legLateral
137     layup.P2[mandrel.V] = legV
138     layup.P2[mandrel.H] = legH
139
140
141
```

```
'''
This function collects the elements between P1 and P2
'''
def collectBoxElements(mandrel, layup):
    minCoords = [0, 0, 0]    #minimum coordinates
    maxCoords = [0, 0, 0]    #maximum coordinates
    P1 = layup.P1
    P2 = layup.P2

    # sort maximum and minimum coordinates
    for i in range(3):
        if (P1[i] < P2[i]):
            minCoords[i] = P1[i]
            maxCoords[i] = P2[i]
        else:
            minCoords[i] = P2[i]
            maxCoords[i] = P1[i]

    # if an axis has been crossed the max/min variable
    # must be mandrel radius to collect all elements
    if layup.crossesHorizontal:
        if sign(P1[mandrel.V]) >  0:
            minCoords[mandrel.H] = -1* mandrel.radius
        else:
            maxCoords[mandrel.H] = mandrel.radius

    if layup.crossesVertical:
        if sign(P1[mandrel.H]) > 0:
            maxCoords[mandrel.V] = mandrel.radius
        else:
            minCoords[mandrel.V] = -1*mandrel.radius

    boxElements = mandrel.elements.getByBoundingBox(
        xMin = minCoords[X_AXIS],
        yMin = minCoords[Y_AXIS],
        zMin = minCoords[Z_AXIS],
        xMax = maxCoords[X_AXIS],
        yMax = maxCoords[Y_AXIS],
        zMax = maxCoords[Z_AXIS])

    return boxElements
```

```
'''
This function determines which elements are crossed by the line
between P1 and P2
'''
def collectLayupElements(mandrel, layup, boxElements):
    P1 = layup.P1
    P2 = layup.P2

    ### determine the line equation for the line between P1 and P2
    # if P1 is in quadrant I or III
    if sign(P1[mandrel.H]) == sign(P1[mandrel.V]):
        a = (
           (P2[mandrel.rotationalAxis] - P1[mandrel.rotationalAxis])
                                    /(P2[mandrel.H] - P1[mandrel.H]))
        b = P1[mandrel.rotationalAxis] - P1[mandrel.H]*a

    # if P1 is in quadrant II or IV
    elif sign(P1[mandrel.H]) != sign(P1[mandrel.V]):
        a = (
           (P2[mandrel.rotationalAxis] - P1[mandrel.rotationalAxis])
                                    /(P2[mandrel.V] - P1[mandrel.V]))
        b = P1[mandrel.rotationalAxis] - P1[mandrel.V]*a

    sectionElements = []

    for element in boxElements:
        numberOfNodes = len(element.connectivity)

        # iterate through the nodes
        for i in range(numberOfNodes):
            currentNode = classes.CustomNode(mandrel, element, i)

            # set points of comparison
            if i == 0:
                minY = maxY =currentNode.XYZ[mandrel.rotationalAxis]
                minX = maxX =currentNode.XYZ[mandrel.H]

                # for quadrant II and IV use vertical axis
                if sign(P1[mandrel.H]) != sign(P1[mandrel.V]):
                    minX = maxX = currentNode.XYZ[mandrel.V]
```

```
            # for quadrant I and III use horizontal axis
            else:
                if (minY > currentNode.XYZ[mandrel.rotationalAxis]):
                    minY = currentNode.XYZ[mandrel.rotationalAxis]

                if (maxY < currentNode.XYZ[mandrel.rotationalAxis]):
                    maxY = currentNode.XYZ[mandrel.rotationalAxis]

                # for quadrant II and IV use vertical axis
                if sign(P1[mandrel.H]) != sign(P1[mandrel.V]):
                    if (minX > currentNode.XYZ[mandrel.V]):
                        minX = currentNode.XYZ[mandrel.V]

                    if (maxX < currentNode.XYZ[mandrel.V]):
                        maxX = currentNode.XYZ[mandrel.V]

                else:
                    if (minX > currentNode.XYZ[mandrel.H]):
                        minX = currentNode.XYZ[mandrel.H]

                    if (maxX < currentNode.XYZ[mandrel.H]):
                        maxX = currentNode.XYZ[mandrel.H]

        ### calculating coordinates for a point on the line
          # corresponding to the min/max values of the element
        Y_min = a*minX + b
        Y_max = a*maxX + b
        X_min = (minY - b)/a
        X_max = (maxY - b)/a

        ### checking if the element is crossed
            by the line between P1 and P2
        appended = False    #variable ensures an element
                                                is only appended once
        if (((minY < Y_min) and (Y_min < maxY)) or
                                ((minY < Y_max) and (Y_max < maxY))):
            appended = True
            sectionElements.append(element)

        if (((minX < X_min) and (X_min < maxX)) or
                                ((minX < X_max) and (X_max < maxX))):
            if appended == False:
                sectionElements.append(element)

    return sectionElements
```

```
'''
This function adds ply to the layup of each relevant element
'''
def addPly (mandrel, layup, sectionElements):
    rotAxes = (AXIS_1, AXIS_2, AXIS_3)
    #winding angle based on machine movement
    alpha = math.degrees(math.atan(Y/mandrel.radius/X))

    for element in sectionElements:
        layupName = 'layup e[%r]' %element.label

        #check if the current element already has a composite layup
        try:
            compositeLayup = mandrel.part.compositeLayups[layupName]

            numPlies = len(compositeLayup.plies)+1
            plyName = 'Ply %r' %numPlies

        # if not: create composite layup for the element
        except KeyError:
            # create composite layup
            compositeLayup = mandrel.part.CompositeLayup(
                name = layupName,
                offsetType = TOP_SURFACE,
                symmetric = False,
                thicknessAssignment = FROM_SECTION)

            plyName = 'Ply 1'

            # set rotation relative to the global coordinate system
            compositeLayup.orientation.setValues(
                orientationType = GLOBAL,
                localCsys = None,
                additionalRotationType = ROTATION_NONE,
                angle = 0.0)

        # format the element to be put into the region
        temp = mandrel.elements.sequenceFromLabels([element.label])

        region1 = regionToolset.Region(elements = temp)

        # add ply to element
        compositeLayup.CompositePly(
            suppressed = False,
            plyName = plyName,
            thicknessType = SPECIFY_THICKNESS,
            thickness = layup.material.thickness,
            region = region1,
            material = layup.material.Name,
            orientationType = SPECIFY_ORIENT,
            orientationValue = alpha,
            axis = rotAxes[mandrel.rotationalAxis])
```

```
'''
This function adds layup to a mandrel model based on:
    - CNC program from file 'f'
    - Abaqus model that has generated its own CNC program 'g'
    - manual input 'm'
'''
def addLayup (mandrel, method):
    # CNC program from file
    if method == 'f':
        fileName = getInput(
            'Enter the file name of the CNC-program:')
        str(fileName)

        file = open(fileName, 'r')

        ### set P1 as tip of dome
        P1 = [0, 0, 0]
        P1[mandrel.rotationalAxis] = mandrel.pointOfOrigin

        # create layup variables
        layup = classes.LayupConstruction(P1)
        addMaterial(mandrel,layup)

        for line in file:
            XY = readGCodes(line)
            # if XY is empty the current line contains
              comments or modal commands
            if not XY:
                continue

            # change winding direction if appropriate
            if (XY[1] < 0):
                mandrel.windingDirection = 1

            ### add layup based on variables from file
            calculateP2(mandrel, layup, XY[0], XY[1])
            boxElements = collectBoxElements(mandrel, layup)
            sectionElements = collectLayupElements(
                mandrel, layup, boxElements)
            addPly(mandrel, layup, sectionElements)

            P1 = P2
```

```
    # layup created based on relevant abaqus model
    elif method == 'g':
        ### set P1 as dome tip
        P1 = [0, 0, 0]
        P1[mandrel.rotationalAxis] = mandrel.pointOfOrigin

        # create layup variables
        layup = classes.LayupConstruction(P1)
        addMaterial(mandrel,layup)

        for i in mandrel.lines:
            line = mandrel.lines[i]
            X = line.X
            Y = line.Y

            #change winding direction if appropriate
            if (Y < 0):
                mandrel.windingDirection = 1

            ### add layup based on variable from
                the 'lines' list of the mandrel
            calculateP2(mandrel, layup, X, Y)
            boxElements = collectBoxElements(mandrel, layup)
            sectionElements = collectLayupElements(
                mandrel, layup, boxElements)
            addPly(mandrel, layup, sectionElements)

            P1 = P2

    # manual input, mostly used for testing and debugging
    elif method == 'm':
        startingPoints = (
            [25, 20, 15],
            [25, 20, -15],
            [25, -20, -15],
            [25, -20, 15])

        XY = (3, 40)

        for i in range(len(startingPoints)):
            layup = classes.LayupConstruction(startingPoints[i])
            addMaterial(mandrel,layup)

            calculateP2(mandrel, layup, XY[0], XY[1])
            boxElements = collectBoxElements(mandrel, layup)
            sectionElements = collectLayupElements(
                mandrel, layup, boxElements)
            addPly(mandrel, layup, sectionElements)
```

E.5 visualCrashTest.py

```
1  ######################################################################
2  #                                                                    #
3  #              FUNCTIONS TO RUN A VISUAL CRASH TEST                  #
4  #                                                                    #
5  ######################################################################
6
7  '''
8  This file contains all the custom made functions necessary to run a
9  visual crash test using the Abaqus model.
10
11 For more information about the functions, how they work and why
12 the procedures have been chosen see
13 "Integration Tools for Design and Process Control of Filament
14 Winding"
15 by Inger Skjaerholt
16 '''
17
18 # necessary Python, Abaqus libraries and files
19 from abaqus import *
20 from abaqusConstants import *
21 import __main__
22
23 import sketch
24 import part
25
26 import time
27
28 import classes
29 reload (classes)
30
31 ### global constants. Do. NOT. Change. These!
32 # constants representing coordinate system values (either axes or
33 coordinates):
34 X_AXIS = 0
35 Y_AXIS = 1
36 Z_AXIS = 2
37
38 ### BODY ###
39 '''
40 This function creates an assembly with a constructed feed-eye and
41 the relevant part
42 '''
43 def createTestSetUp (mandrel, assembly):
44     # creating assembly
45     assembly.assemblyDir = mandrel.model.rootAssembly
46
47     # display the assembly in the viewport
48     session.viewports['Viewport: 1'].setValues(
49         displayedObject=assembly.assemblyDir)
50
51     feedEyePart = mandrel.model.parts[assembly.feedEye]
52     mandrelPart = mandrel.model.parts[mandrel.partName]
53
54
```

```
55        #adding the two parts to the assembly
56        assembly.assemblyDir.Instance (
57            assembly.feedEye, part = feedEyePart, dependent = ON)
58        assembly.assemblyDir.Instance (
59            'Mandrel', part = mandrelPart, dependent = ON)
60
61        # define practical view based on rotational axis
62        # and rotate feed-eye according to model
63        if mandrel.rotationalAxis == X_AXIS:
64            assembly.assemblyDir.rotate(
65               (assembly.feedEye, ), (0,0,0), (0,0,-5), 90)
66            setView = (45, 45, 0)
67
68        if mandrel.rotationalAxis == Y_AXIS:
69            assembly.assemblyDir.rotate(
70               (assembly.feedEye, ), (0,0,0), (0,-5,0), 90)
71            setView = (-45, 0, -45)
72
73        if mandrel.rotationalAxis == Z_AXIS:
74            assembly.assemblyDir.rotate(
75               (assembly.feedEye, ), (0,0,0), (-5,0,0), 90)
76            setView = (45, 135, 90)
77
78        ### move the feed-eye to an initial position
79        offset = [0, 0, 0]
80        offset[mandrel.H] = mandrel.radius + mandrel.radius/4
81        offset[mandrel.rotationalAxis] = mandrel.pointOfOrigin
82        assembly.assemblyDir.translate((assembly.feedEye, ), offset)
83
84        # set appropriate view and fit to screen
85        session.viewports['Viewport: 1'].view.rotate(
86            xAngle=setView[0],
87            yAngle=setView[1],
88            zAngle=setView[2],
89            mode=TOTAL)
90        session.viewports['Viewport: 1'].view.fitView()
91
92
93    '''
94    This function runs a visual crash test based on generated CNC
95    program for the model
96    '''
97    def runTest (mandrel):
98        assembly = classes.Assembly(mandrel)
99        createTestSetUp(mandrel, assembly)
100
101       for i in range(len(mandrel.lines)):
102           assembly.move(
103               mandrel, mandrel.lines[i].Y, mandrel.lines[i].Z)
104           time.sleep(1)
```

E.6 main.py

```
1  ######################################################################
2  #                                                                    #
3  #                          MAIN FUNCTION                             #
4  #                                                                    #
5  ######################################################################
6  '''
7  This is a main function that should be run thorugh Abaqus/CAE
8  It utilises all the Abaqus Winding Integration Tools in order
9
10 For more information about the functions, how they work and why
11 the procedures have been chosen see
12 "Integration Tools for Design and Process Control of Filament
13 Winding"
14 by Inger Skjaerholt
15 '''
16 # necessary lines to use the abaqus functions
17 from abaqus import *
18 from abaqusConstants import *
19 import __main__
20
21 # import and reload the tools
22 import mandrelProperties
23 reload (mandrelProperties)
24 import GCode
25 reload (GCode)
26 import classes
27 reload (classes)
28 import visualCrashTest
29 reload (visualCrashTest)
30 import layup
31 reload (layup)
32
33 ### INPUT ###
34 # Specific model data from the Abaqus model
35 modelName = 'Model-9'
36 partName = 'Part-1-mesh-1'
37
38 # alternatively the user can be prompted for the input
39 # this is, however, impractical during development and as comments
40 '''
41 modelName, partName = getInputs(
42     (('insert modelName: ', 'modelName'),
43     ('insert partName', 'partName')),
44     dialogTitle = 'Input')
45 '''
46
47 settings = classes.MachineParameters('NTNU', 400.0, 4000.0, 4500.0,
48 400.0, 2*3.14)
49 mandrel = classes.CylindricalMandrel(modelName, partName)
50 mandrelProperties.setProperties(settings, mandrel)
51 layup.addLayup(mandrel, 'm')
52 GCode.createCNCprogram(settings, mandrel)
53 visualCrashTest.runTest(mandrel)
```

Appendix F – AWI Variable Reference List

Variable	Description	Used In	Value Type	Type
a	slope variable of linear equation	collectLayupElements	num	f
alpha	winding angle	addPly	num	f
Appended	True' if element is already in 'sectionElements'	collectLayupElements	bool	f
assembly	'Assembly' class object	runTest	obj	f
assemblyDir	pointer to the visual crash test root assembly	Assembly	pointer	c
b	constant variable of linear equation	collectLayupElements	num	f
boxElements	list of elements inside a bounding box created by P1 and P2	collectBoxElements	list	f
Code	GCode object	GCode	obj	f
compositeLayup	pointer to Abaqus composite layup object	addPly	pointer	f
counter	counts number of elements investigated	determineRotationalAxis	num	f
crossesHorizontal	whether P1 and P2 are on separate sides of the horizontal axis	LayupConstruction	bool	c
crossesVertical	whether P1 and P2 are on separate sides of the vertical axis	LayupConstruction	bool	c
currentNode	'node' object	determineRotationalAxis	obj	f
cylinderLength	length of the cylindrical part of the mandrel	CylindricalMandrel	num	c
domeOpening	radius of mandrel dome opening	CylindricalMandrel	num	c
domeVariable	variable dependent on the spatial placement of the mandrel dome along the axis of rotation	CylindricalMandrel	-1/1	c
E_1, E_2, E_3	tensile moduli for material	Material	num	c
element	element object from the 'elements' list	determineRotationalAxis	pointer	f
elements	pointer to the elements list of an Abaqus model	CylindricalMandrel	pointer	c
feedEye	name of feed-eye part	Assembly	str	c
feedEyePart	pointer to Abaqus feed-eye part	createTestSetUp	pointer	f
fileName	name of file from which CNC program blocks are read	addLayup	str	f
	name of file to which CNC program blocks are written	GCode	str	f

f – Function Variable g – Global Variable c – Class Variable

Variable	Description	Used In	Value Type	Type
G_12, G_13, G_23	shear moduli for material	Material	num	c
GCodeFile	File object to which CNC program blocks are written	GCode	str	c
H	horizontal axis of the mandrel	CylindricalMandrel	0/1/2	c
Increment	incremental value for the sequence number	GCode	num	c
layup	layupConstruction' object	addLayup	obj	f
layupName	name of composite layup for element	addPly	str	f
legH	P2 distance from origin along horizontal axis	calculateP2	num	f
legV	P2 distance from origin along vertical axis	calculateP2	num	f
lines	list of CNC program blocs for the mandrel	CylindricalMandrel	list	c
mandrel	'CylindricalMandrel' object	main	obj	f
mandrelLength	total length of mandrel	CylindricalMandrel	num	c
mandrelName	name of part in Abaqus model	Assembly	str	c
mandrelPart	pointer to Abaqus mandrel part	createTestSetUp	pointer	f
Matches	groups of python regular expression matches	readGCodes	-	f
Material	winding material	LayupConstruction	-	c
maxCoords	list of maximum coordinates	collectBoxElements	list	f
maxLength	maximum coordinate value on the mandrel model cylinder	CylindricalMandrel	num	c
maxLength	greatest current length value	determineLength	list	f
maxMandrelLength	maximum length of mandrel including shafts	MachineParameters	num	c
maxMandrelRadius	maximum mandrel radius for the winding machine	MachineParameters	num	c
maxRadius	greatest current radius value	determineRadii	list	f
maxWindingLength	maximum length of part to be wound	MachineParameters	num	c
maxWStroke	maximum rotation of the winding machine feed-eye	MachineParameters	num	c

f – Function Variable g – Global Variable c – Class Variable

Variable	Description	Used In	Value Type	Type
maxX	maximum nodal coordinate value on second axis	collectLayupElements	num	f
maxY	maximum nodal coordinate value on rotational axis	collectLayupElements	num	f
maxZStroke	arm length of winding machine perpendicular to the mandrel	MachineParameters	num	c
minCoords	list of minimum coordinates	collectBoxElements	list	f
minLength	minimum coordinate value on the mandrel model cylinder	CylindricalMandrel	num	c
minLength	smallest current length value	determineLength	list	f
minRadius	smallest current radius value	determineRadii	list	f
minX	minimum nodal coordinate value on second axis	collectLayupElements	num	f
minY	minimum nodal coordinate value on rotational axis	collectLayupElements	num	f
model	pointer to Abaqus model	CylindricalMandrel	pointer	c
modelName	name of Abaqus model	CylindricalMandrel	str	c
		main	str	g
N	sequence number for CNC block	CNCLine	num	c
		GCode	num	c
Name	name of filament winding machine,	MachineParameters	str	c
Name	name of material	Material	str	c
newCoords	new coordinates for the movement of the feed-eye part in visual crash test assembly	Assembly	list	c
nextNode	'node' object	determineRotationalAxis	obj	f
nodes	pointer to the nodes list of an Abaqus model	CylindricalMandrel	pointer	c
nodesOnElement	number of nodes on an element	collectLayupElements	num	f
		determineRadii	num	f
nu_12, nu_13, nu_23	Poisson's ratio for material	Material	num	c
numPlies	number of plies already in composite layup	addPly	num	f

f – Function Variable g – Global Variable c – Class Variable

Variable	Description	Used In	Value Type	Type
offset	feed-eye distance from mandrel upon start-up	createTestSetUp	list	f
P1	starting point of a CNC program block	LayupConstruction	list	c
		addPly	list	f
		collectLayupElements	list	f
		collectBoxElements	list	f
		calculateP2	list	f
P2	ending point of a CNC program block	LayupConstruction	list	c
		collectLayupElements	list	f
		collectBoxElements	list	f
		calculateP2	list	f
part	pointer to Abaqus part	CylindricalMandrel	pointer	c
	pointer to the feed-eye part	Assembly	pointer	c
partName	name of part in Abaqus model	CylindricalMandrel	str	c
		main	str	g
plyName	name of next composite ply	addPly	str	f
pointOfOrigin	coordinate value on the axis of rotation for the mandrel dome opening	CylindricalMandrel	num	c
radii	radii in different planes for a node	CustomNode	list	c
radius	radius of mandrel	CylindricalMandrel	num	c
region1	region (element) on which to add ply	addPly	-	f
Rho	density of material	Material	num	c
rotationalAxis	rotational axis of the mandrel	CylindricalMandrel	0/1/2	c
rotAxCoordinate	node coordinate on axis of rotation	determineLength	num	f
rotAxes	tuple of Abaqus rotational axes definitions	addPly	list	f
sectionElements	list of elements in winding path	collectLayupElements	list	f
settings	'MachineParameters' object	main	obj	f
signH	sign of coordinate value on horizontal axis	calculateP2	-1/1	f
signV	sign of coordinate value on vertical axis	calculateP2	-1/1	f
sketch	pointer to the sketch for the feed-eye part	Assembly	pointer	c
startingPoints	list of manual P1	addLayup	list	f
string	string of a CNC program block	CNCLine	str	c
temp	element formatted to fit in region	addPly	-	f
tempRadius	temporary variable for the radius on a node	determineRadii	num	f

f – Function Variable g – Global Variable c – Class Variable

Variable	Description	Used In	Value Type	Type
test	fail-safe variable storing an axis variable	determineRotationalAxis	0/1/2	f
thickness	material thickness	Material	num	c
totalW	total rotation of the feed-eye	GCode	num	c
totalX	total rotation of mandrel for the CNC program	GCode	num	c
totalY	total lateral movement along the mandrel axis of rotation for the CNC program	GCode	num	c
totalZ	total movement perpendicular to the mandrel	GCode	num	c
U	angle between P1 and horizontal axis	calculateP2	num	f
V	vertical axis of the mandrel	CylindricalMandrel	0/1/2	c
W	rotation of the feed-eye	CNCLine	num	c
	angle between P2 and horizontal axis	calculateP2	num	f
windingDirection	variable describing whether the winding is done in the positive or negative direction	CylindricalMandrel	1/-1	c
X	rotation of mandrel	CNCLine	num	c
		readGCodes	num	f
		calculateP2	num	f
		addLayup	num	f
X_AXIS	denotes x-axis	All	0	g
X_max	maximum line value on second axis	collectLayupElements	num	f
X_min	minimum line value on second axis	collectLayupElements	num	f
XY	manual input for 'X' and 'Y'	addLayup	list	f
XYZ	coordinate values for the node	CustomNode	list	c
Y	lateral movement along the mandrel rotational axis	CNCLine	num	c
		readGCodes	num	f
		calculateP2	num	f
		addLayup	num	f
Y_AXIS	denotes y-axis	All	1	g
Y_max	maximum line value on rotational axis	collectLayupElements	num	f
Y_min	minimum line value on rotational axis	collectLayupElements	num	f
Z	movement perpendicular to the mandrel	CNCLine	num	c
Z_AXIS	denotes z-axis	All	2	g

f – Function Variable g – Global Variable c – Class Variable