Design, Analysis and Instrumentation of the SHARCS Rotor Blade with Three Actively Controlled Systems

By

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Abstract

In helicopters, vibration and noise is a significant problem. The SHARCS (Smart Hybrid Rotor Control Systems) is a pioneering project of Rotorcraft Research Group at Carleton University, with the objective to reduce noise and vibration on helicopters, *simultaneously*.

The Hybrid concept proposed by the group consists of 3 independent control systems (Actively Controlled Flap, Actively Controlled Tip and Active Pitch Link) that are required to be incorporated and independently actuated within a single scaled rotor blade. Such, requirement leads to the unique, unorthodox design of the scaled rotor blade.

In this thesis, the unique composite design of the scaled SHARCS rotor blade was tested for its strength and stiffness using ANSYS software tool. Novel internal connection and reinforcement structure, C-spar, of two halves of the blade was analytically analyzed under thermal loading. The blade’s pin connection points were estimated to withstand higher then 10kN load. Also, in this thesis author has presented assembly technique of the control systems into the blade as well as wires and sensors instrumentation.

The thesis presents a ready for manufacturing, conceptual design of the SHARCS rotor blade and associated components. There are also structural analyses and material selection justification as well as instrumentation guidelines presented in the thesis.
FOR MY PARENTS AND GRANDPARENTES
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**Nomenclature**

- **a** speed of sound
- **b** span
- **BVI** blade vortex interaction
- **c** chord length
- **$C_L$** lift coefficient
- **$C_{\alpha}$** lift curve slope
- **$C_T$** trust coefficient
- **E** Young’s modulus
- **F** force
- **FEM** finite element method
- **G** shear modulus
- **g** gravity acceleration
- **I_b** mass moment of inertia
- **L** length
- **M** Mach number; moment
- **m** mass
- **$N_b$** number of blades
- **Q** Stiffness matrix
- **R** radius
- **S** compliance matrix
- **r** radial co-ordinate
- **t** thickness
- **$V_{tip}$** velocity at the tip of the blade
\( V_\infty \)  
flowfield velocity

\( x \)  
ex co-ordinate

\( y \)  
y co-ordinate

\( y' \)  
distance from neutral axis in y co-ordinate

\( z' \)  
distance from neutral axis in z co-ordinate

\( f \)  
Prandtl’s function

\( \alpha \)  
angle of attack

\( \beta \)  
conning angle

\( \varepsilon \)  
strain

\( \varphi \)  
induced angle

\( \gamma \)  
inflow

\( \lambda \)  
Lock number

\( \mu \)  
aspect ratio

\( \rho_\infty \)  
air density

\( \nu \)  
Poisson’s ratio

\( \theta \)  
pitch angle; twist angle

\( \sigma \)  
solidity factor; stress

\( \tau \)  
shear stress

\( \Omega \)  
rotational speed

**Subscripts**

1, 2, 3  
parallel, perpendicular in and out-of–plane to fibre direction

x, y, z  
span-wise, chord-wise and perpendicular

c  
centrifugal

CG  
center of gravity

N  
segment index
Chapter 1: Introduction

1.1 Vibration and noise on helicopters

Noise and vibration on rotary-wing vehicles (i.e. helicopters) occurs as a result of the unique aerodynamic environment over the rotating blades. Figure 1 illustrates the unique features of the flow-field arising over a helicopter rotor, featuring transonic flow on the advancing blade, dynamic stall on the retreating blade and a characteristic helical tip vortex emanating from each blade (Figure 2). As these vortices impact on the following blades of the main rotor, the tail rotor or the fuselage, they effectively become “chopped up” and will generate the characteristic “slapping” noise of a helicopter, as well as will create aerodynamic perturbations on the following on blades. This phenomenon is known as Blade-Vortex Interaction (BVI) and results in additional aerodynamic loading and vibration.
Figure 1: Typical aerodynamic problem areas on helicopters [2].

Figure 2: The helical tip vortices visualized by air condensation [2].
1.2 Blade-Vortex Interaction: source of noise and vibration

There are three types of BVI interactions: parallel, perpendicular and orthogonal, as illustrated in Figure 3. Parallel and perpendicular BVI occurs on the main rotor, while orthogonal BVI, in which the tip vortex is “chopped” like a cucumber with a knife, occurs on the tail rotor.

A BVI interaction exhibits itself in both noise and vibration, and therefore the ability to control this phenomenon might lead to the reduction of both effects at the same time.

BVI is most critical in low speed descent and low speed forward flight. Once the helicopter starts to operate at the higher forward flight speed, the rotor wake is skewed behind the rotor by the oncoming flow and therefore the number of BVI interactions decreases (Figure 4). However, due to the higher relative flow speed on the advancing blades, the wake intensity changes and therefore generates higher loads applied onto the following blades. This also leads to more intensive “slapping” noise as well as to the change of directivity of the noise associated with it. Since vortices are forced to move behind the rotor disc, they generate higher noise and vibration interactions with the tail rotor, as well as the fuselage of the helicopter. It is estimated that tail rotor (or orthogonal) BVI is responsible for as much as 50% of the BVI noise on helicopters [33] in some flight conditions. The tail has similar rotor noise mechanism than the main rotor, although at higher frequency [1].
1.3 Other sources of noise

Beside BVI noise, there are two other types of noise on helicopters: swishing noise and rotational noise.

Broadband noise is generated as a result of the random lift fluctuations on the blade due to vortex shedding from the blade ahead, from the freestream velocity fluctuations or from flow separation, causing the rotor to generate random **swishing sound**.
Figure 4: Plan view of the tip vortex trajectories as trailed from a two-bladed rotor in forward flight at different advance ratios [2].

Rotational noise, which is known as a thumping noise converting into blade slapping noise as the frequency of the unsteady force applied to the air by the blade increases. This noise is generated by the periodic force applied to the air, such as lift and drag along the azimuth of the rotor disk. As the tip speed increases, rotational noise can also produce acoustic fatigue and vibration to the helicopter structure. The strength of this effect depends on the number of blades the helicopter is equipped with [1].
1.4 Other sources of vibration

Beside BVI vibration, a major cause of vibration on helicopters is flow separation on the rotating blades due to dynamic stall and aerodynamic compressibility effects.

Dynamic stall is known to be a limiting factor of the forward flight speed of a helicopter due to the excessive torsional and vibratory loads on the rotor blades and the pitch link, via which the pilot controls the overall rotor aerodynamics. It occurs on the retreating blade of the rotor disc, where the relative freestream is much lower than on the advancing blade. To prevent roll, the same lift needs to be generated on both sides, which is achieved by imposing higher angle of attack on the retreating blade, ultimately pushing it beyond the stall angle as the forward flight speed increases (Figure 5). Due to the dynamic variation of the blade angle of attack and of the resultant airflow during one rotor revolution, this phenomenon is called “dynamic stall”. On one hand, dynamic stall is advantageous since it delays the onset of flow separation in comparison to static stall, which leads to greater blade lift when the flow is attached to. Even when the flow separates, the characteristic “dynamic stall vortex”, convecting downstream over the airfoil upper surface, will generate higher lift than in static conditions. However, once this vortex is shed downstream, rapid movement of the center of pressure towards the trailing edge of the airfoil occurs, resulting in large nose-down pitching moments on the blade. This leads to the increase of the torsional loads on the blade.
Figure 5: Top View of Rotor Disk in Hover and Forward Flights, represents distribution of incident velocity normal to the leading edge [2].

The nonlinear aerodynamic loads associated with the above phenomena may create critically high blade stresses, vibrations and control loads. One of phenomena associated with dynamic stall is stall flatter, which is potentially a destructive vibration mode occurring when the aerodynamic forces are coupled with the blade’s (i.e. the structure’s) natural modes of vibration, resulting in rapid periodic motion.

Another source of vibration is associated with advancing blade aerodynamics. The advancing blades operate at low angle of attack but high airflow speed, close to the speed of sound, leading to shock-induced boundary layer separation. In other words, as the forward flight speed increases, the advancing blade starts to experience transonic flow regime that create supersonic pockets over the surface of the blade, inherently terminating in strong shock waves (Figure 6).
Figure 6: Transonic flight regime with supersonic flow pockets and the shock wave at the trailing edge region [2].

When these supersonic flow pockets interact with the boundary layer, it induces flow separation, leading to increased drag as well as increased power demand. The periodic occurrence of these conditions over each revolution leads again to vibration and noise.

Thus, vibration on helicopters arises primarily due to rotor aerodynamics, which is illustrated in Figure 7, showing the fluctuating torsional loads versus the blade loading coefficient at the root of the blade at two advance ratios (μ) of 0.2 and 0.5 (Note that the advancing ratio is defined as the ratio of the flight speed over tip speed, i.e. \( \mu = \frac{V_f}{\Omega R} \)). Figure 7 shows that for the blade on the advancing side (\( \mu = 0.2 \)) the root torsional loads are relatively low, which rapidly increase once stall and/or encounters flow separation due to the shock waves effect (approx. at \( C_T/\sigma = 0.11 \), Figure 7). Even higher torsional loads are observed at further increase of the advanced ratio (\( \mu = 0.5 \)), with the stall effect occurring at lower blade loading coefficient this time (approx. at \( C_T/\sigma = 0.095 \), Figure 7). These vibratory loads will generate high stresses that may exceed the fatigue or endurance limits of the rotor and/or control system components. Thus, the
excessive stress and vibrations as a result of the aerodynamic effects will essentially limit the overall operational flight envelope of the helicopter [2].

Figure 7: Retreating blade stall inception in forward flight, deduced from blade root torsional loads [2].

1.5 Operational implications

The aforementioned sources of noise and vibration, such as BVI effects, broadband and rotational noise, dynamic stall, and compressibility effects, all make anyone traveling in a helicopter to feel the cabin being much more “shakier” than on a fixed-wing aircraft (with vibration levels as high as 0.4g’s amplitude versus 0.05g’s amplitude) and will have to use headsets to communicate with fellow passengers or the crew due to the elevated
noise levels (~ 120 dB outside [35]). The current inability of helicopters to offer a “jet smooth” ride is a major drawback in the public acceptance of rotary-wing aircraft, for example for regional transport. All components of the helicopter, such as the rotor blades or the hub, the gearbox, the control system links or the fuselage will experience significant fatigue loads, shortening maintenance periods as well as the service life of these components. Vibrations also shorten the service time of helicopter pilots due to spinal injuries and hearing problems as well as compromises the accuracy of on-board military systems, such as those of weapons or of a camera. As mentioned above, the appearance of excessive vibrations will also limit the forward flight speed of a helicopter to around 280~300 km/h. Note that the top speed is limited by the appearance of excessive vibrations in the control system – especially in the pitch link (Figure 8) – rather than by the maximum power of the propulsion unit. High level of continued vibration in the pitch link is also know as “buffering”, which is strongly related to high-frequency instability caused by airflow separation or shock-wave oscillations. It provides uncomfortable and in some cases not controllable conditions for the pilots to manoeuvre the helicopter.

For these reasons, the rotorcraft industry has set in the past decade the goal to achieve a “jet-smooth ride” by reducing vibration levels to below 0.05g’s, which corresponds to the levels experienced in a jet aircraft [35].
Figure 8: Visual representation of the hub, pitch links, and swashplate mechanism on an AH-64 Apache helicopter [2].

Noise pollution of helicopters is also very significant: a person standing on the ground will hear the characteristic “slapping” noise of a helicopter well before the helicopter is sighted. Contrary to public perception, this noise is not associated with engine noise, but solely with the aerodynamic environment appearing over the blades, i.e. with Blade Vortex Interaction (BVI).

Thus, excessive vibration and noise on helicopters arise due to the blade aerodynamics itself. To control these phenomena, one should implement control systems capable of affecting the aerodynamics of the blades.

1.6 Passive versus active control systems

Vibration and noise can be controlled either via passive or active control systems. Passive control systems, which are currently the industry standard, are able to tackle
either noise or vibration at specific flight regimes only. Active control systems, on the other hand, promise to reduce vibration and noise at a wider range of flight regimes. A more detailed description of both of these systems is presented below.

1.6.1 Passive control systems

Passive devices for reducing vibration and noise become common on production helicopters since the 1980’s. They are usually based on the principle of a mass-spring-damper system. Their advantage is their simplicity, while the main disadvantage is that they can only be tailored to one specific flight regime (e.g. for forward flight at a specific speed) but not for other flight speeds or for climb or descent. Therefore, a passive device is only useful for a very narrow window from the full operational envelope and might compromise the performance of the vehicle in other flight regimes. This gave the impetus for the industry to develop active control systems, which can adaptively change the control parameters depending on the flight regime. Thus, active control systems promise close-to-optimum control of the undesired phenomenon for the entire operational envelope of the helicopter.

1.6.2 Active control systems

Active control systems have been researched for less than two decades and they are currently viewed as the next significant advancement to appear on production helicopters. They can be either of fuselage-based or rotor-based type. In a fuselage-based system, typically a smart material type actuator is resonated at a certain adjustable
frequency to counteract cabin vibrations. Although such system can be very efficient in reducing vibration, rotor-based systems are viewed to be more superior since they can tackle vibration and noise at their source – on the rotor blade itself.

Reduction of vibration and noise on helicopters via actively controlled systems has received plenty of attention lately, with several key players of the industry involved in such research (e.g. Boeing Mesa, Eurocopter, NASA, MIT and US Army). Currently, there are 4 types of rotor-based active control technologies under development around the world, the Active Pitch Link (APL), the Actively Controlled Flap (ACF), the Active Twist Rotor (ATR) and the Actively Controlled Tip (ACT). Note that from these, the APL is a Structural Control device since it is capable of altering the structural response of the blade. All other devices, i.e. the ACF, ATR and ACT are Flow Control devices since they can only change the geometry – and thus the aerodynamics – of the blade.

Table 1 provides an overview of the ongoing research of active control systems worldwide and the level of development they have reached. Note that the development level is represented by the chain of “feasibility study – system design – whirl test – wind tunnel test – flight test”, i.e. the closer a group is to flight tests, the more mature their technology is.
Table 1: Overview of worldwide research on rotor-based Active Control Systems.

<table>
<thead>
<tr>
<th>Institution</th>
<th>Type</th>
<th>Country</th>
<th>Active Control System</th>
<th>Level of Advancement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>ACF</td>
<td>Flight Test (2005)</td>
</tr>
<tr>
<td>Boeing Mesa</td>
<td>Company</td>
<td>U.S.</td>
<td>ACF</td>
<td>Wind Tunnel Test (2008)</td>
</tr>
<tr>
<td>Bell Helicopter Textron</td>
<td>Company</td>
<td>U.S.</td>
<td>ACF</td>
<td>Whirl Test (2007)</td>
</tr>
<tr>
<td>Eurocopter</td>
<td>Company</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KARI</td>
<td>Res. Inst.</td>
<td>Korea</td>
<td>ACF</td>
<td>Feasibility + Design</td>
</tr>
<tr>
<td></td>
<td>Academia</td>
<td></td>
<td></td>
<td>Whirl Test</td>
</tr>
<tr>
<td>University of Michigan</td>
<td>Academia</td>
<td>U.S.</td>
<td>ATR</td>
<td>Feasibility study</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ACF</td>
<td></td>
</tr>
<tr>
<td>University of Maryland</td>
<td>Academia</td>
<td>U.S.</td>
<td>ACF</td>
<td>Whirl Test (2007)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Passive Pitch Link</td>
<td>Whirl Test (2007)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>APL (piezo-electric)</td>
<td>Whirl Test (2008)</td>
</tr>
<tr>
<td>Carleton University**</td>
<td>Academia</td>
<td>Canada</td>
<td>ACF</td>
<td>Whirl Test (2005)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ACT</td>
<td>Whirl Test (2005)</td>
</tr>
<tr>
<td>Carleton University + NRC</td>
<td>Academia</td>
<td>Canada</td>
<td>ATR</td>
<td>Wind Tunnel Test (2008)</td>
</tr>
</tbody>
</table>

Abbreviations:  
APL – Active Pitch Link  
ACF – Actively Controlled Flap  
ATR – Active Twist Rotor  
ACT – Actively Controlled Tip  

Notes:  
* uses APL and ACF separately only  
** uses APL and ACF in a combined way  
(patented by Carleton University)
Three major conclusions can be drawn from Table 1:

- The two most popular (Flow Control) systems nowadays are the Actively Controlled Flap (ACF) and the Active Twist Rotor (ATR).
- The most advanced technology is that of Eurocopter – they are the only one to conduct flight tests.
- No team except Carleton University uses 2 or more types of active systems simultaneously, i.e. no one has employed Structural Control and Flow Control device together before.

Note that the two dominating Flow Control technologies, ACF and ATR, have been identified to work much more efficiently with lower blade torsional stiffness, i.e. when the blade is made more “twisty” whenever the Flow Control system is activated [4]. However, by default, helicopter blades must be designed for high torsional stiffness to avoid resonance problems with other parts of the rotor. Therefore, the need to develop a Structural (or stiffness) Control device, which could adaptively change the blade stiffness, has been identified by a number of scientists in the past 15 years [30][31][32][17]. However, no such “structural control” device has been developed until the recent invention of the piezoelectrically driven Active Pitch Link by Carleton University. Note that as shown in Table 1, Eurocopter has also developed an Active Pitch Link about 15 years ago. This, however, significantly differed from Carleton’s concept in being hydraulically driven and not being able to change the torsional stiffness of a blade,
but rather to control its pitch angle. Despite the promising flight test results, it was concluded by Eurocopter that due to the relatively high weight and low reliability of the hydraulic slip ring, a hydraulically driven rotor-based system was not suitable for practical applications and that development of an electrically driven device was desired.

The main advantage of any active blade control system (e.g. ACF or ATR) is its versatility - i.e. that one single system can tackle several different problems. Obviously, this is only possible because not all problems occur at the same time. For example, noise is to be reduced in low speed descent flight whereas vibration in high-speed level flight. The same control system can be used to tackle both, but at different times.

Unfortunately, the appearance of vibration and noise is strongly coupled on helicopters and it was observed that when one of these phenomenon is reduced, the other gets amplified, i.e. when noise is reduced, vibration increases and vice-versa [6]. Therefore, for the simultaneous reduction of vibration and noise, multiple or "hybrid" active control technologies should be introduced on one single blade.

1.7 The SHARCS project

SHARCS (Smart Hybrid Active Rotor Control Systems) has been the main project of the Rotorcraft Research Group at Carleton University, since 2004. The overall goal of the project is to develop an actively controlled rotor for the simultaneous reduction of vibration and noise on helicopters. The project has been led by Carleton University who have conducted most of the feasibility studies and the design, integration, prototyping and
static testing of separate components related to the project. There were 7 other partners involved from Europe, namely:

- AgustaWestland (Italy/U.K.) – main industrial partner, world no. 4 helicopter manufacturer in terms of turnover
- Sensor Technologies Inc. (Collingwood, ON) – Canadian industrial partner, manufacturer of smart material actuators
- DLR Braunschweig (German Aerospace Research Centre) – centrifugal tests
- University of Rome La Sapienza (Italy) – experimental analysis of structures
- University of Rome 3 (Italy) – aeroelastic simulations for feasibility studies
- National Technical University of Athens (Greece) – CFD development for rotary-wing applications
- Technical University of Munich (Germany) – composite blade manufacturing

To be able to reach the simultaneous reduction of vibration and noise, Carleton University has suggested to use three independent control systems in one single blade: the Active Pitch Link (APL), the Actively Controlled Flap (ACF) and the Actively Controlled Tip (ACT); an arrangement shown in Figure 9.
The unique benefits of such Hybrid Control concept would be:

1) It promises to improve the efficiency of a Flow Control device (i.e. Actively Controlled Flap or Active Twist Rotor) by adaptively lowering the torsional stiffness of the blade.

2) It has the potential to reduce vibration and noise simultaneously by employing two independent control systems to tackle two control objectives.

Note that the second point would mean an entirely novel capability of any active control system, since as mentioned above, experience with present systems shows that when vibration is reduced, noise goes up and vice-versa [38]. This further emphasizes the significance of Carleton University’s novel Hybrid Control concept.
The goal of the SHARCS project is to design and build a 1:5 scaled, 4-bladed rotor for wind tunnel testing, featuring all 3 aforementioned active control subsystems on each rotor-blade. The goal is then to demonstrate via wind tunnel tests the feasibility of such "hybrid" control system for the simultaneous reduction of vibration and noise on helicopters.

1.8 How will it work?

As it was mentioned earlier, a single active control system is capable of suppressing various negative effects in different flight regimes. In the following sections, the various forms of noise and vibration will be reviewed, with the potential control strategies to tackle them. The section is mostly based on Ref [36] and serves two purposes: 1) it highlights that a single control system with a particular actuation strategy is not able to suppress vibration and noise simultaneously; 2) it will enable to identify the desired actuation strategy for the individual subsystems of the SHARCS rotor blade.

1.8.1 Reduction of BVI effects

For the main rotor, parallel BVI is the most critical, which exhibits itself as a pressure jump along the blade as the tip vortex generated by the previous blade interacts with it. This phenomenon, also called as “blade slap”, can be reduced by increasing the miss-distance and/or decreasing the tip vortex strength. The miss distance can be influenced by "blowing" the tip vortices below or above the rotor disk, which can be achieved by
controlling the pitch angle of the blade at the frequency of 2/rev (actuation of the pitch angle twice per one revolution of the blade) and of about 1 degree amplitude [9] (Figure 10). The worst BVI case is during low-speed decent flight since the tip vortices follow helical trajectory downward from the rotor, which are being followed by the descent movement of the helicopter during the descent flight. In the SHARCS concept, the BVI miss distance can be controlled via activating the Actively Controlled Tip (ACT), which would displace the tip vortex as well as will alter its strength.

![Figure 10: Visual representation of the miss-distance of the BVI vortex, generated by the preceding blade.](image)

### 1.8.2 Shock wave noise

Shock wave noise occurs on the advancing blade in forward flight, when the resultant relative flow speed (i.e. the sum of the rotational tip speed and the forward flight speed) reaches the transonic regime. This leads to locally supersonic flow along the blade section, which generates shock wave and produces strong blade slap. This phenomenon can be prevented by high frequency & low amplitude pitch motion of the blade [4]. The
highest noise associated with shock waves obviously occurs during high-speed forward flight.

1.8.3 Cabin vibrations

The cabin/fuselage vibrations are created by excitation of the periodic response of the rotor blades to the non-symmetric rotor inflow. For a four-bladed rotor, the typical frequencies are 3/rev, 4/rev and 5/rev (i.e. \((N_b-1)/\text{rev}\) to \((N_b+1)/\text{rev}\)). These vibrations can be reduced by generating compensating dynamic blade loads at these frequencies by a Flow Control Device, such as the Actively Controlled Flap of the SHARCS blade. Such vibrations may occur in any forward flight regime.

1.8.4 BVI vibrations

Beside the noise, BVI also causes significant vibrations due the aerodynamic loading as a result of vortex interaction with the following blade. Similarly to BVI noise, it can be reduced by 2/rev pitch control of about 0.5 ~ 1.5 degrees of amplitude [4].

Since the same actuation strategy can reduce BVI noise and vibration, a 2/rev pitch control actuations promises to reduce both undesired phenomena simultaneously. The worst case scenario for the BVI vibrations is expected to occur in low-speed descent.

1.8.5 Vibrations due to aerodynamic imbalance

Vibrations due to aerodynamic imbalances arise from manufacturing tolerance errors and/or blade geometry damage during installation, transportation and/or servicing. It causes changes in lift and drag of the respective blade at 1/rev frequency and can be
compensated by steady pitch inputs at the unequal or opposite blade. It occurs in all flight regimes.

1.8.6 Vibrations due to dynamic stall

Vibrations due to the dynamic stall are generated because of the loss of lift and increase in drag as a result of dynamic stall on the retreating blades. It occurs at 1/rev frequency for each blade and can be alleviated by delaying stall onset by achieving the desired lift coefficient at smaller angle of attack. Such condition may be achieved by employing a Flow Control device, such as the Actively Controlled Flap in downward deflected mode [8]. Delaying the stall onset may be achieved by not allowing the retreating blade to pitch to the stall angle of attack. In this case, both the retreating and advancing blade lift has to be decreased to maintain balanced rolling moment, which effect has to be compensated for by generating higher lift (and pitch angles) in the front and aft of the rotor disk. The blade operation in the front and aft regions of the rotor disc typically provides plenty of reserve below the stall angle of attack. Such individual blade pitch actuation is the basic idea behind Higher Harmonic Control (HHC). The worst case scenario of vibrations due to dynamic stall is during high-speed forward flight.

1.8.7 Pitch link vibrations due to stall flutter

Dynamic stall can lead to stall flutter, which is associated with large nose-down pitching moments and negative aerodynamic damping. The pitching moments are transferred into the swashplate and control system via the pitch links (Figure 8) in the
form of excessive vibrations, which often limit the maximum forward flight speed of a helicopter. Stall flutter can be reduced by dynamically deflecting the Actively Controlled Flap upwards on the retreating side of the rotor disk. The deflection amplitude should preferably be as high as possible, in the order of 10~15 degrees [8] [12]. Such deflection of the flap shows little loss of lift while significantly reducing stall flutter. The worst case scenario for pitch link vibrations is high-speed forward flight.

### 1.8.8 The need for multiple control systems

From the sub-sections above, one can see that there are various sources of vibration and noise on helicopters and that they require different - and in some cases contradicting - actuation strategies. For this reason, a single control system, such as the most popular Actively Controlled Flap or the Active Twist Rotor is not able to suppress vibration and noise on its own.

The novelty of the SHARCS concept is the independent operation of multiple active control systems (ACT, ACF, APL) on each blade, which promises to control more than one of the aforementioned phenomena at the same time [10]. The above concept, however, presents unique challenges in the design of a scaled rotor blade with multiple active control systems. To the knowledge of the authors, no such blade has been ever designed.
1.9 Thesis objectives

The goal of this thesis is to complete the design of a scaled SHARCS rotor blade intended for wind tunnel testing of the novel SHARCS control concept. The specific aim of the thesis is to suggest such design concept, which would enable the implementation of 3 actively controlled systems – the APL, ACF and ACT – into one single rotor blade, as well as to propose detailed instrumentation of the blade for control and monitoring purposes. It is also a primary task to perform structural analysis of this blade and to work out the manufacturing technology in detail.

1.10 Thesis outline

The research presented in this thesis concentrates on the design, development, and manufacturing technology of a scaled composite rotor blade.

It starts with discussing the Design Requirements (Chapter 2), on which bases a novel design concept, incorporating multiple control systems is proposed (Chapter 3). This is followed by the structural analysis and manufacturing technology of the composite blade skin (Chapters 3 - 5) and the thermal stress analysis of the so-called C-spar component (Chapter 6). At the end of the thesis, the Flap design and manufacturing technology will be presented (Chapter 7) concluding the document with the detailed instrumentation of the entire blade (Chapter 8).

Note that some elements of the design have been completed by other former members of the Rotorcraft Research Group whose contributions will be clearly indicated throughout the thesis. Their work has been treated as an input in to the overall blade
design and has been included in necessary depth to provide complete documentation on the design integration. The primary task of this author was to integrate these subsystems into a single design and as well as to perform stress analysis, instrumentation and manufacturing guidelines.
Chapter 2: Design requirements

The main goal of the SHARCS project is to reduce noise and vibration on helicopters via the unique hybrid control concept which is planned to be demonstrated on a 1:5 scaled 4-bladed rotor in a wind tunnel environment. This calls for unique design and manufacturing solutions enabling the implementation of 3 actively controlled subsystems at once. The design requirement for such scaled blade as well as its subsystems will be presented in this chapter.

2.1 Top level requirements

The SHARCS scaled rotor must be aerodynamically and structurally equivalent to a typical full-size helicopter rotor. Since the reduction of noise and vibration is the primary goal of the SHARCS project, the following top level design requirements have been set:

- Geometric similarity
- Acoustic similarity
- Dynamic similarity
- Aerodynamic cleanness
- Serviceability
These requirements were the 5 major factors driving the design of the SHARCS rotor blade, which will be expanded in more details below.

2.1.1 Geometric similarity

The scaled rotor is intended to be tested in a wind tunnel with a test section of at least 4 x 4 [m] and 55 m/s wind speed. These parameters dictated the choice of the rotor radius to be 1.096 m. Such blade has approximately one radius gap between from the wind tunnel wall and as such, it should eliminate possible wall effects.

The rotor radius will drive the choice of the rotational speed of the rotor too. This is usually dictated by the tip speed, which is typically around Mach 0.6 for conventional helicopters. This comes from the fact that the higher the tip speed, the lower the angle of attack on the retreating blade for a particular blade area and advance ratio. Therefore, higher tip speed delays the onset of blade stall. However, it also increases the stored rotational energy and therefore reduces design weight. There are multiple other drawbacks of the high tip speed, such as the appearance of compressibility effects on the advancing blade, which increases the requirement on shaft power, as well as elevated noise signature. Thus, lower tip speed would be beneficial to permit higher forward flight speed before the compressibility effects become important [2]. Figure 11 illustrates the limit factors affecting the selection of the tip speed of the rotor. For the aforementioned reasons, the rotor tip speed for conventional helicopters is usually set to about Mach 0.6 (~207 m/s) at sea level, which permits conventional helicopters to achieve about $\mu = 0.40$
advance ratio \((81.6 \text{ m/s} = 293 \text{ km/h})\) in forward flight before the limit factors (shown in Figure 11) start to affect the performance of the rotorcraft.

Thus, the natural choice of the tip speed for the SHARCS blade should also be a Mach 0.6.

![Figure 11: Aerodynamic, noise, and autorotation constraints imposed on the selection of rotor tip speed [2].](image)

However, to maximize the internal space of the blade for the easier incorporation of active control systems (ACF and ACT), a relatively thick NACA 0015 airfoil has been selected for the SHARCS scaled rotor blade. The thickness to chord ratio of such airfoil is 15\%, which yields lower drag divergence Mach number than the conventional (i.e. 12\% thick) airfoil used for rotorcraft (Figure 12). Note that the drag divergence Mach
number represents the sudden rise of the drag coefficient due to the appearance of shock waves at the surface of the airfoil. From Figure 12, it is determined that the compressibility effects will start to appear on the surface of the blade (NACA 0015) at about Mach 0.77 (261.8 m/s), and therefore for the SHARCS rotor to be able to operate at the advance ratio $\mu = 0.40$ (corresponding to the flight speed of 81.6 m/s = 0.24 Mach) the rotational tip speed of the blade should not exceed Mach 0.53 (which is the difference between 0.77 and 0.24 Mach). For the SHARCS rotor, 0.52 Mach was selected, which converts to a tip speed of 178.4 m/s and angular velocity of:

![Figure 12: Drag divergence Mach number of several NACA series airfoils at zero lift [2].](image-url)
This corresponds to a rotational frequency of \( n = 1,555 \) RPM. Note that the selected tip speed would yield an advance ratio of \( \mu = 0.31 \) in a 55 m/s wind tunnel, a ratio that represents well a high-speed forward flight regime where vibration and noise are expected to occur.

Furthermore, the SHARCS rotor will consist of 4 blades with a root cut-out of 126 mm that ends at the location of the attachment bolts, blade chord length of 80 mm and NACA 0015 airfoil all along the blade, except the outer 10% of the radius, when it blends into NACA 0009 leading-edge swept airfoil at the tip.

The sweep leading-edge tip geometry helps the rotor blade to operate at higher tip speeds before compressibility effects occur. It also affects tip vortex formation and its location after it has been generated by the blade [2]. A leading-edge swept tip and a linear twist distribution with an absolute twist of 6.75 deg (illustrated on Figures 13 and 14 respectively) were implemented. Note, that the blade is untwisted between 65% - 90% radius, where the Actively Controlled Flap (ACF) will be located. This was necessitated to keep the shaft of the flap straight so that the rotation (deflection) of the flap is made possible.
2.1.2 Acoustic similarity

Since noise on helicopter rotors is strongly linked to the tip speed, it is important to have the same tip speed on the scaled and full-size rotors in order to generate similar noise levels. This was the secondary reason of selecting the Mach 0.52 tip speed.

Figure 13: Top view of the SHARCS blade with main dimensions.

Figure 14: Twist distribution related to the pitch angle at 75%R.
2.1.3 Dynamic similarity

Dynamic similarity means achieving the same structural response for the scaled blades as for the full-size blades. This is achieved by keeping a similar set of mode shapes and the same Lock number on the scaled and full-size rotors. The natural frequencies of the mode shapes of a conventional helicopter blade – given by the industrial partner, AgustaWestland – are presented in Table 2. These mode shapes are to be achieved for the scaled SHARCS rotor blade to ensure dynamic similarity.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [ /rev]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st rigid lead-lag</td>
<td>0.2 ~ 0.3</td>
</tr>
<tr>
<td>1st rigid flapping</td>
<td>1.02 ~ 1.04</td>
</tr>
<tr>
<td>1st elastic beam bending</td>
<td>2.5 ~ 2.8</td>
</tr>
<tr>
<td>2nd elastic beam bending</td>
<td>4.2 ~ 4.7</td>
</tr>
<tr>
<td>1st elastic chord bending</td>
<td>4.5 ~ 5.5</td>
</tr>
<tr>
<td>1st elastic torsion</td>
<td>5.5 ~ 6.0</td>
</tr>
</tbody>
</table>

The Lock number, representing the ratio of inertial forces to aerodynamic forces, for a scaled helicopter rotor, is typically equal to 5. Recall, that the Lock number is defined as
\[
\gamma = \frac{\rho \cdot C_{la} \cdot c \cdot R^4}{I_b}
\]  

(2)

\[
I_b = \int_0^R my^2 dy
\]  

(3)

where \(I_b\) is the mass moment of inertia of the blade around the flapping hinge and is associated with the mass distribution of the blade, where \(m\) is the mass per unit length and \(y\) is the radial location. Integrating (eq. 3) along the span of the blade and substituting into eq. 2 yields:

\[
\gamma = \frac{3 \cdot \rho \cdot C_{la} \cdot c \cdot R}{m}
\]  

(4)

2.1.4 Aerodynamic cleanness

The actively controlled systems and instrumentation of the scaled SHARCS blade should be incorporated in such manner so that the aerodynamic cleanness of the blade is not compromised. It is especially crucial to meet this criterion at the outboard, high-speed portion of the blade, where the ACT and ACF systems are located (\(R = 60\sim100\%\)). This means that no overhanging or extruding components from the outer surface of the scaled blade should be introduced due to ACT and ACF systems or other supporting equipment.
2.1.5 Serviceability

It was an important design criterion to enable easy access to the actively controlled systems of the blade, so that their maintenance and/or replacement will be relatively easy. Thus, the control systems and its subsystems should be easily "serviceable" in the scaled SHARCS rotor concept.

2.2 Control systems requirements

2.2.1 Active Pitch Link (APL)

The Active Pitch Link (APL) replaces the conventional pitch link connected to the hub of the rotating frame and located at the root of the blade (Figure 8). It is designed to adaptively alter the structural response of the blade and therefore to reduce vibration by “filtering” the loads transferred to the swashplate and to increase the effectiveness of the flow control devices (i.e. ACF, ACT).

The APL shall be located at the following coordinates: span-wise location \( r = 53.22 \) mm, chord-wise location \( x = 28.30 \) mm, which corresponds to the location of the pitch horn. The total length between the APL pivot points should not be larger then 108.5 mm. The APL should not interfere with the lead-lag damper at the extremes of the swashplate location, stroke and/or tilt.

Since the APL is externally connected to the scaled SHARCS rotor blade, this active control unit does not affect the structural design of the blade.
2.2.2 Actively Controlled Flap (ACF)

The Actively Controlled Flap is designed to reduce vibration and/or noise and should be located in the span-wise direction between 65%-85% radius. The relative chord length of the flap should be 15%. These dimensions represent the best trade-off between aerodynamic efficiency and actuator power, for which the flap should be as outboard as possible but not beyond 90% radius of the blade where tip losses would dominate. For more details see References [4] and [18].

As an actuation requirement, the Actively Controlled Flap should be able to deflect 4 degrees downward at 5/rev frequency for the 4 bladed SHARCS rotor model. Feasibility studies of the ACF concept for the scaled SHARCS rotor blades are discussed in details in the References [7] and [8].

2.2.3 Actively Controlled Tip (ACT)

The Actively Controlled Tip is designed to reduce Blade Vortex Interaction (BVI) by displacing the tip vortices to lower vertical locations. The ACT should be located in the span-wise direction between 90%-100% of the scaled SHARCS rotor blade radius.

As an actuation requirement, the ACT should be deflected 20 degrees downward within 30 seconds time interval. Thus, it is designed to be manually actuated by the pilot during higher noise flight regimes (i.e. from which the most critical is forward flight decent).
The ACT for the scaled SHARCS rotor blade is designed to be manually set before each test. Detailed description of the ACT design and feasibility study is presented in Reference [19] [11].
Chapter 3: Conceptual design

The SHARCS rotor incorporates three independent feedback control systems for each blade to reduce vibration and noise simultaneously. Incorporation of three independent control systems into one blade represents a unique design challenge, which calls for an unorthodox design solution. The present chapter provides detailed overview of the conceptual design of the individual subsystems as well as their integration into the scaled blade.

3.1 SHARCS control systems

The unique requirement of the scaled SHARCS rotor blade is the incorporation of three actively controlled systems (ACT, ACF, APL) within one blade. In particular, the ACT and ACF systems as well as a set of sensors and wiring for power supply and data acquisition shall be housed inside the blade. Brief description of the individual concepts of the control systems, their geometrical constraints and their conceptual design will be described in the sections below. Note that the APL, ACT and ACF control systems have been designed and developed by other members of the Rotorcraft Research Group and the task of this author was to incorporate them into one integrated design solution.
3.1.1 Active Pitch Link (APL)

The Active Pitch Link is a closed-loop structural control device, which utilizes the "Smart Spring" concept [13] [14]. The Smart Spring is an active vibration controller using piezoelectric actuators to preferentially vary the dry friction and stiffness of a structure.

The APL will be located at the root of the blade at the location of the conventional pitch link, which is predicted to control structural response of the blade by adaptively varying the stiffness, damping and effective mass of the blade to change its flexural characteristics. This allows to control the aeroelastic response of the entire blade. Since the pitch link controls the pitching motion of the blade, it is expected that the APL will affect primarily the torsional mode. A real-time controller will be employed to identify the variations in the structural dynamics of the blade and to maximize the vibration reduction performance.

Detailed description of the design, development, manufacturing and testing of the APL is presented in Ref. [10] [14]. The sketch of the APL unit is shown in Figure 15.

In summary, the primary role of the APL is to reduce vibrations, although reduction of noise might also be possible if pitch control inputs of about 1 deg magnitude can be implied by the system as it was indicated in Section 1.8.1 (BVI). The total mass of the APL prototype is 0.196 kg. The APL is connected to the blade through the rotor hub and therefore does not affect geometrical design constraints of the blade.
Computational simulations indicate that the APL is capable to reduce vibrations by as much as 80% [37] Whirl tower tests of the APL have been described in Reference [39]. Note that the development of the APL was primary conducted by Andrei Mander former member of the Rotorcraft Research Group, at Carleton University [10] [39] [14].

![Figure 15: 3D model sketch of Active Pitch Link.](image)

### 3.1.2 Actively Controlled Flap (ACF)

The Actively Controlled Flap is a closed-loop flow control device, installed at the outboard portion of the blade (65% - 85% radius) with downward only deflection of 4 degrees and actuation frequency of 4/rev (for 4 bladed rotor). It’s primarily role is to alter the aerodynamics of the blade so that vibration [7] [8] [12] [15] and/or noise reduction can be achieved [4] [16]. The feasibility study of the hybrid ACF + APL system for SHARCS was shown to be very promising and described in Reference [7]. The individual effects of the ACF were investigated in References [8] [12] and [7], while the beneficial effect of the APL alone was computationally demonstrated in Reference [17].
The ACF actuator mechanism concept consists of a slider-cam mechanism (Figure 16) where the linear input displacement given by the piezoelectric actuators is converted to angular displacement of the flap. This is accomplished via a link system, which is optimized for the given actuator.

Figure 16: The sliding-cam concept of the ACF flap mechanism.

The piezoelectric actuators were selected from Cedrat company due to their satisfying performance characteristics as well as their small size due to the space limitation inside the blade, limited to a maximum height of 9.2 mm (to be explained later). The detailed design concept, actuator’s selection, development, manufacturing and testing are presented in References [10].
The mass of the separate components of the ACF mechanism, as well as its combined total mass, center of gravity location, centrifugal load, and geometrical characteristics are presented in Tables 3 and 4. Note that these data will play a key role in designing the SHARCS blade since the ACF will need to fit inside the blade as well as it is going to generate a local point load on the blade structure.

Note again that the ACF subsystem was developed primarily by Greg Davis, Brian Lynch and Demet Ulker from the Rotorcraft Research Group at Carleton University [10] [10] [8] [40].

Table 3: Total mass of all the components of the ACF mechanism.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezo-actuator X2</td>
<td>0.028</td>
</tr>
<tr>
<td>Bracket</td>
<td>0.012</td>
</tr>
<tr>
<td>Front Plate</td>
<td>0.005</td>
</tr>
<tr>
<td>Flexure</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.049</strong></td>
</tr>
</tbody>
</table>

Table 4: ACF system mass, geometry and centrifugal loading acting on the blade structure as are result of ACF incorporation into the blade.

<table>
<thead>
<tr>
<th>Systems</th>
<th>Mass [kg]</th>
<th>System Height [m]</th>
<th>Center of Mass Radial Location [m]</th>
<th>Centrifugal Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACF Mechanism</td>
<td>0.049</td>
<td>0.0092</td>
<td>0.7963</td>
<td>1034.14</td>
</tr>
</tbody>
</table>
3.1.3 Actively Controlled Tip (ACT)

The Actively Controlled Tip device is an open-loop control system, activated by the pilot in certain flight regimes, such as low-speed descent. The ACT system is required to deflect the blade tip to an anhedral position (downwards) by 20° within 30 seconds time period and therefore reduce BVI noise and vibration via:

- increasing the miss distance of the tip vortices by displacing them
- decreasing the tip vortex strength by altering the lift distribution along the blade tip

The most feasible design for the blade tip deflection mechanism, developed and presented in Reference [19], was considered not to be included into the scaled SHARCS rotor blade due to the blade’s weight and size limitations. The main problem was that the ACT design required to implement significant alterations to the blade root due to the properties and size of the ACT mechanism installed at 90% radius of the blade. However, to allow the experimental verification of the aerodynamic performance of the ACT unit, the tip deflection will be enabled to be adjusted manually for each wind-tunnel test. Visual representation of the manually adjusted ACT unit is shown in Figures 17 and 18. The mass of the unit and the centrifugal loads generated by it are shown in Table 5. The counterweight, presented in the Figures 17 & 18, was decided to be manufactured from Titanium material to decrease the total mass of the system and to keep its strength. Note that this data will be critical in designing the SHARCS blade, since this subsection needs to be housed inside the blade and it will represent a point load acting on the blade
structure. Detailed description of the ACT concept and load calculations is presented in Reference [19].

Note again that the ACT unit was developed by Brian Lynch and Matthew Cha of the Rotorcraft Research Group [19] [11].

<table>
<thead>
<tr>
<th>Systems</th>
<th>Mass [kg]</th>
<th>System Height [m]</th>
<th>Center of Mass Radial Location [m]</th>
<th>Centrifugal Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACT Manually Adjustable Mechanism</td>
<td>0.004</td>
<td>0.007</td>
<td>0.9778</td>
<td>139.52</td>
</tr>
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</table>

**Figure 17**: Self-locking, manually adjustable ACT unit with L representing distance of the center of mass of separate components from the center of rotation relative to the blade tip angle of deflection [19].
3.2 The Skeleton & Frame concept

From the above three subsystems, the ACF and ACT needs to be housed inside the blade while the APL is essentially becoming a part of the rotor hub (see Figure 13). The requirement of incorporating two independently operated actively controlled systems into one scaled rotor blade called for an unconventional design concept.

To comply with the requirement of aerodynamic cleanness (Section 2.1.4) both actively controlled systems (i.e. the ACT and ACF) as well as their components must be installed inside the blade. Based on this design criterion, the internal space of the blade had to be maximized, which lead to the selection of a 15% thick NACA 0015 airfoil for
the blade as mentioned earlier in Section 2.1.1. Note that conventional helicopter blades are typically 12% thick.

A completely novel and unorthodox design solution for housing the ACF and ACT systems was developed by proposing a removable "Skeleton" structure inside the blade (Figure 19). The Skeleton can be slid in from the tip of the blade and secured to an internal structure called the Frame via a removable pin. The Frame is permanently attached (glued) to the blade skin and provides a “guiding rail” for the Skeleton to slide in. Thus, it is equipped with nylon insert to reduce frictional forces during installation and to provide support for the Skeleton structure within the Frame.

Thus, when maintenance of the subsystems is required, the Skeleton can be relatively easily pulled out from the blade by removing only the pin holding it. The “Skeleton” sliding assembly concept is presented in Figure 20.

![Figure 19: 3D Visual representation of the Skeleton holding the complete ACF and ACT systems.](image)
3.2.1 Design

The Skeleton design resembles the inside of a classical wing structure: it consists of 4 ribs and a front and a rear spar, with cross-linked reinforcement links for weight reduction (Figure 21). It is held by a removable pin that is inserted from the trailing edge (at the inboard side of the flap (Figure 20)) and is connected to a support structure attached to the blade, the “Frame”. The Frame is glued to the inside of the composite skin and must have sufficient shear strength to withstand the shear load that is created by the centrifugal force acting on the Skeleton. The pin and the hinges on the Skeleton and Frame must be sized to withstand the same load.
There are three types of loads that are estimated to be acting on the Skeleton:

- the centrifugal loads created by the ACF and ACT subsystems
- the centrifugal loads from the Skeleton’s own mass
- the reaction forces from the flap and the blade tip as they are hinged on the Skeleton.

Table 6 shows the numerical values of the centrifugal loads acting on the Skeleton.
The reaction loads from the ACF and ACT are equal and opposite to the forces and moments created by these components, divided among the number of hinge points. Based on the above, the removable pin holding the Skeleton inside the Frame (and thus inside the blade) should be able to withstand a load of 4600 N (Table 6).

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass [kg]</th>
<th>Center of Mass Radial Location [m]</th>
<th>Centrifugal Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACF</td>
<td>0.049</td>
<td>0.7961</td>
<td>1033.88</td>
</tr>
<tr>
<td>ACT+Tip</td>
<td>0.068</td>
<td>1.0159</td>
<td>1830.92</td>
</tr>
<tr>
<td>Skeleton</td>
<td>0.05858</td>
<td>0.849</td>
<td>1318.15</td>
</tr>
<tr>
<td><strong>Skeleton + Systems</strong></td>
<td><strong>0.17558</strong></td>
<td><strong>0.8989</strong></td>
<td><strong>4182.95</strong></td>
</tr>
<tr>
<td>Frame</td>
<td>0.02017</td>
<td>0.78036</td>
<td>417.13</td>
</tr>
<tr>
<td><strong>Full Assembly</strong></td>
<td><strong>0.19575</strong></td>
<td><strong>0.8867</strong></td>
<td><strong>4600.08</strong></td>
</tr>
</tbody>
</table>

The Frame is glued to the inner surface of the composite skin with Redux glue from Hexcel. Its total mass is 20.17 g and its contact surface with the skin has been calculated to be sufficiently large to withstand the shear load from the total centrifugal load acting on the Skeleton and the Frame, i.e. 4,600 N (Table 6).

### 3.2.2 Stress Analysis

Finite Element Analysis (FEA) was performed in Autodesk Inventor Professional V.10 to evaluate the stresses occurring on the Skeleton. The loads were introduced at the
components, where the actuators are attached to the Skeleton, as uniformly distributed masses with the correct locations (Figure 22). The maximum stress was determined at the start of the Skeleton is 637.77 MPa, which is below the yield stress of Titanium. The safety factor of the Skeleton exposed to centrifugal loading is 1.37.

Figure 22: Visual representation of FEM analysis of the Skeleton with uniformly distributed masses of the Control Systems (ACF & ACT) attached to the structure.
3.2.3 Core structure

Conventional helicopter blades are made out of composite material with their inner core being Rohacella foam to prevent skin buckling. Rohacella is a composite material with outstanding thermal and mechanical properties with high strength-to-weight ratio. Other scaled blades from Eurocopter, Boeing, and AgustaWestland are all using foam as the core structure of the composite blades, some in combination with honeycomb. The SHARCS blades are designed with two control systems being held inside the blade with the aid of the Skeleton structure. The Rohacella foam has been selected to be the core structure of the blade for the rest of the blade interior, from the end of the root-transition zone (x = 135 mm from the root of the blade in the radial direction) to the start of the “Frame” (x = 712.4 mm).

3.2.4 Electrical lay-out design

The power supply wires for the ACF and sensors incorporated inside the Skeleton must be of the exact length from the root-transition zone to the skeleton assembly. They must be secured to the inner surface of the blade so that they are not damaged under centrifugal loading. To meet the serviceability requirement (section 2.1.5) and to have permanently connected wires inside the blade, it has been decided to have two pin connectors at the top and bottom of the Skeleton outer wall (Figure 20). This design permits self-guided connection to the power source once the Skeleton is inserted into the blade from its tip end. Note that it is important to have two connectors since voltage required for the ACF system is about 150V while for the sensors is ~10V. To avoid
interference/noise in the data readings, the wires for the control systems and sensors must be installed apart from each other.

### 3.3 Complete rotor configuration

The SHARCS rotor model for wind tunnel testing will feature 4 identical blades to create an isotropic configuration. All 4 blades should be equipped with an APL, ACF and ACT systems and its components (Figure 23).

**Figure 23:** Fully instrumented SHARCS blades in 4-bladed configuration.
Chapter 4: Composite blade design

This chapter presents the methodology and details of the composite blade design for the SHARCS rotor – the main focus of this thesis.

The SHARCS scaled rotor blade will have a composite skin made out of carbon-fiber and glass-fiber laminas with varying lay-ups along chordwise direction (the y-axis in the blade coordinate system) and gradual decrease of layers along the span-wise direction (the x-axis in the blade coordinate system).

The following sections will discuss the geometrical requirements of the scaled blade, the justification for material selection, selection of the manufacturing process and that of the composite material lay-up and finally the stress analysis of the composite blade.

4.1 Blade design requirements

The first and foremost requirement for the design of the composite blade structure is to maintain dynamic similarity with the conventional full-size blade. The natural frequencies for the individual mode shapes should match the mode shapes presented in Table 2 (Section 2.1.3). Recall that these were provided by the industrial partner AgustaWestland, which represent the characteristics of a full-scale rotor not specified
more closely. These blade characteristics provide a narrow range of frequencies in which resonance with other parts of the rotor hub can be avoided.

The second requirement is to maintain geometrical similarity, which is defined as a blade with NACA0015 airfoil, 80 mm chord and 1,096 mm span lengths. The blade should feature two pin-holes of 5.8 mm diameter through which the blade will be attached to scaled rotor hub. The radial location of these holes is 126 mm from the center of rotation, and they are 12.7 mm apart symmetrically along the quarter-chord line. The Lock number of the blade shall be in the range of 5 to 8 as for conventional rotor blades, which represent the dumping factor of the blades.

4.2 Loads

The scaled blade must be designed to withstand the centrifugal and aerodynamic loads acting on it. The following subsections present the description of how these loads were quantified.

4.2.1 Centrifugal Loading

The purpose of this section is to present a technique used for determining the centrifugal load acting on the blade. The further the center of mass from the center of rotation, the higher the loads at the blade root. In general, the centrifugal load can be determined as:

\[ F_c = m\Omega^2 r_{CG} \]  

(5)
where $r_{cc}$ is the radius at which the blade center of mass in the radial direction is located.

Since the individual components integrated into the blade will yield a non-uniform mass distribution along the span and the chord of the blade, the centrifugal load acting on the blade must be integrated along the blade span and variable thickness chord. The elementary centrifugal force acting on an infinitesimally small element of the blade can be determined as:

$$dF_C = dm \cdot \Omega^2 \cdot r$$

where $dm = \rho \cdot dV = \rho \cdot dr \cdot dc \cdot dt$ and ‘r’ is the radius at which the Center of Mass of the blade element is located.

The visual representation of the single section of the blade is presented in Figure 24. Note that the center of rotation of the blade, as well as the attachment point of the blade to the rotor hub lies on its ¼ chord line.

![Figure 24: Visual representation of the mass distribution along the blade.](image)
The center of mass of each finite section of the blade may be located forward or aft from the ¼ chord of the blade, where the center of rotation is located, and therefore each section will experience tangential and radial components of the centrifugal force. This situation is illustrated in Figure 25.

![Figure 25](image)

**Figure 25:** Visual representation of the tangential and radial components of the centrifugal force.

Therefore, radial and tangential components of centrifugal force can be determined as:

\[
dF_{C,\text{Rad}} = dF_C \cdot \cos \alpha
\]  \hspace{1cm} (7)

\[
dF_{C,\text{Tan}} = dF_C \cdot \sin \alpha
\]  \hspace{1cm} (8)

where \( dF_C = dm \cdot \Omega^2 \cdot r_e \), with

\[
r_e = \sqrt{r^2 + y^2}
\]  \hspace{1cm} (9)
The above equations will be integrated for the FEM model created in ANSYS and will be presented later in the thesis. The centrifugal loads for the preliminary design of the scaled SHARCS rotor blade were estimated using the Smartrotor code [20], with the APL, ACF, ACT systems as well as the Skeleton being incorporated into the model. Results will be shown later, after selecting the composite lay-up, when the mass distribution of the blade will be known. However, one can easily estimate that the centrifugal loads will be huge since the centrifugal acceleration at 75% radius (around where the blade center of mass will be expected to be located), will be as high as 2,220 g’s, i.e. each gram of mass of the blade will feel like 2.22 kg.

4.2.2 Aerodynamic Loading

The purpose of this section is to present the technique for determining the highest aerodynamic loads experienced by the blade in the most critical flight regime, forward flight. Note that in forward flight, an asymmetric velocity distribution is generated, as shown in Figure 5. If the blade pitch angle would be constant over one revolution, this would yield more lift on the advancing side of the rotor disc than on the retreating one, causing the helicopter to roll towards the retreating side. For helicopters, this is compensated for by imposing different resultant angles of attacks on the two sides, a low angle of attack on the advancing blade and high angle of attack on the retreating blade. The variation of the resultant angle of attack is achieved via a combination of blade “flapping” (i.e. the blade moving up and down freely under the varying lift force) and cyclic change of the pitch angle via the swashplate tilt. Whatever the mechanism of
varying the resultant angle of attack, it is typically ranging between 3–8° on the advancing blade and around 10–15° on the retreating blade in fast forward flight, at the 75% radius location of the blade. In terms of the bending moment, (for the aerodynamic loads) the most critical case occurs on the advancing blade in forward flight.

Thus, the aerodynamic loading in this thesis was calculated via a simplified method: by using the Blade Element Momentum Theory (BEMT) method for a hover case representative of the advancing blade in forward flight. This was achieved by imposing a linear velocity distribution with a tip speed corresponding to the resultant tip speed in forward flight at the advance ratio of \( \mu = 0.40 \) (i.e. Mach 0.77) instead of the rotational tip speed only (Mach 0.52). At this velocity distribution, the blade’s root pitch angle was set to 6° degrees, yielding 8.75° pitch angle at the 75% radius, where most of the lift is generated. This was estimated to be the worst case scenario for the advancing rotor blade. However, note that since the NACA 0015 rotor airfoil is symmetric, only lift and no pitching moment will be generated by the aerodynamics (see Appendix A for airfoil data). A resultant torsional moment can still be created, if there will be an offset between the elastic axis and the quarter chord, as it will be the case in this thesis as well, but this will not be a torsional moment created by the pitching moment.

The incremental trust coefficient at each segment of the blade, \( dC_{T} \), can be determined based on the Blade Element Momentum Theory in Hover and is obtained as follows:
\[
\frac{dC_T}{dr} = \frac{1}{2} \cdot \sigma_n \cdot C_{L_{n}} \cdot \left(\theta_n \cdot r_n^2 - \lambda_n r_n\right) \cdot \Delta r_n 
\]  
(10)

where \( n \) is the segment index, \( C_{L_{n}} \) is the lift slope of the segment airfoil, which is 6.5903 1/rad for the NACA 0015 airfoil and 6.4455 1/rad for the NACA 0009 airfoil (See Appendix A for the NACA 0015, NACA 0012 and NACA 0009 airfoil section data). Furthermore, \( \theta_n \) is pitch angle of the blade section, determined from the root pitch angle and the twist distribution of the blade (Figure 14), \( \lambda_n \) is the inflow at blade segment \( n \), which already includes Prandtl’s tip loss function. The inflow distribution for hover from Blade Element Moment Theory is obtained as follows:

\[
\lambda_n = \frac{\sigma_n \cdot C_{L_{n}}}{16} \left[ \left(\frac{32}{\sigma_n \cdot C_{L_{n}}} \cdot \theta_n \cdot r_n - 1\right) \right] 
\]  
(11)

Where \( \sigma_n \) is the “local” rotor solidity, i.e.

\[
\sigma_n = \frac{N_h \cdot c_n}{\pi \cdot R} 
\]  
(12)

where
Prandtl’s tip loss function is essentially a shape function, forcing the lift distribution to drop to zero value at the blade tip [22] according to:

\[
F_{\text{prdtl}} = \left( \frac{2}{\pi} \right) \cdot \cos^{-1} \cdot f_n^{-1}
\]  

(13)

where

\[
f_n = \frac{N_b}{2} \cdot \left( \frac{1-r_n}{r_n - \phi_n} \right)
\]  

(14)

and

\[
\phi = \frac{\lambda_n}{r_n}
\]  

(15)

with \( \lambda_n \) equal to the initial inflow distribution (without tip losses).

Incorporating equation 14 into equation 12 yields:

\[
\lambda_{\text{prdtl}} = \frac{\sigma_n \cdot C_{L_n}}{16 \cdot F_{\text{prdtl}} \cdot \left[ 1 + \frac{32 \cdot F_{\text{prdtl}} \cdot \theta_n \cdot r_n} {\sigma_n \cdot C_{L_n}} - 1 \right]}
\]  

(16)
Note that since $F_{prndt\_n}$ is a function of $\lambda_{prndt\_n}$ and therefore equation 17 must be solved iteratively.

The thrust distribution along the blade for 6° root pitch angle is presented in Table 7. Visual representation of the distribution is presented in Figure 26.

<table>
<thead>
<tr>
<th>N [segment]</th>
<th>Twist Angle [rad]</th>
<th>$C_{La}$</th>
<th>r/R</th>
<th>$\Delta R$ [m]</th>
<th>$\sigma$</th>
<th>$\lambda_i$</th>
<th>$\lambda_{prndt}$</th>
<th>$\Delta C_T$</th>
<th>dT [N]</th>
<th>dT / blade [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.025</td>
<td>0.0548</td>
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**Table 7:** Aerodynamic loading acting on the SHARCS rotor disc consisting of 4 scaled blades.

Total  0.00786  1156.244  289.061
Figure 26: Thrust distribution along the span of twisted scaled SHARCS rotor blade in hover with 6° degree root pitch angle.

The pitching moment on a blade section is the moment that is produced by the aerodynamic force, which is applied at the aerodynamic center of the airfoil. For the case of symmetric airfoil, [i.e. NACA0015, NACA 0009] the lift force is acting through the same point, center of pressure, through all the angles of attack the blade is exposed to and it does not move forward or aft from as much as the cambered airfoil does. Therefore the pitching moment coefficient for symmetric airfoil is zero and so is the moment about the aerodynamic center of this airfoil. It can be observed that the aerodynamic moment coefficient about ¼ chord of NACA 0012 and NACA 0009 (Figure A.2 & A.3) is constant with angle of attack, indicating that the aerodynamic center is located close to ¼
chord and is equal to zero. This characteristic is the same for all symmetric airfoils. Therefore, the scaled SHARCS rotor blade generates no pitching moment on the advancing side, since the blade is going to operate well below the static stall angle of attack (~15 deg).

4.3 Material selection

4.3.1 Overview

The SHARCS rotor blade will not be exposed to high temperatures or excessive humidity conditions, however, they will experience extreme centrifugal loads (around 2000 g’s at the tip). Thus, the material for the blade design has been selected to be polymers because of their low density and great strength-to-weight ratio. Although polymers have lower Young’s modulus and lower service temperature than metals or ceramics, they have great resistance to environment and chemicals, as well as they are relatively inexpensive and easy to manufacture.

For the matrix selection, two options have been looked at: Thermoset and Thermoplastic materials; these will be briefly reviewed below. Note that the following sections are based on the information available in Reference [24],
Thermoset

- Thermoset resins are brittle; they have a relatively low strain-to-failure factor and are very sensitive to damage. This is due to its highly cross-linked structure that does not allow elastic deformation. Also, cross-linked structures make materials non-recyclable, since the molecular structure chains cannot be separated. Thermosets also absorb moisture that decreases their mechanical properties. The major advantage of thermoset materials is that they have very low viscosity stage prior to a fully cured state that allows easy embedding of small diameter fibers into the matrix. The curing temperature and pressure are relatively low as well.

Thermoplastics

- Thermoplastic materials, on the other hand, have better mechanical properties and are used for high-performance composites. They have linear molecular chain reaction that leads to higher strain-to-failure factor since their elastic modulus is higher. Therefore they have higher impact resistance than thermoset material. Thermoplastics have higher resistance to moisture than thermosets, and therefore better mechanical properties in hot/wet operation conditions. A thermoplastic material is fully cured, and produces no chemical change during curing process that saves time during manufacturing. However, since it is fully cured prior to heating and forming, it has higher viscosity than thermosets. Thus, it will require very high temperatures and pressures to form this material into a desired state and to cure it.
Thermosets are less expensive to fabricate due to their low viscosity and resulting low temperature and pressure requirements. With additives, the toughness of thermoset materials can be improved and the tacky property of uncured thermoset pre-preg lowers the cost of labor and allows for more accurate design. For the SHARCS rotor blades, which will not be exposed to any hot and/or wet conditions, thermoset has been selected for the composite material blade design, as well as for all other moving components (i.e. flap and tip units).

4.3.2 Resins

Thermosetting resin systems have many different types of materials and are designed for different applications. The most widely used thermoset resins, especially in aerospace applications are: epoxies, polyesters, vinyl-esters, phenolics, bismaleimid, polymide, and cyanate. They will be reviewed briefly below, with a selection made at the end of the section.

Epoxy

- The Epoxy resin can be mixed with different additives to optimize its properties for a specific application. Addition of curing agents and/or hardeners affects significantly the safety of the material, including possible increase in toxicity. Epoxy resin can lower viscosity of a raw material, increase its elastic modulus, as well as increase its ductility. Epoxy alleviates shrinkage during curing; the toughness of the epoxy matrix does not degrade with time and has high fatigue strength.
Polyester

- Polyester has an excellent environmental durability, low viscosity, and is easy to fabricate. The cure condition can be modified by an experienced operator. It is a very widely used material, but does have its drawbacks, one of which is the very high shrinkage during curing process that leads to a poor matrix-fiber bond and therefore to the decrease in mechanical properties. Furthermore, polyesters are brittle and additives are not accepted by its chemical structure; therefore, they have a lower strain-to-failure factor than epoxy and low chemical resistance.

Vinyl-Ester

- Vinyl-Ester has improved characteristics compared to polyesters. It is chemically resistant and is as easy to fabricate, just as polyester material. It has a higher strain-to-failure factor due to the double bond at the end of the chemical chain structure. The shrinkage rate is lower resulting in an improved fiber to matrix bond, but it is still lower than in epoxy resin. The cost of vinyl-ester is significantly higher compared to polyester.

Phenolic

- Phenolic resin has a very high temperature/fire resistance. Phenolic also has very high void content that reduces mechanical properties of resin. During fabrication, it requires high pressure loads that increases complication, thereby increasing the cost of the process.
Bismaleimide

- Bismaleimide has excellent thermal-stability at high service temperatures. It is a brittle material, but its fracture toughness can be increased with a mix of additives into it with the penalty of decreasing the service temperature. This resin material is expensive and difficult to fabricate.

Polymide

- Polymide is very similar to bismaleimide, it is just as stable at high temperature and is resistant to chemicals. Additives can have an effect on mechanical properties and keep the service temperature in higher ranges. Just as bismaleimide, polymide is expensive and very hard to manufacture.

Cyanate

- Cyanate has low moisture absorption characteristic, high temperature strength and high toughness. It has been found that cyanate have degradation problems when exposed to long term moisture conditions.

Phenolic, bismaleimide, polymide and cyanate are designed for high temperature applications. Cyanate is particularly well suited for moisture conditions as well as for the full-scale design of the SHARCS rotor blades. The cyanate and bismaleimide are good candidates for actual helicopters. However, the particular design of the scaled SHARCS
rotor blade will not be exposed to high temperatures or wet environments; therefore, epoxy, polyester, and vinyl-ester are the best candidates for the scaled blade design.

Epoxy is used in 80% of all polymer designs; it is the most popular material used as a matrix in polymer composite material structures. Epoxy has a similar density range as polyester, but it can have mechanical properties to be tailored for the loads acting on the blade with additives; it also has no shrinkage effect during curing. Having no shrinkage is very important for a scaled rotor blade like that of SHARCS and especially its components that have high tolerance requirement. Polyester is less expensive and easy to fabricate, but it shrinks and has low chemical resistance. Vinyl-ester resin has improved mechanical properties compared to polyester, but it still has a shrinkage effect. Epoxy has been selected for the design of the scaled SHARCS rotor blade. Comparison of matrix properties is presented in Table B.1, Appendix B. Summary of advantages and disadvantages of the resins are presented in Table B.2, Appendix B.

4.3.3 Fibers

The most widely used fibers are: glass fibers, carbon fibers, aramid fibers, and polyethylene fibers.

Glass Fiber

- Glass fibers are relatively inexpensive with high tensile strength, modulus, and impact resistance. It is brittle and any surface damage will decrease the properties of the fiber; thus, the fibers are embedded in a matrix and protected by it. These fibers have relatively high fatigue strength. Glass fibers are resistant to chemicals
and moisture, but once the moisture enters the flow of the fiber, its tensile strength reduces significantly (by approximately 50%). The reduction of strength of one fiber in the bundle of fibers has an insignificant effect on the structure, but under a static fatigue load could create microcracks, delamination and other problems.

**Carbon Fiber**

- Carbon fibers have very high tensile strength and modulus, and are more expensive than Glass Fibers. Carbon fibers retain their properties at high service temperatures and have negative temperature coefficient that provides very high stiffness and dimensional stability to the fibers. Just as glass fibers, it has low impact resistance and high fatigue strength. The bulk of carbon fibers are PAN-based, where PAN is an acrylic textile fiber and PAN-based fibers are high strength and low to high modulus fibers. Carbon fibers are also made pitch-based, where pitch is a relatively cheap precursor material. Pitch-based fibers do not require tension to maintain the orientation required for high modulus and strength. They are more porous and therefore have lower strength than PAN-based fibers, although they also have very high elastic modulus that leads to an extremely stiff property.

**Aramid Fiber**

- Aramid fibers have high specific strength and stiffness, and a high strain-to-failure factor; they are very pliable and easily woven. Fatigue strength is high in these fibers, but it has poor compression properties and a high creep rate and may fail under constant centrifugal loads acting on the flap.
**Polyethylene Fiber**

- Polyethylene fibers, just as aramid fibers, have high strength that increases under loading, excellent impact resistance, high specific mechanical properties but poor compression strength and low creep resistance.

Since aramid and polyethylene fibers have low creep resistance, the best candidates for a rotor blade are carbon and glass fibers due to the constant centrifugal loading they will be exposed to. Property comparisons of these two material characteristics are presented in Table B.3, Appendix B. Even though the tensile strength for both materials is in the same range, the tensile modulus is much lower for the glass fiber. Also, the weight of the glass fiber is higher than that of carbon fiber. Based on the requirements of lowest possible weight and higher stiffness due to the desired low Lock number of the scaled SHARCS rotor blade, carbon fiber was selected. Also, it has been decided to incorporate some layers of glass fiber into leading edge section to bring center of gravity of the blade closer to the \( \frac{1}{4} \) chord. The use of carbon fiber will increase the cost of a single unit significantly, but for the prototype design, this aspect is not as important as a perfectly designed scaled rotor blade sustaining all loads and meeting the mode shapes of the conventional rotor blade. In the future, the price issue shall be revisited.

PAN based carbon fiber (T-300) has the lowest density, a relatively low cost, high tensile strength and an acceptable tensile modulus. Properties of this material are presented in Table B.3, Appendix B.
4.3.4 Material selection

The SHARCS rotor blade should be manufactured at a company specializing in composite blade manufacturing in Germany. Their suggestion for the material selection was Carbon Fiber T300/ Epoxy E022, which was offered for sale in SGL Technologies Gmbh (Germany), with 60% fiber volume and 12,000 filaments with an approximate thickness of 0.29 mm. This, however, operated to be too thick for the particular application. Note that the SHARCS scaled blade is only 12 mm high and for this, the blade skin thickness on one side should occupy no more then 0.5~1.0 mm as a preliminary estimate. The remaining 10~11 mm should incorporate the Frame, Skeleton and actuators, which height in itself is 9.2 mm. Therefore, every tenth of a millimeter was critical in the design and every effort was made to minimize blade skin thickness. Thus, it was decided that the thickness of a single layer of carbon fiber /epoxy should ideally be in the range of 0.15 mm. However, such material from the suggested T300 / Epoxy E022 was not available on the market, although could be manufactured in a custom order by SGL Technologies Gmbh – at very high cost though. Fortunately, this company suggested using Carbon Fiber T700S/ Epoxy E022 as a substitute of the initially selected material. The properties of this material are very similar to the initial selection and the thickness of the proposed material is stated to be 0.15 mm. Properties of the fibers T300 and T700S are presented in Appendix B, Figures B.1 and B.2 respectively.

For the purpose of moving the center of mass of the blade closer to its ¼ chord, as well as because of the requirement to match the mode shapes given in Table 2, the
stiffness of the blade led to be carefully fine-tuned. For this reason, S-2-Glass Fiber / Epoxy E022 was suggested to be incorporated into the Leading Edge section of the scaled SHARCS rotor blade. Thickness of each S-Glass Fiber / Epoxy E022 layer is estimated to be 0.11 mm.

4.4 Selection of manufacturing process

Selection of the manufacturing process was driven by the type of reinforcement, such as fiber type and length, as well as the resin viscosity, the desired geometry of the reinforcement, as well as the fiber direction in 1D, 2D, or 3D space. [24] (Refer to Figure C.1 and Figure C.2 in Appendix C). Other factors driving the selection of manufacturing process has the complexity of the part and production volume (Refer to Figure C.3, Appendix C).

Since the scaled SHARCS rotor blade is intended for the feasibility study of the SHARCS “hybrid” concept via wind tunnel testing, it will not be installed on a helicopter and will not be manufactured in large quantities. It is planned that five scaled rotor blades will be manufactured altogether: the first one for static and dynamic testing while the other four blades for the actual wind tunnel tests of the SHARCS concept. The scaled SHARCS rotor blade is selected to be designed from a low viscosity polymer – epoxy, a thermoset material. It should have a 2-D continuous fiber orientation as a minimum.
4.4.1 Manufacturing process overview

Referring back to Figure C.1 through C.3 in Appendix C, the most suitable manufacturing processes for the prototype-like SHARCS blades are resin-transfer molding, pultrusion, filament winding and hand lay-up. These will be briefly reviewed below with a selection made at the end of this section.

Hand lay-up

- Hand lay-up is the most common and most popular composite manufacturing method in aerospace engineering. It can involve wet lay-up of fibers into the mold, which is then covered it with resin. Wet lay-up provides a very hazardous working environment due to volatile fumes and also geometrical inconsistencies and materials characteristics change due to non-uniform resin thickness. The alternative, hand spray lay-up, sprays the resin and short fibers onto the tool simultaneously. However, this also creates hazardous environment due to volatile fumes, and requires experienced technicians.

- Prepreg is one of the most common forms of ‘raw’ composite material. It is typically made of unidirectional fibers embedded in a polymer matrix creating a pre-made lamina. During prepreg hand lay-up, the prepreg is cut to the desired shape and applied onto the mold creating a laminate. Once the laminate is ready and the excessive resin along with the possible voids is removed using sludgy and vacuum/pressure respectively, it is put into an autoclave and cured under controlled heat, pressure, vacuum or airflow if necessary. Prepreg usage has controlled resin
and fiber direction angle in the final product, volatiles exploring is reduced, and a more accurate fiber orientation is achieved. The labor cost is estimated to be a little higher than the quarter of the part cost. Note that in this approach, the excessive material can be compared to other manufacturing methods. This appears to be the most suitable manufacturing process for the first iteration of the scaled SHARCS rotor blades without investing into too sophisticated equipment.

Resin-transfer molding

- Resin-transfer molding was adapted approximately ten years ago for manufacturing of blades. In this method, the fibers are placed in a two-sided sealed mold, after which resin is injected under pressure and/or vacuum. It takes less time for the part to be fabricated than in hand-lay-up, with much more friendly health conditions in the composite material shop than those for a hand lay-up process. If done correctly, the surface of the finished part can be equivalent to hand lay-up and 70% fiber content can be achieved based on weight. Reduction in time and labor cost, along with the weight saving, results in approximately 20% cost reduction. It is a very favorable process and can be adopted for the full scale rotor blade manufacturing, but for the particular scaled SHARCS rotor blade with 5 blades to be manufactured, tooling cost and set up of equipment is very cost inefficient.
Pultrusion

- Pultrusion process involves pulling fibers continuously through a resin pool, after which the fibers are pooled through heated die and cured. This process can lower the cost of the previously hand laid-up part by 30~40%. Fast curing resin must be used in the pultrusion process so that it does not stick to the dies; epoxy tends to stick to the dies and therefore must be avoided from the pultrusion process. In addition, as earlier explained, the tooling cost for such a small number of blade units will be very expensive, and for these reasons renders this process unsuitable at the moment.

Filament winding

- Filament winding has continuous fibers pulled through the resin pool or previously impregnated by resin and continuously wound over a mandrel, which resembles a part shape, to form a final part. Cost savings are possible, compared to the hand lay-up, but tooling cost and set up time would be very high for such small number of units. Parts manufactured using filament winding are strong, but the surface finish is not very smooth which could result in the occurrence of the aerodynamic load which then could affect not only the hinge points but also the actuation system. This method can be used to manufacture the internal core of the blade, but only for a large number of units.
Based on the above overview, the prepreg hand lay-up has been selected for the manufacturing process for the scaled SHARCS rotor blades. Prepregs have continuous carbon fibers (T700S) and epoxy resin E022. They are cut into the desired shape and laid layer by layer with different fiber orientation angles – onto the scaled blade mold to create a laminate. Each layer is smoothed to remove voids and wrinkles. After the laminate is ready, it is put into a vacuum bag and all the excess resin along with the voids and volatiles are removed from the part during controlled heat and pressure curing process – autoclaving. The pin connection points and the trim at the trailing edge are cut using water-jet. Water-jet cutting have high cutting speeds, does not create heat-affected zones, and has absolutely no dust.
Chapter 5: Blade structural design

To determine the blade composite layup, an iterative process has been employed. The blade layup will affect the stiffness and mass distribution along the blade, which then determines the natural frequencies and mode shapes of the blade. These shall match the mode shapes presented in Table 2. Adding composite layers to the blade increases its total mass and therefore increases centrifugal loading acting on the blade that must be accounted for.

To circumvent this problem, an iterative process of determining the blade layup has been developed and described in detail in Reference [25]. Here, only a brief overview of the process will be provided. Three software packages were used for the process:

- LamTech [26], which is able to calculate the loads, stiffness and inertia properties of composites
- SMARTROTOR [20], which can calculate the aerodynamic and centrifugal loads and also utilizes a beam model for structural analysis
- ANSYS, which is able to analyse the stresses experienced by the blade, and utilizes a 3D Finite Element model.
Initial guesses of a uniform mass and stiffness distribution were established based on the eigenfrequency targets provided in Table 2. As mentioned earlier, the aerodynamic and centrifugal forces in hover and forward flight were calculated using BEMT and SMARTROTOR, respectively. Centrifugal loads expected to be several orders of magnitude larger than the aerodynamic loads, and thus to dictate the design.

To be able to meet the desired eigenfrequencies, a blade layup was proposed. Mass and stiffness properties for this layup were calculated using LamTech. Once these were determined, mass and stiffness properties of the blade were inserted into the SMARTROTOR beam model. Here, an eigenvalue analysis was performed to ensure that the eigenfrequencies fall into the target range. If the target range of eigenfrequencies were not met, the lay-up of the model was altered in LamTech until the desired mode shapes were achieved in Smartrotor. Once a satisfying lay-up was achieved via these iterations, the blade was modeled in ANSYS to check for the stresses in the blade. Note that these iterations with initial selection were done by Dr. Mehrdaad Ghorashi with the help of Greg Oxley, former members of Rotorcraft Research Group, at Carleton University. Also note that in the following sections, the lay-up for the final iteration is presented.

5.1 Blade composite material lay-up

The lay-up of the composite material of the scaled SHARCS rotor blade is the stack of prepreg layers called laminate with determined fiber’s orientation angle for each lamina. The lay-up sequence will be presented in this section.
Figure 27 represents the SHARCS scaled rotor blade as it is divided into four different imaginary regions.

The lay up of the scaled SHARCS rotor blade is composed of:

**Region 1: Root cupone**

The “Root Cupone” is the region that is located in the root of the blade and in total contains 72 composite material (T700S/E022) layers. 36 layers are laid at the top and other 36 at the bottom halves of the scaled rotor blade with the following lay up:
where the numbers represent the orientation angles of the fibers in degrees.

Once cured, the upper and lower halves of the scaled SHARCS blade sections are glued together, forming a symmetry line at the middle of Region 1 and along the leading edge and trailing edge of the blade.

The thickness of the prepreg was estimated to be 0.15 mm, and therefore the total thickness of the “Root Cupone”, including a 0.15 mm thick layer of the adhesive yields 10.23 mm creating a 1.77mm opening at the center line, which will be filled with adhesive/matrix to strengthen the bonding between the upper and lower halves of the blade, as well as to meet the height requirement of 12mm at the root. Visual representation of the “Root Cupone” symmetry line opening is shown in Figure 49, Section 5.3.1.

The composite lay-up presented for Region 1 is a symmetric angle ply laminate, which means there is no stiffness coupling force and moment terms, in other words an applied axial force will not resulting in a curvature or vice-versa. However, the lay-up is an angle ply laminate, which means the bending and twisting coupling is possible, that means a pure bending load will result in twisting of the laminate and vice-versa. On the other hand, due to the large number of laminates and of 45/-45 degrees plies, to
strengthen the composite unit in torsion and shear applications, bending and twisting coupling in the Region 1 is expected to be eliminated.

Region 2: Root transition zone

Region 2 represents the Root Transition Zone that translates 36 layers from Region 1 into Regions 3 and 4. It is represented by the gradual decrease of layers from the middle of the blade, i.e. the symmetry line (see Region 1) towards the skin of the upper and lower halves of the blade concurrently. An illustration of the root transition zone is provided in Figure 27.

The gradual decrease of the layers starts from layer number 36, located at the radial distance of x = 20 mm from the root of the blade. All layers are gradually terminated along Region 2 until it approaches layer 7 of Section A and layer 4 in Section B, shown in Figure 28 as a visual representation of the gradual decrease of the layers along the Root Transition Zone in the span-wise direction. Note that Section A represents the Leading Edge layers, whereas Section B represents the Trailing Edge layers, shown in cross-sectional view of the SHARCS rotor blade, Figure 29. These and the remaining other layers will then represent the skin of the SHARCS scaled rotor blade, starting from the radial location of x = 135 mm from the root of the blade and spanning until the tip of the blade.
Figure 28: Visual representation of the gradual decrease of the layers along the Root Transition Zone in the span-wise direction (all dimensions are in [mm]).

Figure 29: Visual representation of the cross-section of the scaled SHARCS rotor blade with sections A and B being connected to the Figure 28.
Region 3: Leading edge

The skin of the blade in Region 3 is represented by four carbon fiber/epoxy and four glass fiber/epoxy layers, with a virtually symmetric lay-up between the upper and lower halves of the blade. Glass fiber has higher density than carbon fiber and therefore it was incorporated into the leading edge region to move the center of mass of the blade closer to the ¼ chord. Glass fiber has good physical and mechanical properties and shall meet the requirements set earlier for the blade. The lay-up of the Leading Edge region of the blade is as follows:

- [45CF/-45CF/45GF/-45GF/-45GF/45GF/-45CF/45CF]

where CF stands for carbon fiber and GF stands for glass fiber; and the numbers again represent the orientation angles in degrees.

These layers start at the end of Region 2, (at radial location \( x = 135 \text{ mm} \) from the blade root), and continue along the span of the blade until the tip. In the chord-wise direction, it starts at the Leading Edge region of the blade, and ends at \( y = 28.8 \text{ mm} \) from the leading edge. Figure 29 shows the airfoil cross-section of the blade to complement the above definition.

The first two layers that are made out of carbon fiber, numbered as 1 and 2, are bonded to the following four layers made out of glass fiber. These four glass fiber layers are placed in the leading edge as a substitution of the previously dropped/removed three
carbon fiber layers in the Root Transition Zone (numbered as 3, 4, & 5), shown in Figure 28.

The last two layers of carbon fiber, numbered 6 and 7 are made separately from the first six layers mentioned above, and are not separated at the symmetry line of the blade. These two layers are numbered as 6CF and 7CF and they together form the C-spar. A detailed description of the C-spar will be presented later.

The upper and lower halves of the SHARCS scaled rotor blade are glued together at the symmetry line, along the leading edge and trailing edge of the blade. The C-spar is placed in between the two half’s of the scaled rotor blade and starts at the end of layers 6 and 7, at radial location $x = 149$ mm and $x = 155$ mm, respectively, from the root of the blade and ends at the tip of the blade. Layers numbered 6 and 7 end at different radial locations to have a gradual decrease in layers, to avoid high concentration loads due to sudden decrease of multiple layers. Figure 30 represents cross-sectional view of the SHARCS blade where the C-spar regions and symmetry glue lines are presented.

![Figure 30: Cross-sectional view of the scaled SHARCS rotor blade.](image)
Region 4: Trailing edge

The skin of the SHARCS rotor blade in Region 4 (Section B) is composed of four continuous layers, made out of carbon fiber with the following lay-up:

- [45/-45/-45/45]

Note that Region 4 starts at the end of Region 2 at the radial location of \( x = 0.135 \) m from the root of the blade and chord length from the leading edge of \( y = 0.0288 \) m. The four layers extend to the tip of the blade in the span-wise direction and to the trailing edge in the chord-wise direction. These layers are a continuation of the skin of the scaled SHARCS rotor blade started at the Root Cupone in Region 1.

Similarly as for Region 1, Region 4 has a symmetric angle ply laminate, which has no coupling with axial force and bending. Due to the low number of layers in this region, bending-twisting coupling may be present, but it is expected to be strengthened by the Region 3 lay-up and 45/-45 degrees angle plies that strengthen the laminate for torsion and shear applications.

As a summary, the gluing sequence will be the following: once the upper and lower halves of the blade are fully cured, they are glued together at the leading and trailing edges, with the C-spar connecting them at leading-edge (Figure 30). The assembly of the SHARCS blade will start with incorporating the Frame and the Foam into the fully
instrumented C-spar (instrumentation reviewed later in the thesis) and continued with initial assembly by being first placed into the lower half of the blade after which closed and glued with the upper half. The glue named Redux, from Hexcel, should be used for these steps. The glue should be applied to only one of the surfaces to be bonded. The frame and the foam are expected to provide extra strength to the blade halves and the C-spar, for it not to crash during assembly and gluing press. Note that in the preliminary design concept, the assumed glue thickness was 0.15 mm.

After gluing, the total thickness of the root of the scaled SHARCS rotor blade (Region 1: Coupon) should not exceed 12 mm. This is the space limitation within the cuff (the part of the rotor hub into which the blade slides in) to which the blade is connected via two pins.

5.2 Mass distribution of the blade

The total mass of the “clean” blade, which means the mass of the composite skin is only 0.233 kg. The center of mass of the skin is located at $x = 465.62$ mm (42.5% of radius) from the root and $y = 30.47$ mm (38% of chord) from the leading edge, in span and chord-wise directions, respectively. The mass and its location were estimated using the ANSYS software package in which all the above layers were modeled. Adding all active control systems (ACF & ACT), the Skeleton mechanism and frame and their components, the foam and connectors yields a total added mass of 0.191 kg and therefore
the new center of mass of the fully assembled blade would be located at \( x = 526.29 \text{ mm} \) (48% of radius) and \( y = 28.58 \text{ mm} \) (35% of chord).

As it has been mentioned above (Section 4.2.2), the aerodynamic moment coefficient about the aerodynamic center, located at the \( \frac{1}{4} \) chord for the symmetrical airfoil, is equal to zero for a symmetric airfoil unless the stall angle of attack is exceeded. Therefore, to be able to keep the pitching moment at zero and to have a stable aerodynamic blade, the center of mass of the blade must be located at the \( \frac{1}{4} \) chord as well. Also, since the elastic axis of the blade for the conventional helicopter is located at approximately 35~40% of the chord, it is important to have the center of mass ahead of the elastic axis to eliminate bending-twisting coupling effect of the blade, to meet desired mode shapes of the blade and for the blade not to flutter.

In order to bring the blade center of mass close to the \( \frac{1}{4} \) chord line of the scaled SHARCS rotor blade, Tungsten mass ballast was implemented in the Leading Edge region. It is also incorporated into the “Skeleton” and the tip of the blade. The “Skeleton” and its “Frame” are also designed with the intention to have their own center of mass closer to the \( \frac{1}{4} \) chord of the scaled SHARCS rotor blade.

The blade leading edge ballast starts at the beginning of Region 3, at the radial location of \( x = 135 \text{ mm} \) from the root of the blade and stops just before the “Frame” at \( x = 702.4 \text{ mm} \). It consists of Tungsten rods of 37.67 mm in length and 4.00 mm in diameter, glued to the leading edge. Each Tungsten rod is separated by 8.47 mm space, which is filled with the inner core foam structure. This is to avoid adding extra stiffness
in bending or torsion to the blade (as one long Tungsten rod would). The space is filled with foam to avoid a shift of the leading edge ballast due to the centrifugal loading. This distribution continues until Tungsten rod number 10 is placed. The total mass of the blade leading edge ballast is 0.091 kg.

Since adding aforementioned leading edge ballast only moved the center of mass to \( y = 24.09 \) mm from the leading edge in the chord-wise direction (30% of chord), it was decided to incorporate more Tungsten rods into the skeleton and the tip. Thus, a 4 mm diameter hole is supposed to be drilled into the leading edge of the Skeleton from both sides, to be able to incorporate 5 additional pieces of 30 mm by 4mm Tungsten rods. Each rod will be separated here by 5 mm balsa wood inserts. The end of the skeleton should then be secured by the threaded cup. Balsa wood and the secured cup are required to prevent the Skeleton leading edge ballasts from shifting due to the centrifugal loading acting on it. The tip should also be designed to incorporate a single 40 mm by 5.5 mm Tungsten rod. Figure 31 shows the 3D models of the leading edge openings in the Skeleton and the tip. The total mass of the added Tungsten rods is 0.054 kg, which yields the total mass of the SHARCS blade of 0.578 kg. The center of mass in the span-wise and chord-wise directions is \( x = 628.02 \) mm (57.3% of radius) and \( y = 22.86 \) mm (28.5% of chord) respectively. Top view of the fully assembled blade is presented in Figure 32.
The internal space of the blade from the root transition zone to the frame is filled – just like most of the conventional helicopter blades - with Rohacella Foam. This is required to prevent buckling under bending. The total mass of the foam is 0.015 kg and its center of mass located at $x = 480.3$ mm (43.8% of radius) and $y = 34.395$ mm (47% of chord).

The Skeleton assembly, including the “Frame”, ACF and ACT mechanisms, internally incorporated leading edge ballast and the flap have the total mass of 0.182 kg. The center of mass of the Skeleton system in the radial direction at $x = 836.49$ mm
(76.3% of radius) from the center of rotation and $y = 21.86$ mm (27.3% of chord) from the leading edge.

The tip of the blade, including connection pins and the leading edge ballast has the total mass equal to 0.064 kg and the location of its center of mass at $x = 1016.79$ (92.8% of radius) and $y = 24.373$ mm (30.5% of chord) from the center of rotation in the span-wise direction and from the leading edge in the chord-wise direction, respectively.

After the SHARCS scaled rotor blade is manufactured, 2 through holes are required to be drilled, with it’s centers 10 mm form the root of the blade, with diameter of 5.8 mm. Metal inserts with the outer diameter of 5.8 mm and inner diameter of 4.8 mm are required to be installed into these holes. The metal inserts should be made, preferably, out of steel 4140 or 4340. The inserts must be primed and then bonded at the earlier drilled holes. Bonding should be done with Hysol structural adhesive or equivalent to avoid layer’s delamination at the hole’s internal surfaces. Two connectors shall be incorporated into the Root Transition Zone which will be described in detail in the following sections.

Figure 33 presents the visual representation of the metal inserts and the connectors.

Adding up all the component weights, the total blade mass and the resultant centrifugal force acting on the hub could be determined. Table 8 shows the mass breakdown for the scaled SHARCS rotor blade.
**Figure 33:** Visual representation of the metal inserts and connectors.

**Table 8:** Center of mass and mass data for the entire SHARCS blade. (Note: the blade radius is 1096.00 mm, the chord 80.00 mm while the rotational frequency 1,555 RPM).

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass [kg]</th>
<th>Center of Mass Radial Location</th>
<th>Center of Mass Chord Location</th>
<th>Centrifugal Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>absolute [mm]</td>
<td>relative [%]</td>
<td>absolute [mm]</td>
</tr>
<tr>
<td>Blade</td>
<td>0.233</td>
<td>465.62</td>
<td>42.48</td>
<td>30.47</td>
</tr>
<tr>
<td>Blade Tungsten Ballast</td>
<td>0.091</td>
<td>439.8</td>
<td>40.13</td>
<td>3.56</td>
</tr>
<tr>
<td>Foam</td>
<td>0.015</td>
<td>480.3</td>
<td>43.82</td>
<td>34.39</td>
</tr>
<tr>
<td>Skeleton Assembly</td>
<td>0.17</td>
<td>836.49</td>
<td>76.32</td>
<td>21.86</td>
</tr>
<tr>
<td>Tip</td>
<td>0.064</td>
<td>1016.79</td>
<td>92.77</td>
<td>24.373</td>
</tr>
<tr>
<td>Inserts and Connectors</td>
<td>0.005</td>
<td>0.1961</td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td>Total</td>
<td>0.578</td>
<td>628.02</td>
<td>57.30</td>
<td>22.86</td>
</tr>
</tbody>
</table>
Table 8 leads to important observations. The blade is relatively heavy (0.578 kg) in comparison to conventional “clean”, scaled rotor blades of the same size, which are typically in the order of 0.300 kg. This is because the heavy piezoelectric actuators and the associated control mechanisms for ACF and ACT, as well as the “Skeleton” and “Frame” adding significant mass to the blade. Tungsten ballast is also significant, which is required to bring the blade center of mass closer to the quarter chord. Note that the center of mass of the entire blade lies 3.5% behind the ¼-chord line, which – although not ideal – was judged to be a sufficient compromise.

The center of mass of the fully assembled blade was estimated with the aid of the ANSYS software package and Autodesk Inventor Professional V.10. The blade with the marked center of mass is presented in the Figure 34.
5.3 Stress analysis of the blade

5.3.1 FEM model

The purpose of stress analysis is to estimate the strength of the blade in the rotating frame under centrifugal loading only (i.e. Whirl Tower Testing) as well as under combined centrifugal and aerodynamic loading (i.e. Wind Tunnel Testing).

Analyses were performed with ANSYS version 11 using command language interface in combination with the Graphical User Interface (GUI). The blade’s numerical model was created using the command language modeling technique: this is attached in electronic format in Appendix D, CD1. The model created in ANSYS for this analysis
closely follows the description of the composite material lay-up described in section 5.1. It represents a “Root Cupone” with 72 layers in total for both halves of the blade, the root transition zone where from the “Root Cupone” the lay-up is gradually decreased to eight layers in the leading edge section and to four in the trailing edge on the upper and lower halves of the blade and continues unchanged until it reaches the tip of the blade. Figure 35 shows the ANSYS blade model and the zoomed-in view of the composite material lay-up of the “Root Cupone”.

Two models of the blade - twisted and untwisted - were created. The twisted model had the same twist distribution as presented in Figure 14, section 2.1.1 and is analyzed later. The untwisted model had zero twist and presents the base model of the blade. Results of the base model simulations will serve as a reference to the twisted model and will show any differences that may occur in regards to the strength and stiffness due to the twist distribution.

The untwisted model is created by the combination of 32 airfoil sections (35 for the twisted model), in the span-wise direction. Airfoil sections here created by combining 65~135 key-points into 2 lines for the upper and lower halves of the blade, respectively. The upper and lower halves of the blade section are divided into three separate lines to have a consistency in geometry due to the necessity of three sections in the separate regions of the blade (i.e. “Root Cupone”, blade). Each half of the “Root Cupone” needs to be divided into three sections to be able to incorporate pin holes in the model. The blade requires three sections for the similar mass distribution as the real blade. The root-
transition section, i.e. the section between the “Root Cupone” and the blade is split into three sections on each half of the blade, for the consistent connection of the shell elements form the root to the tip of the blade. Once the airfoil section connections are created, areas are assigned to each of these divisions to which ANSYS element SHELL181 (described later) are assigned with the specified material properties, number of layers and their thicknesses. Once the geometrical model is ready, it is meshed and the boundary conditions are assigned. Then it can be analyzed for the stress observed by the blade and its stiffness. The ANSYS scaled blade model can be observed in Figure 35.

**Figure 35:** ANSYS model of the scaled SHARCS rotor blade, with-out twist, with composite material root “Cupone” lay-up.
5.3.2 Centrifugal loading: untwisted blade without actuators

The FEM analysis was divided into separate cases that represent “real-life”, future test set-ups. First analysis of pure rotation (no aerodynamic loads) were conducted of the blade with the center of rotation set up so that the root attachment pins are located at \( x = 126 \) mm radial location at the \( \frac{1}{4} \) chord of the blade. The angular velocity was set to 162.8 rad/s. To simplify the analysis, the aerodynamic loads were neglected in this test. The first test includes a “clean” blade, which means only the blade skin, i.e. without Skeleton, frame, ACF, ACT, and mass ballast. The boundary conditions of this FEM analysis are presented in the form of the constraint of the 0 m displacement and 0 degrees of rotation in and about X,Y,Z axis of the nodes located at the upper and lower surfaces of the blade pin holes, at the “Root Cupone” (Figure 36).

The “clean” blade, without the twist, is meshed with 5 mm elements and the total estimated mass of the blade, of the composite material lay-up only, is equal to 0.233 kg. The center of mass of this blade is located at \( x = 349.62 \) mm (31.9% of radius), \( y = 10.467 \) mm (13.1% of chord), based on the ANSYS output for the model. In this case, the maximum stress observed is 163 MPa (Figure 37), which occurs at the edge of the root transition.
**Figure 36:** Boundary Condition in the form of constraint of 0 m displacement and 0 degrees angle of rotation in and about X,Y,Z axis, at the pin hole’s nodes in the root “Cupone”.

**Figure 37:** Untwisted “clean” blade: under centrifugal load only; Von Misses stress contours in [Pa] units.
Note that the ultimate tensile and compressive stresses in the axial direction of the applied carbon-fiber composite material (T700S/E022) are 2550 MPa and 1470 MPa respectively. However, the strength of the material in the transverse and inter-laminar directions of the selected material is estimated to be only 10% of the previous values. The “10% Rule” was developed by the pioneer in using composites in aerospace engineering, L.J. Hart-Smith [24], for example, the all composite civilian aircraft, the Lear Fan, was sized using the “10% Rule”. The tensile strength of the glass-fiber/epoxy material (S-2-Glass/E022) is very similar to the carbon based material (T700S/E022) and is equal to 2500 MPa in tension and 1400 MPa in compression. Using the “10% Rule” again, this yields transverse and inter-laminar strength of 10% of the axial. The shear strength for T700S/E022 and S-2-Glass/E022 is 90 GPa and 85GPa, respectively.

Once the stresses are determined, failure analysis is performed. The first analysis is done using Maximum Stress Failure Theory. This is the simplest of all failure theories. The lamina (a single layer) is considered failed if any of the following conditions are not met:

\[-\left(\sigma_1^{c}\right)_{ult} < \sigma_1 < \left(\sigma_1^{T}\right)_{ult}\]  \hspace{1cm} (17)
\[-\left(\sigma_2^{c}\right)_{ult} < \sigma_2 < \left(\sigma_2^{T}\right)_{ult}\]  \hspace{1cm} (18)
\[-\left(\tau_{12}\right)_{ult} < \tau_{12} < \left(\tau_{12}\right)_{ult}\]  \hspace{1cm} (19)

where $\sigma_1$ and $\sigma_2$ are longitudinal and transverse stresses, respectively, and $\tau_{12}$ is the shear stress of the testing laminate.
The second failure analysis is the Tsai-Wu Failure Analysis. The failure of the lamina occurs when the following condition is violated:

\[ H_1 \sigma_1 + H_2 \sigma_2 + H_6 \tau_{12} + H_{11} \sigma_1^2 + H_{22} \sigma_2^2 + H_{66} \tau_{12}^2 + 2H_{12} \sigma_1 \sigma_2 < 1 \]  \hspace{1cm} (20)

where the ‘H’ constants are determined by applying failure stress in each direction and solving the resulting equations. The ‘H’ constants can be found as follows:

\[ H_1 = \frac{1}{(\sigma_1^U)_{ult}} - \frac{1}{(\sigma_1^C)_{ult}} \hspace{1cm} H_2 = \frac{1}{(\sigma_2^U)_{ult}} - \frac{1}{(\sigma_2^C)_{ult}} \]

\[ H_6 = 0 \hspace{1cm} \text{(Due to symmetric angle play lay-up)} \]

\[ H_{11} = \frac{1}{(\sigma_1^U)_{ult} \cdot (\sigma_1^C)_{ult}} \hspace{1cm} H_{22} = \frac{1}{(\sigma_2^U)_{ult} \cdot (\sigma_2^C)_{ult}} \]

\[ H_{66} = \frac{1}{(\tau_{12}^U)_{ult}^2} \]

and based on the “Misses-Hencky criterion” \[ H_{12} = -\frac{1}{2} \sqrt{\frac{1}{(\sigma_1^U)_{ult} \cdot (\sigma_1^C)_{ult} \cdot (\sigma_2^U)_{ult} \cdot (\sigma_2^C)_{ult}}} \]
The aforementioned failure theories and the examples can be found in Reference [24].

The maximum stress failure analysis was performed using ANSYS, and yields a strength ratio for the “clean” blade a value of 6.13. This means that under these conditions, the blade is safe to operate. Figure 38 presents a visual analysis of the maximum stress failure theory. The legend units are 1/Strength Ratio. Similarly, based on the Tsai-Wu failure theory, the Tsai-Wu criterion, determined using ANSYS, does not exceed 1 and yields slightly higher Strength Ratio of 6.19.

**Figure 38:** Maximum Stress failure analysis of “clean” untwisted blade. Measured in [1/Strength Ratio].
5.3.3 Centrifugal loading: untwisted blade with actuators

The scaled SHARCS rotor blade has been designed to incorporate the Actively Controlled Flap and Actively Controlled Tip subsystems, which are mounted into the dedicated “Skeleton” and “Frame” structure and glued to the inner skin of the blade. For the purposes of modeling the complete SHARCS rotor blade in ANSYS, the mass of the tip of the blade was incorporated into the mass of the “Skeleton” assembly itself, since the tip of the blade is connected directly to the “Skeleton” (note that the mass of the tip is 0.064 kg). The mass of the leading edge ballast described in the previous section, as well as the foam were also modeled as mass distribution along the span of the blade. The combined mass of all additional components of the blade was equivalent to 0.345 kg and the combined total mass of the blade added up to 0.578 kg.

The addition of all of the aforementioned components into the blade will move the center of mass of the blade further outbound towards the tip and closer to the ¼ chord of the blade. The added weight and shifted center of mass, compared to the “clean” blade (numerically) tested earlier, will lead to more realistic case with higher centrifugal loads being observed by the blade.

The addition of the “Skeleton” assembly, control actuators, leading edge ballast, foam and other components are presented in ANSYS by imposing higher density for the last inner layer of the composite material lay-up. Note that the properties of the composite material remain unchanged, only the density changes in a way so that the real mass distribution in the span-wise and chord-wise is matched for the real blade. Note that it is
important to have realistic mass distribution for the blade so that observed excessive
centrifugal loads and moments around center of mass of each section are avoided during
simulation.

First, the lower layers of areas 175 and 180 shown in Fig. 38 have their density set to
53,789 kg/m³, which represents the total mass of the leading edge ballast and the foam
located at this region. These areas start at the end of Region 2 (x = 135 mm) and end at
the beginning of the “Frame” (x = 712.4 mm) in the span-wise direction. Chord-wise, it
starts from the leading edge (y = 0) and finishes at (y = 12 mm). The thickness of the
lower layer is equal to 0.15 mm.

Next, the lower layers of areas 182 and 185 shown in Figure 39 have their density set
to 187,501 kg/m³, which represents the Frame, Skeleton, Tip and actuators located in this
end of the blade. These areas start at the beginning of the “Frame” (location x = 712.4
mm) and end at the tip of the blade in the span-wise direction. In the chord-wise
direction, they start at y = 12 mm and finish at the end of region 3 (y = 28.3 mm).
Similarly to areas 175, 180, the thickness of the lower layer is 0.15 mm. Figure 39 shows
the locations of the areas of interest (175 & 182) on the upper surface that do have a
mirror image of the areas (180 & 185) on the lower surface.
Figure 39: Areas where the density of the lower layers is changed on the upper and lower halves.

The total mass of the blade, including the weight of all the components, is equal to 0.578 kg with the center of mass located at $x = 628.02$ mm (57.3 of radius) and $y = 22.86$ mm (28.5% of chord). The total centrifugal load observed by the blade is equal to 9620.75 [N].

The boundary conditions for this case were kept the same as for the “clean” blade, with all 6 degrees of freedom constrained to 0 m displacement and 0 degrees of rotation at the nodes of the pin holes at the “Root Cupone” of the blade. The angular velocity was equal to 162.8 rad/s with the center of rotation set up in a way so that the root attachment pins are at $x = 126$ mm in radial location at its $\frac{1}{4}$ chord of the blade. The maximum Von Misses stress observed at the blade is 660 MPa. Note that this is approximately 4 times
lower than the strength of the composite material in the axial direction. Visual representation of the stress analysis results on the upper and lower halves of the blade is shown in Figure 40.

The maximum stress failure analysis performed using ANSYS, yields a strength ratio for the fully assembled blade exposed to the centrifugal loading of 1.41. This means that under these conditions the blade is safe to operate. Figure 41 depicts the visual representation of the maximum failure stress analysis. The legend is measured in [Pa] units.
1/Strength Ratio. Similarly, based on the Tsai-Wu failure theory, the Tsai-Wu criterion, determined using ANSYS, does not exceed 1 and yields slightly higher Strength Ratio of 1.47. Note that the loads observed by the blade are in both, the axial and transverse directions due to uneven mass distribution along the blade.

![Figure 41: Maximum Stress failure analysis of untwisted fully assembled blade. Measured in [1/Strength Ratio].](image)
5.3.4 Centrifugal loading: twisted fully assembled blade

For the more realistic test simulation of the scaled SHARCS rotor blade, it was analyzed with the designed twist distribution along the span of the blade. The twist distribution is presented in Figure 14, section 2.1.1. The ANSYS blade model is present in Appendix D, CD 1.

Similar stress analysis for the twisted SHARCS blade as for the untwisted one, presented above, must be performed. Twist in the blade may create different stress concentration locations, as well as change the stiffness of the blade due to the change of the composite material, fiber’s angle direction.

Applying the same boundary conditions and angular velocity than for the untwisted case in the previous section yields the following results. The maximum stress observed by the twisted “clean” blade is 181 MPa (Figure 42) while for the fully assembled one 656 MPa (Figure 43). The results are almost identical to the untwisted model since the total mass and the center of mass does not change, which shows that addition of twist does not change the blade strength.

The Strength Ratio (SR) for the clean blade, based on the maximum stress and Tsai-Wu failure theories, yields values of 5.78 and 5.83, respectively. This means a great safety margin for the “clean” blade. Performing similar failure analyses for the fully assembled twisted blade shows the SR being 1.41 for the maximum stress failure theory and 1.47 based on the Tsai-Wu failure criterion, which are values very much within the range used in aerospace engineering (typically between 1.1~1.5).
Thus, this model can be exposed to both centrifugal and aerodynamic loading for the final stress analysis, as will be shown in the next section.

5.3.5 Aerodynamic and centrifugal loading: twisted blade with actuators

Rotor blades create lift, which is the resultant force from the stress distribution over the blade – a vertical force perpendicular to the rotor disk. Lift will occur in the wind tunnel tests and thus need to be considered in the stress analysis. Lift force will also
create different type of loads than the centrifugal loads alone (i.e. addition of bending instead of only the tensile stress). Only the final configuration (i.e. twisted, fully assembled SHARCS blade model) will be tested.

**Figure 43:** Twisted fully integrated blade: under centrifugal load only; Von Misses stress contours in [Pa] units.

Displacement and rotational constraints were kept the same as for the centrifugal tests, i.e. 0 m displacement and 0 degree angle of rotation in and about the X,Y,Z coordinate axis, applied at the nodes around the pin-holes of the blade. The angular
velocity was again set to 162.8 rad/s with the center of rotation at 126 mm inboard from the pin-holes’ center, located along the ¼ chord of the blade.

To test the ANSYS blade model under aerodynamic and centrifugal loading, the aerodynamic loads were determined based on Section 4.2.2. Theses loads were determined for the rotor blade at 6° root pitch angle. They were applied onto the upper half of the blade as distributed load acting at the ¼ chord, along the full span of the blade. Figures 26 represent the lift force distribution along the span of the blade for 6° root pitch angle condition. The corresponding nodes, their coordinates in X and Z axis directions and aerodynamic load applied on the blade are presented in Table A.1, Appendix A. For this loading, combined with the centrifugal loading, the ANSYS scaled rotor blade exhibits a maximum stress of 2630 MPa in 6° degrees root pitch angle condition. Figure 44 shows the results of the stress analysis for the combined centrifugal and aerodynamic loading in forward flight. Note that the analysis is performed for a cantilever-like boundary condition at the root, which is a conservative assumption since in real life, the blade will be allowed to flap (rotate along the axis) via the rotor hub hinges, and is explained later in this section.

From the failure analysis it is observed that the blade fails under combined aerodynamic and centrifugal loading with the cantilever-like test boundary conditions. From the maximum stress failure analysis and from Tsai-Wu analysis it shows that it is not safe to perform tests with such boundary conditions.
The maximum safe load suggested at the tip of the blade for the blade to be tested with cantilever-like boundary conditions is estimated to be 70 N. Based on the failure analysis performed by ANSYS this would equal to 1.45 Strength Ratio based on the maximum stress failure theory and would not violate the Tsai-Wu failure theory either, since the criterion was estimated to be lower than one.

However, as mentioned earlier, helicopter rotors are articulated and it is known that rotor blades do not observe such high bending moments as presented above for the cantilever-like test boundary conditions. Fully articulated blade is operating at
equilibrium conditions that are determined by the balance of centrifugal and aerodynamic forces. Figure 45 shows coning up blade at equilibrium.

Figure 45: Conning upwards blade at equilibrium of aerodynamic and centrifugal forces [2].

Centrifugal and aerodynamic forces are determined based on sections 4.2.1 and 4.2.2. Taking into account only axial centrifugal load to determine flapping moment about flapping hinge (once the blade starts to cone) yields:

\[ M_{CF} = \int_{eR}^{R} m_e \Omega^2 y^2 \beta dy \]  

(21)
The hinge moment due to the aerodynamic distribution along the span of the blade is determined as

\[ M_\beta = \int_{eR}^{R} Lydy \]  \hspace{1cm} (22)

Therefore, the coning angle is determined as

\[ \beta = \frac{\int_{eR}^{R} Lydy \Omega^2 y^2 \beta dy}{\int_{eR}^{R} dm \Omega^2 y^2 \beta dy} \]  \hspace{1cm} (23)

The simplified analysis at the center of the mass of the blade has showed that the conning angle would be 5.37 degrees for the hover case. As the mass of the blade or the rotational speed increases the conning angle decreases due to the increasing dominance of the centrifugal load. In the case of the acceleration of the free stream velocity to 55 m/s for the SHARCS blade, the conning angle for the wind tunnel test may cone as high as 12 degrees. The conning angle of the conventional helicopters in hover flight regime is in the range of 3~6 degrees.

The conclusion of all the above is in essence that although the blade fails in a cantilever-like boundary condition, it would not do so in articulated boundary conditions.
5.3.6 Blade torsional loading

The blade’s elastic deformation due to the torsional force created as a result of the aerodynamic loads and the actuation of the flow control devices (i.e. ACF) and of the structural control device (i.e. APL) can become significant.

Based on the Smartrotor simulations performed by G. Oxley [17], the loads experienced by the pitch link are presented in Figure 46.

![Smartrotor simulation of the vibratory loads reduction with the Active Pitch Link](image)

**Figure 46:** Smartrotor simulation of the vibratory loads reduction with the Active Pitch Link [17]

From Figure 46 it is observed that the average loads through the pitch link are around 120 N. The pitch link horn, which is part of the rotor hub and connects the blade root to the pitch link, is 33.67 mm long (Figure 47). This will be essentially the moment arm for the pitch link.
Thus, the moment created by the blade is about 4.04 Nm. Assuming the rotation point at the center of the airfoil, two equal and opposite forces of 50.5 N were applied at the tip of the blade onto the furthest leading edge and trailing edge nodes of the ANSYS blade model. Constraining the blade at the “Root Cupone” pin holes to 0 m displacement and 0 degrees rotation about the X,Y,Z axis yields a maximum torsional stress of 283 MPa at the nodes where the forces were applied (Figure 48). Root transition region that has showed the highest stress during centrifugal and aerodynamic loading is showing the stress in the range of 65 N under torsional loading. The strength ratio of the composite material, as a result of the overestimated torsional load, is determined by ANSYS and equal to 4.71, based on the maximum stress failure theory. These results predict sufficient strength of the blade in torsion.
Figure 48: Twisted, fully integrated blade: under torsional load only; Von Misses stress contours in [Pa] units.

5.4 Root Cupone testing

The blade root is reinforced by introducing a full blade thickness composite structure called the “Root Cupone”, which enables the smooth distribution of the loads to the upper and lower halves of the scaled SHARCS rotor blade (Figure 49). The root coupon consists of 72 layers of alternating directions of carbon fibre laminas.
The location of the attachment bolts, connecting the blade root to the rotor hub were predetermined by the geometry of the scaled rotor hub planned to be used for testing. This caused an added complication concerning the root coupon design: the attachment bolts lied too close to the inner edge of the root of the blade, so that stress concentration around the holes could become critical.

Stress concentration at the pin holes of the “Root Cupone”, through which two bolts are being connected inside the hub to support the blade, are predicted to be of a concern due to its close location to the edge of the root. Location of the pin holes in the “Root Cupone” to its edge are nearly 50% of the standard ratios. The standard dimension ratios, to avoid bearing, shear and tensile failure are presented in Figure 50.

**Figure 49**: Illustration of the “Root Cupone”, reinforcement of the blade root.
To assess the ultimate load of the root coupon attachment holes, sample root coupons were fabricated and put to static tests. Figure 51 shows a tested specimen of the “Root Cupone”. The design load for the “Root Cupone” was expected to be at least 10 kN, however, the static testing showed that the root coupon could withstand more than 45 kN of force. At this point, the steel bolts used for testing started to yield, so the ultimate load of the root coupon itself is likely to be even higher.

Detailed description of the composite material lay-up and static testing are presented in the sections below.
5.4.1 Lay-up and Guidelines

The “Root Coupon” is made out of two halves, Upper and Lower, each consisting of 36 layers of carbon-fiber composite material. The carbon fiber composite consists of E022 matrix and T700S fibers with 60% volume fraction. Predicted lamina thickness is 0.15 mm.

The layup of the 36 layers, of each half, has the following structure:

\[[45/-45/45/-45/45/0/45/0/-45/0/45/0/-45/0/45/0/-45/0/45/0/-45/0/45/0/45/0/45/0/45/0/45/0/-45/0/45/0/-45/0/45/0/-45/0/45/0/45/0/-45/0/45/0/-45/0/45/0/-45/0/45/0/45/0/45/0/45/0/45/0]\]

Similarly as for the scaled SHARCS rotor blade manufacturing guidelines, for all the above gluing processes, glue type Redux from Hexcel should be used. The glue should be
applied to only one of the surfaces to be bonded. The assumed glue thickness was 0.1 mm. The total thickness of the “Root Cupone” must not exceed 12 mm, which is the space limitation within the cuff of the rotor hub intended for testing.

Three “Root Cupone” specimens were manufactured by Invent GmbH (Germany). It included drilling of four through holes, each with the diameter of 5.8 mm. Incorporation of metal inserts (Steel 4140) with the outer diameter of 5.8 mm and inner diameter of 4.8 mm to avoid delamination at the hole’s internal surfaces, was performed at Carleton University. For exact dimensions of the “Root Cupone”, please refer to Figure E.1 in Appendix E.

5.4.2 Static tests

Static tests were performed to determine the strength of the “Root Cupone” and the stress experienced by the scaled SHARCS rotor blade root under centrifugal loading. The objective of the static tests was to simulate centrifugal loads acting on the root of the blade so that the fact that the stress concentration around the bolts is not critical could be verified with full confidence.

The tests were performed at Carleton University. Each test had its own purpose. The first test set up provided 10 kN tensile load on the “Root Cupone” in the MTS (Tensile Stress) machine. The second test was a creep test with the applied tensile load of 10 kN onto the “Root Cupone” and held this part at the constant applied load for 22 minutes. The third test was done on the “Root Cupone” with the maximum applied load the specimen can withstand to determine ultimate strength of the part and therefore the
maximum load the blade is able to withstand. Figure 52 presents an exploded view of the specimen holder that was used in the MTS machine. Figure 53 shows the picture of the actual clip-full assembly used to test the “Root Cupone” specimen. Detailed drawings of the clip-full assembly are presented in Figures E2 – E4 in Appendix E.

Figure 52: “Root Cupone” specimen and the clip-full assembly.
5.4.3 Test #1

This test was performed with the maximum applied load of 10 kN, gradually increasing from 0 N within 60 seconds and decreasing back to 0 N in the next 3~4 seconds. 60 seconds is the estimated time to achieve the nominal 1555 RPM in the whirl tower tests. As the load gradually increased from 0 to 10 kN, the displacement in the test apparatus has been recorded to be 1.21 mm, as can be observed in Figure 54.

From Figure 54, it can be clearly seen that the displacement is not linear at the beginning of the test while the apparatus is being adjusted to the gradual increase in load. The first sudden jump in the load can be explained by the imperfect alignment of the
specimen, and it means that the initial load is not supported by all four bolts. Due to the increase in the load at one place it starts to deform until the load is being equally distributed among all four bolts. After the load is equally divided among all bolts, nearly linear displacement can be observed until the load reaches the maximum set load of 10 kN. The largest displacement is due to the initial setup of the specimen and that is corrected at the equal load distribution phase. The rest can be assigned to the deformation of the epoxy layer between the steel insert and the specimen itself as well as due to small deformation of steel.

Visual observation of the specimen did not show delimitation of fiber layers neither near nor around the holes, nor did it show the elongation of the specimen. Therefore, it can be concluded that the specimen did not fail and is able to support at least 10 kN load – equivalent to the centrifugal loads during the whirl tower test to be observed by the scaled SHARCS rotor blade.
5.4.4 Test #2

This test was performed again with the maximum applied load of 10 kN gradually increasing from 0 N to 10 kN within 60 seconds. However, this test is a creep test, therefore after the load of 10 kN has been reached, the load was kept constant and held for 22 minutes. During the first 60 seconds, at the time of the load increase the displacement was observed to be 0.618 mm, as can be observed in a Figure 55. It can be seen that similar load jumps occur as in the first test due to the misalignment of the specimen, as discussed earlier. After almost linear increase in tensile load to 10kN and axial displacement to 0.618 mm, the specimen is kept at this condition for the next 22 minutes to simulate possible creep of the specimen. Within the first 3 minutes of the test after the maximum applied load has been reached, the axial displacement increased by
0.0254 mm and stayed constant afterwards. Due to the insignificant change in the axial displacement, it has been decided to perform test number 3 using the same specimen that has been used for test number 2. In conclusion of test number 2, the “Root Cupone” did not elongate or delaminated at the critical points, so the “Root Cupone” does not creep under 10 kN load.

![Graph](image)

**Figure 55:** Force vs. Displacement Graph, Creep Test, “Root Cupone” specimen # 220-01-SB-04

### 5.4.5 Test #3

The final test was performed to estimate the maximum load the “Root Cupone” specimen can withstand before yielding. As the requirement for this test was not to damage the MTS machine, the maximum load was set to be applied 80 kN and maximum axial displacement of 0.1 in (2.54 mm). Whichever is achieved first, that will stop the
test. During the test, the load was gradually increasing until it reached the maximum load of 48 kN at which the apparatus recorded displacement of 0.1 in (2.54 mm). The test has been stopped and the specimen was visually observed. Figure 56 shows the force versus displacement graph, indicating linear displacement over two minutes time period. The major deflection occurred in the bolts, where the specimen itself was not damaged critically. It also has been observed that the specimen itself started to delaminate in the direction of applied load, although not significantly. This proves that although the bolts are the weakest part of the root, they are able to withstand the estimated centrifugal loads of 10 kN comfortably.

Figure 56: Force vs. Displacement Graph, Ultimate strength test, “Root Cupone” specimen # 220-01-SB-04
Chapter 6: C-spar Manufacturing Analyses

The C-spar is an integral part of the scaled rotor blade, located on the inside of the blade and used as a reinforcement and connection between the upper and lower halves of the blade (Figure 57).

![Figure 57: Cross-sectional view of the scaled SHARCS rotor blade](image)

The C-spar is a C-shaped composite element, located in the leading edge region of the blade. Its thickness is 0.28 mm and spans from root-transition zone (x = 135 mm) to the blade tip. It consists of two layers of composite carbon-fiber material, (T700S/E022), with the orientation of [-45/45]. Chord-wise length of the part is 27.74 mm, the span 734.4 mm and the maximum internal width of 9.77 mm (Figure 58).
The problem with manufacturing the C-spar is twofold:

- The curing process is likely to generate residual stresses that may cause the part to spring-in and twist when removed from the mold. It is of interest to determine the residual stress present in the C-spar once “forced” into its original shape in the case of deformation from thermal loading.
- The C-spar needs to be opened-up to install the strain gauges on the inner surface. It is of interest to determine the force needed to open the C-spar without damaging the material.

6.1 Thermal Loading

Before manufacturing the C-spar, analytical analyses to analyze the behavior of the part during the cool down stage of the curing process cycle must be performed. The thermal loading acting on the composite material part during this stage may create significant residual stresses inside the cured part, which may cause the composite material to change its original, designed shape. The most optimal curing temperature of the resin Epoxy E022 is 130°C that must be held for 90 minutes with autoclave pressure.
equal to 40 MPa and vacuum level at 1 MPa (Figure 59). Previous composite material manufacturing, performed for the SHARCS project, of the root of the blade called “Root Cupone”, used the same material as the one being selected for the C-spar and was cured under identical conditions as the ones selected for the C-spar manufacturing.

The last step of the curing process, once the part is fully cured, is to cool it down to below 60°C at a rate of four degrees per minute and eventually cool it down to room temperature of 25°C, which yields an overall change in temperature of -105°C.

Figure 59: Typical autoclave curing cycle of E022 (Epoxy Resin)

Before analyzing, using FEM, the residual stress from thermal loading in the C-spar itself, analytical calculations of the residual stresses in a simple laminate plate using classical laminate plate theory were performed. Such analytical calculations were decided
to be done to validate the computational (FEM) analyses and its results performed for the C-spar laminate part.

6.2 Residual Stress Analysis

Flat plate analyses were performed using the Laminate Plate Theory; an extension of beam theory, outlined in reference [24] and consisting of the following assumptions:

- Plane sections remain plane and normal to the mid-surface of the plate
- The material is incompressible in the through thickness direction
- Layers are perfectly bonded, allowing no slip at the interfaces

Below is an outline of the material used, geometry, loading and assumptions considered for the laminate plate analyses as well as of the calculation technique and results.

6.2.1 Test Case

For calculating the residual stresses in the simple laminate plate, the following details and assumptions were taken into consideration:

- Composite Material (SHARCS Material ID#1):
  - E022 epoxy matrix
  - T700S carbon fibers
- 60% fiber volume fraction of the composite material
• Bond between the fiber and the matrix is perfect
• Fiber diameters, and the space between the fibers are uniform
• Fibers are continues and parallel
• Fibers and matrix are linear elastic, and following Hook’s Law, the fibers are all the same strength and the elastic module of the fibers and matrix are constant
• Composite contains no voids
• Each layer thickness is assumed to be 0.15 mm
• Lamina contains two layers
• Lay-up is [-45/45]
• Thermal gradient is 4°C/min with total temperature difference -105°C

6.2.2 Calculation technique

The first step before determining the residual stresses in the composite laminate plate is the calculation of the composite properties of this laminate. These properties are determined with micromechanics technique using rule of mixture, Appendix F. Composite material properties have been compared to the average values for similar material from Reference [27] and the results are similar and are within acceptable range.

Composite material (T700S/E022) properties:
• $E_1 = 139.56$ GPa
• $E_2 = 5.95$ Gpa
• $\rho_c = 1536$ kg/m$^3$
• $\nu_{12} = 0.24$
• $G_{12} = 1.49$
• $\alpha_1 = 2.4697 \times 10^{-7}$
• $\alpha_2 = 4.6467 \times 10^{-5}$

The next step is to analyze each layer of the simple composite material plate; details of which are present in Test Case section above. Once the composite material prepreg’s properties are known, compliance and stiffness properties of the composite material layer of the laminate were found in matrix form, where $[S]$ and $[Q]$ are compliance and stiffness matrices respectively.

$$[S] = \begin{bmatrix}
\frac{1}{E_1} & -\frac{\nu_{12}}{E_1} & 0 \\
-\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & 0 \\
0 & 0 & \frac{1}{G_{12}}
\end{bmatrix}$$

(24)

$$[Q] = \begin{bmatrix}
\frac{E_1}{1-\nu_{21}\nu_{12}} & \frac{\nu_{12}E_2}{1-\nu_{21}\nu_{12}} & 0 \\
\frac{\nu_{12}E_2}{1-\nu_{21}\nu_{12}} & \frac{E_2}{1-\nu_{21}\nu_{12}} & 0 \\
0 & 0 & G_{12}
\end{bmatrix}$$

(25)

where $[Q]$ is simply an inverse of the compliance matrix.
The next step was to determine the global stiffness matrices for each ply in the laminate, which meant that the angle ply’s stiffness must be determined in the global coordinate system x-y-z. This was achieved by transforming the local stiffness matrix of each ply using transformation matrices.

\[
[Q] = [S]^{-1} = [T]^{-1}[Q][T^*]
\]

where \([T]^{-1}\) is the inverse of transformation matrix for stress and \([T^*]\) is the transformation matrix for strain and are presented below,

\[
[T]^{-1} = \begin{bmatrix}
c^2 & s^2 & -2sc \\
s^2 & c^2 & 2sc \\
sc & -sc & c^2 - s^2
\end{bmatrix}
\]

\[
[T^*] = \begin{bmatrix}
c^2 & s^2 & sc \\
s^2 & c^2 & -sc \\
-2sc & 2sc & c^2 - s^2
\end{bmatrix}
\]

where “c” stands for cosine and “s” for sine. These are initial steps for the full laminate analysis.
From the thermal loads acting on the composite material laminate plate, forces and moments in the global coordinate system are determined and therefore using global stiffness formulation, mid-strains and curvatures can be calculated, as shown below

\[
\begin{align*}
\left\{ \varepsilon^O \right\} &= \left[ A \right]_{3 \times 3} \left[ B \right]_{3 \times 3}^{-1} \left\{ N \right\} = \left[ A' \right]_{3 \times 3} \left[ B' \right]_{3 \times 3}^{-1} \left\{ N \right\} \\
\left\{ \kappa \right\} &= \left[ D \right]_{3 \times 3} \left\{ M \right\} = \left[ C' \right]_{3 \times 3} \left[ D' \right]_{3 \times 3}^{-1} \left\{ M \right\}
\end{align*}
\] (29)

where \( [A] = \sum_{k=1}^{n} [\Omega]_k \cdot t_k \) represents extensional stiffness of the beam,

\( [B] = \sum_{k=1}^{n} [\Omega]_k \cdot t_k \cdot \bar{z}_k \), represents the coupling stiffness of the beam, and

\( [D] = \sum_{k=1}^{n} [\Omega]_k \left( t_k \bar{z}_k^2 + \frac{t_k^3}{12} \right) \) is the bending stiffness of the beam.

The thermal forces and moments, \( \{N\} \) and \( \{M\} \), respectively, do not actually exist. These forces and moments are a representation of the residual stresses and are called “fictitious hydrothermal loads”. Such forces and moments can be determined as follows:

\[
\begin{bmatrix} N^\text{temp}_x \\ N^\text{temp}_y \\ N^\text{temp}_z \end{bmatrix} = \Delta T \cdot \sum_{k=1}^{n} [Q_g]_k (\alpha) \lambda \left( \bar{z}_k - \bar{z}_{k-1} \right)
\]

(30)
where “z_k“ is the distance from the center of the laminate to the k^{th} layer and \( \{\alpha\}_k \) is the coefficient of thermal expansion and is determined as:

\[
\begin{bmatrix}
\alpha_x \\
\alpha_y \\
\alpha_{xy}
\end{bmatrix} =
\begin{bmatrix}
c^2\alpha_1 + s^2\alpha_2 \\
s^2\alpha_1 + c^2\alpha_2 \\
2sc(\alpha_1 - \alpha_2)
\end{bmatrix}
\]  

(32)

Substituting these parameters back into the strain and curvature equation presented above (eqn. 31) would yield mid-strain and curvature values.

Once the mid-strain and curvature parameters are determined, total strains and stresses at the top and the bottom of each lamina are calculated using the following formulas:

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}_I = \begin{bmatrix}
\varepsilon^O_x \\
\varepsilon^O_y \\
\gamma^O_{xy}
\end{bmatrix} + z_I \begin{bmatrix}
K_x \\
K_y \\
K_{xy}
\end{bmatrix}
\]

(33)
\[
\begin{pmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{pmatrix}_I = [\bar{Q}]_k \begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{pmatrix}_I
\] (34)

where \( I \) is the location of interest at each ply and \([\bar{Q}]_k\) is the stiffness matrix of that ply.

Local strains and stresses of each lamina are then determined by using the aforementioned transformation matrices.

Mechanical strains are the ones that result in residual stresses in the composite material laminate and therefore mechanical strains are determined as follows:

\[
\begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{pmatrix}^{\text{mech, env}} = \begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{pmatrix}^{\text{total}} - \begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{pmatrix}^{\text{th}}
\] (35)

where total strain is the strain at the specified location through the thickness of the laminate and the free expansion strains, thermal (th), are the strains that would have been caused by free expansion of each layer and are found as:

\[
\begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{pmatrix}^{\text{th}} = \begin{pmatrix}
\alpha_1 \\
\alpha_2 \\
\alpha_{12}
\end{pmatrix} \cdot \Delta T
\] (36)

Stresses are then calculated in a similar manner as from the total strain presented above.
6.2.3 Results

Analytical analysis of the composite material laminate plate was successfully completed using self-written Matlab code provided in Appendix G. The maximum global residual stress, during the cooling step of the curing process, from this simple laminate plate analysis, is +/-49.282 MPa with the maximum local residual stress at each layer being estimated -119.44 MPa and +84.36 MPa. Tables 9 and 10 show global and local stresses through the thickness of the plate laminate.

Table 9: Estimated global stresses to be present after curing process through the thickness of the plate laminate.

<table>
<thead>
<tr>
<th>Layer</th>
<th>y [mm]</th>
<th>$\sigma_{XX}$ [MPa]</th>
<th>$\sigma_{YY}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>49.282</td>
<td>49.282</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>-49.282</td>
<td>-49.282</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-49.282</td>
<td>-49.282</td>
</tr>
<tr>
<td>2</td>
<td>-0.15</td>
<td>49.282</td>
<td>49.282</td>
</tr>
</tbody>
</table>

Table 10: Estimated local stresses to be present after curing process through the thickness of the plate laminate.

<table>
<thead>
<tr>
<th>Layer</th>
<th>y [mm]</th>
<th>$\sigma_{XX}$ [MPa]</th>
<th>$\sigma_{YY}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>84.3627</td>
<td>14.2</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>-119.44</td>
<td>20.88</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-119.44</td>
<td>20.88</td>
</tr>
<tr>
<td>2</td>
<td>-0.15</td>
<td>84.3627</td>
<td>14.2</td>
</tr>
</tbody>
</table>
The highest local residual stress occurs at the bottom and top surfaces of the 1st and 2nd layers respectively. Due to the lamina angle of \(-/+ 45^\circ\), not only the global stresses in the X and Y directions are equal through the laminate plate, but also the symmetry of local and global residual stresses, through the thickness of the laminate plate is observed. Visual representation of the results presented in Tables 9 and 10 are shown in Figure 60.

**Figure 60:** Visual representation of the residual stresses through the plate laminate estimated to be present after curing process.
6.2.4 Numerical methods

Results received for the composite material laminate plate analysis using self-written code in Matlab (Appendix G) are compared to the analysis done using the commercial software such as LAP, ESA Comp 3.4, Cadec, and ANSYS. These numerical methods will be described below.

1) LAP (Laminate Analysis Program) is a software tool for the design and analysis of composite material laminates. It was developed by Anaglyph Ltd., and is distributed in co-operation with the center of Composite Materials at Imperial College, London, UK. The solution algorithms employed are based on the Classical Laminated Theory that is partially presented in Section 6.2.2. Detailed explanation of the Classical Laminate Theory is presented in references [24] and [27].

2) ESAComp 3.4 is a software tool for analyses and design of composite material laminates. It was developed by Componeering Inc., under contract from the European Space Agency. The solution algorithms employed are based on the Classical Laminate Theory for constitutive and thermal/moisture expansion behaviour of solid and sandwich laminates.

3) CADEC (Computer Aided Design Environment For Composites), version 99.04.20 is developed by Ever J. Barbero. It is a compliment to “Introduction to Composite Materials Design” textbook, by Taylor and Francis in 1999. It is a freeware software developed for analyses and design of the laminates and is based on the Classical Laminate Theory including Thin Wall Beams section.
4) ANSYS (Multiphysics) is a general-purpose finite element analysis (FEM) software package that is developed for design and optimization of complex systems. FEM is a numerical method of dividing complex systems into small pieces (elements). The FEM solver uses equations that govern the behaviour of such elements and solves them, to represent an overall behaviour of the whole system [28]. This software tool is developed by Ansys Inc., and it is comprehensive coupled physics tool combining structural, thermal, computational fluid dynamics (CFD), acoustics and electromagnetic simulation capabilities in a single engineering software solution.

Results for the composite material laminate plate analysis, using commercial software, with two layers of carbon fiber / epoxy lay-up laminate with orientation [-45/+45] and the thermal loading of -105°C, showed the same residual stresses through the laminate as calculated and presented in the section 6.2.2. The outline of the software used and its results are presented in the Appendix H.

6.3 C-spar results

Once the analytical analyses of the laminate plate were completed, similar approach for the composite material C-spar laminate was employed. Such analyses were performed using ANSYS software package. Below is the outline of the C-spar twisted and untwisted ANSYS models, as well as their validation and residual stress results.
6.3.1 Untwisted C-spar: Numerical Model

To perform analyses of the composite material C-spar, an ANSYS model needs to be created. The ANSYS C-spar model is the initial step to the residual stress analyses of the composite C-spar laminate that are caused by the same thermal loading as was assumed for the composite material laminate plate due to the cool down stage of the curing process cycle. The C-spar model is developed by creating a cross-sectional shape of semi-airfoil from the key points, combining them into lines and dragging the combined lined pattern along a path (Figure 61).

![Figure 61: Untwisted C-spar ANSYS model](image)

A real life C-spar geometrical shape incorporates twist in the span-wise direction (z-axis in the particular model). However, the first ANSYS model of the C-spar (Figure 61) is made intentionally untwisted in order to compare and validate the FEM results of the C-spar with the analytical analysis performed for the flat plate.
6.3.2 Untwisted C-spar: Validation

Validation of the ANSYS model is required to ensure correctness of its construction and its properties. Therefore, as the first step, validity of the ANSYS model is performed. Before analysing the C-spar deformations due to the thermal loading, a simple simulation of gravity load acting on the blade part, C-spar, was done. The deflection caused by the weight of the C-spar itself was monitored. The mass of the C-spar is 0.0201 kg.

To be able to perform such analysis, the C-spar was associated with ANSYS element SHELL181, which is suitable for analyzing thin shell structures. It is a 4-node element with six degrees of freedom at each node: translation and rotation in all 3 directions. The boundary condition of such simulation is full constraint of one end of the C-spar ANSYS model, creating a cantilever-like environment. The Real time for such simulation was measured to be ten minutes, with the results presented in Figure 62. It shows the unconstrained end of the C-spar, being deflected by approximately 11 mm. The maximum stress of about 9.5 MPa occurs closer to the constrained end. The simulation has created with the ANSYS command ACEL, which specifies the linear gravitational acceleration of the structure. Appendix I present a detailed outline of the ANSYS code of this particular analysis.

To verify results from the numerical simulation, analytical calculations of a similar gravity environment were performed. Due to the complexity of the model geometry, theoretical calculations were performed with the simplified geometrical shape presented in Appendix J. Analytical calculations showed approximate deflection of the part of 3
mm, which is less than the results from ANSYS. The order of magnitude is in the same range as predicted by ANSYS and due to the difference in the geometrical shape of the part deflected, it can be assumed that the simulation method used in ANSYS is correct. It shows that the coordinate system and the strength of the C-spar are as predicted. Also, from visual observation of the model, there are absolutely no discontinuities in the model or in its construction lines and areas. The gravity force affects the entire model and not parts of it. This simple test shows that the C-spar model created in ANSYS is ready for deformation analysis due to the thermal loading.

Figure 62: Untwisted C-spar ANSYS model: under gravitational load; Von Misses stress contours in [Pa] units.
6.3.3 Untwisted C-spar: residual stresses

Once the simple validation of the ANSYS model of the C-spar without the twist was done, stress analyses, due to thermal loading, were performed. Due to only the thermal loading acting on the model, ANSYS allows the removal of all constraints to analyze the model in free space, in a similar manner than the laminate plate was analyzed earlier (presented in Appendix H.4). The thermal loading analysis was performed as a combined simulation of thermal and structural analysis, with association of ANSYS elements that are SHELL 131 and 181 respectively. SHELL131 is a 3-D layered shell element having in-plane and through-thickness thermal conductivity capability. The element has four nodes with 32 degrees of freedom at each node [29]. The SHELL 181 element has already been described in the previous section.

Initially, thermal surface load (convection) was applied onto the outer surface of the C-spar ANSYS model with the assumption of free convection for gases. Heat transfer coefficient for the above mentioned condition was assumed, based on the average values for still air, i.e. 6 [W/m$^2$ K]. The bulk/outside temperature was assumed to be room temperature, equal to 25°C. The next step was to switch the SHELL element of the model from 131 to 181 in order to estimate the residual stresses created during the aforementioned thermal conditions at the assumed C-spar body temperature of 130°C, which yields a temperature difference of -105°C. Appendix K outlines the ANSYS simulation code.
As a result, the maximum Von Misses Stress observed was 74.5 MPa (Figure 63), indicating similar residual stresses in the X and Y directions as they were calculated analytically for the laminate plate. A short list of nodal solutions in the x-coordinate direction is presented in Figure 64. This simulation serves as the second validity test and represents the error free model, and the correct analysis approach.

Figure 63: Untwisted, unconstrained C-spar ANSYS model: under thermal load; Von Misses stress contours in [Pa] units.
Figure 64: Nodal global residual stress solution in the x-coordinate direction. Visual representation of the results derived using ANSYS.

In order to measure the magnitude of deformation of the C-spar model, deformation must be measured relative to some point of reference; therefore, it was analyzed with one end being constrained. The maximum von Misses stress at the line of constraint, at one end, was calculated to be 135 MPa with the maximum displacement of the other end of the model of 218.37 mm, Figure 65. From consultation with André Steinmetz, composite materials specialist at the Technical University of Munich (Technische Universität München), Institute of Light Weight Structures (Lehrstuhl für Leichtbau), it has been confirmed that the results from the simulation analysis performed using ANSYS software, for the C-spar model, made sense and appeared to be realistic. Also, forcing the model into its original shape after the curing process is not expected to create any damage to the part due to its size and therefore high flexibility that will allow using it as a
connecting part of the upper and lower halves of the blade. Even though the residual stresses created during the curing process were relatively small compared to the strength of the material used, applying force to the cured and cooled down C-spar part will create internal reaction forces that will be seen as a load once the blade halves are enclosed. These stresses will be approximately equal to the residual stresses created by the thermal loading.

![Figure 65: Untwisted, constrained at one end, C-spar ANSYS model: under thermal load; Von Misses stress contours in [Pa] units.](image)

### 6.3.4 Twisted C-spar: numerical model

To perform a slightly more realistic simulation of the C-spar part undergoing the cooling process, as a last stage of the curing process cycle, a new twisted C-spar ANSYS model was created, Figure 66. This twisted model has the same twist distribution as the scaled SHARCS rotor blade, shown in Figure 14. Such twisted C-spar part is designed to be able to have a perfect fit in between two halves of the blade and also to be able to
provide solid connection support to these halves. This analysis is required to estimate the shape change of the twisted part as the twist may change general behaviour of the C-spar.

The model created from 12 sections, each with the angle twist relative to the SHARCS rotorcraft blade twist distribution graph, Figure 14. With a similar approach as was taken for the untwisted blade, the twisted C-spar model was developed by generating a half-airfoil sections from the key points, connecting them with lines and dragging these line patterns through the line path from section to section, thereby generating the full C-spar model.

![Twisted C-spar ANSYS model.](image)

6.3.5 Twisted C-spar: validation

In the same manner as before, the new ANSYS C-spar model needs to be tested for any abnormalities with the gravity load simulation. Similarly than for the untwisted ANSYS model, the twisted model was created with SHELL181 elements with the same mesh division of 0.5 of an element (5 mm), and the part’s weight of 0.0201 kg. It is a
cantilever-like environment testing model, with one end constrained and the other free in space with only gravity load acting on it. Figure 67 shows the results of such test. There are no discontinuities observed and the maximum von Misses stress of the twisted part, at the constrained end, is calculated to be 10.1MPa, which is slightly larger than that calculated for the part without twist. The displacement is the same as estimated for the model without the twist – 11 mm. These results show that the second model is also valid for further stress analysis.

Figure 67: Twisted C-spar ANSYS model: under gravitational load; Von Misses stress contours in [Pa] units.
6.3.6 Twisted C-spar: residual stresses

Similar methodology than for the model without twist was used for the stress analysis for the C-spar with twist. The residual stress calculations for the twisted model were performed as the combined analysis of thermal and structural simulations and the use of SHELL131 and 181 was applied. Identical boundary conditions and loads were used. The thermal gradient was 4 °C/min with total temperature difference of -105°C and with free convection load at the surface of the model. The heat transfer coefficient was again equal to 6 [W/m² K] and the bulk temperature was 25°C. Constraining one end of the part showed the maximum stress at the constraint end to be 136 MPa, while the maximum deflection was 217.9 mm (Figure 68). These results are the same as those calculated for the model without the twist. It is predicted that the twist pattern will be maintained once the model is forced to its original shape after it is fully cured / manufactured.

Figure 68: Twisted, constrained at on end, C-spar ANSYS model: under thermal load; Von Misses stress contours in [Pa] units.
6.4 Mold for C-spar

The mold for the C-spar manufacturing is presented in Figure 69. It has been designed to minimize the manufacturing costs and to simplify the C-spar production. It consists of an upper part, which represents the actual shape of the C-spar, and the base that is used to keep the upper part vertical during the manufacturing process. Detailed drawings of both of these parts are presented in Appendix L.

Due to the small size of the part, it is important to have all the sections of each layer of the prepreg to be cut slightly larger than needed and apply accurately at specified angles to reduce possible errors and therefore waste. The height of the upper part of the mold is slightly larger than the actual height of the C-spar, which meets the aforementioned request for the use of larger prepreg sections.

Two slots on the side of the mold provide guiding for the cutting tool after the prepreg curing process is finished. All sharp corners of the mold are rounded off to avoid damage to the vacuum bag that will be put around the mold to create the specified environment. The autoclave environment is presented in Figure 59.
6.5 Manufacturing guidelines

Manufacturing of the C-spar will take place at the Technical University of Munich (Technische Universität München), Institute of Light Weight Structures (Lehrstuhl für Leichtbau). It would involve hand lay-up of two layers of composite material prepreg, carbon fiber T700S/Epoxy E022, at [-45/45] degrees. The initial estimation for the curing autoclave environment is presented in Figure 59.
Chapter 7: Flap manufacturing

The purpose of this section is to describe the design of the flap unit for the ACF system. The ACF system is designed to deflect the flap that is located at 65% - 85% of the rotor radius (corresponding to 219.2 mm flap span) and 16.8% of the rotor blade chord length (13.5 mm flap chord), to a downward angle of 3 ~ 4 degrees. Recall that the blade has a NACA 0015 airfoil shape with a span of 1096 mm and chord length of 80 mm. 3D drawing of the flap is presented in Figure 70.

7.1 Design requirements

Once the blade is fully assembled, it will be tested in the wind tunnel, in a room temperature environment, without excessive humidity conditions. The flap unit will be exposed to three different types of loads: aerodynamic loads, centrifugal loads, and inertial loads.
7.1.1 Inertial loads

Inertial loads exist due to the flap actuation system that deflects the flap at maximum frequency of 150 Hz, which is equivalent to 7 full deflections of four degrees, per one revolution of the blade. It represents the limit of actuator performance and therefore the “worst case” condition that flap will experience due to actuation. Such high repetitive mode of the flap deflection imposes a requirement of high fatigue strength. The hinge moment from inertial loads was estimated to be 0.00636 Nm. The calculation of this load was performed by another member of Rotorcraft Research Group - F. Demet Ulker [40].

Figure 70: 3D drawing of the composite material flap unit for scaled SHARCS rotor blade.
7.1.2 Centrifugal Loads

Centrifugal loads are acting on the flap at its center of mass, which creates a righting moment that is acting against the actuators attempting to bring the flap back to the initial position. It also applies radial force, parallel to the span-wise direction of the blade (Figure 71). The magnitude of two components of centrifugal force are illustrated in Table 11.

**Table 11:** Radial and tangential components of centrifugal acceleration and force acting on a composite flap of 10g mass.

<table>
<thead>
<tr>
<th>Center of Mass Location [m]</th>
<th>α [deg]</th>
<th>Acceleration [g’s]</th>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>span-wise</td>
<td>chord-wise</td>
<td>a Rad</td>
<td>a Tan</td>
</tr>
<tr>
<td>822.03</td>
<td>71.696</td>
<td>3.55°</td>
<td>2221</td>
</tr>
</tbody>
</table>

**Figure 71:** Loads acting on the Flap unit of the scaled SHARCS rotor blade and ACF.
7.1.3 Aerodynamic loads

Aerodynamic loads are the highest in the fully deflected position of the flap and theoretically at the maximum angle of attack of the blade. From Computational Fluid Dynamics (CFD) analysis, the pressure coefficient along the blade’s airfoil at 75%R has been determined for 10 degrees angle of attack and maximum flap deflection of 4 degrees (Appendix M). This was assumed to be the maximum possible angle occurring on the advancing blade, thus creating a “worst case” scenario for the blade flap. This can be achieved by setting the blade pitch angle to 3.25 degrees, which then – due to the twist distribution of the blade – creates 10 degrees angle of attack at 75%R. The aerodynamic load will create a hinge moment acting against actuators. The hinge moment per unit length of the flap span was evaluated by integrating the pressure along the chord length of the flap from CFD. This value was then multiplied by the span of the flap, 0.219 m, to obtain the total aerodynamic hinge moment. The total hinge moment from the aerodynamic loads was found to be 0.048 Nm.

7.1.4 Total hinge moment on flap

Based on the above analysis, the resultant “worst case” hinge moment acting on the flap at 4 deg deflection, which must be accompanied by the ACF actuators, was calculated to be:

\[
M_{tot} = M_{aer} + M_{inertial} + M_{centrifugal} = \\
= 0.048 + 0.006 + 0.004 = \\
= 0.058 \text{ Nm}
\]
7.1.5 Other design requirements

The flap must be stiff enough so that there is no deformation of the flap once it is fully deflected. The maximum deflection of the flap shall be 4 degrees. The possible deformation of the flap using less stiff material may decrease this already small angle, which can adversely affect the performance of the blade.

Weight of the designed part must be the lowest possible; this is important since the increase in centrifugal forces is due to an increase in the weight of the flap. This will not only increase the stress at the hinges, but may also affect the auction system. Estimation of the actuator’s power has been done assuming 13.5 g is the weight of the flap; the weight estimation has been done based on the blade skin lay-up. The newly designed flap must not exceed the weight of the first estimation of 13.5g.

The flap should not be damaged at any time through its service life. The test environment must be set up in a way that all parts of the blade and equipment are fully secured on and around the blade. The only allowable and possible interaction of the blade with any foreign objects may occur during human handling. Pushing the flap out of curiosity is expected, although the load from this appears to be insignificant compared to the allowable loads acting on the flap itself; this may damage, however, the actuation mechanism. Therefore, a security cup shall be designed. In addition, there is still a possibility of the flap being damaged during transportation, movement, assembly etc.; therefore it must have a relatively high impact resistance.
For these reasons the same material as for the blade (T700S/E022) has been selected as the material for the flap. Similarly, prepreg hand lay-up process was selected as the manufacturing method.

7.2 Component analysis

Firstly, there should be no bending in the flap so that it does not deforming once it is fully deflected, as well as it does not affect the performance of the blade. Bending, if exist, can be decreased by stacking the largest axial stiffness plies farthest away from the mid-plane of the laminate. A cross-ply sequence must also be considered, so that the normal stress applied to the laminate does not create shear coupling terms. To avoid coupling of the force and moments acting on the flap, symmetric ply sequence must be incorporated in the laminate. Finally, possible torsion of the flap unit should be eliminated by including 45 degrees plies in the laminate. Therefore, the laminate for the flap should be symmetric with the axial plies located further away from the mid-plane of the laminate. For each 0 degrees ply, there should be a 90 degrees ply incorporated.

From the 3D model of the flap (Figure 70) it is shown that a pin is inserted through the flap; it is located 1.5 mm from the leading edge. Including a thin (0.6 mm) wall circular insert for the pin, the wall thickness allows for the thickness of the laminate to be 0.9 mm. With the carbon-fiber (T700S) reinforcement and epoxy E022 matrix, the thickness of the lamina selected is 0.15 mm, which in total allows for six plies to be incorporated into the laminate. Due to the aforementioned requirements for the laminate,
the suggested lay-up is as follows: \([0/45/90]_s\). Gradual change in the angle decreases the possible inner-laminar stresses and therefore delamination of the laminate.

It is expected for the flap to withstand aerodynamic and centrifugal loads acting on it during whirl tower and wind tunnel testing, but it is strongly recommended to perform ANSYS analyses of the flap for the SHARCS blade before manufacturing.
Chapter 8: Instrumentation

8.1 Requirements

The ultimate goal of the SHARCS project is to test the multiple control systems (APL, ACF and ACT) simultaneously in a closed-loop control system or in other words a “full controllable” rotor. For this, the blade needs to be “fully observable” as well, i.e. it has to be equipped with different sensors for monitoring:

- Performance (displacements) of the actuators
- Structural response (vibrations) of the blade

To meet these criteria, the test facility shall have a large number of data transfer channels (in the order of ~200 channels), enough for four fully assembled blades with the monitoring and active control of all four blades simultaneously. Conventional whirl tower and wind tunnel test facilities are usually not able to accommodate more than 100 channels; therefore it was an aim not to exceed this limit with the power supply and data transfer channels.
8.2 Control system sensors

The active control systems installed on each blade (APL and ACF) will require the continuous monitoring of vibratory loads on each blade individually. Based on these inputs, the control algorithm can then decide about the best actuation strategy for each blade so that Individual Blade Control (IBC) can be accomplished. Hence, it is not sufficient to measure only the overall vibratory loads on the rotor shaft and the fuselage of the helicopter, these must also be monitored in the rotational frame – on each blade individually – which is a major source of vibration.

Figure 72 shows the sensors location for a fully controllable and fully observable blade. Accelerometer P.AC1 installed on the APL (pitch horn side) shall capture vibratory loads created by the blade, which will serve as an input into the control algorithm. Accelerometer P.AC2 will measure the vibratory loads seen by the swashplate. When the APL is in the solid link mode, the two signals should be identical. However, when the APL is activated and the load is transferred via the secondary spring, the difference of the two signals will give the vibratory load. Alternatively, Hall sensor P.HS1 can be used to monitor the same parameter via the displacement on the APL secondary spring. Note that due to the limit in the channel number, either the Hall sensor or the accelerometers has to be used. All aforementioned sensors are preferred to be installed on the APL for redundancy as well as for reference and more accurate results.

Strain gage B.SG1 serves a safety purpose and monitors the centrifugal load at the blade root. It is installed from outside on the blade skin. Going further outboard, Hall
sensor F.HS1 measures the flap deflection of the ACF, while F.HS2 (mounted on the Skeleton and hidden inside the blade) measures the displacement of the ACF piezo-actuator. This can become important to assess the effects of inertial loads on the ACF flap due to the blade flapping motion occurring in forward flight. The two accelerometers B.AC2.LE and B.AC2.TE are monitoring the blade torsional motion, while accelerometer B.AC1 monitors the flapping motion. Note that the last four sensors (F.HS2, B.AC2.LE, B.AC2.TE, B.AC1) are embedded into the Skeleton, thus allowing very simple installation and maintenance and not compromising blade drag. The ACT is manually set to a fixed angle at this stage of the design, so no sensors were used for this control system.

The total number of channels per blade, required to accommodate the aforementioned sensors, is 16. Table 16 provides a summary of all sensors, their purpose and channel requirements.
Figure 72: Sensor locations for the SHARCS scaled rotor blade.

Table 12: List of sensors and channels required for the hybrid control tests.

<table>
<thead>
<tr>
<th>Actuator/Sensor</th>
<th>Purpose</th>
<th>Amount</th>
<th>Channels per unit</th>
<th>Channels per Blade</th>
<th>Total for 4 blades</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>APL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezotechnik Pst 150x7x7</td>
<td>actuation</td>
<td>2</td>
<td>2 (parallel link)</td>
<td>1 x 2 = 2</td>
<td>4 x 2 = 8</td>
</tr>
<tr>
<td>Accelerometer P.AC1</td>
<td>pitch link top displ.</td>
<td>1</td>
<td></td>
<td>1 x 2 = 2</td>
<td>4 x 2 = 8</td>
</tr>
<tr>
<td>Accelerometer P.AC2 or Hall Sensor P.HS1</td>
<td>pitch link bot displ.</td>
<td>1</td>
<td>1 x 2 = 2</td>
<td>4 x 2 = 8</td>
<td></td>
</tr>
<tr>
<td><strong>ACF</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cedrat APA 200 M</td>
<td>actuation</td>
<td>2</td>
<td>2 (parallel link)</td>
<td>1 x 2 = 2</td>
<td>4 x 2 = 8</td>
</tr>
<tr>
<td>Hall Sensor F.HS1</td>
<td>flap deflection</td>
<td>1</td>
<td></td>
<td>1 x 2 = 2</td>
<td>4 x 2 = 8</td>
</tr>
<tr>
<td>Hall Sensor F.HS2</td>
<td>piezo-displacement</td>
<td>1</td>
<td></td>
<td>1 x 2 = 2</td>
<td>4 x 2 = 8</td>
</tr>
<tr>
<td><strong>ACT</strong></td>
<td>Manual setup</td>
<td></td>
<td>no channels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strain Gage B.SG1</td>
<td>root stress monitoring</td>
<td>1</td>
<td></td>
<td>1 x 2 = 2</td>
<td>4 x 2 = 8</td>
</tr>
<tr>
<td>Accelerometer B.AC1</td>
<td>flapping mode (on c/4)</td>
<td>1</td>
<td></td>
<td>2 x 2 = 4</td>
<td>1 x 4 = 4</td>
</tr>
<tr>
<td>Accelerometer B.AC2</td>
<td>torsional mode</td>
<td>2</td>
<td></td>
<td>2 x 2 = 4</td>
<td>1 x 4 = 4</td>
</tr>
<tr>
<td><strong>Hub Loads</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerometer H.AC1</td>
<td>Fx force</td>
<td>1</td>
<td></td>
<td>n/a</td>
<td>2</td>
</tr>
<tr>
<td>Accelerometer H.AC2</td>
<td>Fy force</td>
<td>1</td>
<td></td>
<td>n/a</td>
<td>2</td>
</tr>
<tr>
<td>Accelerometer H.AC3</td>
<td>Fz force</td>
<td>1</td>
<td></td>
<td>n/a</td>
<td>2</td>
</tr>
</tbody>
</table>
8.3 Blade’s structural response sensors

All 4 blades will be equipped with a total of 32 strain gages distributed among 5 span-wise stations to capture the bending, torsion and lead-lag mode shapes. The 32 strain gages are grouped into 8 “patches” of 4 strain gages, where each group of 4 strain gages is connected into full Wheatstone bridge for strain measurement. Then, 3 patches are used for measuring torsion, 4 for measuring flapping (span-wise bending) and 1 for measuring lead-lag (chord-wise bending). The distribution of the strain gages is shown in Table 17. Detailed drawing of the strain gauges location and installation notes are presented in Appendix N. Note that there is no strain gage placed for flapping at the root, since for an articulated blade, as SHARCS, this is obsolete.

Table 13: Number of strain gauges, their type and their distribution

<table>
<thead>
<tr>
<th>Radial Station [mm] (From the Root of the blade)</th>
<th>Torsion</th>
<th>Flapping</th>
<th>Lead-Lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>150.00</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>294.08</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>438.16</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>582.24</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>726.32</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

8.3.1 Strain gauges and wires installation guidelines

It has been decided to implement the strain gauges onto the inner surface of the blade. However, note that in such solution, 30 out of 32 strain gauges shall be installed onto the inner surface of the C-spar. The width of the C-spar is only 9.77 mm, which
shows great complication to implement 30 strain gauges, and therefore 60 wires (Figure 73).

Installation of the strain gauges is a difficult and challenging process due to the miniature size of the C-spar part itself. Implementation of the strain gauges and the wires onto the raw material of the inner surface of the C-spar before the curing process may lead to deformation and failure of the strain gauges once the part is fully cured; it may occur due to residual stresses and therefore deformation of the C-spar part itself. Also, thermal loading may damage the wires and the strain gauges. Calibration of the strain gauges may not be possible for the accurate measurements due to possible savvier damage of such equipment.

To make the installation of the strain gauges feasible, it has been decided to “open” the C-spar during installation, to provide easier access. This will be achieved by fixing one side of the C-spar (the span-wise direction edge) and applying force onto the other side (the opposite edge in the span-wise direction) to open the section, and vice-versa. This scenario was analysed in ANSYS to estimate the maximum force allowable to open the C-spar without damaging it and therefore to estimate the maximum opening area as an outcome (Figure 74).

**Figure 73:** Visual representation of the strain gauges location on the inner surface of the theoretically fully open C-spar.
8.3.2 C-spar ANSYS model

The ANSYS model creation process is identical to the method presented in Section 6.3.1. A SHELL181 ANSYS element has been employed, with the meshing division of 0.5 per unit length. Analysis for opening the C-spar model was performed by applying a load of 0.05 N to one side and constraining the other. This led to the maximum von Misses stress at the leading edge of the part being 141 MPa. The maximum displacement, under the same load conditions, was calculated to be 15.3 mm, which is, together with the initial opening, equal to 25.07 mm that provides more room for the strain gauges installation to take place.

From previous analysis, it was calculated that due to the thermal loading during the curing process, the C-spar part develops residual stresses and therefore, it slightly deforms. The current analysis of the C-spar opening process shows an application of the load to the zero residual stress model. Knowing that residual stresses will exist in this C-
spar model, a more realistic environment was created. Combining the curing process effect with the “opening” load applied to the C-spar leads to a maximum von Misses stress of 240 MPa and maximum displacement of 24.7 mm at one end and 11 mm on the other end of the opposite side from the constrained one (Figure 75). Therefore, the average displacement is equivalent to the displacement of the previous analysis, which provides a better environment for the installers to be able to install the strain gauges and wires. Appendix D, CD1, provides the ANSYS simulation details for the combined analysis.

Figure 75: Visual representation of ANSYS C-spar. Stress analysis of the combination of residual stress and the opening load.
8.3.3 Strain Gauge set-up:

Each blade will be equipped with the following strain gauges:

a) Torsional strain gauge patch:
   - total number of 6 strain gauge patches
   - each patch contains two strain gauges oriented 90 degrees relative to each other
     with a permanent connection between them
   - three output wires from each patch will be led to the connector at the root of the blade
   - the total resistance of each strain gauge is 350 Ohm
   - the maximum allowable voltage is 16 Volts

b) Span-wise bending strain gauge patch:
   - total number of 8 strain gauge patches
   - each patch contains two strain gauges oriented parallel to each other; no connection between these two is made
   - all the wires are to be lead to the connector at the root of the blade
   - total resistance of each strain gauge is 350 Ohm
   - maximum allowed voltage is 13 Volts

c) Chord-wise bending strain gauge
   - total number of 4 strain gauges
   - all the wires from each strain gauge to be lead to the connector at the root of the blade
   - total resistance of each strain gauge is 350 Ohm
   - maximum allowed voltage is 15 Volts
The above strain gauges are to be installed on the inner surface of the C-spar of the blade. Due to the miniature size of the C-spar at its final configuration, strain gauges must be installed onto the opened C-spar shape. All wire connections to the strain gauges must be made at the same time and routed along a span-wise direction at 1/4 chord line of the blade; wires must be routed around the strain gauge stations accordingly.

The span-wise bending and torsional strain gauge patches are to be installed at their center on the ¼-chord line of the blade. Span-wise bending strain gauges are to be installed in the following manner: two strain gauges are to be installed on the upper and lower inner sides of the C-spar closer to the leading edge of the blade (at 6.90 mm from the LE), and the other two strain gauges, completing the full bridge configuration, are to be installed on the upper and opposing lower, inner surfaces of the blade closer to the trailing edge of the blade (at 6.90 mm from TE). The detailed drawing of the cross-section of the blade and the location of the strain gauges mentioned above is shown in Appendix N.

8.3.4 Strain gauge selection

Resistance of the strain gauges has no effect on the sensitivity of the signal in the full bridge configuration that is explained later. Higher resistance of the strain gauge allows higher voltage to pass through it. The passage of high voltage through low resistance strain gauges increases current and therefore the “operating” temperature of the wires, which is leading to the strain gauge that may burn and damage adjacent surface
material. Since the maximum selected voltage of the signal to the strain gauges is 10 Volts, the aforementioned strain gauges have been selected with the maximum allowed voltage being higher than 10 Volts. Selection of 350 Ohm resistance strain gauges has been done due to the maximum available resistance in the flap-wise bending strain gauge patch. To have consistency with all the strain gauges on the blade, and not to have any confusions and unnecessary human errors during the measuring process, all other strain gauges have been selected to be in the range of 350 Ohm. The benefit of the smaller resistance of the strain gauges is the smaller size of it. Appendix N shows drawings and characteristics of the selected strain gauges.

8.3.5 Wire harness

All the wires must be brought outside the blade at one point. This will be facilitated via a connector located at the root-transition section of the blade. It will be here, at this connector, where all strain gauges will be connected to the full Wheatstone bridge configuration (Figure 76). Note the opposite signs of each adjacent strain gauge in Figure 76.
The total strain is the sum of the measured strain from each strain gauge. If all the strain gauges would measure positive strain, then the total voltage output would stay unchanged. For span-wise and chord-wise bending, all wires must be brought to the root of the blade so that the strain gauges on the opposite sides of the blade are connected between each other following the Wheatstone bridge configuration. Strain gauges that measure torsional strain, oriented at 45 degrees to the span of the blade, are to be connected to each other on the upper and lower halves of the blade, creating half bridge configuration at each half of the blade, and the full bridge configuration is to be performed on the outside of the blade.

The power source wires to the flap actuators are routed separately from the signal wires, and lead through the foam to the skeleton in the center of the blade. This location is designed to avoid strong interference between high voltage (~150V) and low voltage (~10V) signals. Power source wires are lead to the flap actuators.
The wires selected for the power supply are American Wire Gauge (AWG) wire number 26 that has 0.4 mm diameter and is able to carry high voltage (>150V) and current of 0.363 Amps before the wire temperature exceeds its melting point. The wires for the strain gauges do not require high voltage or current and therefore AWG wire number 34 has been selected. The outer radius of the AWG 34 wire is 0.14 mm.

All the wires (32 x 2 = 64 in total) are lead to the blade root into a male connector, where the full Wheatstone bridges are created. It initially connects all the wires into eight full bridges of Wheatstone configurations, creating four new connection points per bridge. These consist of two connection points for the voltage supply and two for the voltage reading. Each connector has a single power source connection line – 10 and 0 Volts to which the power supply for all the strain gauges is connected. The other two connection points from each full bridge configuration are lead outside of the connector to the voltmeter device to measure output voltage from the strain gauges. Both connectors have a total of 16 output wires and 2 input wires that only require 18 channels for data transfer through the slip rings for strain gage measurements.

8.3.6 Channels

It is intended for the data acquisition and power supply to be accomplished via a slip ring unit consisting of 100 channels. From these, a minimum of 28 channels are required to be used for monitoring the blade flapping, feathering and lead-lag angles for trimming
purposes, as well as the blade stresses and blade modes and the 3 components of hub loads ($F_x$, $F_y$, $F_z$). Also, a minimum of 2 slip rings should be left empty as spares.

For the blade structural response monitoring via strain gauges, another 18 channels must be allocated.

The total number of channels required for a single blade to be fully monitored is 48 that leave 52 channels available. Note that in this configuration only 1 blade and all 4 APLs will be fully observable and fully controllable. The other 3 blades will be fully controllable only.

8.4 Connector selection

With more than 64 wires connected to the strain gauges on the inner surface of the blade, a connector is required for the blade to be mobile and for the contacts and wires to be fixed and identified. Initially a single micro connector (PSM) with a double row of 74 contacts in total was selected, Figure 77. The design included openings in the blade molds to account for the connector and the wires. The connector itself is designed to be put into the insert and later incorporated into the blade halves, Figure 78.
From the recent experience with testing the Active Pitch Link – one of the components of the SHARCS blade project – at the DLR test facilities in Brunschweig, Germany, it has been concluded that the outside connector must be very well secured to the inner connector that is permanently fixed in the blade. However, the micro connector PSM has only a plastic latch that would hold both mother and father connectors together. This type of locking system does not provide a very tight and secure connection, which may lead to loosening of the contacts and weak signal. Also, the entire connector may disconnect completely, which may cause damage to the blade itself and to the
surrounding equipment. Therefore, a new, single row, 37 contacts, bi-lobe connector with secured connection has been selected, for the final configuration of the SHARCS blade, Figure 79.

![Figure 79: Miniature, single row, bi-lobe connector.](image)

The new connector has 37 contacts. In order to meet the number of the sensors wires that are required to be brought outside of the blade, it is necessary to use two connectors, Figure 80. The new connectors are made from Aluminum, which increases weight by 2 g relative to the initial choice. The final selection provides better support to the outside connector, better contacts and it also increases safety during testing.
Figure 80: Visual representation of two connectors in between two halves of the blade at the root-transition zone of the SHARCS blade.
Chapter 9: Conclusions and Results

The main objective of the SHARCS project is to reduce noise and vibration on the helicopters by implementing three independent active control systems (i.e. ACF, ACT, APL) into each blade of the rotorcraft. For the ‘hybrid’ concept feasibility study and testing, the rotor blade must meet geometric similarity to be tested in 4 m x 4 m wind tunnel test facility. It must also meet acoustic and dynamic similarities to the full size blade, as well as the requirements of aerodynamic cleanliness and serviceability. In this chapter, it will be examined one-by-one, whether these design requirements have been met.

Geometric and Acoustic Similarities

The blade geometrical characteristics are presented in Table 18. This allows the blade to be tested in 4 m x 4 m wind tunnel section, as one of the requirements of the SHARCS blade design, with at least one rotor radius distance from the wall of the section to eliminate blade wall effects.
Table 14: The SHARCS Scaled Rotor Blade Dimensions

<table>
<thead>
<tr>
<th>Root Cut-out [mm]</th>
<th>Span [mm]</th>
<th>Chord [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>980</td>
<td>80</td>
</tr>
</tbody>
</table>

To be able to perform feasibility study of the SHARCS concept blade, two active control systems require to be installed inside the blade, that requires extra space compared to conventional blades. In order to avoid compromising the requirements of aerodynamic characteristics aerodynamic cleanness and acoustic similarity a relatively thick NACA 0015 airfoil was selected to be used for the SHARCS scaled blade. To avoid compressibility effects at the tip of the blade and to comply with the acoustic similarity to the full size blade, the rotational tip speed was selected to be 0.52 Mach, somewhat lower than the conventional 0.6 Mach. Therefore the rotational speed of the blade was set to 162.8 rad/sec or 1,555 RPM. Table 19 shows the summary of the selected aerodynamic criteria for the scaled SHARCS rotor blade.

Regarding acoustic simulations, once again: despite the somewhat lower tip speed, the noise levels are expected to be in the typical range for helicopters (100~130 dB).

Table 15: Summary of the selected airfoil and its critical, and operational speeds.

<table>
<thead>
<tr>
<th>SHARCS Scaled Blade</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Airfoil</td>
<td>NACA 0015</td>
</tr>
<tr>
<td>Critical Mach #</td>
<td>0.77 Mach</td>
</tr>
<tr>
<td>Rotational Tip Speed</td>
<td>0.52 Mach</td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>162.8 rad/s</td>
</tr>
</tbody>
</table>
**Dynamic Similarity**

The total mass of the fully assembled SHARCS rotor blade is equal to 0.578 kg. The estimated location of the center of mass of this blade is at $x = 628.02$ mm (57.3% of radius), $y = 22.86$ mm (28.5% of chord), $z = 0$ (vertically at the center of the blade). The centrifugal loading observed by the blade is equal to 9,621 N.

Based on these data, one can calculate the actual Lock number for the scaled SHARCS rotor blade as

$$\gamma = \frac{3 \cdot 1.225 \cdot 6.088 \cdot 0.080 \cdot 1.096}{0.578} = 3.39$$

This Lock number is less than the one set in the requirements, which was 5–8. However, the lock number was set based on “empty” blades, i.e. without active control systems and this results show that the mass of the blade inherently increases with the addition of active control systems. The lower Lock number represents lower dumping factor for the SHARCS blade than for conventional blades.

The above description is further supported by the words of Bernhard and Chopra [3] who discussed construction of a Mach scaled rotor blade with actively controlled tip and have achieved a Lock number of 2.55 due to the high mass of the blade with the active control system. This has led to the decrease of the tip speed due to the high centrifugal loading [3].
Next, the stiffness properties, i.e. the mode shape frequencies were compared with the required mode shapes. Note that the results below pertain to a cantilevered blade, although mode shapes for the fully articulated SHARCS blade, i.e. the design proposed in the thesis, have been determined by the Rotorcraft Research Group member Greg Oxley, using the Smartrotor simulation code. Table 20 presents the mode shape frequencies for the SHRACS rotor blade. It is not expected to create dynamic response amplification due to the APL operation, which increases the dumping of the rotor.

From Table 20, showing the actual SHARCS natural frequencies at the nominal RPM in comparison to the required frequencies from Table 2. It can be seen from Table 20 that all target natural frequencies for the articulated blade could be met, except the 1st elastic chord bending, which is slightly below the required value (4.26/rev instead of 4.5/rev).

**Table 16:** The natural frequencies of the mode shapes for the cantilever and articulated SHARCS blades and the required frequencies to be maintained.

<table>
<thead>
<tr>
<th>Mode</th>
<th>SHARCS (cantilever)</th>
<th>SHARCS (articulated)</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; rigid lead-lag</td>
<td>1.19</td>
<td>0.23</td>
<td>0.2 ~ 0.3</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; rigid flapping</td>
<td>1.48</td>
<td>1.03</td>
<td>1.02 ~ 1.04</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; elastic beam bending</td>
<td>3.55</td>
<td>2.76</td>
<td>2.5 ~ 2.8</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; elastic beam bending</td>
<td>6.17</td>
<td>4.59</td>
<td>4.2 ~ 4.7</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; elastic chord bending</td>
<td>7.08</td>
<td>4.26</td>
<td>4.5 ~ 5.5</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; elastic torsion</td>
<td>9.94</td>
<td>6.03</td>
<td>5.5 ~ 6.0</td>
</tr>
</tbody>
</table>
The total lift force acting on the blade at the highest root pitch angle of 10° yields total thrust force of 1913.48 N (per 4 blades). Such high lift force creates excessive load at the root of the blade that leads to its structural failure. It has been estimated that for current design the maximum normal force that is permitted to be applied, is equal to 70 N. Note, however, that these results are for a cantilevered blade. Since conventional helicopter rotors are fully articulated, the blades operating at high forward flight speeds do not actually observe such high bending moments as for the cantilever like boundary conditions. Fully articulated blades are operating at equilibrium conditions that are determined by the balance of centrifugal and aerodynamic forces.

The “Root Cupone” was tested and showed outstanding performance. The design load for the “Root Cupone” was expected to be at least 10 kN, however, the static testing showed that the root coupon could withstand more than 45 kN of force. At this point, the steel bolts used for testing started to yield, so the ultimate load of the root coupon itself is likely to be even higher. Therefore, the root of the blade (the pin holes) are able to withstand centrifugal load in axial direction.

The torsional strength of the blade has also been tested and determined to be able to withstand a moment of 3.37 Nm, created by the aerodynamic forces.

In summary, it can be concluded, that the blade is able to operate in fully articulated environment and is able to meet required mode shapes. However, during the static / cantilever-like testing environment, transverse and inter-laminar (normal to the surface) forces must not exceed 70 N.
Aerodynamic Cleanness and Serviceability

A completely novel and unorthodox design solution for housing the ACF and ACT systems was developed by proposing a removable "Skeleton" structure inside the blade. The Skeleton can be slid in from the tip of the blade and secured to an internal structure called the “Frame”, which is permanently attached to the blade skin, via a removable pin. This unique Skeleton sliding assembly concept offers great benefits and meets earlier stated requirements and more:

Serviceability:

• The Skeleton sliding assembly concept provides ease in disassembling and extracting the Skeleton from the blade. It also offers excellent access to the ACF and ACT systems once the Skeleton is outside the blade.

Modularity:

• Various ACF or ACT control mechanisms designs can be tested in the same composite blade structure using the Skeleton sliding assembly concept. If necessary, a new custom made Skeleton for other actuator sizes can be manufactured. Various tip shapes can be easily exchanged and tested as well.

Structural Integrity and Aerodynamic Cleanness:

• The Skeleton concept does not require an opening to be made in the skin of the composite blade for the control system to be incorporated. This offers a clean, uninterrupted load path from the tip to the root of the blade. Also, no cavities due to the bolts or panel edges are present, which ensures
aerodynamic cleanness in the all-important 60 to 90% radius portion of the blade, where most of the lift is generated.

**Scalability:**

- The Skeleton concept is entirely suitable for scaling up to full-size applications, therefore translating advantages of the aforementioned benefits to the full-scale rotor blades.

The contact area of the Frame and the skin has been calculated to be sufficiently large to withstand the shear load of 4,600.08 N, i.e. the total centrifugal force acting on the Skeleton and Frame. The pin and the hinges were also sized to withstand the same load.

Both the Skeleton and the Frame will be machined out of Titanium. This appeared to be the fastest and most precise way of manufacturing these components.

The total mass of the entire configuration, including the control systems (i.e. ACF, ACT) is 195.75 g, from which 20.17 g falls on the Frame and 58.58 g on the Skeleton. These masses proved to be very competitive in comparison to manufacturing of these parts from composite materials, yet the manufacturing of these parts form Titanium is much simpler and feasible.

**Instrumentation of the Blade**

The estimated number of available channels at the test facility is limited to 100. For fully active control and monitoring of the blade, 48 available channels, are needed to be occupied. Therefore to be able to meet the limited number of channels the
instrumentation requirements were “streamlined” by easing some of the criteria. In particular, it was decided that it will be sufficient if the SHARCS system for wind tunnel testing will:

- consist of 4 fully controllable blades
  - which means supplying power to all actuators (ie. APL, ACF, ACT) of the 4 blades, plus monitoring the vibration levels on all 4 APL’s (to enable their closed-loop control in an Individual Blade Control fashion).
- with 1 blade fully observable
  - which means full instrumentation of only one blade for monitoring its stresses, blade modes, and vibration levels, again to enable IBC type closed-loop control by the Actively Controlled Flap system.
- strain gages and control systems will not be monitored at the same time
  - which allows to save on the total number of slip rings required for testing

The preliminary design of the SHARCS scaled rotor blade has been performed and finalized. Numerical analyses and physical tests of separate components of the blade were performed to estimate the strength and feasibility of the SHARC blade concepts design and the next step in the manufacturing of the blades.
Reference:


[5] Imperial College London, South Kensington Campus, London – Department of Aeronautics, Modeling of rotorcraft blade-vortex interaction


[28] Carnegie Mellon University, Department of Mechanical Engineering, PA, USA


[34] Darrieus windturbine-analysis.com


Appendix A: Aerodynamic Data

Figure A.1: Aerodynamic characteristics of NACA0015 airfoil
Figure A.2: Aerodynamic characteristics of NACA0012 airfoil
Figure A.3: Aerodynamic characteristics of NACA0009 airfoil
Table A.1: Aerodynamic loads applied to the upper surface of the blade at the nodes closest to the ¼ chord of the scaled SHARCS rotor blade.

<table>
<thead>
<tr>
<th>Nodes [#]</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>dT [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>430</td>
<td>-0.176</td>
<td>0.00116</td>
<td>0.560</td>
</tr>
<tr>
<td>1217</td>
<td>-0.251</td>
<td>0.00116</td>
<td>2.220</td>
</tr>
<tr>
<td>4310</td>
<td>-0.30061</td>
<td>0.00116</td>
<td>3.704</td>
</tr>
<tr>
<td>4321</td>
<td>-0.35519</td>
<td>0.00116</td>
<td>5.466</td>
</tr>
<tr>
<td>4332</td>
<td>-0.40976</td>
<td>0.00116</td>
<td>7.282</td>
</tr>
<tr>
<td>4343</td>
<td>-0.46434</td>
<td>0.00116</td>
<td>9.234</td>
</tr>
<tr>
<td>4354</td>
<td>-0.51891</td>
<td>0.00116</td>
<td>11.259</td>
</tr>
<tr>
<td>4365</td>
<td>-0.57348</td>
<td>0.00116</td>
<td>13.295</td>
</tr>
<tr>
<td>4376</td>
<td>-0.62806</td>
<td>0.00116</td>
<td>15.277</td>
</tr>
<tr>
<td>4387</td>
<td>-0.68263</td>
<td>0.00116</td>
<td>17.141</td>
</tr>
<tr>
<td>6585</td>
<td>-0.73731</td>
<td>0.00116</td>
<td>19.645</td>
</tr>
<tr>
<td>6596</td>
<td>-0.79211</td>
<td>0.00116</td>
<td>23.323</td>
</tr>
<tr>
<td>6607</td>
<td>-0.84691</td>
<td>0.00116</td>
<td>27.340</td>
</tr>
<tr>
<td>6618</td>
<td>-0.90171</td>
<td>0.00116</td>
<td>31.678</td>
</tr>
<tr>
<td>6629</td>
<td>-0.95651</td>
<td>0.00116</td>
<td>101.638</td>
</tr>
</tbody>
</table>
Appendix B: Composite Material Data

Table B.1: Resin Material Properties

<table>
<thead>
<tr>
<th>Resin Material</th>
<th>Property</th>
<th>Epoxy</th>
<th>Polyester</th>
<th>Phenolic</th>
<th>Polymide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Density (g/cm^3)</td>
<td>0.96~1.41</td>
<td>1.12~1.46</td>
<td>1.24~1.32</td>
<td>1.22~1.43</td>
</tr>
<tr>
<td></td>
<td>Young's Modulus, E, (Gpa)</td>
<td>0.007~3.4</td>
<td>2.06~4.41</td>
<td>2.76~4.83</td>
<td>3.2~5.2</td>
</tr>
<tr>
<td></td>
<td>Tensile Strength, ,(Mpa)</td>
<td>14~90</td>
<td>28~89.7</td>
<td>34.5~62.1</td>
<td>30~570</td>
</tr>
<tr>
<td></td>
<td>Compressive Strehg, , (Mpa)</td>
<td>7~170</td>
<td>83~260</td>
<td>83~100</td>
<td>190~280</td>
</tr>
<tr>
<td></td>
<td>Fracture Toughness,</td>
<td>0.6</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(Mpa/m^0.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Expansion, 10-6/C</td>
<td>81~117</td>
<td>100~180</td>
<td>122</td>
<td>15~50</td>
</tr>
<tr>
<td></td>
<td>Strain at Tensile Ultimate, ,%</td>
<td>3~6</td>
<td>1.7~2.6</td>
<td>1.5~2</td>
<td>1~8</td>
</tr>
<tr>
<td></td>
<td>Poisson's Ratio</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain at Tensile Ultimate, %</td>
<td>3~6</td>
<td>1.7~2.6</td>
<td>1.5~2</td>
<td>1~8</td>
</tr>
<tr>
<td></td>
<td>Cost ($US/kg)</td>
<td>3~4</td>
<td>1.5~4.40</td>
<td>9.4</td>
<td>(estimated 10)</td>
</tr>
</tbody>
</table>

*Polymide will represent bismaleimides and cyanate material due to its similarity

*Plomyde price has been estimated

*All properties have been taken from lecture [23] and [24]
Table B.2: Resin Advantages and Disadvantages Summary

<table>
<thead>
<tr>
<th>Resin Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxies</td>
<td>-formulation of optimum properties</td>
<td>-high cost</td>
</tr>
<tr>
<td></td>
<td>-control of fracture toughness</td>
<td>-moisture sensitive</td>
</tr>
<tr>
<td></td>
<td>-low volatiles</td>
<td>-limited high-temp performance</td>
</tr>
<tr>
<td></td>
<td>-low shrinkage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-high strength</td>
<td></td>
</tr>
<tr>
<td>Polyester</td>
<td>-initial low viscosity</td>
<td>-can not be toughened</td>
</tr>
<tr>
<td></td>
<td>-low cost</td>
<td>-many volatiles</td>
</tr>
<tr>
<td></td>
<td>-easy to manufacture</td>
<td>-poor chemical resistance</td>
</tr>
<tr>
<td></td>
<td>-excellent environmental durability</td>
<td>-high cure shrinkage</td>
</tr>
<tr>
<td></td>
<td>-fire resistant</td>
<td></td>
</tr>
<tr>
<td>Vinyl-Ester</td>
<td>-high chemical resistance</td>
<td>-high cost</td>
</tr>
<tr>
<td></td>
<td>-easy processing</td>
<td>-higher shrinkage level then epoxies</td>
</tr>
<tr>
<td></td>
<td>-better mechanical properties</td>
<td></td>
</tr>
<tr>
<td>Phenolic</td>
<td>-high temperature resistance</td>
<td>-difficult to manufacture</td>
</tr>
<tr>
<td></td>
<td>-fire resistance</td>
<td>-higher cost</td>
</tr>
<tr>
<td></td>
<td>-low mechanical properties</td>
<td>-low mechanical properties</td>
</tr>
<tr>
<td></td>
<td>-high volatile content</td>
<td>-high volatile content</td>
</tr>
<tr>
<td>Bismaleimide</td>
<td>-thermal stability</td>
<td>-high cost</td>
</tr>
<tr>
<td></td>
<td>-thermal resistance</td>
<td>-difficult to manufacture</td>
</tr>
<tr>
<td>Polymide</td>
<td>-high temperature resistance</td>
<td>-high cost</td>
</tr>
<tr>
<td></td>
<td>-resistant to most chemicals</td>
<td>-difficult to process</td>
</tr>
<tr>
<td></td>
<td>-formulation of mechanical properties</td>
<td></td>
</tr>
<tr>
<td>Cyanate</td>
<td>-high short term thermal stability</td>
<td>-low stability in long-term moisture exposure</td>
</tr>
<tr>
<td></td>
<td>-high toughness</td>
<td></td>
</tr>
</tbody>
</table>
### Table B.3: Fiber Properties

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Typical Diameter (μm)a</th>
<th>Specific Gravity</th>
<th>Tensile Modulus (Gpa)</th>
<th>Tensile Strength (Gpa)</th>
<th>Strain to Failure (%)</th>
<th>CTE (10^-6/C)</th>
<th>Poisson's Ratio</th>
<th>Cost ($US/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Glass</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-glass</td>
<td>10</td>
<td>2.54</td>
<td>72.4</td>
<td>3.45</td>
<td>4.8</td>
<td>5</td>
<td>0.2</td>
<td>1.9~3.3</td>
</tr>
<tr>
<td>S-glass</td>
<td>10</td>
<td>2.49</td>
<td>86.9</td>
<td>4.3</td>
<td>5</td>
<td>2.9</td>
<td>0.22</td>
<td>&gt;4</td>
</tr>
<tr>
<td><strong>PAN carbon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-300c</td>
<td>7</td>
<td>1.76</td>
<td>231</td>
<td>3.65</td>
<td>1.4</td>
<td><del>0,6, 7</del>12</td>
<td>0.2~0.25</td>
<td>31.5~41.5</td>
</tr>
<tr>
<td>AS-1d</td>
<td>8</td>
<td>1.8</td>
<td>228</td>
<td>3.1</td>
<td>1.32</td>
<td>-</td>
<td>-</td>
<td>31.5~41.5</td>
</tr>
<tr>
<td>AS-4d</td>
<td>7</td>
<td>1.8</td>
<td>248</td>
<td>4.07</td>
<td>1.65</td>
<td>-</td>
<td>-</td>
<td>31.5~41.5</td>
</tr>
<tr>
<td>T-40c</td>
<td>5.1</td>
<td>1.81</td>
<td>290</td>
<td>5.65</td>
<td>1.8</td>
<td>~0.75</td>
<td>-</td>
<td>70~105</td>
</tr>
<tr>
<td>IM-7d</td>
<td>5</td>
<td>1.78</td>
<td>301</td>
<td>5.31</td>
<td>1.81</td>
<td>-</td>
<td>-</td>
<td>70~105</td>
</tr>
<tr>
<td>HMS-4d</td>
<td>8</td>
<td>1.8</td>
<td>345</td>
<td>2.48</td>
<td>0.7</td>
<td>-</td>
<td>-</td>
<td>175~225</td>
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<tr>
<td>GY-70e</td>
<td>8.4</td>
<td>1.96</td>
<td>483</td>
<td>1.52</td>
<td>0.38</td>
<td>-</td>
<td>-</td>
<td>175~225</td>
</tr>
<tr>
<td><strong>Pitch carbon</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-55c</td>
<td>10</td>
<td>2</td>
<td>380</td>
<td>1.9</td>
<td>0.5</td>
<td>-1.3</td>
<td>-</td>
<td>~200</td>
</tr>
<tr>
<td>P-100c</td>
<td>10</td>
<td>2.15</td>
<td>758</td>
<td>2.41</td>
<td>0.32</td>
<td>-1.45</td>
<td>-</td>
<td>~200</td>
</tr>
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</table>
### Figure B.1: Carbon Fiber T300/FT300 mechanical properties

<table>
<thead>
<tr>
<th>Item</th>
<th>Property</th>
<th>Unit</th>
<th>Filaments</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TORAYCA® Yarn Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Tensile Strength</td>
<td>MPa (kgf/mm²)</td>
<td></td>
<td>3530 (360)</td>
</tr>
<tr>
<td></td>
<td>Tensile Modulus</td>
<td>GPa (10³ kgf/mm²)</td>
<td></td>
<td>230 (23.5)</td>
</tr>
<tr>
<td></td>
<td>Elongation</td>
<td>%</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
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<td>MPa (kgf/mm²)</td>
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<td>-0.38</td>
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<td>Elongation</td>
<td>%</td>
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<td>127 (13.0)</td>
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<tr>
<td>0 ° ILSS</td>
<td>MPa (ksi/mm²)</td>
<td>90 (9)</td>
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**Figure B.2:** Carbon Fiber T700S mechanical properties
Appendix C: Composite material manufacturing data

Figure C.1: Resin Viscosity vs. Reinforcement Aspect Ratio

Figure C.2: Fiber direction vs. reinforcement Aspect Ratio
Figure C.3: Part complexity vs. Annual volume production
Appendix D: SHARCS rotor blade ANSYS model

Two ANSYS code files for the twisted and untwisted SHARCS blade ANSYS models are attached in electronic format on CD.1.
Appendix E: The “Root Cupone” Data

Figure E.1: Detailed drawing of the “Root Cupone” for manufacturing guidelines.
Figure E.2: Drawing of the “Cupon Clip” – inner plate; “Root Cupone” test apparatus.
Figure E.3: Drawing of the “Cupon Clip” – outer plate; “Root Cupone” test apparatus.
Figure E.4: Drawing of the “Cupon Clip” – full assembly; “Root Cupone” test apparatus.
Appendix F: Micromechanics for Composite Materials

Micromechanics are the analyses of the composite laminates on the level of individual materials that constitute such laminates. Below is the mathematical calculation of the properties of the composite material prepregs used in the initial laminate plate and is also selected for the C-spar laminate. Such properties are calculated using micromechanics technique that includes rule of mixture. Mathematical formulas and the results are presented bellow.

**Matrix:**

\[
E_m = 2.41 \text{ GPa} \\
V_m = 0.4 \\
\rho = 1200 \frac{kg}{m^3} \\
\nu_m = 0.3 \\
G_m = \frac{E_m}{2(1 + \nu_m)} \\
\alpha_m = 90 \times 10^{-6} C^{-1}
\]

**Fiber:**

\[
E_f = 231 \text{ GPa} \\
V_f = 0.6 \\
\rho = 1760 \frac{kg}{m^3} \\
\nu_f = 0.2 \\
G_f = \frac{E_f}{2(1 + \nu_f)} \\
\alpha_f = -0.38 \times 10^{-6} C^{-1}
\]
Composite Material Calculations

\[ E_1 = E_f V_f + E_m V_m = 139.56 \text{ GPa} \]

\[ \frac{1}{E_2} = \frac{1}{E_f} V_f + \frac{1}{E_m} V_m = 0.168 \text{ GPa} \]

\[ \rho_c = \rho_f V_f + \rho_m V_m = 1536 \text{ kg/m}^3 \]

\[ \nu_{12} = \nu_f V_f + \nu_m V_m = 0.24 \]

\[ \frac{1}{G_{12}} = \frac{1}{G_f} V_f + \frac{1}{G_m} V_m = 0.6701 \]

\[ \alpha_1 = \left( \frac{1}{B_1} \right) \cdot \left( \alpha_f \cdot E_f \cdot V_f + \alpha_m \cdot E_m \cdot V_m \right) = 2.4697 \times 10^{-7} \]

\[ \alpha_2 = (1 + \nu_f) \cdot \alpha_f \cdot V_f + (1 + \nu_m) \cdot \alpha_m \cdot V_m - \alpha_1 \cdot \nu_{12} = 4.6467 \times 10^{-5} \]
Appendix G: MatLab Code for thermal stress analysis

Appendix G presents Matlab code that allows to calculate residual stresses at 2 layered C-spar-like laminate plate under thermal loading.

**INPUT:** Includes location of interest through the thickness of the laminate, thermal gradient, thickness of the layer and number of the layers.

\[
\begin{align*}
z_{\text{location}} & = 0.000; \\
\delta_T & = -105; \degree C \\
t_k & = 0.00015; \mu m \\
i_{\text{max}} & = 2;
\end{align*}
\]

**STEP 1:** Calculation of the composite material properties using micromechanics technique (Appendix F).

%Matrix Eng Properties
\[
\begin{align*}
E_m & = 2.41; \text{ GPa} \\
\nu_m & = 0.4; \\
\rho_m & = 1200; \text{ kg/m}^3 \\
\nu_{Um} & = 0.3; \text{ Poissons Ratio} \\
G_m & = \frac{E_m(2(1+\nu_{Um}))}{2}; \\
\alpha_{m} & = 90E-6; \degree C
\end{align*}
\]

%Fiber Eng Properties
\[
\begin{align*}
E_f & = 230; \text{ GPa} \\
\nu_f & = 0.6; \\
\rho_f & = 1800; \text{ kg/m}^3 \\
\nu_{Uf} & = 0.2; \text{ Poissons Ratio} \\
G_f & = \frac{E_f(2(1+\nu_{Uf}))}{2}; \\
\alpha_{f} & = -0.38E-6; \degree C
\end{align*}
\]

% Composite Material (Laminate) Eng Properties
\[ E_1 = E_f V_f + E_m V_m; \]
\[ E_2 = \frac{1}{((1/E_f) V_f) + ((1/E_m) V_m)}; \]
\[ \text{roc} = \text{rof} V_f + \text{rom} V_m; \]
\[ VU_{12} = VU_f V_f + VU_m V_m; \]
\[ G_{12} = \frac{1}{((1/G_f) V_f) + ((1/G_m) V_m)}; \]

% Coefficient of Thermal Expansion
\[
\text{alpha}_1 = \frac{1}{E_1} (\text{alpha}_f E_f V_f + \text{alpha}_m E_m V_m);
\]
\[
\text{alpha}_2 = (1+VU_f) \text{alpha}_f V_f + (1+VU_m) \text{alpha}_m V_m - \text{alpha}_1 VU_{12};
\]

STEP 2: Calculation of the properties of each layer that includes local and global compliance and stiffness matrices as well as the calculation of the forces and moments as a result of the thermal loading (Section 4.2)

% Compliance Matrix \([S]\)
\[
S = \begin{bmatrix}
\frac{1}{E_1} & -\frac{VU_{12}}{E_1} & 0 \\
-\frac{VU_{12}}{E_1} & \frac{1}{E_2} & 0 \\
0 & 0 & \frac{1}{G_{12}}
\end{bmatrix};
\]

% Stiffness Matrix \([Q]\)
\[
Q = \text{inv}(S);
\]

\[
N_{\text{sum}} = 0;
\]
\[
M_{\text{sum}} = 0;
\]
\[
A_{\text{sum}} = 0;
\]
\[
B_{\text{sum}} = 0;
\]
\[
D_{\text{sum}} = 0;
\]

for \( i = 1:1:i_{\text{max}}; \)
% Laminae Angle
if \( i <= 1 \)
\[
\theta = -45((\pi)/180);
\]
\[
z_{k_1} = -0.00015; \text{%mm}
\]
\[
z_k = 0; \text{%mm}
\]
% Transformation Matrices
\[
T_{1} = [(\cos(\theta))^2 (\sin(\theta))^2 2*(\sin(\theta))*(\cos(\theta))];
\]
\[
(\sin(\theta))^2 (\cos(\theta))^2 (-2)*(\sin(\theta))*(\cos(\theta));
\]
\[
(-1)*((\sin(\theta))*(\cos(\theta))) ((\sin(\theta))*(\cos(\theta))) ((\cos(\theta))^2 - (\sin(\theta))^2)];
\]
\[
T_{\text{star} 1} = [(\cos(\theta))^2 (\sin(\theta))^2 2*(\sin(\theta))*(\cos(\theta))];
\]
\[
(\sin(\theta))^2 (\cos(\theta))^2 (-1)*(\sin(\theta))*(\cos(\theta));
\]
\[
(-2)*((\sin(\theta))*(\cos(\theta))) 2*((\sin(\theta))*(\cos(\theta))) ((\cos(\theta))^2 - (\sin(\theta))^2)];
\]
\[
T_{\text{inv} 1} = [(\cos(\theta))^2 (\sin(\theta))^2 (-2*(\sin(\theta))*(\cos(\theta))];
\]
\[
(\sin(\theta))^2 (\cos(\theta))^2 2*(\sin(\theta))*(\cos(\theta));
\]
\[
((\sin(\theta))*(\cos(\theta)) (-\sin(\theta))*(\cos(\theta))) ((\cos(\theta))^2 - (\sin(\theta))^2)];
\]
% Stiffness Matrix for angle laminae [Qbar]
Qbar_1 = Tinv_1 * Q * Tstar_1;

% CTE in global coordinates - transformation from the angle of the
% specified laminae
CTEglobal_1 = [(cos(theta))^2]*alpha1 + ((sin(theta))^2)*alpha2;
        (sin(theta))^2)*alpha1 + ((cos(theta))^2)*alpha2;
2*(sin(theta))*(cos(theta))*(alpha1-alpha2)];

% Finding fictitious thermal forces and moments
N_sum = N_sum + (Qbar_1*CTEglobal_1*(zk - zk_1));
M_sum = M_sum + (Qbar_1*CTEglobal_1*(((zk)^2)-((zk_1)^2)));
A_sum = A_sum + Qbar_1*tk;
B_sum = B_sum + Qbar_1*tk*0.5*(zk+zk_1);
D_sum = D_sum + Qbar_1*(tk*0.5*(zk+zk_1)^2) + (tk^3)/12);

if i >= 2
    theta = 45*(pi)/180;
    zk = 0.00015; % mm
    zk_1 = 0; % mm

% Transformation Matricies
T_2 = [(cos(theta))^2 (sin(theta))^2 2*(sin(theta))*(cos(theta));
        (sin(theta))^2 (cos(theta))^2 (-2)*(sin(theta))*(cos(theta));
        (-1)*((sin(theta))*(cos(theta))) ((sin(theta))*(cos(theta))) ((cos(theta))^2 - (sin(theta))^2)];

Tstar_2 = [(cos(theta))^2 (sin(theta))^2 (sin(theta))*(cos(theta));
        (sin(theta))^2 (cos(theta))^2 (-1)*(sin(theta))*(cos(theta));
        (-2)*((sin(theta))*(cos(theta))) 2*((sin(theta))*(cos(theta))) ((cos(theta))^2 - (sin(theta))^2)];

Tinv_2 = [(cos(theta))^2 (sin(theta))^2 (-2*(sin(theta))*(cos(theta));
        (sin(theta))^2 (cos(theta))^2 2*(sin(theta))*(cos(theta));
        (sin(theta))*(cos(theta)) (-sin(theta))*(cos(theta)) ((cos(theta))^2 - (sin(theta))^2)];

% Stiffness Matrix for angle laminae [Qbar]
Qbar_2 = Tinv_2 * Q * Tstar_2;

% CTE in global coordinates - transformation from the angle of the
% specified laminae
CTEglobal_2 = [(cos(theta))^2]*alpha1 + ((sin(theta))^2)*alpha2;
        (sin(theta))^2)*alpha1 + ((cos(theta))^2)*alpha2;
2*(sin(theta))*(cos(theta))*(alpha1-alpha2)];

% Finding fictitious thermal forces and moments
N_sum = N_sum + (Qbar_2*CTEglobal_2*(zk - zk_1));
M_sum = M_sum + (Qbar_2*CTEglobal_2*(((zk)^2)-((zk_1)^2)));
A_sum = A_sum + Qbar_2*tk;
STEP 3: Determination of the final forces and moments acting onto the laminate plate as well as the stiffness matrix for the laminate plate. It is followed by the calculations of the mid-strain and curvature values (Section 4.2)

\[
N = \delta_T \times N_{sum}; \\
M = 0.5 \times \delta_T \times M_{sum}; \\
A = A_{sum}; \\
B = B_{sum}; \\
D = D_{sum}; \\
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Residual\_stress\_local = T\_1*\text{Residual\_stress\_global}\nStrain\_thermal = CTE\text{global\_2}*\text{delta}_T;\n\text{Strain\_mechanical} = \text{Strain\_total\_global} - \text{Strain\_thermal};\n\text{Residual\_stress\_global} = Qbar\_2*\text{Strain\_mechanical}\n\text{Residual\_stress\_local} = T\_2*\text{Residual\_stress\_global}\nend
Appendix H: Composite Material Software Tool Kits

A.1 ESA Comp 3.4

ESAComp 3.4 is a software tool for analysis and design of composite material laminates.

Analysis presented below outlines a general input of the composite material laminate plate properties. It outlines only the general information without a record of the properties of the layers of the laminate, properties of which are determined and inputted using micromechanics, Appendix F.

An output presents stiffness and compliance matrices of the laminate under curing load that is equal to thermal gradient of -100 °C. It outlines local stress and strain values through the laminate and its graphical representation.

Visual representations of the ESAComp3.4, general input data and results as an output are presented below.
INPUT:

sLaminate : Laminate
Modified : Tue Jul 29 13:20:58 2008

Lay-up
(-45a/+45a)
Ply t (mm) Modified
a T700S_epoxy 0.15 Tue Jul 29 13:19:44 2008
n = 2 m_A = 540 g/m² T_ref = 20 °C
h = 0.3 mm rho = 1800 kg/m³ m_ref = - w%

Classification
Ply types : Solid;Reinf.
Lay-up : Antisym.;Balanced
Constit. beh. : AseBtDse

OUTPUT:

Stiffness matrix

<table>
<thead>
<tr>
<th>[A]</th>
<th>[B]</th>
<th>(N/m)</th>
<th>(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[B]</td>
<td>[C]</td>
<td>(N)</td>
<td>(Nm)</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
1.17181e+07 & 1.03481e+07 & 0 & 0 & 0 & 744.897 \\
1.03481e+07 & 1.17161e+07 & 0 & 0 & 0 & 744.897 \\
0 & 0 & 1.06062e+007 & 744.897 & 744.897 & 0 \\
0 & 0 & 744.897 & 0.0878705 & 0.0776105 & 0 \\
0 & 0 & 744.897 & 0.0776105 & 0.0878705 & 0 \\
744.897 & 744.897 & 0 & 0 & 0 & 0.0795466
\end{bmatrix}
\]

Compliance matrix

<table>
<thead>
<tr>
<th>[a]</th>
<th>[b]</th>
<th>(m/N)</th>
<th>(1/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[b]^T</td>
<td>[c]</td>
<td>(1/N)</td>
<td>(1/Nm)</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
4.27124e-007 & -3.0387e-007 & 0 & 0 & 0 & -0.00115419 \\
-3.0387e-007 & 4.27124e-007 & 0 & 0 & 0 & -0.00115419 \\
0 & 0 & 2.56407e-007 & -0.00115419 & -0.00115419 & 0 \\
0 & 0 & -0.00115419 & 56.9499 & -40.516 & 0 \\
0 & 0 & -0.00115419 & -40.516 & 56.9499 & 0 \\
-0.00115419 & -0.00115419 & 0 & 0 & 0 & 34.1875
\end{bmatrix}
\]
Lay-up: (-45°/+45°)  h = 0.3 mm

Ply
a T700S_epi

Load: curing load
Modified: Fri Aug 08 18:38:50 2008
Type: Forces and moments (Var., T)

\[ N_x = 0 \text{ N/m} \quad M_x = 0 \text{ Nm/m} \]
\[ N_y = 0 \text{ N/m} \quad M_y = 0 \text{ Nm/m} \]
\[ N_{xy} = 0 \text{ N/m} \quad M_{xy} = 0 \text{ Nm/m} \]
\[ Q_x = 0 \text{ N/m} \]
\[ Q_y = 0 \text{ N/m} \]
\[ T = 120 \degree C \]

Delta T = 100 \degree C

Actual stress, Eq. strain (\(^\varepsilon\))

<table>
<thead>
<tr>
<th>Ply</th>
<th>theta</th>
<th>sig_1</th>
<th>sig_2</th>
<th>tau_12</th>
<th>eps_1</th>
<th>eps_2</th>
<th>gam_12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>-45°</td>
<td>-83.86</td>
<td>-14.11</td>
<td>0.00</td>
<td>-0.0583</td>
<td>-0.2246</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td></td>
<td>118.73</td>
<td>-20.76</td>
<td>0.00</td>
<td>0.0896</td>
<td>-0.3726</td>
</tr>
<tr>
<td>2</td>
<td>a</td>
<td>45°</td>
<td>118.73</td>
<td>-20.76</td>
<td>0.00</td>
<td>0.0896</td>
<td>-0.3726</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td></td>
<td>-83.86</td>
<td>-14.11</td>
<td>0.00</td>
<td>-0.0583</td>
<td>-0.2246</td>
</tr>
</tbody>
</table>

Layer stresses - sig_1

Layer strains - eps_1
A.2 LAP

LAP (Laminate Analysis Program) is a software tool for the design and analysis of composite material laminates.

In this analysis, presented below, initial step is to input geometry and properties of the laminate. This package only performs macromechanics calculations and it requires an input of the properties of the prepregs used (Appendix F), its geometry and orientation as well as the loading onto the laminate.

An output of the analysis is the stiffness matrix of the laminate, resultant stresses and strains.

Visual representation of the LAP software package and the results are presented below

INPUT:
Material:

Lay-up:
Loading:

![Loading Diagram]

The diagram shows the loading conditions with specific parameters such as name, type, magnitude, order, and steps. It also includes fields for operating temperatures and moisture content. The reference for strain loadings can be specified as at operating conditions or as cured.
**OUTPUT:**

![Graphical User Interface Screenshot]

### Effective Stiffness

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Flexural</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{xx}$</td>
<td>7.82364</td>
</tr>
<tr>
<td>$\varepsilon_{yy}$</td>
<td>7.82364</td>
</tr>
<tr>
<td>$\gamma_{xy}$</td>
<td>13.0344</td>
</tr>
<tr>
<td>$\nu_{xy}$</td>
<td>0.7126</td>
</tr>
<tr>
<td>$\nu_{yx}$</td>
<td>0.7126</td>
</tr>
<tr>
<td>$E_{xx}$</td>
<td>1.76032e-11</td>
</tr>
<tr>
<td>$E_{yy}$</td>
<td>1.76032e-11</td>
</tr>
<tr>
<td>$G_{xy}$</td>
<td>1.1778e-10</td>
</tr>
</tbody>
</table>

### Effective Coefficients

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Flexural</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{xx}$</td>
<td>9.20298e-06</td>
</tr>
<tr>
<td>$a_{yy}$</td>
<td>9.20298e-06</td>
</tr>
<tr>
<td>$a_{xy}$</td>
<td>0.</td>
</tr>
<tr>
<td>$b_{xx}$</td>
<td>0.</td>
</tr>
<tr>
<td>$b_{yy}$</td>
<td>0.</td>
</tr>
<tr>
<td>$b_{xy}$</td>
<td>0.</td>
</tr>
</tbody>
</table>

### Matrices

**Load Vector**

<table>
<thead>
<tr>
<th>(effective stress)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{xx}$</td>
</tr>
<tr>
<td>$N_{yy}$</td>
</tr>
<tr>
<td>$N_{xy}$</td>
</tr>
<tr>
<td>$M_{xx}$</td>
</tr>
<tr>
<td>$M_{yy}$</td>
</tr>
<tr>
<td>$M_{xy}$</td>
</tr>
</tbody>
</table>

**Strain Vector**

<table>
<thead>
<tr>
<th>$\varepsilon_{xx}$</th>
<th>$\varepsilon_{yy}$</th>
<th>$\varepsilon_{xy}$</th>
<th>$\gamma_{xx}$</th>
<th>$\gamma_{yy}$</th>
<th>$\gamma_{xy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-9.20298e-02</td>
<td>-9.20298e-02</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>-9.709</td>
</tr>
</tbody>
</table>

**ABD matrix**

| 1.17933e-02 | 1.04228e-02 | 0. | 0. | -7.50151e-07 |
| 1.04228e-02 | 1.17933e-02 | 0. | 0. | -7.50151e-07 |
| 0. | 0. | 1.06799e-02 | 7.50151e-07 |
| 0. | 0. | 7.50151e-07 | 8.84498e-11 |
| 0. | 0. | -7.50151e-07 | 7.81709e-11 |
| -7.50151e-07 | -7.50151e-07 | 0. | 0. | 8.0093e-11 |

**Inverse ABD matrix**

| 1.17933e-02 | 1.04228e-02 | 0. | 0. | -7.50151e-07 |
| 1.04228e-02 | 1.17933e-02 | 0. | 0. | -7.50151e-07 |
| 0. | 0. | 1.06799e-02 | 7.50151e-07 |
| 0. | 0. | 7.50151e-07 | 8.84498e-11 |
| 0. | 0. | -7.50151e-07 | 7.81709e-11 |
| -7.50151e-07 | -7.50151e-07 | 0. | 0. | 8.0093e-11 |
Global Stress
Local Stress
A.3 Computer Aided Design Environment for Composites (CADEC) 2007

CADEC is developed for analysis and design of the laminates.

Analysis presented below shows input data of the laminate including its geometry and properties that are calculated using micromechanics earlier, Appendix F.

An output shows mid-strains and curvatures of the composite material laminate plate as well as laminate extensional and bending stiffness matrices. Finally it presents global and local residual stresses as a result of thermal loading.

Visual representation of the CADEC software package and the results are presented below.

**INPUT:**

![Input Data Screenshot](image-url)
### OUTPUT:

**Analysis for Degraded Material**

**Mid-Strains and Curvatures**

<table>
<thead>
<tr>
<th>$E_x^0$</th>
<th>$E_y^0$</th>
<th>$\gamma_{xy}^0$</th>
<th>$K_x$</th>
<th>$K_y$</th>
<th>$K_{xy}$</th>
</tr>
</thead>
</table>

**Thermal Loads**

<table>
<thead>
<tr>
<th>$N_x^T$</th>
<th>$N_y^T$</th>
<th>$N_{xy}^T$</th>
<th>$M_x^T$</th>
<th>$M_y^T$</th>
<th>$M_{xy}^T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-5.948E-08$</td>
<td>$-5.948E-08$</td>
<td>$0.000$</td>
<td>$2.078E-24$</td>
<td>$2.078E-24$</td>
<td>$2.078E-09$</td>
</tr>
</tbody>
</table>

**Hygroscopic Loads**

<table>
<thead>
<tr>
<th>$N_x^N$</th>
<th>$N_y^N$</th>
<th>$N_{xy}^N$</th>
<th>$M_x^N$</th>
<th>$M_y^N$</th>
<th>$M_{xy}^N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.000$</td>
<td>$0.000$</td>
<td>$0.000$</td>
<td>$0.000$</td>
<td>$0.000$</td>
<td>$0.000$</td>
</tr>
</tbody>
</table>

**Analysis for Degraded Material**

\[ [A] = \begin{bmatrix}
0.117932E-01 & 0.104232E-01 & 0.000E00 \\
0.104232E-01 & 0.117932E-01 & 0.000E00 \\
0.000E00 & 0.000E00 & 0.105799E-01 \\
\end{bmatrix} \]

\[ [B] = \begin{bmatrix}
0.000E00 & 0.000E00 & 0.750151E-06 \\
0.000E00 & 0.000E00 & 0.750151E-06 \\
0.750151E-06 & 0.750151E-06 & 0.000E00 \\
\end{bmatrix} \]

\[ [D] = \begin{bmatrix}
0.94448E-18 & 0.701709E-18 & 0.000E00 \\
0.701709E-18 & 0.94448E-18 & 0.000E00 \\
0.000E00 & 0.000E00 & 0.899532E-10 \\
\end{bmatrix} \]

\[ [H] = \begin{bmatrix}
0.258002E-03 & 0.000E00 \\
0.000E00 & 0.258002E-03 \\
\end{bmatrix} \]
### Ply Face

#### Global Stresses - Degraded Material

<table>
<thead>
<tr>
<th>Hygrothermal Stress</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
<th>$\sigma_{xy}$</th>
<th>$\sigma_{yz}$</th>
<th>$\sigma_{xz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TOP</td>
<td>5.17E-01</td>
<td>5.17E-01</td>
<td>3.64E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2 BOT</td>
<td>-5.17E-01</td>
<td>-5.17E-01</td>
<td>-7.77E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 TOP</td>
<td>-5.17E-01</td>
<td>-5.17E-01</td>
<td>7.77E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 BOT</td>
<td>5.17E-01</td>
<td>5.17E-01</td>
<td>-3.64E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical Stress</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
<th>$\sigma_{xy}$</th>
<th>$\sigma_{yz}$</th>
<th>$\sigma_{xz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TOP</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2 BOT</td>
<td>-0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 TOP</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 BOT</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Stress</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
<th>$\sigma_{xy}$</th>
<th>$\sigma_{yz}$</th>
<th>$\sigma_{xz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TOP</td>
<td>5.17E-01</td>
<td>5.17E-01</td>
<td>3.64E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2 BOT</td>
<td>-5.17E-01</td>
<td>-5.17E-01</td>
<td>-7.77E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 TOP</td>
<td>-5.17E-01</td>
<td>-5.17E-01</td>
<td>7.77E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 BOT</td>
<td>5.17E-01</td>
<td>5.17E-01</td>
<td>-3.64E-01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

---

### Ply Face

#### Material Stresses - Degraded Material

<table>
<thead>
<tr>
<th>Hygrothermal Stress</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
<th>$\sigma_4$</th>
<th>$\sigma_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TOP</td>
<td>-1.25</td>
<td>1.12E+16</td>
<td>1.12E+16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 TOP</td>
<td>-1.25</td>
<td>1.12E+16</td>
<td>1.12E+16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 BOT</td>
<td>-1.25</td>
<td>1.12E+16</td>
<td>1.12E+16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical Stress</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
<th>$\sigma_4$</th>
<th>$\sigma_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TOP</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2 BOT</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 TOP</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 BOT</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Stress</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
<th>$\sigma_4$</th>
<th>$\sigma_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 TOP</td>
<td>-1.25</td>
<td>1.12E+16</td>
<td>1.12E+16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
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<td>-1.25</td>
<td>1.12E+16</td>
<td>1.12E+16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 TOP</td>
<td>-1.25</td>
<td>1.12E+16</td>
<td>1.12E+16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1 BOT</td>
<td>-1.25</td>
<td>1.12E+16</td>
<td>1.12E+16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
A.4 ANSYS

ANSYS is general-purpose finite element analysis (FEM) software package that is developed for design and optimization of complex systems. Composite material laminate plate is analyzed below with the help of ANSYS software package. An input consist of the self written code that involve geometrical shape of the laminate plate, element association with it and the properties of the composite material. It is a thermal and structural combined analysis and therefore this code represents thermal and structural environments, meshing and element sizes.

An output shows visual representation of the Von Misses Stress observed as a result of the thermal loading as well as the global residual stresses in the unconstrained laminate plate model. X and Y component global stresses present similar results as the ones found analytically using classical laminate theory. It proves validity of the model and the methodology for the analysis of such stresses

The code and the results are presented below.

INPUT:

ANSYS command script:

FINISH
/CLEAR,START
   /CWD,'C:\Documents and Settings\Kostya\My Documents\Kostya\Carleton\SHARCS
   MAIN\GERMANY\ANSYS\Plate'
/TITLE,Csection
/REPlot
/Prep7

! Dimensions of the plate
B = 0.4   ! Width
L = 0.8   ! Length
\[ t_{\text{CFRP}} = 0.125 \times 10^{-3} \] ! Single layer thickness

\[ n = 40 \] ! Number of layers

\[ m_{\text{size}} = 5 \] ! Factor determining the density of the mesh

Blc4,,B,L

ET,1,SHELL131
KEYOPT,1,3,1
KEYOPT,1,4,2
KEYOPT,1,6,0

!NOTE: Attached to the solid tool at the bottom - paint option

R,1,0.0003

!Section for ET1

SECTYPE,1,SHELL,,C-SPAR
SECDATA,0.00015,1,45,5,C-SPAR-TOP-LAYER
SECDATA,0.00015,1,-45,5,C-SPAR-BOTTOM-LAYER

! Material properties - STRUCTURAL - (CFRP, T300, Epoxy, Vf = 60%)

MP,EX,1,138e9
MP,EY,1,5.9e9
MP,GXY,1,2.28e9
MP,GXZ,1,2.28e9
MP,GYZ,1,5.9e9/(2*(1 + 0.24))
MP,DENS,1,1800
MP,PRXY,1,0.24
MP,KXX,1,11
MP,KYY,1,1.11

AATT,1,1,1,0,1

!association of element attributes with the selected, unmeshed areas

ESIZE,0.1
AMESH,ALL

physics,write,thermal

physics,clear

ET,1,SHELL181
KEYOPT,1,1,0
KEYOPT,1,3,0
KEYOPT,1,8,2
!KEYOPT,1,9,0
!KEYOPT,1,10,0
R,1,0.0003

!Real constant, set2 - thickness of 0.3 mm

!Section for ET2

SECTYPE,1,SHELL,,C-SPAR2
SECDATA,0.00015,1,45,5,C-SPAR-TOP-LAYER
SECDATA,0.00015,1,-45,5,C-SPAR-BOTTOM-LAYER

! Material properties - THERMAL - (CFRP, T300, Epoxy, Vf = 60%)
MP,EX,1,138e9
MP,EY,1,5.9e9
MP,GXY,1,2.28e9
MP,GXZ,1,2.28e9
MP,GYZ,1,5.9e9/(2*(1 + 0.24))
MP,DENS,1,1800
MP,PRXY,1,0.24
MP,ALPX,1,2.4697e-07
MP,ALPY,1,4.6467e-05

!ACLEAR,ALL
!AATT,1,1,1,0,1

!ESIZE,0.5
!AMESH,ALL

physics,write,struct
physics,clear
finish
/solu
antype,0
physics,read,thermal
SFA,ALL,2,CONV,6,20

solve
save
finish
/solu
physics,read,struct
LDREAD,temp,,,,,,rth
TREF,125
SOLVE
save
FINISH
/POST1
/EFACET,1

PLNSOL, S,EQV, 2,1.0
OUTPUT

Von Misses Stress

Global stresses

X-component of stress – 51.4 MPa

Y-component of stress – 51.4 MPa
Appendix I: ANSYS model validation

Below is the validation code for untwisted ANSYS, c-par, model. It consists of the geometry of the model that includes keypoints outline, combination of the lines enclosed by these keypoints and the drag of the combined lines along the C-spar geometry path. It also outlines geometry and properties of the laminate section/model, gravity load and the solution commands.

FINISH
/CLEAR,START
/CWD,'C:\Documents and Settings\Kostya\My Documents\Kostya\Carleton\SHARCS MAIN\ GERMANY\ANSYS\Gravity'
/TITLE,Csection_no_twist
/REPL0T
/PREP7
K,1,0.0003035,0,,
K,2,0.0003962,0.0003489,,
K,3,0.0005477,0.0006575,,
K,4,0.0007575,0.0009357,,
K,5,0.0010255,0.0011938,,
K,6,0.0013511,0.0014422,,
K,7,0.001731,0.0016878,,
K,8,0.0021428,0.0019213,,
K,9,0.00257,0.0021366,,
K,10,0.0030113,0.002336,,
K,11,0.0034655,0.0025215,,
K,12,0.0039306,0.0026952,,
K,13,0.0044028,0.0028575,,
K,14,0.0048812,0.0030092,,
K,15,0.0053652,0.0031513,,
| K | 16.0 | 0.0058539 | 0.0032845 |
| K | 17.0 | 0.003463 | 0.0034096 |
| K | 18.0 | 0.006842 | 0.0035271 |
| K | 19.0 | 0.0073409 | 0.0036376 |
| K | 20.0 | 0.0078424 | 0.0037418 |
| K | 21.0 | 0.0083458 | 0.0038399 |
| K | 22.0 | 0.0088509 | 0.0039322 |
| K | 23.0 | 0.0093577 | 0.0040189 |
| K | 24.0 | 0.009866 | 0.0041003 |
| K | 25.0 | 0.0103757 | 0.0041768 |
| K | 26.0 | 0.0108867 | 0.0042485 |
| K | 27.0 | 0.0113989 | 0.0043157 |
| K | 28.0 | 0.0118121 | 0.0043787 |
| K | 29.0 | 0.012226 | 0.0044376 |
| K | 30.0 | 0.0126407 | 0.0044926 |
| K | 31.0 | 0.0130561 | 0.0045438 |
| K | 32.0 | 0.0134721 | 0.0045914 |
| K | 33.0 | 0.0138889 | 0.0046356 |
| K | 34.0 | 0.0143064 | 0.0046765 |
| K | 35.0 | 0.0147238 | 0.0047142 |
| K | 36.0 | 0.015042 | 0.0047489 |
| K | 37.0 | 0.0153606 | 0.0047806 |
| K | 38.0 | 0.0156792 | 0.0048095 |
| K | 39.0 | 0.0160987 | 0.0048356 |
| K | 40.0 | 0.0164193 | 0.0048593 |
| K | 41.0 | 0.0168381 | 0.0048799 |
| K | 42.0 | 0.0171581 | 0.0048985 |
| K | 43.0 | 0.0174784 | 0.0049138 |
| K | 44.0 | 0.0178009 | 0.0049272 |
| K | 45.0 | 0.0181246 | 0.0049383 |
| K | 46.0 | 0.0184493 | 0.0049472 |
| K | 47.0 | 0.0187716 | 0.0049539 |
| K | 48.0 | 0.0190942 | 0.0049584 |
| K | 49.0 | 0.0194184 | 0.0049661 |
| K | 50.0 | 0.0197433 | 0.0049616 |
| K | 51.0 | 0.0200685 | 0.0049604 |
| K | 52.0 | 0.0203937 | 0.0049573 |
| K | 53.0 | 0.0207197 | 0.0049523 |
| K | 54.0 | 0.021046 | 0.0049495 |
| K | 55.0 | 0.0213734 | 0.0049372 |
| K | 56.0 | 0.0216586 | 0.0049271 |
| K | 57.0 | 0.021989 | 0.0049154 |
K,58,0.0275009,0.004902,  
K,59,0.028023,0.0048871,  
K,60,0.0280231,-0.0048869,  
K,61,0.0275009,-0.0049018,  
K,62,0.0269788,-0.0049152,  
K,63,0.0264568,-0.0049269,  
K,64,0.0259348,-0.004937,  
K,65,0.0254129,-0.0049454,  
K,66,0.024891,-0.0049521,  
K,67,0.0243692,-0.004957,  
K,68,0.0238474,-0.0049601,  
K,69,0.0233257,-0.0049614,  
K,70,0.0228042,-0.0049608,  
K,71,0.0222827,-0.0049582,  
K,72,0.0217615,-0.0049536,  
K,73,0.0212404,-0.0049469,  
K,74,0.0207195,-0.0049381,  
K,75,0.0201987,-0.004927,  
K,76,0.0196782,-0.0049136,  
K,77,0.0191579,-0.0048978,  
K,78,0.0186378,-0.0048796,  
K,79,0.018118,-0.0048588,  
K,80,0.0175985,-0.0048354,  
K,81,0.0170792,-0.0048093,  
K,82,0.0165603,-0.0047804,  
K,83,0.0160417,-0.0047486,  
K,84,0.0155235,-0.0047139,  
K,85,0.0150057,-0.0046762,  
K,86,0.0144884,-0.0046353,  
K,87,0.0139717,-0.0045912,  
K,88,0.0134557,-0.0045436,  
K,89,0.0129403,-0.0044923,  
K,90,0.0124256,-0.0044373,  
K,91,0.0119117,-0.0043784,  
K,92,0.0113985,-0.0043154,  
K,93,0.0108863,-0.0042482,  
K,94,0.0103753,-0.0041765,  
K,95,0.0098655,-0.0041001,  
K,96,0.0093572,-0.0040186,  
K,97,0.0088504,-0.0039319,
*DO,i,1,58
   L,%i%,%i%+1
*ENDDO
*DO,j,60,116
   L,%j%,%j%+1
*ENDDO
L,117,1
LCOMB,ALL,0
NUMMRG,ALL
NUMCMP,ALL
K,,0.028023,0.0048871,0.736
*GET,maxkp(KP,,NUM,MAX
L,1,maxkp
ADRAG,1,1,2

! Define element type, material properties and real constants
ET,1,SHELL181
KEYOPT,1,1,0
KEYOPT,1,3,0
KEYOPT,1,8,2
!KEYOPT,1,9,0
!KEYOPT,1,10,0
R,1,0.0003  !Real constant - thickness of 0.3 mm

'Section for ET1
SECTYPE,1,SHELL,,C-SPAR1
SECDATA,0.00015,1,45
SECDATA,0.00015,1,-45
SECOFFSET,BOT

! Material properties - THERMAL - (CFRP, T300, Epoxy, Vf = 60%)
MP,EX,1,138.9640e9
MP,EY,1,5.9318e9
MP,EZ,1,5.9318e9
MP,GXY,1,2.28e9
MP,GXZ,1,2.28e9
MP,GYZ,1,5.9318e9/(2*(1 + 0.45))
MP,DENS,1,1560
MP,PRXY,1,0.24
MP,PRXZ,1,0.24
MP,PRYZ,1,0.45
MP,ALPX,1,2.4697e-7
MP,ALPY,1,4.6467e-5
AATT,1,1,1,0,1  !association of element attributes with the selected, unmeshed areas

ESIZE,0.0015
AMESH,ALL

/solu
antype,0  !Static Analysis

!STRUCTURAL CONSTRAINS
DL,1,,ALL,0

ACEL,,9.8

SOLVE
save
FINISH

/POST1
/EFACET,1
    PLNSOL, S,EQV, 2,1.0
Appendix J: Verification of the ANSYS C-spar model

Below is the theoretical calculation and analysis of the similar C-spar geometrically shaped model that is being fixed at one end and undergoes gravitational force to verify the output results determined with the aid of ANSYS software tool, for the similar simulation environment created for untwisted C-spar model.

\[ Y = \frac{1}{8} \frac{wL^4}{EI} \]

\( Y \) – is the displacement magnitude of the opposite end of the model from the constrained end.

Where:

\( L \) – is the length of the model in the span-wise direction

\( w \) – is the weight of the model

\( I \) – is the second moment of inertia of the cross-section of the model

and are found as follows:
\[ L = 0.7344 \ [m] \]

\[ w = gm = \left( \frac{9.81 \left[ \frac{m}{s^2} \right]}{0.7344 \ [m]} \right) \cdot (0.0201 \ [kg]) = 0.197191 \ [N] \]

\[ I = \frac{1}{12}bh^3 = 1.028 \times 10^{-9} \ [m^4] \]

The second moment of inertia was calculated for simplified shaped of C-spar, presented in Figure J.1, and consists of three rectangles.

Therefore, \[ Y = 0.003 \ [m] \]

**Figure J.1:** Simplified C-spar geometrical shape, used as a substitution for the C-spar during theoretical results verification calculations.
Appendix K: ANSYS code for untwisted C-spar residual stress analyses

Below is the residual stress analysis simulation code for untwisted model. Outline of the geometry construction is shortened due to its similarity with the code for the validity analysis model (Appendix G). ANSYS code below presents association of elements SHELL 131 and 181 with the geometrical model. It is thermal and structural combined analysis. Commands and structure of the analyses presented in the code below.

```
FINISH
/CLEAR,START
/CWD,'C:\Documents and Settings\Kostya\My Documents\Kostya\Carleton\SHARCS MAIN\GERMANY\ANSYS\test1'
/TITLE,Csection
/REPLT
/PREP7
K,1,0.0003035,,
K,2,0.0003962,0.0003489,,
K,3,0.0005477,0.0006575,,
.
.
K,116, 0.0005474, -0.0006555, ,
K,117, 0.000396, -0.0003482 , ,
*DO,i,1,58
  L,%i%-%i%+1
*ENDDO

*DO,j,60,116
```
L,%j%,%j%+1
*ENDDO

L,117,1
LCOMB,ALL,,0
!LSYMM,Y,ALL
NUMMRG,ALL
NUMCMP,ALL
K,,0.028023,0.0048871,0.7354
*GET,maxkp,KP,,NUM,MAX
L,1,maxkp
ADRAG,1,,,,,,2
! Define element type, material properties and real constants
ET,1,SHELL131
KEYOPT,1,3,1
KEYOPT,1,4,2
!KEYOPT,1,2,1
KEYOPT,1,6,0
%!NOTE:Attached to the solid tool at the bottom - paint option
R,1,0.0003
%Real constant, set1 - thickness of 0.3 mm
!Section for ET1
SECTYPE,1,SHELL,,C-SPAR
SECDATA,0.00015,1,45
SECDATA,0.00015,1,-45
SECOFFSET,BOT
! Material properties - STRUCTURAL - (CFRP, T300, Epoxy, Vf = 60%)
MP,EX,1,138.9640e9
MP,EY,1,5.9318e9
MP,EZ,1,5.9318e9
MP,GXY,1,2.28e9
MP,GXZ,1,2.28e9
MP,GYZ,1,5.9318e9/(2*(1 + 0.24))
MP,DENS,1,1560
MP,PRXY,1,0.24
MP,PRXZ,1,0.24
MP,PRYZ,1,0.24
MP,KXX,1,11
MP,KYY,1,11
MP,KZZ,1,11
%!association of element attributes with the selected, unmeshed areas
AATT,1,1,1,0,1
%!AATT,mat,real,type(ET),esys,secn
ESIZE,0.0015
%!element size
AMESH,ALL
%!generate nodes and area elements within areas
physics,write,thermal
%!write physics environment as thermal physics,clear
! Define element type, material properties and real constants
ET,1,SHELL181
KEYOPT,1,1,0
KEYOPT,1,3,0
KEYOPT,1,8,2
!KEYOPT,1,9,0
!KEYOPT,1,10,0
R,1,0.0003
!Real constant, set2 - thickness of 0.3 mm

!Section for ET2
SECTYPE,1,SHELL,,C-SPAR2
SECDATA,0.00015,1,45
SECDATA,0.00015,1,-45
SECOFFSET,BOT

! Material properties - THERMAL - (CFRP, T300, Epoxy, Vf = 60%) MP,EX,1,138.9640e9
MP,EY,1,5.9318e9
MP,EZ,1,5.9318e9
MP,GXY,1,2.28e9
MP,GXZ,1,2.28e9
MP,GYZ,1,5.9318e9/(2*(1 + 0.24))
MP,DENS,1,1560
MP,PRXY,1,0.24
MP,PRXZ,1,0.24
MP,PXYZ,1,0.24
MP,ALPX,1,2.4697e-7
MP,ALPY,1,4.6467e-5
AATT,1,1,1,0,1
! association of element attributes with the selected, unmeshed areas
!AATT,mat,real,type(ET),esys,secn
!ESIZE,0.5
!AMESH,ALL

physics,clear

!write physics environment as thermal
physics,write,struct
physics,clear
finish
/solu
antype,0
physics,read,thermal

SFA,ALL,2,CONV,6,25
!Surface loads on the selected Areas
solve
save
finish
/solu
!read in the struct environment
!apply loads derived from thermal environment

physics,read,struct
LDREAD,temp,,,,,,rth
TREF,130
SOLVE
save
FINISH
/POST1
/EFACET,1
   PLNSOL, S,EQV, 2,1.0
Appendix L: C-spar Mold Drawings

Figure L.1: Detail drawing of the Base of the C-spar mold, designed in collaboration with Technical University of Munich, Germany.
Figure L.2: Detail drawing of the upper part of the C-spar mold, designed in collaboration with Technical University of Munich, Germany.
Appendix M: CFD analyses of aerodynamic loads acting on the SHARCS flap unit

The purpose of this work is to produce a surface pressure distribution along the NACA 0015 airfoil in the chord-wise direction, with the deflected flap of 15% of the chord length at the trailing edge of the airfoil. These analyses are needed for further calculation of the flap hinge moments. The pressure distribution was determined through CFD analysis using CMB code and ANSYS ICEM CFD Mesh generator. A NACA 0015 airfoil model has been created with 5° flap deflection angle. These analyses have been run in the following estimated environment: helicopter forward flight at 55 m/s with the rotation of the blades at 162.8 rad/s. All the simulations were done at sea level conditions.

One of the objectives of the SHARCS rotorcraft project is to actuate the flap three times per one revolution of the blade, from which one actuation must be done at the retrieving side, which would lead the following two actuations to be actuated on the advancing side region. Considering a specific element at the center of the flap, the velocity at the flap radius (75%R) on the advancing side has been calculated to be Mach 0.5 (see Appendix M.1). This velocity has been used for CFD simulation and considered as the highest possible load the flap will experience with one rotation.
The SHARCS rotorcraft project team estimated that the maximum angle of the flap deflection will be 4°, yet during the experiments it has been observed that in several specific conditions, the flap appears to be in a resonance state and its deflection becomes as high as 6°. Based on these analyses and observations the decision was finalized to run the CFD simulations for the 5° flap deflection angle.

The airfoil model has been generated using ANSYS ICEM CFD V.10 program, after which it was converted into the CMB code. The mesh has 28,140 nodes. The deflection of the flap is represented by the rotation of all the points of the flap (15% chord) around the flap hinge (Figure M.2.1, Appendix M.2).

Appendix M.2 represents the Cp plot versus airfoil chord as a unit. This plot was created using the resultant data received from the CFD simulation using CMB code. The resultant data was then analyzed and used to calculate the flap hinge moments created by the aerodynamic loads; these calculations were done by another member of the Rotorcraft Group – Fatma Demet Ulker. To prove the validity of the CFD simulations, a new model of NACA 0015 airfoil was created with a 30% chord flap and with 0°, and 5°, angles of flap deflection. New cases were then run with the following angles of attack: 0°, 5°, 6°, 8°, 10°. The resulting hinge moments were then compared to the experimental data and a strong correlation was observed. This proves the validity of the pressure distribution results achieved through CFD analysis.
Appendix M.1: Specific element velocity and corresponding Reynolds number calculation.

\[ x = 668.4 \text{mm} \quad - \quad \text{Location of the center of the flap in the span-wise direction} \]

\[ V_1 = 161.3 \times \frac{\text{rad}}{s} \times 668.4 \text{[mm]} = 107.8 \frac{m}{s} \quad - \quad \text{Angular velocity at the center of the flap} \]

\[ V_2 = 55 \frac{m}{s} \quad - \quad \text{Free stream velocity} \]

\[ V = V_1 + V_2 = 162.8 \frac{m}{s} \quad - \quad \text{Total velocity at the centre of the flap} \]

\[ a_{sl} = 340.29 \frac{m}{s} \quad - \quad \text{Speed of sound at sea level} \]

\[ M = \frac{V}{a} = 0.4784 \equiv 0.5 \quad - \quad \text{Mach speed at sea level} \]

\[ \nu = 1.51 \times 10^{-5} \frac{m^2}{s} \quad - \quad \text{Kinematic viscosity at } T=20^\circ \text{C} \]

\[ L = 0.08 \text{[m]} \quad - \quad \text{Chord length of the SHARCS rotor blade} \]

\[ \text{Re} = \frac{VL}{\nu} = 901430.46 \quad - \quad \text{Reynolds number} \]
Appendix M.2: Visualization of NACA 0015 airfoil mesh.

Figure M.1: NACA 0015 airfoil mesh, Flap angle of deflection = 5°

Figure M.2: Pressure coefficient vs. NACA0015 airfoil chord length. AOA = 10°; δ = 5°
Appendix N: Strain gauges

Below is the detailed drawing of the strain gauges at their locations.
**Strain gauge configuration and specification:**

1) Chord-wise bending strain gauge: \{1-LY4(x)-6/350\}

2) Flapwise bending strain gauge patch: \{1-DY4(x)-6/350\}

3) Torsional strain gauge patch: \{1-XY4(x)-6/350\}
Table P.1: Specifications and size configuration of the selected strain gauges

<table>
<thead>
<tr>
<th>Stock Types</th>
<th>Variants</th>
<th>Nominal resistance</th>
<th>Dimensions (mm)</th>
<th>Max. Perm. Effective</th>
<th>Solder Terminals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ω</td>
<td>Measuring grid</td>
<td></td>
<td>bridge excitation voltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Steel</td>
<td>Aluminum</td>
<td>Others</td>
<td>350</td>
<td>6</td>
<td>2.8</td>
</tr>
<tr>
<td>1-DY41-6/350</td>
<td>1-DY4x-5/350</td>
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<td></td>
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</tr>
<tr>
<td>1-XY41-6/350</td>
<td>1-XY4x-6/350</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1-LY41-6/350</td>
<td>1-LY43-6/350</td>
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<tr>
<td>1-LY4x-6/350</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
<td>350</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Steel</td>
<td>Aluminum</td>
<td>Others</td>
<td>350</td>
<td>6</td>
<td>2.7</td>
</tr>
<tr>
<td>1-DY41-6/350</td>
<td>1-DY4x-5/350</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1-XY41-6/350</td>
<td>1-XY4x-6/350</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>1-LY41-6/350</td>
<td>1-LY43-6/350</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-LY4x-6/350</td>
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