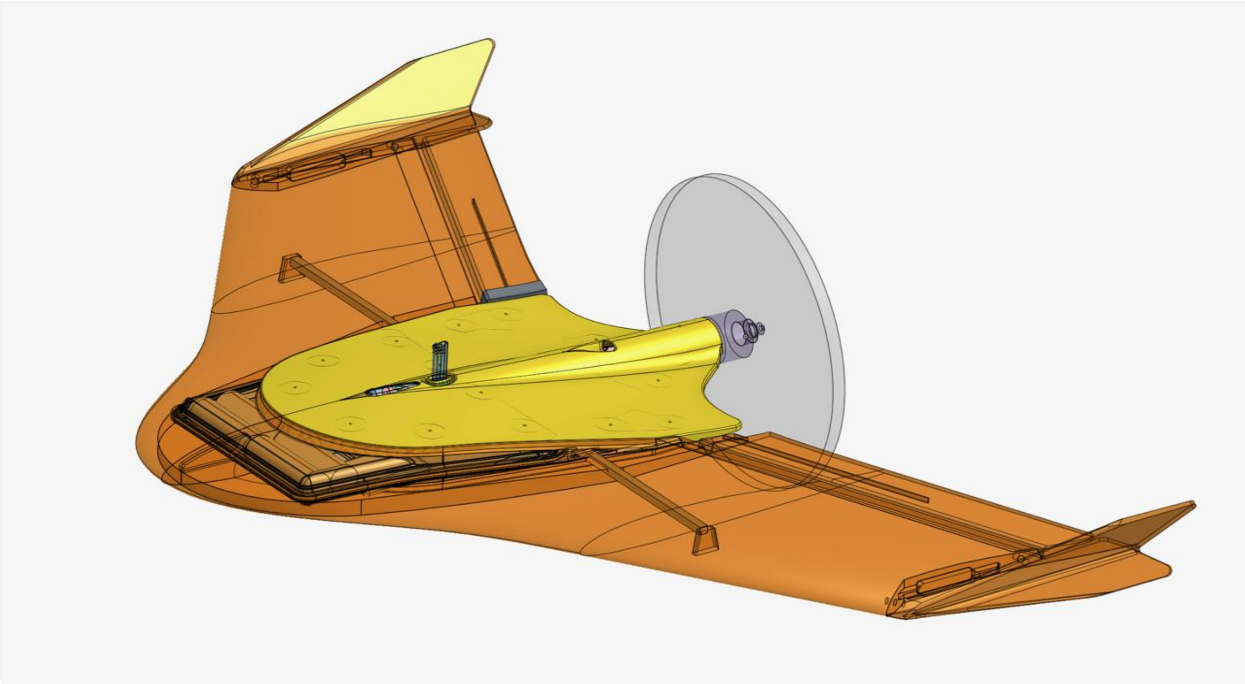

Winged drone impact study

Examensarbete inom högskoleingenjörsprogrammet maskinteknik

Olof Johansson
Måns Modig

INSTITUTIONEN FÖR
MEKANIK OCH MARITIMA VETENSKAPER

CHALMERS TEKNISKA HÖGSKOLA
Göteborg, Sverige 2024
www.chalmers.se

Winged drone impact study

Examensarbete inom högskoleingenjörsprogrammet maskinteknik

OLOF JOHANSSON

MÅNS MODIG

Institutionen för Mekanik och Maritima vetenskaper
Avdelningen för fordonssäkerhet
CHALMERS TEKNISKA HÖGSKOLA
Göteborg, Sverige 2024

Winged drone impact study

Examensarbete inom högskoleingenjörsprogrammet maskinteknik
OLOF JOHANSSON
MÅNS MODIG

Institutionen för Mekanik och maritima vetenskaper
Avdelningen för fordonssäkerhet
Chalmers tekniska högskola
SE-412 96 Göteborg
Sverige
Telefon: + 46 (0)31-772 1000

Omslag:
Bevingad drönare utvecklad av SSRS

Tryckeri /Institutionen för Mekanik och maritima vetenskaper
Göteborg, Sverige 2024

Abstract

The Swedish Sea Rescue Society (SSRS) is planning to start using a remotely piloted UAV with a camera to gain faster access to information about active accident sites in the archipelago. With images from the accident site, decisions about the size of rescue boats can be made more effectively and provide a psychological advantage for the personnel.

The UAV that has been developed is of the flying wing type constructed in EPP, which is a soft foam material. As the UAV in many cases will need to fly beyond the operator's line of sight, the Swedish Transport Agency requires SSRS to present a risk assessment according to a format called SORA (Specific Operations Risk Assessment). SSRS is currently in the final stages of the assessment where potential risks associated with the use of the UAV are being examined. In a previous thesis conducted for SSRS, the risks of potential skull fractures in humans if the UAV were to fall were investigated, but no previous studies have been conducted on the potential impact of the UAV on other aircraft in the event of a collision until now.

Interviews with Fredrik Falkman at SSRS and former helicopter pilot Paul Hedrén, as well as a literature review, were conducted. With information from these sources, potential aircraft that the UAV could theoretically encounter in the airspace over the archipelago and their most sensitive components were determined. Technical documents from helicopter manufacturers were also used to determine safety factors during loads. A mathematical collision model was established for the UAV and its collision scenarios with the various critical components.

The different components were then modeled in Catia V5 or retrieved from CAD libraries online to be used in collision simulations in Ansys Workbench using the LS-DYNA plugin tool. In Ansys, several different collision scenarios were created for each component depending on the angles of incidence and velocity directions for the different components.

The results show that the UAV, with its lightweight and soft foam material, as well as the durable materials of helicopters, should not cause any damage to critical components in the event of a collision.
For the future, real tests should be conducted using a test rig where the UAV can be propelled towards materials of the same type as the used collision components to see if the simulated results are accurate.

Keywords

UAV, Risk assesment, Critical components, Collision simulating, LS-DYNA

Sammanfattning

Sjöräddningssällskapet (SSRS) planerar att börja använda sig av en fjärrstyrd drönare med kamera för att få tillgång till snabbare information om aktiva olycksplatser i skärgården. Med hjälp av bilder från olycksplatsen kan beslut om storlek på räddningsbåt bli effektivare samt ge en psykologisk fördelning för personalen.

Drönaren som utvecklats är av typen flygande vinge konstruerad i EPP, som är ett mjukt skummaterial.
Då drönaren i många fall kommer behöva flyga utanför synhåll för operatören, kräver Transportstyrelsen att SSRS presenterar en riskbedömning enligt ett format som kallas för SORA (Specific Operations Risk Assessement). SSRS är för tillfället i slutskedet av bedömningen där eventuella risker som användandet av drönaren kan leda till undersöks. I ett tidigare examensarbete som gjorts åt SSRS undersöktes riskerna för eventuella skallfrakturer hos människor om drönaren skulle falla, men inga tidigare studier har gjorts på drönarens eventuella inverkan hos andra flygfordon vid en eventuell kollision förrän nu.

Intervjuer med Fredrik Falkman på SSRS samt tidigare helikopterpilot Paul Hedrén samt en litteraturstudie genomfördes. Med hjälp av information från dessa källor kunde potentiella flygfordon som drönaren teoretiskt sett kan stöta på i luftrummet över skärgården samt deras känsligaste komponenter bestämmas. I tekniska dokument från tillverkare av helikoptrar kunde också säkerhetsfaktorer vid laster bestämmas. En matematisk kollisionsmodell upprättades för drönaren samt dess kollisionsscenarion med de olika kritiska komponenterna.

De olika komponenterna modellerades sedan i Catia V5 eller hämtades från CAD bibliotek från nätet för att kunna användas i kollisionssimulering i FEM mjukvaran Ansys Workbench med hjälp av plugin verktyget LS-DYNA. I Ansys skapades flera olika kollisionsscenario för varje komponent beroende på kollisionens infallsvinklar samt hastighetsriktningar för de olika komponenterna.

Resultaten visar att drönaren, med dess lätta vikt och mjuka skummaterial samt helikoptrars tåliga material, inte bör orsaka någon skada på kritiska komponenter vid en eventuell kollision.
För framtiden bör riktiga test genomföras med hjälp av en testrig där drönaren kan slungas mot material av samma typ som komponenterna för att se huruvida de simulerade resultaten stämmer.

Nyckelord

Drönare, Riskbedömning, Kritiska komponenter, Kollision simulering, LS-DYNA

Acknowledgements

This report presents the work and results that were produced in the course MMSX25 (15 credits) at the Department of Mechanics and Maritime Sciences, Chalmers University of Technology. The work was carried out during the spring semester of 2024 by students in the Bachelor of Science in Mechanical Engineering program (180 credits) on behalf of the non-profit organization Swedish Sea Rescue Society via Sigma Energy & Marine.

The examiner and supervisor for the project was Robert Thomson, assistant head of department and professor at the department of Mechanics and Maritime Sciences at Chalmers University of Technology.
Manager of Design Engineering at Sigma Energy & Marine, Fredrik Borg acted as external supervisor at the company. Client and contractor was Fredrik Falkman, Innovation Engineer at SSRS.

We would like to express our deepest gratitude to all the people mentioned above, as well as to all the personnel at Sigma Energy & Marine for taking their time to listen to our interim reports along the way.

We would also like to thank Jim Brouzoulis, at the department of Mechanics and Maritime Sciences at Chalmers University of Technology for providing answers related to Ansys software.

A special thanks to Paul Hedrén, former helicopter pilot, for taking his time to share his knowledge about aircrafts and their functionality.

Table of contents

1. Introduction to thesis

SSRS is a non-profit association that conducts maritime rescue operations [1]. The organization intends to introduce unmanned aerial vehicles (UAV) into its operations to facilitate maritime rescue work. Currently, it is not permitted to fly UAVs beyond line of sight. This means that operators are forced to control the UAV from the rescue boat instead of using it pro actively to gain a better overview of the accident site.

Obtaining information about the accident site in advance is crucial from both a logistical and psychological perspective. It enables rescue personnel to assess in advance what type of boat is needed for the accident while mentally preparing them for the situation ahead. SSRS believes this can increase the chances of accidents not escalating into life-threatening situations.

For SSRS to be able to use their UAVs in their daily operations they first must prove to governing authorities that their UAV will not pose any danger to anyone that they risk colliding with.

The UAV intended for use is a fixed-wing aerial vehicle measuring approximately 80 cm between the wings and weighing around 0.9 kg. The UAV has a maximum speed of approximately 30 m/s. The UAV is planned to have both GPS and cameras installed to facilitate navigation and visibility.

1.1 Purpose

The purpose of this study is to practically investigate how an UAV can affect other aircraft in the event of a collision by simulating different collision scenarios using FEA. Despite the minimal risk posed by the UAVs design and weight to larger aircraft such as helicopters and airplanes, complications may arise if the UAV collides with, for example, a helicopter's main rotor hub.

1.2 Problem

Two questions that complicate SSRS's use of UAVs are:

1. Are there any airborne vehicles that the UAV may collide with given its operating location?
2. Would a collision with a critical component of another airborne vehicle pose any risk of damaging that component?

If these questions are answered when the regulations regarding UAVs change, it could expedite the process for SSRS to put their UAVs into use. A previous thesis from 2021 addressed the probability and consequences of low altitude collisions with humans, but the question regarding the forces that occur in the event of a collision and the potential consequences of these remained unanswered [2].

1.3 Delimitations

The study will only consider the type of UAV developed by SSRS.

The study will not provide information on how collisions can be avoided or develop improvement proposals on construction and material selection to reduce risks.

Given that the UAV will operate in the archipelago, this study will focus solely on analyzing collisions involving other airborne vehicles that could potentially operate within this area.

The study will only address the consequences of the impulse generated by the collision itself and will not address any potential consequences of drone parts detaching upon collision.

2. Operating events and properties of the UAV

In this chapter a quick summary of how the UAV is planned to be used by SSRS is given. The UAV's technical and material properties are also explained further.

2.1 Operating events

According to Fredrik Falkman at SSRS [3] the typical series of events leading up to UAV use would be:

1) A rescue call is made to the SSRS from a location at sea.

2) The rescue team assemble to prepare for the mission.

3) The drone operator launches the drone which aims to get to the location before the rescue team leaves. If not, the team will not wait for the information gathered by the UAV.

4) In the event of early information from the UAV, decisions may be made for different sizes of boats or specific equipment to bring. The information gathered can consist of location specifics such as narrow pathways or ongoing emergences that were not communicated in the first rescue call.

5) The UAV circles the location until the rescue team arrives.

6) The drone operator lands the UAV in the water, and it is picked up by the rescue team on their way back to headquarters.

2.2 Operating properties

The UAV is designed to operate at a maximum altitude of 30 meters above sea level to ensure maximum safety while also optimizing its performance. During takeoff and shortly after, it will reach a maximum velocity of approximately 30 m/s to enable a swift deployment to the rescue location. Once it reaches its targeted area, the UAV will transition to a slower circling speed when surveying the location to allow for more precise and comprehensive imagery capture of the location in question. The UAV will be able to be used beyond line of sight of its operator.

2.3 Design & material properties

The UAV consists of three main parts: the body with two wings and a solid, removable cassette containing GPS, camera and battery and the propulsion system. The body itself will be made of Expanded Polypropylene (EPP) foam. The EPP foam is a soft material with the following material properties as seen in Table 2.1.

Table 2.1: Material properties of EPP

Material property	**Value**
Density	55 *[kg/m^3]*
Young's modulus	6 *[MPa]*
Poisson's ratio	0.28460
Tensile Yield Strength	0.2 *[MPa]*
Tensile Ultimate Strength	0.6 *[MPa]*

The energy absorption of EPP foam is a key property to why this material is being used in drones. To further protect the more valuable parts of the UAV in case of a collision, this specific UAV will also contain a deformation zone of approximately 3.5 cm between the “nose” and the solid cassette containing GPS, camera and engine. A detailed CAD view of the UAV is presented below in Figure 2.1.

The solid, removable cassette holding the vital and fragile parts is made of 5 thin layers of polycarbonate (PC). A better overview of the UAVs physical properties is presented in Table 2.2.

Table 2.2: Physical properties of the UAV

Weight	0.9 kg
Wingspan	0.8 m
Width	0.7 m
Center of mass	0.225 m behind drone nose
Material UAV	Expanded polypropylene (EPP) foam
Material “cassette”	Polycarbonate (PC)

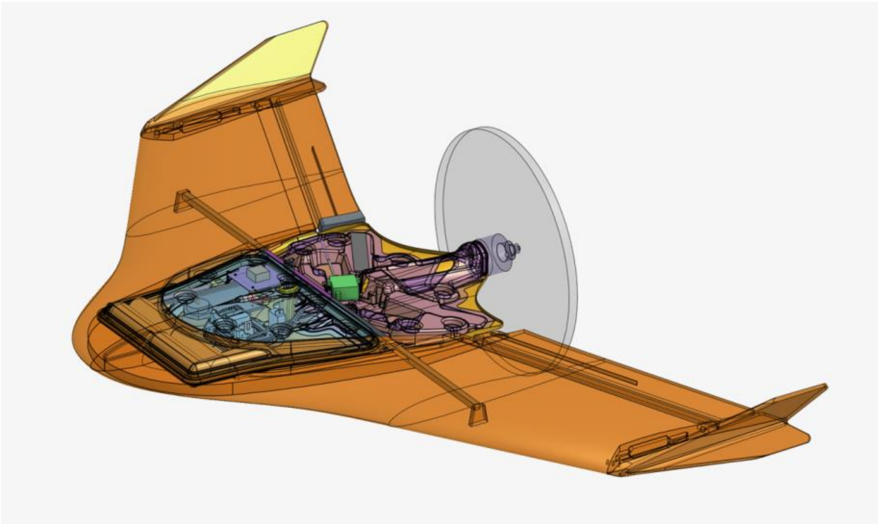

Figure 2.1: The UAV showcasing all components.

3. Method

3.1 Risk assessment and regulations

The risk assessment was consisted of a literature study and interviews with helicopter pilot Paul Hedrén. By comparing the results from the literature study with the interviews the most probable collision objects and their critical components could be identified.

3.2 Mathematical model

A mathematical model of the collisions was developed to be able to verify the results from the simulations. An equation to calculate the deformation of the collision object using beam theory was used.

3.3 CAD models

The CAD models used for the simulations were either provided by SSRS, developed using the CAD software Catia v5 or downloaded from the CAD forum GrabCAD.com. To further prepare the models for simulations they were adjusted in Spaceclaim in Ansys.

3.4 Simulations

The software used for the collision simulations was the FEA software Ansys with plug in tool LS-Dyna. The correct boundary conditions were set to simulate the real-life conditions of the collision to provide the most accurate results. To determine the critical collision scenarios a risk assessment was made. The risk assessment was consisted of a literature study and interviews with helicopter pilot Paul Hedrén. By comparing the results from the literature study with the interviews the most probable collision objects and their critical components could be identified.

4. Risk assessment and regulations

4.1 European Aviation Safety Agency

The European Aviation Safety Agency (EASA) is an EU agency responsible for ensuring aviation safety and promoting environmental protection in the European Union. Regarding Unmanned Aerial Vehicles (UAVs), EASA has been actively involved in regulating their operation to ensure safety and integration into airspace alongside manned aircraft. EASA has developed regulations and standards for UAVs, covering aspects such as registration, pilot licensing, and operational rules. These regulations aim to address safety concerns while fostering innovation and growth in the UAV industry within the EU [4].

There are three different categories, presented below in Figure 4.1, that the UAVs are divided into depending on its design and how it will be operated. Depending on which category the UAV falls under the regulations will vary [5].

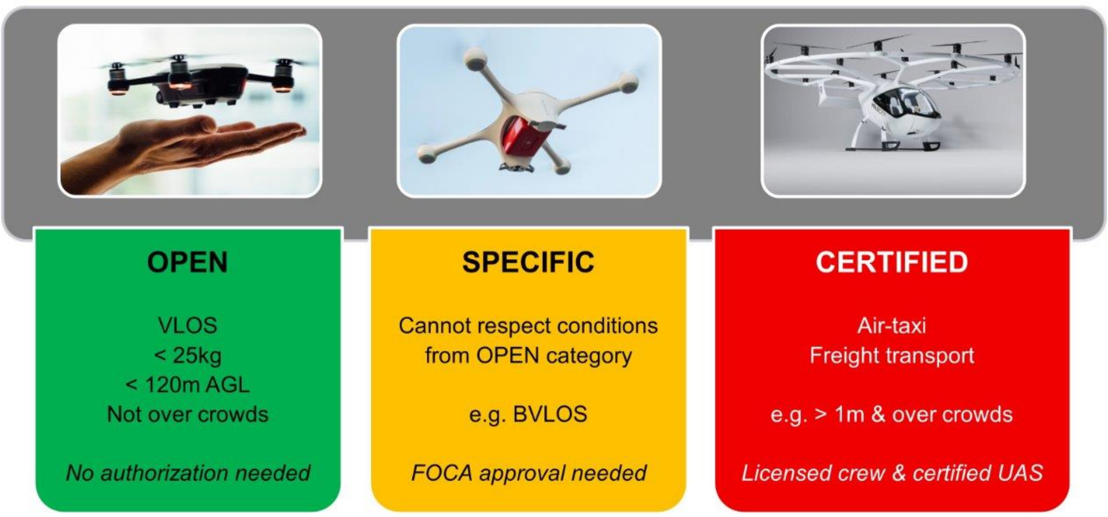

Figure 4.1: Regulation categories for UAVs.

4.2 Open category

The open category is intended for UAV operations with the least risk of harming or interfering with other vehicles, animals, people or the environment in general. No prior authorization is needed. However, it is not permitted to fly beyond visual line of sight which makes the UAV used by SSRS invalid for this category.

4.3 Specific category

If one of the criteria for the open category is not met, the UAV will fall under the specific category. UAV operations in the specific category must receive an operational authorization for its intended use. This is the classification under which SSRS operations will be categorized. The required authorization for this case would be a SORA (Specific Operation Risk Assessment), which is a method for risk analysis where SSRS needs to describe how UAV will be used and prove that they maintain a sufficiently high level of safety.

4.4 Certified category

UAV operations with high risk for the public requires both certification and registration of the drone itself. Such operations may include flying over assemblies of people, transporting people or dangerous goods that may result in high risk for third parties in case of an accident.

4.5 Specific Operations Risk Assessment

As mentioned above, the UAV operations conducted by SSRS will be classified within the specific category. To obtain permission to fly the UAV beyond line of sight in the archipelago area, a risk analysis for the intended use, known as SORA, must be conducted.

The Specific Operations Risk Assessment (SORA) is a systematic approach designed to evaluate and manage the risks associated with the operation of unmanned aircraft systems (UAS), commonly known as drones, within specific operational contexts. Developed by the EASA, SORA provides a structured framework for assessing the risks posed by UAS operations and implementing appropriate risk mitigation measures.

The process involves ten steps which can be summarized into assessing the risk of a drone hitting a person (GRC) and colliding with other aircraft (ARC). After implementing mitigating measures, determining the final GRC and remaining ARC is crucial. Compliance with performance requirements to reduce collision risks and defining safety objectives are key steps. Finally, creating a safety portfolio to demonstrate risk reduction measures and regulatory compliance is essential [6]. At the time of this thesis, SSRS has started a SORA process.

4.6 Possible encounters

The UAV developed by SSRS will operate at an altitude of 30 meters. Nonetheless, an additional buffer zone of 30 meters may need to be considered due to the challenges associated with remotely steering the UAV and maintaining a precise altitude. Consequently, a more accurate risk zone for potential collisions with other airborne vehicles extends to 60 meters.

Based on interviews with helicopter pilot Paul Hedren and prior investigations conducted by SSRS, several additional types of vehicles capable of operating at this altitude in the archipelago have been identified. These include ambulances, rescue and police helicopters, smaller recreational helicopters, and recreational sea airplanes. However, none of these vehicles should typically occupy the airspace on this altitude except during take-off, landing, and potentially when helicopters are undergoing loading procedures. These are the vehicles most susceptible to colliding with UAVs, presenting potential safety hazards [7]. If a helicopter operates below an altitude of 60 meters, its average velocity is expected to be 5 m/s according to research made by SSRS.

4.7 Critical components of a helicopter

In our talks with the helicopter pilot Paul Hedrén we identified three main components that may be exposed to the drone whilst also being critical to the helicopter's overall functionality. The smaller the helicopter or airplane, the higher risk the collision is of becoming dangerous. Larger vehicles often have better reinforced components that can withstand higher forces upon impact [7].

Figure 4.2: 1. Windshield, 2. Pitch-links, 3. Tail rotor

4.7.1 Windshield

Windshields pose the greatest risk of collision due to their larger surface area and forward-facing orientation. The design of windshields varies depending on the type of helicopter. Generally, smaller helicopters have more fragile windshields, while larger helicopters are equipped with sturdier windshields often certified to withstand bird strikes, which may be to some extent comparable to impacts from UAVs.

If a collision with the windshield were to occur, a UAV might potentially penetrate the cockpit. This would not affect the helicopters critical functions, however if the UAV strikes or disorients the pilot it could have serious consequences.

4.7.2 Pitch-links

If the pitch-links of a helicopter are damaged, it can have serious consequences for the helicopter's flight capability and stability. Pitch-links are crucial components used to control the helicopter's main rotor blades, thus adjusting the lifting force and steering. Their primary function is to alter the angle of the rotor blades and thereby the steering and maneuvering of the helicopter. Depending on the extent of the damage, the helicopter's pilot may lose the ability to control altitude, direction, and rotation, increasing the risk of a serious accident.

The pitch-links are small and not very likely to be struck in a collision as they are protected by the main body of the helicopter and the main rotary blades. However, their diminutive size also renders them potentially vulnerable to direct strikes from flying objects, such as UAVs. The pitch links are marked in Figure 4.3 below.

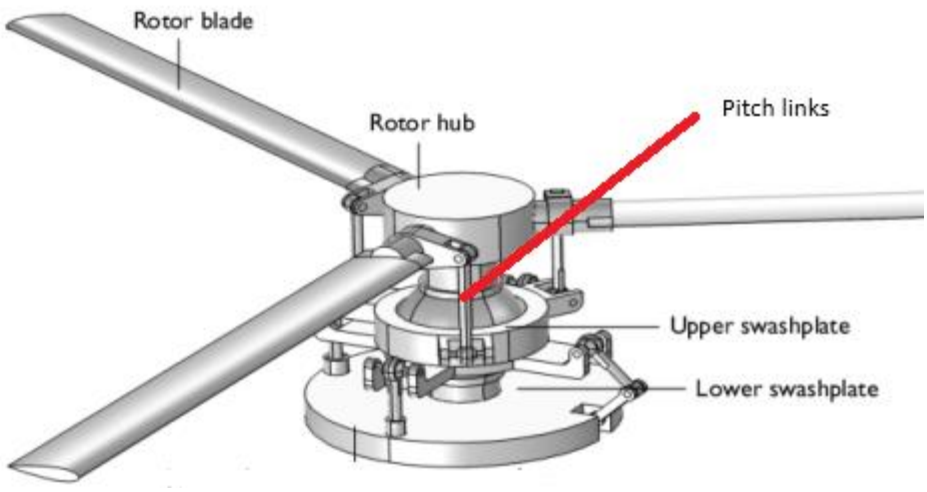

Figure 4.3. Detailed view of the rotor hub and the pitch link.

4.7.3 Tail rotor

The tail rotor assists in counteracting the torque generated from the main rotor, preventing the helicopter from spinning out of control due to this torque. While it is possible to fly and land the helicopter safely with the tail rotor out of function, it could pose a serious issue if the helicopter at the time of the collision carries a hanging load.

4.8 Air worthiness of helicopter

Helicopter manufacturers are obligated to comply with regulatory standards during the design and fabrication phases to ensure the airworthiness of their aircraft. These standards encompass various criteria, including the structural integrity demands imposed on individual components. Within Europe, the European Union Aviation Safety Agency (EASA) assumes responsibility for promulgating these regulations. Compliance requirements vary depending on the classification of the rotorcraft. For instance, smaller rotorcraft such as the Jet Ranger fall under the purview of CS27 [8], Certification Specifications for Small Rotorcraft, while larger counterparts like the AW139 adhere to CS29 [9].

4.8.1 Factor of safety

In the previously mentioned documents, CS27 and CS29, it is stated that *"Unless otherwise provided, a factor of safety of 1.5 must be used. This factor applies to external, and inertia loads unless its application to the resulting internal stresses is more conservative*" [8,9].

4.8.2 Bird strike

It is not uncommon for helicopter pilots to encounter birds while flying. There are multiple known collision cases between birds and helicopters, in which some have resulted in serious damage to the helicopter or even the pilot. The UAV is not completely unlike a bird in terms of geometry and occurrence in the airspace and could therefore be compared to one another in the case of a collision. Previously made studies have shown that a collision between an UAV and a helicopter will be more dangerous due to the bird having more fluid mechanical properties than a rigid UAV [10].

Some helicopters, mostly larger ones, can receive a certificate that proves they are able to withstand bird strikes. The criteria for receiving this certificate according to EASA CS 29.631 is as follows: “The rotorcraft must be designed to ensure capability of continued safe flight and landing (for Category A) or safe landing (for Category B) after impact with a 2.2-lb (1.0 kg) bird when the velocity of the rotorcraft (relative to the bird along the flight path of the rotorcraft) is equal to VNE or VH (whichever is the lesser) at altitudes up to 8,000 feet” [9]. This criterion could be used to determine whether a collision with SSRS UAV will be dangerous to the helicopter or not when struck on the windshield.

5. Mathematical model of the impact

To verify the results from the simulations in LS-Dyna, a mathematical model was developed. Only one collision case will be used to verify the simulation in the results chapter.

5.1 Deformation of the pitch links

To calculate the deformation of the pitch links, they will be modeled as beams fixed at both ends (Figure 4.3).

$$\Delta_{max} \text{ (at point of load)} = \frac{\mathrm{Fa^3b^3}}{\mathrm{3EIL^3}} \quad (5.1)$$

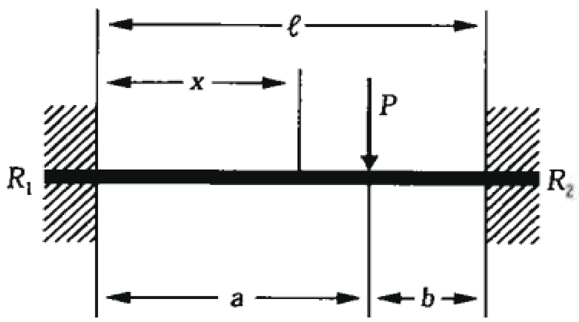

Figure 5.1: Beam fixed at both ends elementary case [11].

The rotation of the pitch links around the rotor hub will lead to a higher collision velocity. To calculate the velocity of the pitch links due of the rotation the following equations will be used:

$$v = \omega * r \quad (5.2)$$

$$\omega = n\frac{2\pi}{60} \quad (5.3)$$

n is equal to revolutions per minute. For the main rotor this number is approximately 300 rpm.
ω is equal to the angular velocity of the pitch links.
r is equal to the radius between the pitch links and their rotational center.

5.2 Deformation of the tail rotor blade

The deformation of the tail rotor blade will also be modeled as a cantilever beam. It will feature a fixed support in one end at the rotor hub and will be free in the other end. The rotation of the tail rotor blade will be neglected as the equations needed to calculate this are deemed too complex for this project. Below equation is used to calculate the deformation the rotor blade:

$$\Delta \text{ (at point of load)} = \frac{Fb^3}{3EI} \quad (5.4)$$

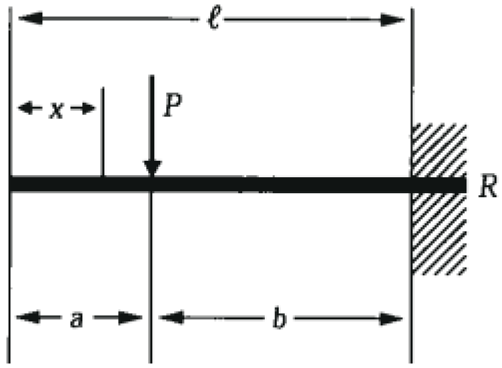

Figure 5.2: Cantilever beam elementary case [11].

5.3 Deformation of the windshield

The deformation of the windshield could theoretically be modelled as a rectangular plate fixed at all edges and subjected to a point load. As the local curvature of the windshield is deemed too complex to use as verification, and the windshield deemed to be the least dangerous component when struck by the UAV, a mathematical model of this component was not made.

6. CAD Models

To prepare for the simulation in LS-Dyna the collision objects were either developed using CAD-software Catia v5, Spaceclaim or downloaded from Grab-CAD.

6.1 Modelling the UAV

The UAV CAD model was provided by SSRS. For a better simulation experience the UAV design has been simplified without excluding key components of a collision test. The winglets were removed due to their complex geometry making meshing more difficult.
The cassette containing the fragile components is not modelled. With EPP assigned as material to the model, the final mass is roughly 0.2 kg. A point mass of 0.7 kg is added at the location of the missing cassette to make up for the missing weight due to geometry defeature. This makes the final weight 0.9 kg.

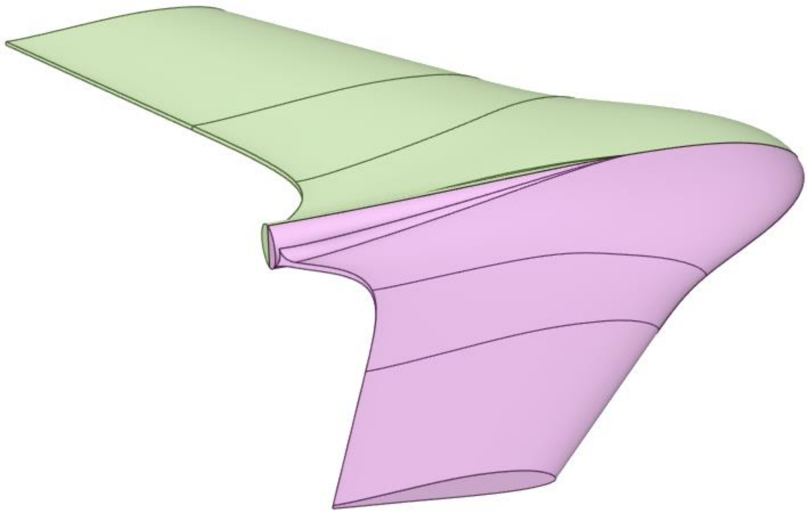

Figure 6.1: CAD model of the UAV.

6.2 Modelling the windshield

The windshield model used for simulation was downloaded from [12]. It has the same geometry and dimensions used on the Bell 429 helicopter. While it does not fully represent the windshield of an AW139 helicopter, the thesis's primary focus, it is deemed good enough for approximately measuring the stress. Boundary conditions, which is the same for both helicopters, play a much bigger role in receiving an accurate result than exact geometry if the impact is simulated at a distance from the boundary conditions.

Material used was PMMA (cast sheet). PMMA was chosen due to it being the least durable of the two types of helicopter windshield materials, the other being laminated glass.

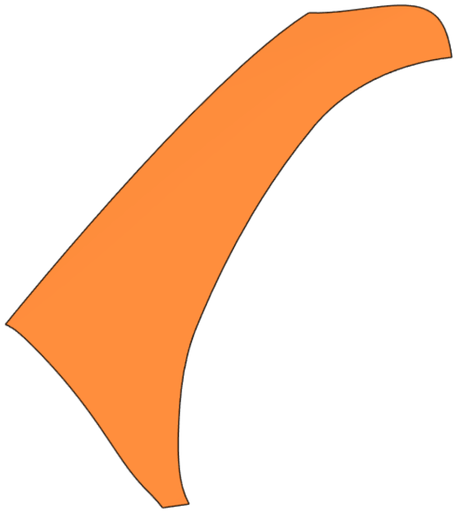

Figure 6.2: CAD model of Bell 209 windshield.

6.3 Modelling the pitch-link

The pitch-link was modelled using Ansys Spaceclaim. It is modelled as a solid rod with the following dimensions:
Length: 300 mm.
Radius: 10 mm.
The material used was titanium alloy [13].

Figure 6.3: CAD model of AW139 pitch-link.

6.4 Modelling the tail rotor blade

A tail rotor blade was modeled using Catia v5. To determine the appropriate size, dimensions, and materials of the blade technical documentation for the AW139 helicopter model and previously made collision studies were reviewed. It was found that the structure of the blades is very complex and varies among different helicopter models. Most of the rotor blades are made up of two parts: the core with a honeycomb structure and the spar which is attached to the rotor hub. The blade is typically constructed from aluminum alloys or carbon fiber reinforced polymers on the more modern models [12,13].

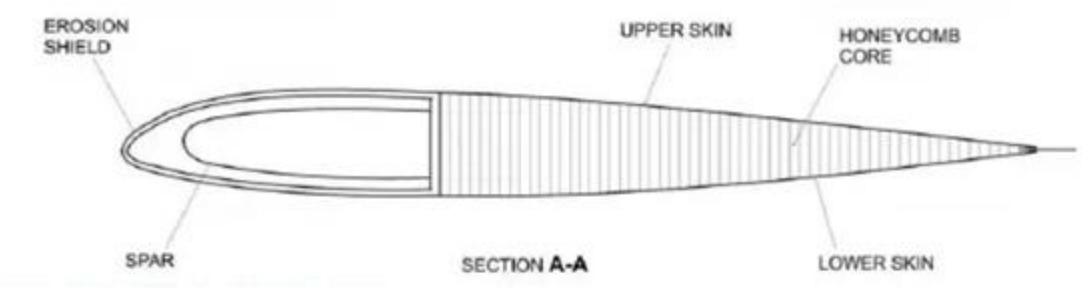

Figure 6.4: Structure of a tail rotor blade.

With these designs as inspiration a simplified rotor blade was modeled, which is shown in Figure 6.5, below. It consists of the honeycomb core, the spar which connects the blade to the rotor and a protective skin.

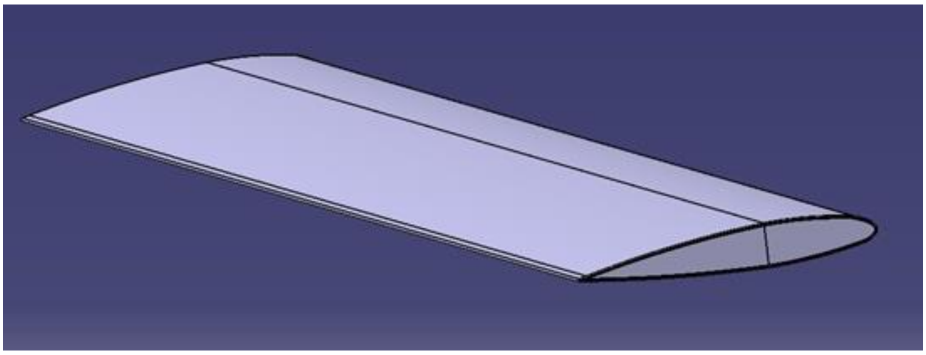

Figure 6.5: CAD model of tail rotor blade.

6.5 Narrowing down the scope

Due to this project's time limits, a decision was made to focus on the windshield and pitch links. The selection for which components to proceed with for the simulations were based on the probability of being involved in a collision and the severity of the consequences in the event of a collision. The probability of the component being involved in a collision was based on the surface area of the component where the windshield has the largest surface area and the components orientation. The severity of the collision was based on the opinion from helicopter pilot Paul Hedrén.

7. Preparing the finite element analysis

The FEA will be done in Ansys workbench using the plug-in tool LS Dyna which is an extremely powerful 3D Finite element analysis program. LS-Dyna employs an explicit FEM formulation, making it ideal for simulating high speed collisions and dynamic events. Explicit methods are well-suited for scenarios where inertia effects dominate and rapid changes occur within short time frames, such as impact events and crashes. It also serves as an ”all in one” software which offers both geometry generating (CAD), geometry setup, material assignment, boundary conditions, load setup and much more, making it ideal for our thesis.

The preparation was aided by senior lecturer Jim Brouzoulis at the department of Mechanics and Maritime Sciences at Chalmers University of Technology.

7.1 Geometry setup

To set up a scenario where the impact between the UAV and the helicopter component happens immediately the two CAD files were imported into Ansys geometry interface SpaceClaim. The two models were then aligned so that their boundaries were just touching each other. This is done so that our end time (simulation time) can be highly reduced to save computational time. Figure 7.1 showcases a load case involving the pitch link aswell as the coordinate system used.

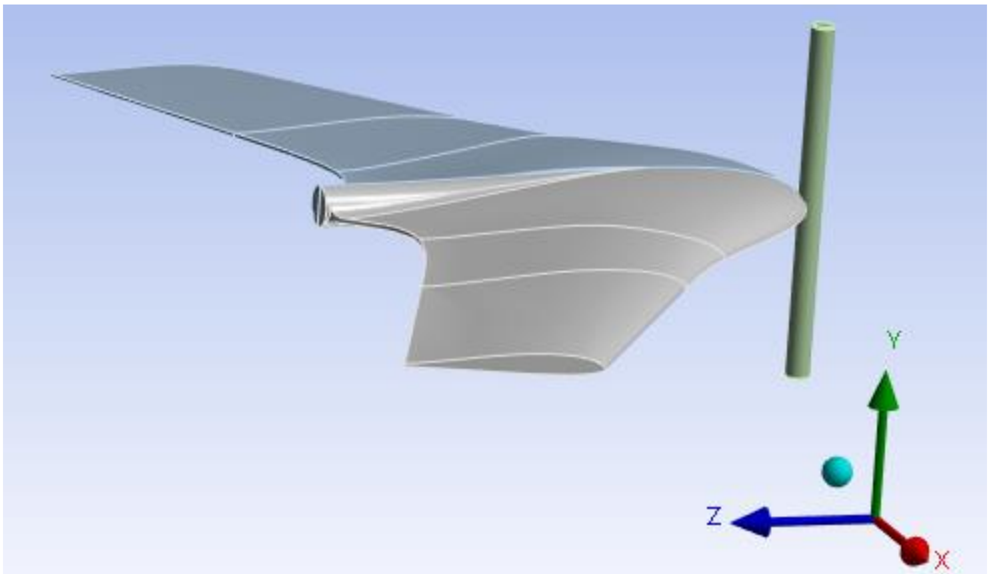

Figure 7.1: Geometry setup and coordinate system.

7.2 Meshing

A good mesh is crucial for achieving accurate and reliable results in FEA simulations. It serves as a discretization of the geometry, dividing it into small elements that approximate the system's behavior. To counter the complex geometry of some of the models, the mesh element type used was tetrahedral meshing. Tetrahedral elements can conform well to curved boundaries (such as the UAV body or the windshield model) allowing for accurate representation of geometric features without excessive refinement.

In talks with our supervisor, Robert Thomson, the decision was made to use a mesh element size of 5 mm on the analyzed components. This is due to it being the standard mesh element size in the industry when conducting collision simulations.

7.2.1 Meshing the UAV model

The meshing of the UAV was done using a single body sizing mesh command. As the UAV is not of primary interest in this analysis there was no need for the 5 mm size as used on other components.
Mesh element size used was 20 mm.
This resulted in 13 303 elements.

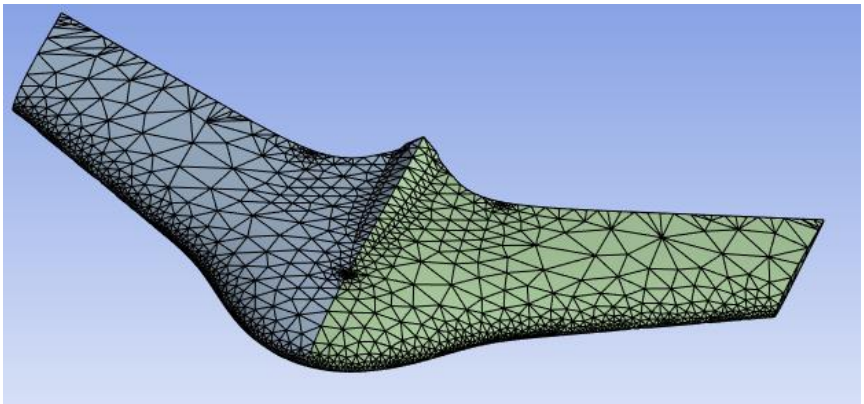

Figure 7.2: Generated mesh on the UAV

7.2.2 Meshing the windshield model

The meshing of the windshield was done using a single body sizing mesh command.
The mesh element size used was 5 mm.
This resulted in 16 808 elements.

Figure 7.3: Generated mesh on the windshield.

7.2.3 Meshing the pitch-link model

The meshing of the pitch link rod was done using a single body sizing mesh command.
The mesh element size used was 5 mm.
This resulted in 5616 elements.

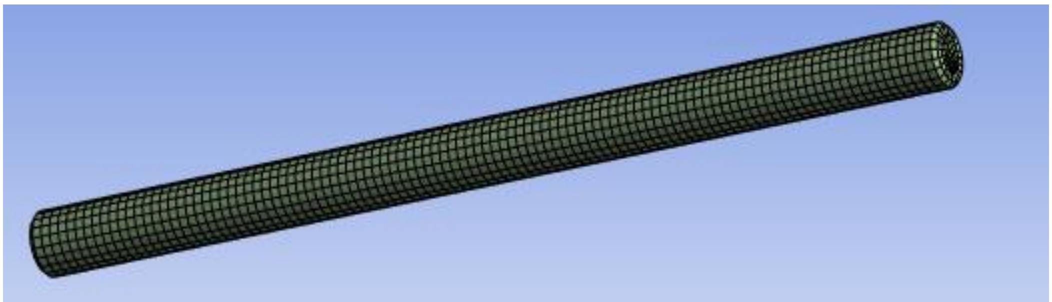

Figure 7.4: Generated mesh on the pitch-link.

7.2.4 Stress singularities and mesh refinement

In simulations conducted with Ansys, stress singularities present a challenge due to their potential to compromise the accuracy and the results of analyses. Stress singularities refers to areas within a model where stress levels become infinitely high that usually occur at geometry features such as fillets, sharp corners or other areas of change in geometry or material properties. As some of the models used in this project exhibit these properties that may result in stress singularities, mesh refinement was used to try to counter this. The mesh refinement command in Ansys provides the user with a tool to enhance the accuracy of the finite element models by allowing the refinement of the mesh element size in specific regions of interest. Regions of interest in this case were determined to be surfaces and edges close to the fixed supports where the maximum stress levels theoretically would appear. Edge fillets were also added to models to avoid sharp corners causing stress concentrations.

To evaluate whether a result is correct or a stress singularity, a parameter study of element size and maximum equivalent stress will be made. If, when reducing the element size of studied model, the equivalent stress is increased it is highly likely that it is the result of a stress singularity and may be ignored. If the maximum equivalent stress converges, it is not considered a stress singularity.

7.3 Initial conditions

In Ansys LS Dyna, three distinct options are available for defining initial conditions:

- **Velocity:** This option is used to apply an existing velocity to the model at the simulation's start. Velocities can be specified either as vectors or components.

- **Angular velocity:** Used to apply an angular velocity that is already acting upon the model when the simulation starts. Angular velocities can be specified either as vectors or components. This would theoretically be used in the cases involving the pitch-link but is left out due to the swashplate not being modelled. Instead, a load case considering the tangential velocity of the rotation is added to the study.

- **Drop height:** This option enables the application of a specific height to a model from which it undergoes free fall during the simulation. Given that the impacts under investigation in this thesis are strictly horizontal, this initial condition will not be utilized.

7.3.1 Initial conditions of the UAV

The UAV will commence simulations with an initial velocity of 30 m/s, representing its maximum operational speed. If analyses indicate potential structural stress issues at this velocity, subsequent trials will involve lower velocities to assess compliance with requirements. The velocity will be applied in different directions depending on the load case studied. No initial angular velocity will be applied to the UAV.

7.3.2 Initial conditions of the windshield

The windshield will be assigned an initial velocity of 5 m/s, reflective of typical helicopter surveying speeds. This velocity will oppose the UAV's motion, directed along the -z axis, akin to scenarios where the helicopter encounters the UAV during survey missions. No initial angular velocity will be applied to the windshield.

7.3.3 Initial conditions of the pitch-link

Like the windshield, the pitch link will be initialized with a velocity of 5 m/s, with the same reasoning as for windshield conditions. One load case will also feature a scenario where the UAV is instead hit by the pitch-link with a tangential velocity due to the rotating swashplate. This tangential velocity is calculated to approximately 6 m/s on top of the previously mentioned 5 m/s using Eq. 4.9 and Eq. 4.10.

7.4 Loads and boundary conditions

To emulate real-world impact scenarios, gravitational loading corresponding to standard Earth conditions will be applied in the -y direction at approximately 9.82 m/s^2. Additionally, all models will feature appropriate fixed supports to represent their attachment to the helicopter. While the objects theoretically would be better modelled allowing for translational and rotational movements in certain directions, there is an argument to be made that fixed support will give a more conservative result when analyzing the stress. To facilitate the setup, the decision is made to start the simulations using fixed supports on all models and thereby restricting all translational and rotational degrees of freedom at the attachment regions.

To demonstrate the conservative results using fixed supports versus a support that allows for some degrees of freedom to be free, each component will also feature a load case where a comparison between fixed and simply supported results are presented.

7.5 Contact formulation

Frictional contact formulation will be employed between the UAV and helicopter components to enhance simulation realism. Given the absence of precise friction coefficient data between EPP and the various helicopter component materials, an estimated coefficient of approximately 0.3 will be utilized using typical values from table data [15].

8. LS-DYNA Results

The results of the simulations will be presented in three load cases for every analyzed component. Every new load case for the same component will be done with a new geometry setup so that different impact angles or impact locations may be studied. A short description of the setup will be available for the reader for every new case.

Apart from geometry setup, every result section will feature a graph imported from the solution file of Ansys. The graph depicts the factor of safety with regards to yield stress subjected onto the component.

8.1 Yield stress

With safety being of utmost importance when analysing collisions, the factor of safety with regards to yield stress is a good metric of evaluating the integrity and potential failure of materials involved in collisions. It indicates how close a material is to permanent deformation and thus potential loss of function of the component. As collisions usually involve a big unpredictability in terms of impact velocity, impact angles and distribution of loads, the factor of safety will act as a buffer against these elements.

8.2 Load cases results

To facilitate referencing, the load cases will be labelled with a letter and a number to represent the part being analyzed as well as the number of the case. The letters to represent the part are P for pitch-link and W for windshield.

In this chapter, only one load case per helicopter component will be presented. The rest of the results will be found in the appendix. For the load cases presented in this chapter, each case will feature:

- A screenshot showing velocity and geometry setup.
- One factor of safety graph using fixed support boundary conditions.
- One factor of safety graph using simply supported boundary conditions.

All results have been compiled in Table 8.1 in the end of this chapter.

CASE P1

UAV moving in Z- direction with a velocity of 30 m/s.
Pitch-link moving in Z+ direction with a velocity of 5 m/s.

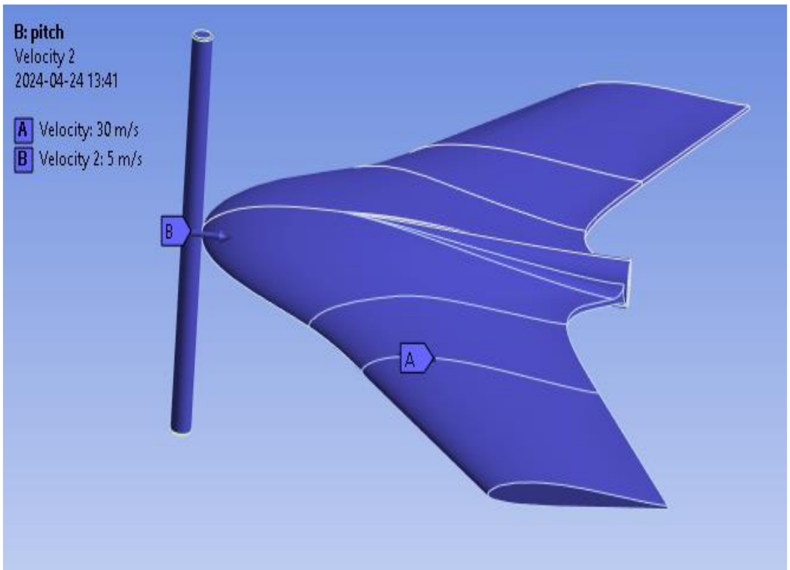

Figure 8.1: Load case P1 velocity setup.

From Figure 8.2 and Figure 8.3 the safety factor with respect to yielding reaches a value of 2.49 while using fixed supports and 3.48 while using simply supported.

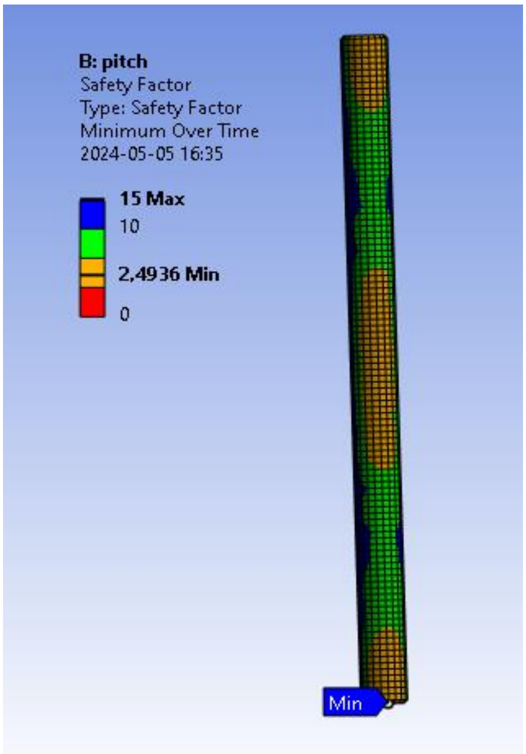

Figure 8.2: Load case P1 stress graph using fixed supports.

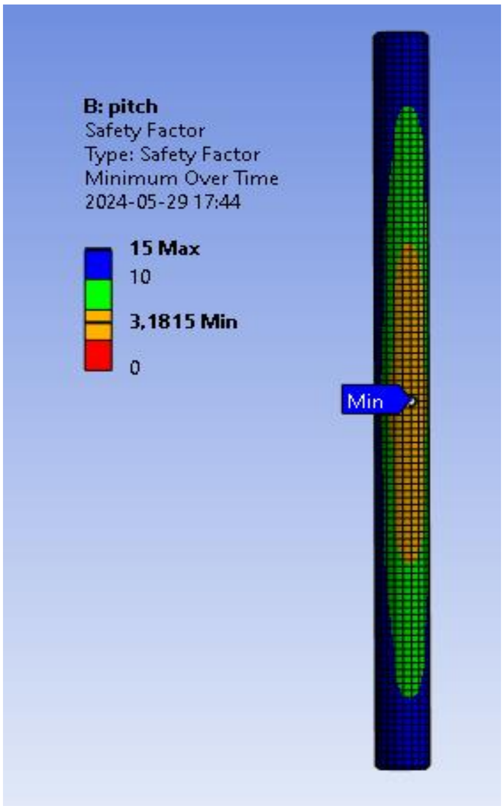

Figure 8.3: Load case P1 stress graph using simply supported.

CASE W1

Figure 8.4 illustrates that the UAV is hitting the lower end of the windshield. The windshield and the UAV are moving in opposite directions.

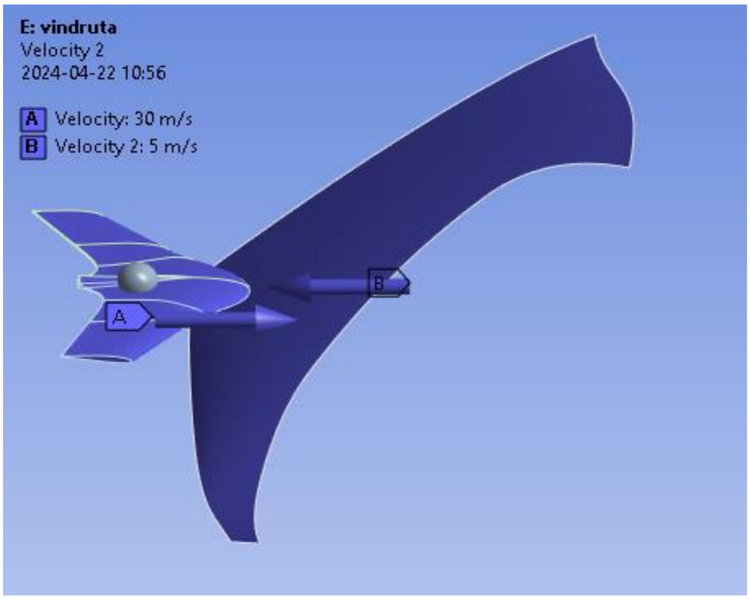

Figure 8.4: Load case W1 velocity setup.

As per Figure 8.5 and 8.6 the resulting values for factor of safety with respect to yielding for this case are 1.99 when using fixed supports and 2137 when using simply supported.

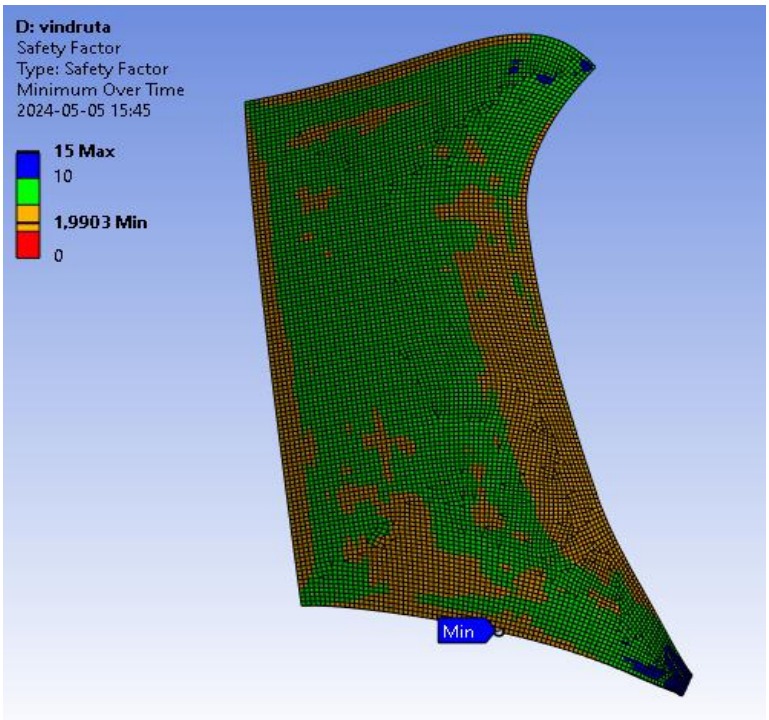

Figure 8.5: Load case W1 stress graph using fixed supports.

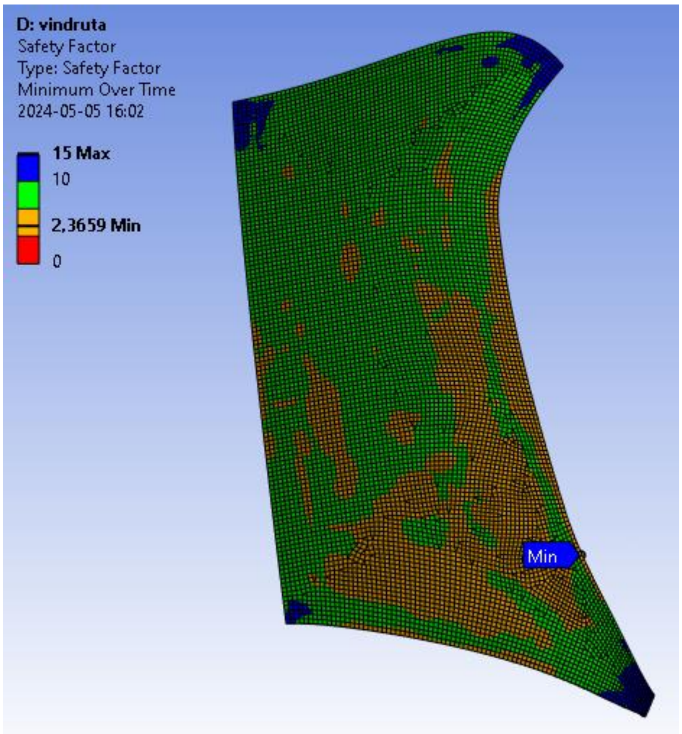

Figure 8.6: Load case W1 stress graph using simply supported.

8.3 Verifying the results

To ensure accuracy and simulation reliability, it is important to be able to verify the simulation results with handwritten calculations. In this case however, as the impact force of the collision also includes a dampening part when the UAV deforms and partly absorbs the energy involved it is not that simple. It is therefore too complex for this project's scope to fully verify the results with the mathematical solution presented in chapter 4. In talks with the supervisor of this project, Robert Thomson, a different approach to verify the simulated results is instead decided on:

1. A load case is chosen for verification.
2. The UAV is assigned a stiffer material (structural steel) with a Young's modulus of $E = 200\ GPa$ which will negate the spring effect present in the impact.
3. The same simulation setup is run to ensure all other parameters are the same.
4. The contact force between the objects is extracted from the result data.
5. The contact force is inserted as impact force in the equations presented in Chapter 4.

8.3.1 Verification of load case P1

Load case P1 is chosen for this comparison as it is the simplest of the 6 load cases. When running the simulation, a contact force of $F = 186\,000\ N$ is extracted.

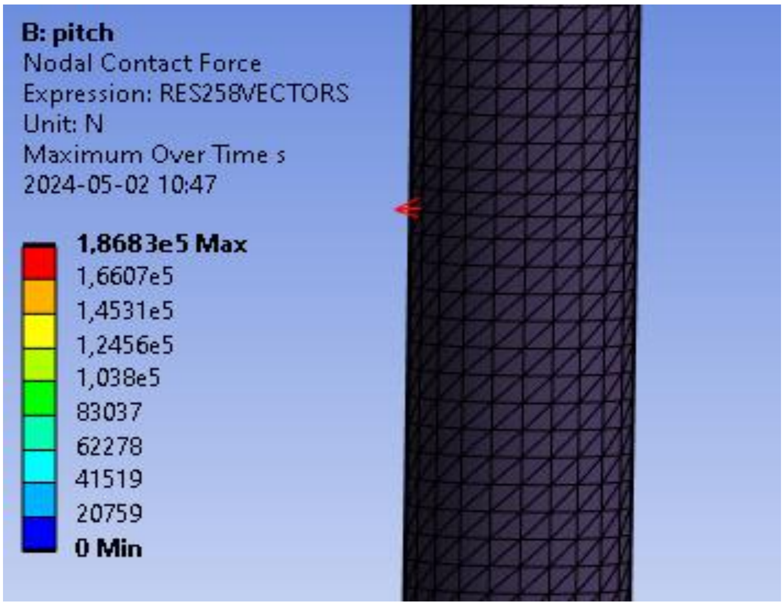

Figure 8.7: Load case P1 contact force using verification setup.

Geometry and material data is calculated for the pitch-link:

$I = 0.000000008\ m^4$	(Second moment of inertia for pitch-link)
$E = 96\ GPa$	(Young's modulus for titanium alloy, material assigned to pitch-link)
$a = b = 0.15\ m$	(Distance from point of collision to boundary conditions of pitch-link)
$L = 0.3\ m$	(Length of pitch-link)

With these values in Eq. 5.1 a maximum calculated deformation (Z-axis) of:

$$\Delta_{max}\ (\text{at point of load}) = \frac{\mathrm{Fa^3b^3}}{\mathrm{3EIL^3}} = \frac{186 \times 10^3 \times 0.15^3 \times 0.15^3}{3 \times 96 \times 10^9 \times 8 \times 10^{-9} \times 0.3^3}$$

$\Delta_{max}\ (calculated)\ \approx\ 0.03421\ m$ is given.

To receive the maximum simulated deformation a directional deformation with regards to the Z-axis is inserted in LS-Dyna. The maximum deformation in this case is presented as the minimum deformation in the graph as the pitch-link is bent in the -Z direction.

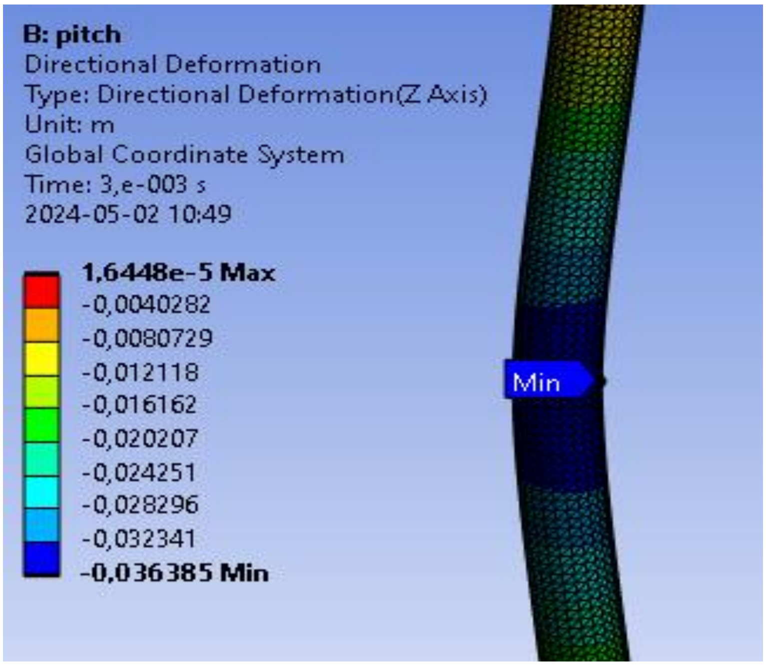

Figure 8.8: Load case P1 directional deformation graph using verification setup.

With the calculated and simulated maximum deformation determined, they are compared to each other:

$$\frac{\Delta_{max}(calculated)}{\Delta_{max}(simulated)} \approx 0.94$$

This comparison shows that the simulation exhibits a 94% accuracy with regards to theoretical equation of beam theory which is deemed to be a good accuracy. While the process is not optimal to fully verify the scenarios realism, it does prove that the material properties and the contact formulation is being taken into account by the software.

Table 8.1. Compilation of results

Case	Minimum Factor of Safety (Fixed support)	Minimum Factor of safety (Simply supported)	Over factor of safety 1,5 (Yes/No)
P1	2.49	3.48	Yes
P2	2.24	-	Yes
P3	1.14	-	No
W1	1.99	2.37	Yes
W2	2.0	-	Yes
W3	2.22	-	Yes

9. Discussion

In this chapter, both a discussion based upon the results that the simulation shows aswell as a general discussion on the subject will be presented. A recommendation for future work will also be presented.

9.1 Result discussion

The results show, for the most part, that the UAV's design and operational properties are no threat to a helicopters different components and functionality. The results also provides a clear view of how using the fixed supports is a more conservative way to calculate the results, whilst unfixing some degrees of freedom might provide a more accurate result.

There is however one case where the factor of safety does not exceed 1.5 as demanded by the technical documentation presented in this study. In case P3, where the UAV is hit by the pitch-link whilst it is rotating, the factor of safety is instead approximately 1.135. This load case is determined to be extremely rare, as it implies that the UAV is near the main rotor hub and contacts a pitch-link at the time when one of the four links has a maximum tangential velocity in the opposite direction of the UAV at the time of impact.

Although its low probability to occur, this thesis main aim is to provide SSRS with a good analysis of the potential harm their UAV may inflict on another airborne vehicle. Thus, a closer study of load case P3 will be presented here.

9.1.1 Study of case P3

To begin with, we will present a graph that showcases the factor of safety for each time step during the 0.003 s that the simulation is running.
Y-axis shows the factor of safety w.r.t yielding (unitless)
X-axis shows the running time (seconds)

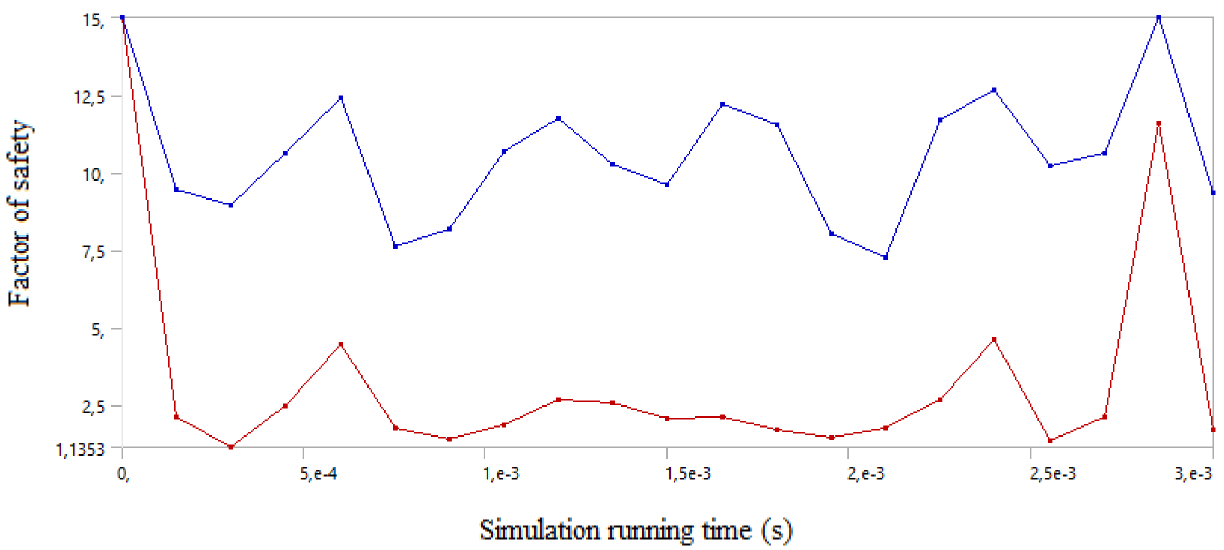

Figure 9.1: Average and minimum factor of safety graph

Tabular Data

	Time [s]	Minimum	Maximum	Average
1	0,	15,	15,	15,
2	1,5e-004	2,0988	15,	9,4386
3	2,9992e-004	1,1353	15,	8,9382
4	4,4993e-004	2,441	15,	10,619
5	5,9998e-004	4,4375	15,	12,418
6	7,4998e-004	1,7496	15,	7,6239
7	8,9998e-004	1,4072	15,	8,1678
8	1,0499e-003	1,8432	15,	10,656
9	1,2e-003	2,6665	15,	11,725
10	1,35e-003	2,5416	15,	10,265
11	1,4999e-003	2,0514	15,	9,582
12	1,65e-003	2,1027	15,	12,205
13	1,7999e-003	1,7116	15,	11,543
14	1,95e-003	1,4166	15,	8,0032
15	2,1e-003	1,743	15,	7,2367
16	2,25e-003	2,6677	15,	11,676
17	2,4e-003	4,6088	15,	12,647
18	2,55e-003	1,344	15,	10,232
19	2,6999e-003	2,1254	15,	10,64
20	2,85e-003	11,56	15,	14,986
21	2,9999e-003	1,6942	15,	9,3625
22	3,e-003	1,6942	15,	9,3625

Figure 9.2: Tabular data for factor of safety graph

By looking at Figure 9.2 showing tabular data of how the factor of safety changes with each time step, we can see that there are four FOS values that do not meet the requirements. If we combine the tabular data with the graph (Figure 9.1) of both minimum (red) and average FOS (blue) it can be assumed that the time during which the pitch-link is subjected to a yield inducing stress is very low and could potentially be ignored. By looking at the average FOS, we can see that it is significantly higher than the minimum FOS, which may indicate that the minimum value is in fact a stress singularity. To determine this, a parameter study is made to see if the result converges when mesh element size is reduced. The student license for Ansys does not allow for high numbers of elements, so to receive an accurate result six new design points were added with a mesh element size that varied between 3 and 8 mm (Figure 9.3).

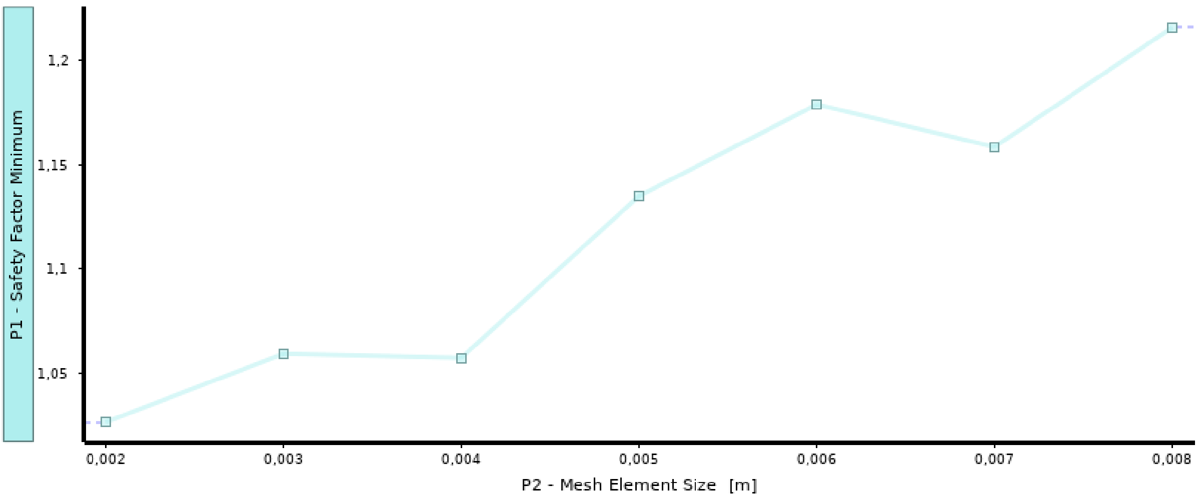

Figure 9.3: Parameter study of load case P3 w.r.t mesh element size

9.1.2 Conclusion of case study

While the parameter study shows that the minimum FOS received from load case P3 may be a stress singularity as the stress seemingly goes towards infinity as mesh element size is reduced, we cannot say that for a fact. However, combining the parameter study with the time-step graph (Figure 9.1) we can conclude that the high stress acting upon the component will only be present for a very small period of time. This time period should not be enough to cause permanent damage due to deformation on the component as the FOS is calculated w.r.t yielding and not w.r.t ultimate stress where the material breaks instantly. One more important thing to keep in mind is that this result is calculated conservatively. By looking at the results in Figure 8.2 and Figure 8.3 it can be noted that using a simply supported boundary condition on the pitch link model increases the minimum factor of safety by roughly 0.69 (an increase in FOS by approximately 28%) In reality, the boundary conditions would be chosen to mimic how the windshield and pitch links are attached to the helicopter in a better way to provide a more realistic result.

We therefore believe that this result is safe to ignore as the average FOS is well above the number that is required.

9.2 General discussion

Due to the complexity of collision analysis and the resource and time constraints in this project, simplifications were made to ensure the arrival of a conclusion. These simplifications were made in consultation with the supervisor for this project, to ensure that the results are affected as little as possible.

As mentioned earlier in the report, the cases studied with the pitch-link are unlikely to ever occur due to the small surface of the links aswell as their position close to the main rotor. The main rotor, rotating with approximately 300 RPM will cause a turbulent air flow that makes it unlikely for the lightweight UAV to ever make it close to this area. Wíth this in mind, aswell as the rare occurance of load case P3 where the pitch-link has a tangential velocity in the opposite direction of the UAV, it is safe to say that the pitch-links has a low probability of being damaged by the UAV.

The number of different airborne vehicles that operate in the archipelagic area are many. The decision to only analyze the collision with helicopters was made due to them being the most frequent in the same air space as SSRS' UAV. For example, sea airplanes were excluded from the study due to the low number registered in the area and that they only fly at higher altitudes, except during landing and takeoff. Therefore, considering the project's time constraints, it was deemed appropriate to only proceed with analyzing collisions between the UAV and helicopters.

The types of helicopters and their sizes also vary. Larger helicopters generally have a sturdier build and are more resilient to impacts, while smaller helicopters are more vulnerable to impacts. During the research on which models are predominant in the archipelago the AW139 was the one that stood out and consequently was the model of focus in the simulations.

With this in mind, the results from the simulations in this study may not reflect what would happen in the event of a collision between the UAV and another type of airborne vehicle.

9.3 Recommendations for future work

To proceed with the project, there are several areas where improvements could be made.
As mentioned earlier, a clear connection between the complex mathematical model that was established and the simulated results from LS-DYNA was not made due to the time limit of the project. With more time, this connection could be made to provide the simulation with more reliability.
Physical tests should be conducted to further investigate whether the UAV poses any risk to helicopters or other airborne vehicles. These tests could be done through drop-tests where the UAV is dropped from a height that allows for the UAV to reach the appropriate velocity before colliding into the windshield or pitch link. A “catapult”-test where the UAV is launched into the collision object could also be a feasible option for verification.

As the tail rotor blade was deemed too complex and time demanding for this project further work to simulate collisions involving this component could be done.

References

[1] Sjöräddningssällskapet. Om oss – Frivillig sjöräddning sen 1907. [Internet]. Available from: https://www.sjoraddning.se/om-oss

[2] Nilsson S. Winged drone impact study. [Master's Thesis on the internet]. Stockholm. 2021. Available from: https://www.diva-portal.org/smash/get/diva2:1613304/FULLTEXT01.pdf

[3] F. Falkman, SSRS, Private conversations.

[4] European Union Aviation Safety Agency (EASA). The Agency [Internet]. Available from: https://www.easa.europa.eu/en/the-agency/the-agency

[5] European Union Aviation Safety Agency (EASA). Easy access rules for Unmanned Aircraft systems. 2022. [Online]. Available from https://www.easa.europa.eu/en/document-library/easy-access-rules/online-publications/easy-access-rules-unmanned-aircraft-systems. Accessed: [2024-04-19].

[6] Transportstyrelsen. SORA – En metodik för riskanalys [Internet]. Available from: https://www.transportstyrelsen.se/sv/luftfart/Luftfartyg-och-luftvardighet/dronare/tillstand-for-dronare/kategori-specifik/sora--en-metodik-for-riskanalys/

[7] P. Hedrén, Private conversations.

[8] European Union Aviation Safety Agency (EASA). Easy access rules for Small Rotorcraft (CS-27). (Amendment 10). [Online]. Available from https://www.easa.europa.eu/en/document-library/easy-access-rules/online-publications/easy-access-rules-small-rotorcraft-cs-27 Accessed: [2024-03-28].

[9] European Union Aviation Safety Agency (EASA). Easy access rules for Large Rotorcraft (CS-29). (Amendment 11). [Online]. Available from https://www.easa.europa.eu/en/document-library/easy-access-rules/online-publications/easy-access-rules-large-rotorcraft-cs-29-0 Accessed: [2024-03-28].

[10] Zinzuwadia C, Olivares G, Espinosa de los Monteros J, Raj Kota K, Gomez L, Jayakody N, J. Baldridge R, Trent R, Aldag T. Volume 3 – UAS Airborne Collision Severity Evalutation – Fixed wing [Internet]. Washington: Alliance for System Safety of UAS through Research Excellence. 2017. Available from: https://assureuas.com/wp-content/uploads/2021/06/A3-Volume-3.pdf

[11] American Forest & Paper Association. (2007). Beam design formulas with shear and moment diagrams. https://engineering.purdue.edu/~ce474/Docs/DA6-BeamFormulas.pdf

[12] Ayoola O. "Free CAD Designs, Files & 3D Models | The GrabCAD Community Library". Bell429 helicopter, 2017, [Online]. Available from: https://grabcad.com/library/bell-429-helicopter-1

[13] Leonardo Helicopters. AW139 Helicopter Technical Documentation.

[14] Eren Z, Tataroğlu S, Balkan D, Mecitoglu Z. Modeling of Bird Strike on a Composite Helicopter Rotor Blade. American Institue of Aeronautics and Astronautics. (2017). 10.2514/6.2017-1991.

[15] INEOS Olefins & Polymers, Typical Engineering Properties of Polypropylene. Available from: https://www.ineos.com/globalassets/ineos-group/businesses/ineos-olefins-and-polymers-usa/products/technical-information--patents/ineos-engineering-properties-of-pp.pdf

Appendix

Appendix 1

CASE W2

In this case, presented in Figure A1, the UAV is moving in the Z- direction, hitting the upper end of the windshield while the windshield is moving in the Z+ direction.

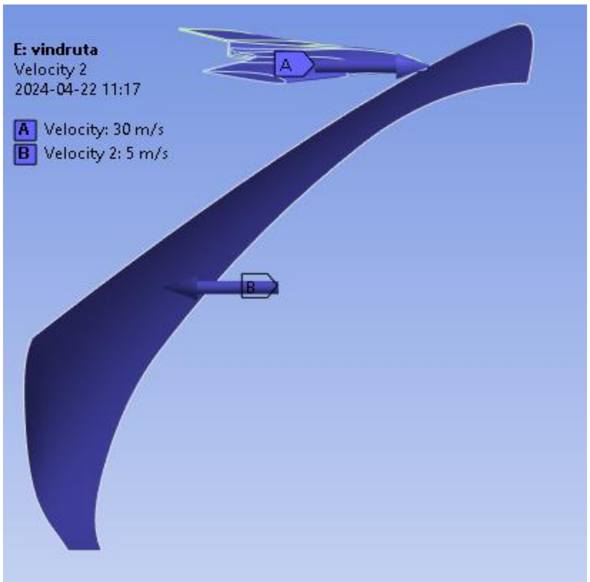

Figure A1

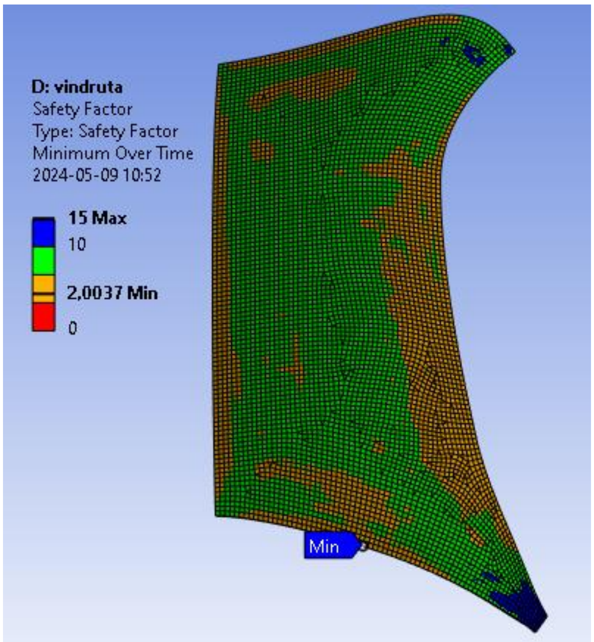

Figure A2

CASE W3

The UAV moving with a 45° angle, hitting the windshield at its support as per Figure A3. The windshield moving in the Z+ direction.

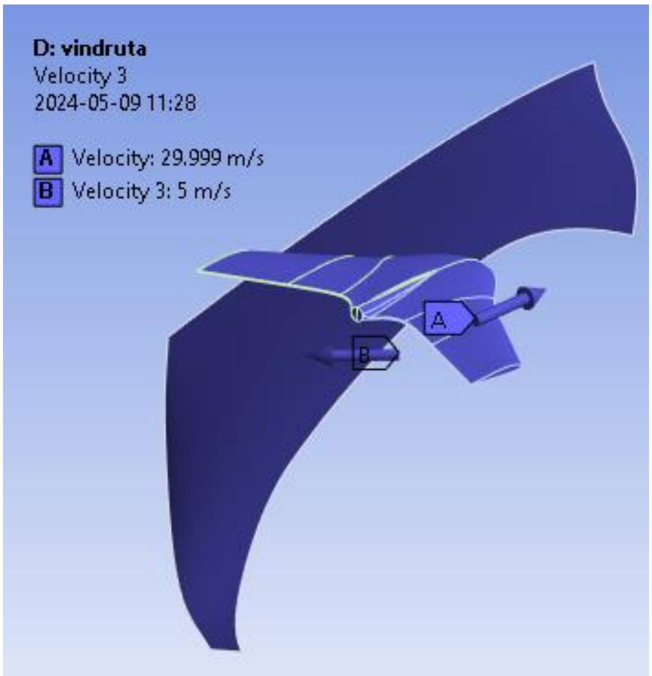

Figure A3

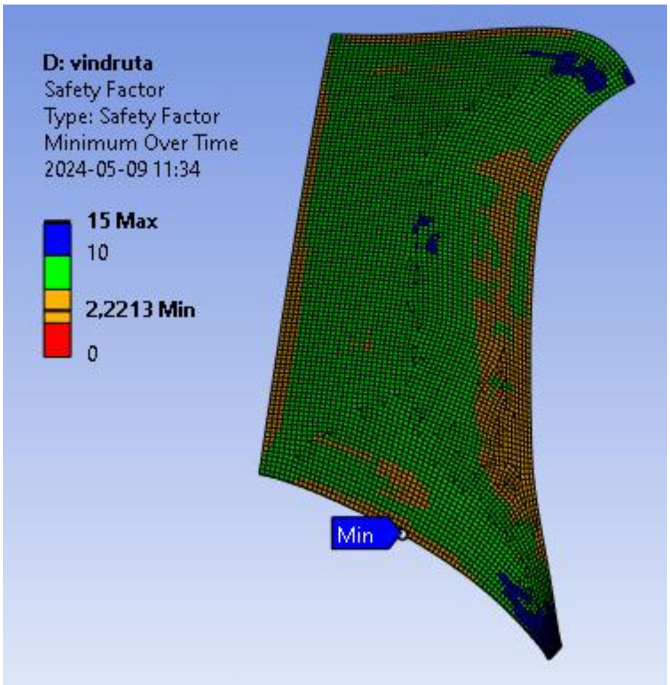

Figure A4

CASE P2

The set up for case P2 is presented in Figure A5 where the UAV is moving in the Z- direction, hitting the pitch-link close to the support.
The pitch-link is moving in the Z+ direction.

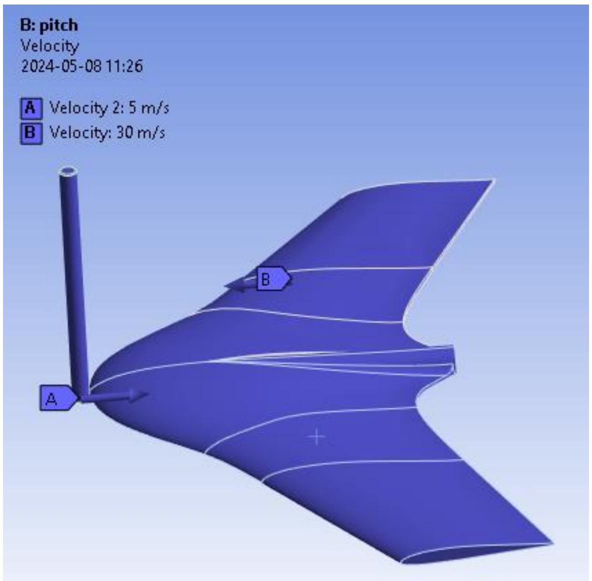

Figure A5

In this case the factor of safety reaches a value of 2.24, as presented in Figure A6.

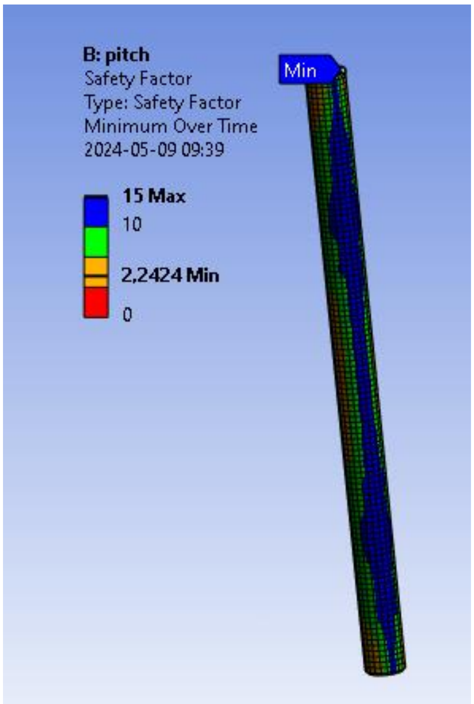

Figure A6

CASE P3

For this case the UAV is moving in the Z- direction.
The pitch-link is moving in the Z+ direction with tangential velocity of rotating swashplate (6 m/s) as well as helicopter velocity (5 m/s). See Figure A7.

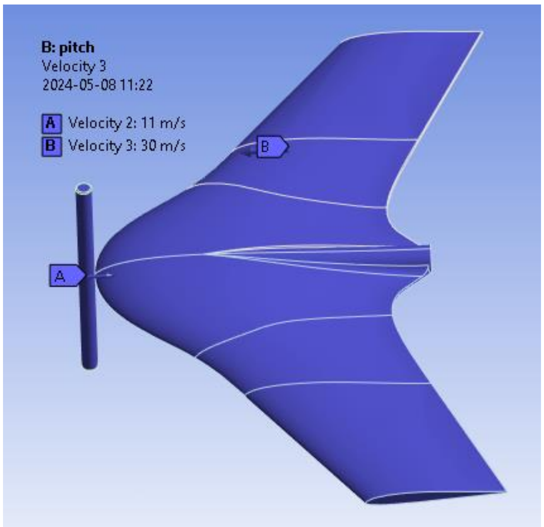

Figure A7

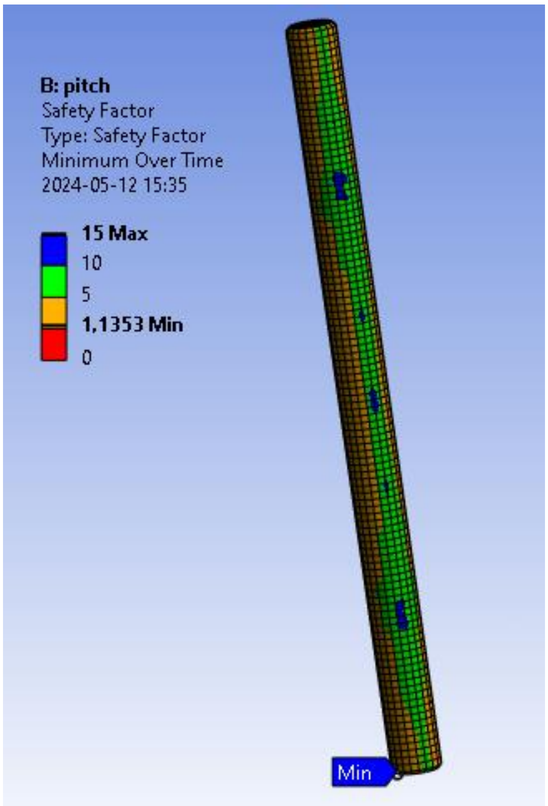

Figure A8

INSTITUTIONEN FÖR
MEKANIK OCH MARITIMA VETENSKAPER
CHALMERS TEKNISKA HÖGSKOLA
Göteborg, Sverige 20xx
www.chalmers.se

CHALMERS