Assessing the Impact Damage Risk on Composite Structures

Using metal damage data to predict impact damage risk on composite aircraft fuselage by combining probability of detection and a decision risk matrix

Master of Science Thesis

L.C. Veldkamp

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Using metal damage data to predict impact damage risk on composite aircraft fuselage by combining probability of detection and a decision risk matrix

by

L.C. Veldkamp

to obtain the degree of Master of Science
at Delft University of Technology,
to be defended publicly on the 21st October 2021

Student number:	1397788
Project duration:	01/09/2020 - 21/10/2021
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Cover image: https://mainblades.com/wp-content/uploads/2020/08/Aircraft-engineer-inspecting-aircraft-2048x1152.jpeg

TU Delft

Acknowledgements

This thesis marks the final part for obtaining the MSc degree in Aerospace Engineering at Delft University of Technology. TU Delft has given me many opportunities to develop both soft skills and engineering skills. Both the city and the university shaped me as a person. I have had the opportunities to expand my horizon by joining study excursions, being active in students associations and having internships. Moving 7447 km across the Atlantic Ocean, leaving my home, family, friends and dogs behind and adapting to the new weather and culture has been a big challenge. But it was a sacrifice worth to take since studying Aerospace Engineering was a goal since I was a little girl.

Even though working on this thesis was a bit of challenge due to the pandemic and stressful during the final stage, I enjoyed working on this subject very much. Not least, this was thanks to my supervisor dr. Marcia Lourenço Baptista. I have learned a lot from all the different steps within the project. I want to show my gratitude to dr. Baptista for guiding me throughout the process and discussing many ideas with me. I learned a lot from her and she was more than just my supervisor. I am very happy to have had worked together with dr. Marcia Lourenço Baptista. I would also like to thank dr. ir. Bruno Santos for his valuable feedback and guidance and showing interest in this subject. I would also like to thank dr. V.S.V Dhanisetty who was my initial supervisor for guiding me through the first stage and who was still willing to guide me even after he left the university. Not forgetting Wim Verhagen , who I would also like to thank for brainstorming together with me despite the large difference in time zones.

Studying in Delft would not have been possible without the support of my family and friends. My lifetime friends Daniela, Sulaika and Nii Manor who I have met at the university and who made me longing for my home country much less. My childhood friend Shiromani who always had the best advices. I am grateful to have my sister Shanny, my brother in-law Wouter and cousin Mireille who stood by my side particularly during the first years in the Netherlands. I would also like to thank my study friends Dyan and Karlo who supported me during this project and listened to my endless amount of ideas and not being tired of me. And I want to thank my life partner Joeri for all the mental support, believing in me and cooking for me during all these busy years. I especially want to thank my widowed mother who sacrificed a lot to give me the opportunity to pursue my studies abroad and for believing in me. Without all of you studying in Delft would not have been possible. Lastly I want to thank my employer CAA-NL for giving me the last few months off so I was able to finish this thesis.

In memory of my late beloved father, Eduard Veldkamp.

Lindsay Veldkamp
Delft, October 2021

Contents

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List of Abbreviations

CDF	Cumulative Distribution Function
D_i	Damage level i
DET	Detailed visual inspection
DMRA	Decision Matrix Risk Analysis
E	Energy
FAA	Federal Aviation Administration
FC	Flight Cycles
FH	Flight Hours
GVI	General visual inspection
MIDAS	Modelling Impact Damage on Composite Structures
MRO	Maintenance Repair and Overhaul organisation
ND	Non-Detectable
NDT	Non Destructive Testing
POD	Probability of Detection
R	Radius
SDCM	Sum of Squared Deviations from the Class Means
SRM	Structural Repair Manual
SSE	Sum Squared Error
VI	Visual Inspection
WSS	Sum of Squared Errors within clusters

Introduction

Older generation civil aircraft such as Boeing 777 and Airbus A330 were mainly manufactured using aluminium. Recent generation aircraft such as Boeing 787 and Airbus A350 are build using composite materials for more than 50% of the structural weight [1-3]. These materials are light weight, have high resistance against corrosion and high strength [4]. With the increase in the use of composite materials in aircraft there will be an increase in demand for maintenance on composite structures [5].

Aircraft encounter damage of varying severity of which a significant amount of damages is caused by impact related events [6]. The Civil Aviation Authority claims that impact damages accounts for approximately 80% of the total damages to composite aircraft structures [7]. In comparison, Chen *et al.* [6] and V.S.V. Dhanisetty [5] show that impact is the cause of approximately 50% of damage. These studies show that impact damages have a significant effect on aircraft maintenance ultimately resulting in flight delays and cancellations. Impact on metal structures causes damage either clearly or reasonably visible to the naked eye [8]. Whereas, damage in composite structures remains undetected [6].

Due to the limited experience of recent generation in-service composite aircraft in operations, a complete understanding of impact damage to be expected over a long operation lifetime is lacking. This lack of experience increases maintenance cost [7]. The risks of impact damages on composite structures are still unknown in maintenance engineering. As a consequence maintenance strategies and planning are not yet accommodated to composite aircraft but to older generation metal aircraft [5].

This study aims to provide information about the risks of impact damage on aircraft composite structures. The goal is to perform a quantitative risk analysis by including the probability of detection. The research question is how the risks of impact threats on composite aircraft and impact damages can influence maintenance strategies in terms of inspection. The study assesses the risks of damage threats and types of impact damage on composite structures. The goal is based on the hypothesis that an area with a large amount of damages does not necessarily lead to the area with the highest risk. Knowing the risks makes it possible to evaluate the maintenance strategies and to adapt or optimize the maintenance tasks in terms of inspection.

This study focuses on analysing the risks of impact damages on the aircraft fuselage. Composite damage properties are predicted based on industry's metal damage data by using an impact damage model developed by P. Massart [9]. To perform a more accurate risk analysis data is generated based on these composite damage data. The risk analysis consists of damage severity and frequency but also the probability of detection of the damage.

The thesis consists of three parts. Part I contains the research paper which describes the research project methodology and results. It includes the research methodology and the explanations of the methods used, the process steps for performing the risk assessment and the results of the assessment. Part II contains the literature study performed at the start of the project. The literature study consists of a review of the impact damage model used for the research, inspection techniques and risk assessment methods. Finally, Part III, includes the supporting work as part of the research project which shows the data pre-processing steps, impact damage model work flow, the results of finding the best fit distribution and the augmentation.

I

Scientific Paper

Assessing the Impact Damage Risk on Composite Structures

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Abstract

Impact on composite structures shows a different damage behaviour compared to metal structures. Due to the current short operational life time of composite aircraft the risks of impact damages on composite structures are unknown. This paper proposes a new method for quantitative risk analysis of low velocity impact damages on composite aircraft structures by combining a conventional risk analysis with the probability of detection of the damages. Real damage data of metal structures is used to estimate impactors and to predict damages on composite structures by means of an aircraft impact damage model. To create a large set of impact events and to conduct a more accurate analysis impactor data estimated from the real metal damage data is augmented. Three fuselage sections with a significant difference in amount of damages have been selected to compare the different risk results. The outcome of a conventional risk analysis and the outcome of the probability of detection of damages show that the section with the highest amount of damages results into the highest risk. However, the proposed method by combining the probability of detection of the damages with a conventional risk analysis shows different and more revealing results. The fuselage section with nearly 50% less damages compared to the section with the highest damages appears to be the highest risk section but the difference with the other fuselage sections is small. The proposed risk analysis method intends to be a useful tool for aircraft maintenance organisations for a different approach of assessing the risks of impact damages on composite structures.

1 Introduction

Composite materials are light weight, have high resistance against corrosion, high strength and high resistance against fatigue [1]. These advantages led to use these materials in current aircraft. The use of composite materials has increased in the new generation aircraft such as Boeing 787 and Airbus 350. However, composite materials also have disadvantages. Low velocity impact on structures of these materials can result in minor indentation while delamination on the subsurface damage is present [2]. These subsurface damages are hidden and therefore difficult to detect with the naked eye. Inspection of aircraft is carried out for 80% by visual inspection [3].

Aircraft maintenance organisations are dealing with impact damages on aircraft on a daily basis. FAA Airworthiness Assurance Center reported in the survey of structural health monitoring technology that impact damage identification is one of the most important current needs in the

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aerospace industry [4]. Due to current short operational life time of new generation composite aircraft there is limited experience with damages on these aircraft. Hence, in contrast with metal aircraft, a complete understanding of types of impact damage on composite aircraft seems to be lacking. Due to the lack of damage data on composite aircraft the effect of impact damages on composite structures in terms of inspection strategies are unknown. As a consequence inspection strategies and planning are still not accommodated to composite aircraft but to older generation metal aircraft only. Additionally, damages on composite structures which are difficult to detect are a significant threat to structural integrity and may result in failure before the end of the aircraft expected life time [5]. Large visible impact damages might be severe for the airworthiness of the aircraft, but small non-detectable impact damages can be severe as well as they can have large subsurface damages. The effect of small surface damages containing non-visible subsurface damages is unknown. Furthermore an aircraft area with a large amount of damages does not necessarily lead to the highest risk area. Therefore the hypothesis is: an aircraft zone with a large number of damages does not necessarily result in the highest risk zone. To examine this hypothesis the detectability of surface dents is analysed by determining the probability of detection of damages with visual inspection. Knowing the probability of detection of the composite damages can possibly improve inspection strategies. V.S.V. Dhanisetty stated that damage risks can be further extended to prioritizing area of inspection on aircraft [6]. This led to the following research question: how can the risks of the predicted impact damages influence the inspection strategies of new generation composite aircraft.

The motivation to execute the research is to quantify the risks of low velocity impact damages by performing a risk analysis. To this risk analysis the probability of detection of the damages is added. Knowing the risks and the probability of detection of damages, makes it possible to evaluate the inspection strategies. By adapting the inspection strategies damages can be detected earlier, safety and reliability can be improved which could eventually lead to cost savings. The research assesses the risks of damage threats and types of impact damage on composite structures.

The methodology in this research consists of estimating impactor data based on industry's data of damages on metal aircraft using an impact damage model [7]. The impactor data is augmented to generate more impactor scenarios and to eventually perform a more accurate risk analysis. Using the impact damage model [7], damages on composite structures are estimated based on the augmented impactor data. A quantitative probabilistic risk analysis of the composite damages is performed using the frequency of occurrence and severity of the damage. To the probabilistic risk analysis the method Probability of Detection (POD) of the damages is added.

In Section 2 the methodology and the steps within this study are described in more detail. This includes raw data pre-processing, data augmentation, data classification and the risk analysis method. The results of the study are presented and discussed in Section 3. Section 4 concludes the work and the results of the study. Recommendations are also given in this chapter.

2 Processing Impactor and Damage Data on Composite Structures

Methodology

The methodology followed in this research is illustrated in Figure 2.1. Raw data was provided by a Maintenance Repair and Overhaul Organization (MRO). The raw data contained not only impact damages, but of damages such as wear as well. In addition a significant amount of the raw data consisted of lightning strike events. Furthermore many data entries were incomplete. In order to use complete impact damage data, the raw data needed to be pre-processed. Afterwards the data is augmented using the best fit distributions of the original data. A machine learning technique is applied to cluster the data which was necessary for classification. With the augmented data a conventional risk analysis is performed based on the Decision Risk Matrix Assessment (DMRA) method [8]. To the conventional DMRA risk analysis method the Probability of Detection of the damages is included to perform a novel risk assessment tailored for low velocity impact damages on composite structures.

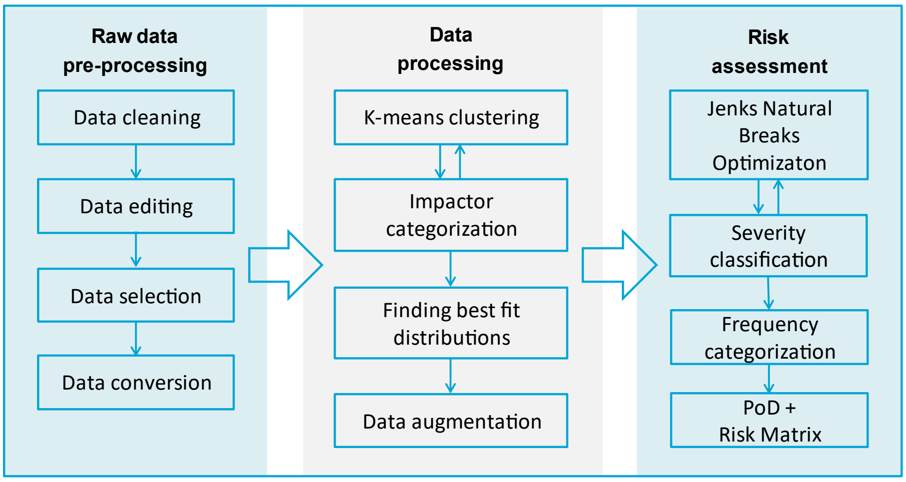


Figure 2.1: Methodology

The steps within the research are illustrated in Figure 2.2. The process consists of two parts named the input side and the output side. On the input side consists of raw metal damage data pre-processing, estimating impactor properties and impactor data augmentation are executed. The input of the process is the impactor input data. The output side consists of the risk assessment of the damages on composite structures including the analysis of the probability of detection of the composite damages. The output are the risk matrices. The numbers in the boxes indicate in which subsection of this paper the step is explained.

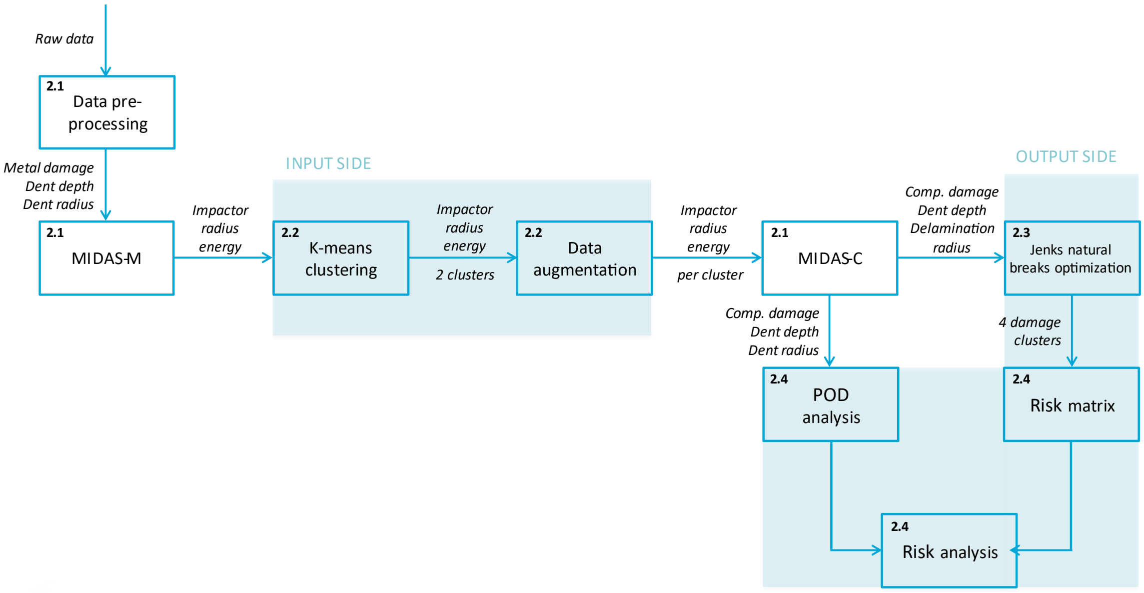


Figure 2.2: Process Steps

2.1 Damage modelling & Data

MIDAS

Due to the short operation life of new generation composite aircraft there is limited data about damages on the composite structures. To be able to predict the damages on the composite structures a model was developed at Delft University of Technology by P. Massart [7] named Modelling Impact Damages on Aircraft Structures (MIDAS). This model is able to predict damages on composite structures based on existing damages of in-service metal aircraft. Most of the time inspection engineers do not exactly know the impact source which causes the damage, but are only able to measure the size of the damage when detected. MIDAS consists of two parts, MIDAS-M and MIDAS-C as can be seen in Figure 2.3. MIDAS-M deduces the impactor properties radius and energy from the damage properties dent radius and dent depth on metal aircraft. For the development of MIDAS-M P. Massart [7] used the modelling methods of Shivakumar *et al.* [9], Abrate [10], Simonsen and Lauridsen [11] and Lee *et al.* [12]. With the deduced impactors from MIDAS-M, MIDAS-C induces the damages on composite structures in terms of dent radius, dent depth and delamination. For the development of MIDAS-C P. Massart [7] continued on the work of Cairns[13] and Olsson and Block [14].

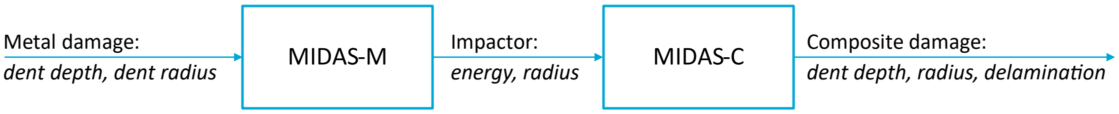


Figure 2.3: MIDAS Work Flow

It should be noted that MIDAS-M has some limitations. Only blunt metal impactors are modelled. This means that impact damages caused by hail and bird strikes cannot be predicted by MIDAS. Hail and birds behave differently during impact compared to metal impactors, which requires other methods for modelling damage on composite structures caused by these impactors. Furthermore a flat plate is assumed as contact area whereas in reality aircraft fuselage plates are curved and the impact is assumed to be in the centre of the plate. This results in a less accurate representation of the impact damage. The final limitation is that damage dents are assumed to be circular.

Despite these limitations MIDAS provides a unique possibility to predict impact damages on composite structures. It shows a good estimate of the damages to be expected caused by low velocity impactors. As MIDAS makes it possible to use historical damage data of metal aircraft it will give a sufficient approximation of expected damages on composite structures. This makes it possible to study the risks these damages pose on inspection strategies and develop mitigation strategies which can decrease aircraft down-time and reduce maintenance costs. MIDAS has previously been used in a research of a composite maintenance decision-making process for impact damage by V.S.V. Dhanisetty [6].

Data

Previous generation aircraft have been operating for more than 20 years. Maintenance organisations were able to gather damage data of these aircraft. A database of the Boeing 777 fleet of one airline consisting of damages was provided to execute this study. This database consists of data of approximately 10.000 damages. This data was pre-processed manually in order to be able to create operable input for MIDAS. The database consisted of low descriptive and incomplete data. This led to a relative small subset of the data which could be used effectively.

The research area scopes only the fuselage, hence damages on wings, empennage and landing gear are eliminated from the raw data. More than 50% of the damages were caused by lightning strikes which is out of scope of this research project. Pre-processing the data led to approximately 180 damages containing complete dent sizes which could be used for this research. The damage sizes in the database are given in terms of length, width and depth. In reality, damages are not perfectly circular. MIDAS approximates circular dents, hence the dents are converted to circular damages by equating the area of the elliptical damage to the area of an equivalent circle. The area of the circle can be used to determine the radius of the approximated circular dent:

$$\pi ab = A_{ellipse} = \pi r_{approximated}^2 \tag{2.1}$$

$$\sqrt{ab} = r_{approximated} \tag{2.2}$$

Where:

$a =$ the semi-major axis of the elliptical dent,
$b =$ the semi-minor axis of the elliptical dent and
$r_{approximated} =$ the radius of approximated circular dent

The aim of this research is to predict the risks of impact damages on composite structures. The hypothesis is that a fuselage section with a high density of damages does not necessarily lead to the highest risk fuselage section compared to sections with a low density of damages. In order to test this a selection of three fuselage sections was made. Two different sections with a significant difference in amount of damages were selected. Another section with a significant low difference in amount damages compared to the other section is selected as well. A sketch and overview of the selected fuselage sections is given in Figure 2.4. The location of the damages is found by using the Structural Repair Manual (SRM) of the B777 together with the given frame numbers from the database. The damage properties dent radius and dent depth are the input for MIDAS-M which outputs the impactor properties radius and energy.

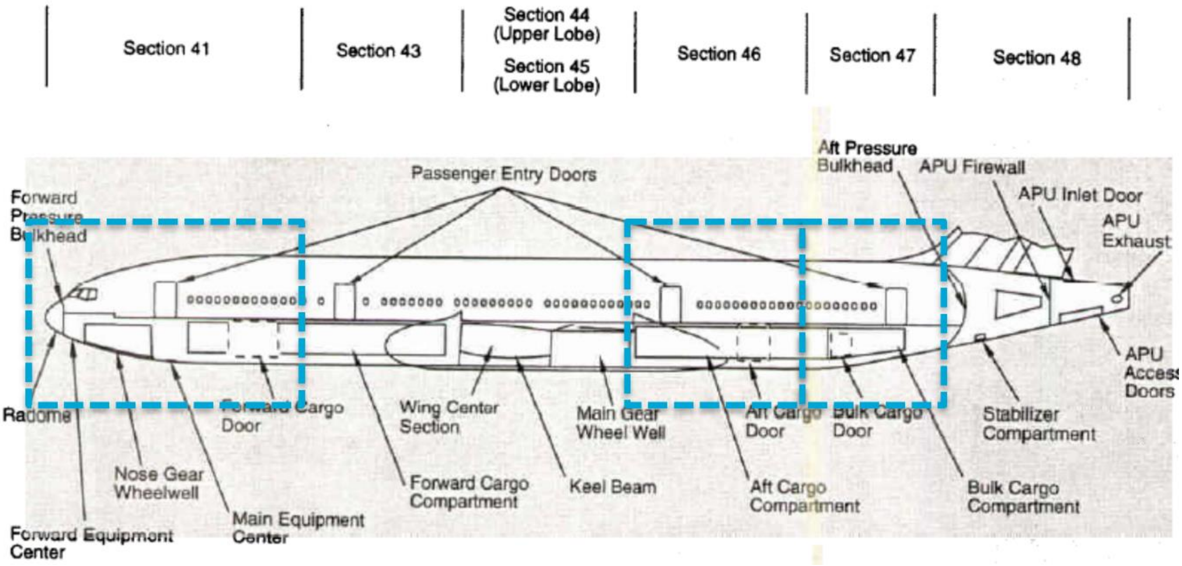


Figure 2.4: Fuselage Sections of Boeing 777

2.2 Data Augmentation

The impactor properties from metal damages deduced by MIDAS-M are based on passed events. However in reality the events can be slightly different each time, meaning that the impactor properties radius and energy can take different values. The events will not be exactly the same every time. The same impactor can variate in velocity hence variate in energy. Furthermore the radius of the impactor is an estimation based on the metal damages, however this depends on how and under which angle the impactor strikes the aircraft. This results in slightly different estimations for the real radius.

Due to many other possibilities of impactor events radius and energy data of the impactor is augmented. Doing this damages of other possible scenarios will be able to be studied. Furthermore, the dataset of only 180 datapoints does not contribute to a solid risk analysis. Augmenting the data makes the research more solid and provides a more accurate risk analysis of the damages these impactors cause. Moreover impactors which can take different sizes and different energies leading to more different damages than the ones covered by the original data.

Before augmentation it is chosen to classify the impactors by using a machine learning technique named K-means clustering. K-means clustering is a well-known clustering algorithm which groups data together. This clustering method is able to cluster two-dimensional data and is therefore appropriate since the impactor properties consist of two variables: radius and energy. The K-means algorithm is used to classify each data point into a specific group, where data points within each group have similar properties. Hence it minimizes the distance between data points within each cluster and maximizes the distances of data points in different clusters [15]. The value of k is the numbers of clusters which should be determined by the user.

To determine the best number of k's the Elbow Method is used. The Elbow method determines the optimal number of clusters by calculating the Sum of Squared Errors within clusters (WSS) for different values of k. Figure 2.5 shows the Elbow method plot where an arm with an elbow at a certain value for k indicates the optimal number of clusters. Looking carefully at the plot, both k = 2 and k = 3 can be the optimal number of clusters. To verify weather k = 2 or k = 3 is the optimal number of clusters for the impactor data the Silhouette method is used. This method measures the similarity of a point to its own cluster compared to other clusters. The highest score of the Silhouette value gives the optimal value for k. As can be observed from Figure 2.6 the highest Silhouette score is at k = 2 as well. Hence the impactors are classified in two types: impactor type 1 and impactor type 2 (very small impactors and small impactors).

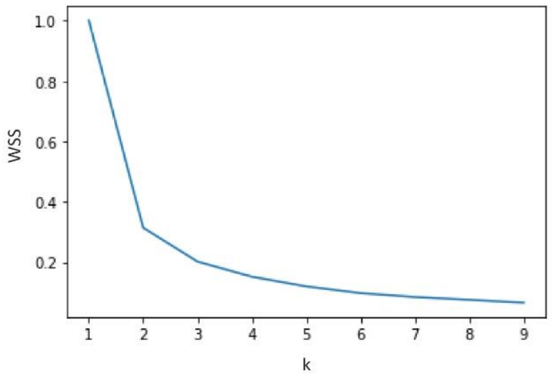


Figure 2.5: The Elbow Method

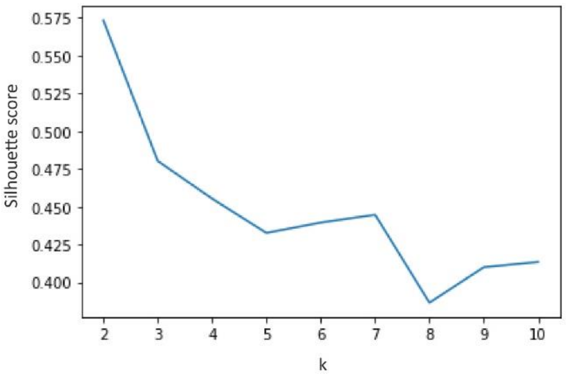


Figure 2.6: The Silhouette Method

Before augmentation the best fit distributions of the impactor data radius R and energy E is obtained. Finding the best fit distributions for each type of impactor in each fuselage section is determined by the Sum Squared Error (SSE) method. The used method gives the best five distributions and the SSE. A lower SSE means a better fit. Tables 2.1a - 2.1c give an overview of the chosen best distributions for radius R and energy E for each impactor type in each fuselage section. With the parameters of the best fit distributions, data is generated for R and E for each impactor type in each fuselage section.

Section 41			
		SSE	Parameters
Impactor 1			
R	Gamma	0.000045	(2.65 ; 41.36)
E	Gamma	0.000014	(4.33 ; 20.02)
Impactor 2			
R	Uniform	0.000071	(116.42 ; 208.58)
E	Gamma	0.000049	(3.67 ; 19.92)

Table 2.1a: Best Fit Distributions Section 41

Section 46			
		SSE	Parameters
Impactor 1			
R	Gamma	0.000157	(2.31 ; 18.01)
E	Expon.	0.000091	(46.02)
Impactor 2			
R	Normal	0.000123	(156.47 ; 37.63)
E	Normal	0.000093	(51.11 ; 16.88)

Table 2.1b: Best Fit Distributions Section 46

Section 47			
		SSE	Parameters
Impactor 1			
R	Gamma	0.000113	(2.39 ; 40.01)
E	Gamma	0.000052	(1.25 ; 12.49)
Impactor 2			
R	Uniform	0.000040	(95.57 ; 127.77)
E	Gamma	0.000293	(8.33 ; 8.67)

Table 2.1c: Best Fit Distributions Section 47

After augmentation the data set consisted of approximately 10.000 impactors. With these new and original impactor properties the damage properties on composite structures is deduced using the P. Massart's model MIDAS-C [7].

2.3 Classifying damages

Conventionally, the severity level of damages is defined within risk analysis. In risk analysis there is not one right approach to determine the levels of severity [16]. The level of severity is commonly defined based on the size of the damage and other factors such as costs. In this study the severity level of the composite damages is solely defined based on the size of the damage. Figure 2.7 shows that the dent radius and delamination radius are linear with the delamination radius being approximately ten times larger than the dent radius. Hence, it was chosen to use the delamination radius to classify the severity of the damage.

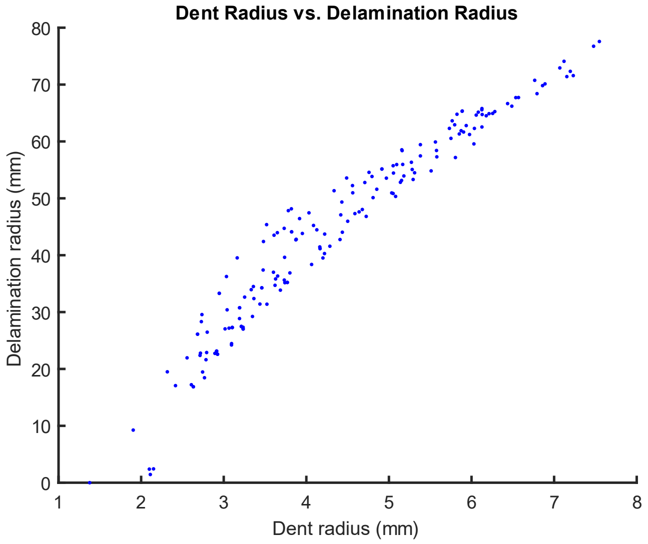


Figure 2.7: Dent Radius vs. Delamination Radius

Similarly, in a research conducted at the German Aerospace Center (DLR), J. Baaran [17] classified the severity levels based on the delamination area only. J. Baaran defined four categories of severity as can be seen in Table 2.2.

Size	Delamination length
1	< 10 mm
2	10 mm - 30 mm
3	30 mm - 50 mm
4	> 50 mm

Table 2.2: Baaran's Damage classification [17]

Size	Delamination length
1	< 16.64 mm
2	16.64 mm - 35 mm
3	35 mm - 50 mm
4	> 50 mm

Table 2.3: K-means Clustered Damages

Using J. Baaran's work as a starting point it was chosen for this study to categorize the damages in four groups. For categorizing the composite damages the Jenks Natural Breaks Optimization method is used. This method is a one-dimensional clustering algorithm which calculates the Sum of Squared Deviations from the Class Means (SDCM). This process is iterated until break combinations with the lowest SDCM selected.

Table 2.3 shows the classification of the composite damages. Comparing this with J. Baaran's [17] classification ranges, the classification determined in this study shows similarity.

2.4 Risk of impact damages on composite structures

As described in Section 1, due to a lack of data of impact damages on composite structures, an understanding of the risks of impact damages is still unknown. Therefore the aim of this study is to perform a risk analysis of the predicted damages on composite structures. The risk analysis is conducted in two ways: a conventional risk analysis and the analysis of Probability of Detection (POD) of damages.

Risk Matrix

In conventional risk analysis hazards are identified, the events these hazards can cause are determined and the consequences of the events are evaluated. Afterwards mitigation measures are decided. This study includes only the analysis of the consequences of the events. In this paper the hazards are defined as ground operations around the aircraft and Foreign Object Debris (FOD) around the taxiways. The events are defined as the impactors striking the aircraft fuselage due to these ground operations and FOD. The consequence is the impact damage on the composite fuselage structure due to ground operations and FOD.

Several methods exist for assessing risks [8, 16]. In this research the conventional risk analysis is based on the Decision Matrix Risk Analysis (DMRA) method [8]. In this method a risk matrix is generated to have a clear overview of the risk levels. The risk matrix consists of severity levels of the damage on the horizontal axis and the frequency of occurrence on the y-axis. Multiplying the severity and the frequency gives a value of the risk.

$$R = S * F \tag{2.3}$$

Where:

S = the severity of the damage,

F = the frequency of occurrence of the damage and

R = the risk of the damage

The severity levels are defined using the classification from the Jenks Natural Breaks Algorithm. From the clustering results it can be seen that the clusters are defined by the size of the delamination. Therefore it is chosen to determine the severity levels based on delamination size which is the same as Baaran's work [15].

For both the severity and frequency a grade was assigned. The severity level ranging from low to very high is assigned the grades 1 to 4 with corresponding delamination radius. For the frequency level ranging from low to very high the same grades from 1 to 4 is assigned. An overview of the level grading is represented in Tables 2.4 and 2.5.

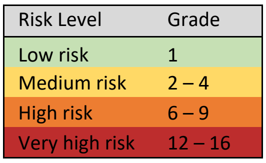
Severity		
Damage radius	Level	Grade
< 16.4 mm	Low	1
16.4 - 35 mm	Medium	2
35 - 50 mm	High	3
> 50 mm	Very High	4

Table 2.4: Severity Levels

Frequency		
Occurrence	Level	Grade
0 %	Low	1
0 - 5 %	Medium	2
5 - 10 %	High	3
> 10 %	Very High	4

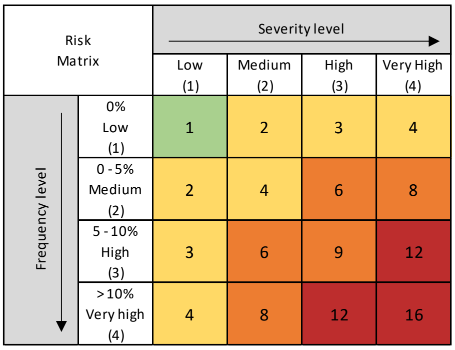
Table 2.5: Frequency Levels

Multiplying severity and frequency of the damage type gives the level of risk for that type of damage. A colour coding is assigned for the risk levels as shown in Table 2.6. A representation of the risk matrix with the defined severity levels and probability of occurrence is shown in Table 2.7.



Risk Level	Grade
Low risk	1
Medium risk	2 – 4
High risk	6 – 9
Very high risk	12 – 16

Table 2.6: Risk Level Colour Coding



Risk Matrix		Severity level Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level	0% Low (1)	1	2	3	4
	0 - 5% Medium (2)	2	4	6	8
	5 - 10% High (3)	3	6	9	12
	> 10% Very high (4)	4	8	12	16

Table 2.7: Risk Matrix

Probability of Detection

The conventional risk analysis only consists of assessing the damage by considering the size of the damage itself. However in composite structures the damage is usually not visible to the naked eye and can be left undetected. Small surface dents can be undetectable while it contains severe subsurface damage. This adds another important element to the risk analysis.

For inspection of aircraft many Non Destructive Testing techniques (NDT) exist. Among them, Visual Inspection (VI) is a primary NDT technique for in-service inspection of composite structures [3, 18]. It is widely used due to its simplicity and low cost [19, 20]. With VI being the primary used technique it was chosen to concentrate this study on this technique.

The outcome of VI depends on many factors. Dent depth, dent diameter and the colour of the structure are internal factors. External factors which influence the quality of VI are detection distance, detection angle, detection type, type of personnel, illumination and cleanliness.

Jiang et al. [21] proposed a method for quantitative assessment of visual detectability of low velocity impact damages on composite structures. The method is based on a logistic regression model. Many researchers have used logistic regression models to study the probability of detection of damages using a certain NDT technique. Jiang tested external factors such as detection angle, detection distance, detection type, personnel's gender, age and experience. The internal factors are the dent depth, dent radius and paint colours. Factors such as illumination and cleanliness were excluded.

$$logit(x) = \ln\left(\frac{P}{1-P}\right)$$
$$= -4.351 + 3.862x_{depth} + 0.338x_{diameter} - 1.261x_{distance} + 1.266x_{type} + 0.579x_{qualifications} + 0.620x_{gender} - 0.268x_{age} - 0.158x_{colour_1} + 0.082x_{colour_2} - 0.016x_{colour_3} + 0.017x_{angle} \quad (2.4)$$

The parameters calculated by Jiang determine the influence of the factor. Jiang concluded that the depth and diameter of the dent are critical factors for visual detectability [21].

The probability is calculated as follows:

$$POD = \frac{e^{-4.351 + 3.862x_{depth} + 0.338x_{diameter} + \ldots + 0.017x_{angle}}}{1 + e^{-4.351 + 3.862x_{depth} + 0.338x_{diameter} + \ldots + 0.017x_{angle}}} \quad (2.5)$$

A POD of one indicates the damage is detectable with 100% certainty and a POD of zero indicates that the damage is not detectable. Everything in between may or may not be detectable. Other studies define barely visible impact damage as the minimum impact damage evidently detectable by scheduled inspection corresponding to a POD of 0.9 [22-24].

For this study the model proposed by Jiang is used assuming detailed visual inspection (DET) with a detection distance of 0.5 m performed by a well-trained male inspector between the age of 25 and 35 years old with inspection angle of 45° on a white panel. Tables 2.8 and 2.9 represent the visual inspection factors and coding.

Factors	Value	Coding
Colour	Black	1
	Red	2
	White	3
	Blue	4
Type	GVI	0
	DET	1
Distance	0.5 m	0.5
	1 m	1
	1.5 m	1.5
Angle	15°	15
	45°	45
	65°	65
Qualifications	Rookie	0
	Trained	1
	Well-trained	2
Gender	Female	0
	Male	1
Age	Age < 25	1
	25 < Age ≤ 35	2
	35 < Age ≤ 45	3
	Age > 45	4

Table 2.8: Parameter Coding [21]

Colour	Frequency	Parameter coding		
		Colour_1	Colour_2	Colour_3
Black	6240	0	0	0
Red	5280	1	0	0
White	5198	0	1	0
Blue	6000	0	0	1

Table 2.9: Parameter Coding for Panel Colour [21]

For the assessment of this research all external factors were kept fixed and only the generated damage data consisting of dent depth and dent diameter are used. The highlighted factors with corresponding code are the ones selected in order to calculate the POD. Jiang stated that the depth of the dent is the pivotal factor for POD. However they also argue that depth and diameter are both critical factors for visual detectability. The POD plots for dent depth and radius are given in Figures 2.8 - 2.13.

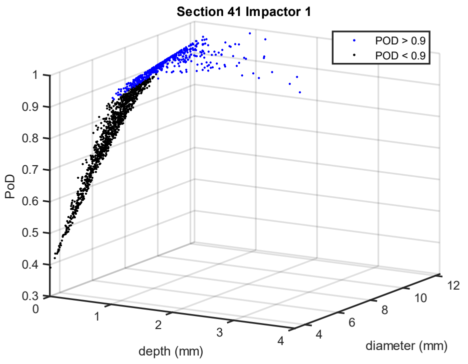


Figure 2.8: POD Section 41 Impactor Type 1

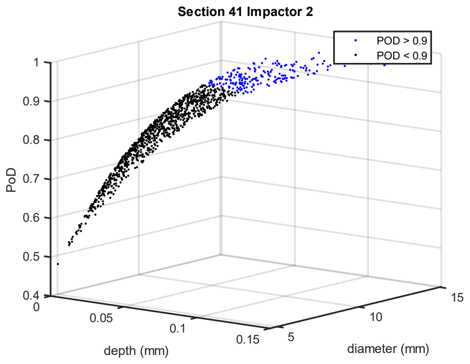


Figure 2.9: POD Section 41 Impactor Type 2

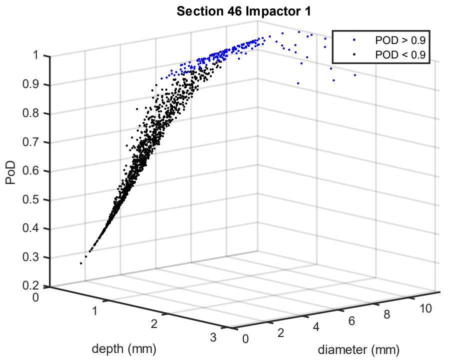


Figure 2.10: POD Section 46 Impactor Type 1

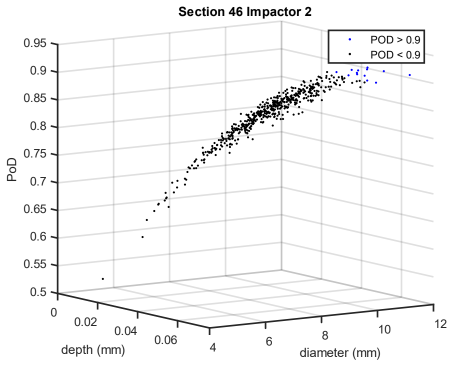


Figure 2.11: POD Section 46 Impactor Type 2

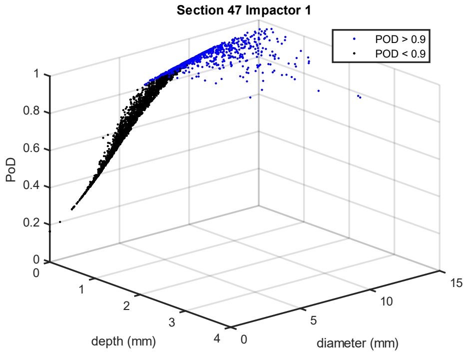


Figure 2.12: POD Section 47 Impactor Type 1

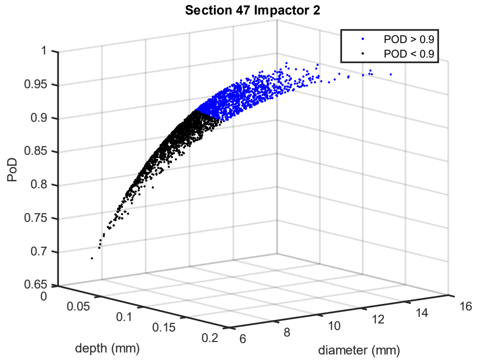


Figure 2.13: POD Section 47 Impactor Type 2

The POD values of the damages range from zero to one. From these values two classes are defined based on the definition of A. Tropis *et al.*, E.Morteau and A.J. Fawcett [22-24]: detectable damages corresponding to a POD larger than 0.9 and non-detectable damages corresponding to a POD lower than 0.9.

Combining Conventional Risk Assessment and Probability of Detection

For the reason that the behaviour of impact damages on composite structures differentiates from metal aircraft structures the conventional risk assessment is combined with the Probability of Detection model. Moreover, separate risk results of the conventional risk assessment and the POD model do not clearly provide the overall risks of the damages on composite structures.

The defined classes above, non-detectable damages and detectable damages, were assigned to a grade. A grade of one was given for POD values ≥ 0.9 and a grade of five was assigned to POD values lower than 0.9.

The POD grade was added to the severity grade. The outcome of this summation was defined as 'Criticality'. In Table 2.10 the numbers of the POD grading, severity grading and criticality level are given.

Severity level	1	2	3	4	1	2	3	4	
POD	D	D	D	D	ND	ND	ND	ND	
POD grade	1	1	1	1	5	5	5	5	+
Total grade	1	2	3	4	6	7	8	9	
	Low		Medium		High criticality		Very High		
Criticality level	1		2		3		4		
	Detectable ◀					▶ Non-detectable			

Table 2.10: Combined Risk Model Grading

The criticality grades one and two are assigned to low criticality with detectable damages of low to medium severity. The criticality grades three and four are classified as medium criticality as these damages are detectable but still ranging from high severity to very high severity. The grades six and seven are classified as high criticality and contains low and medium severity damages which are non-detectable. Criticality grades of eight and nine are classified as very high criticality. This classification contains high and very high severity damages which are not detectable.

A 'seriousness' map was produced by multiplying the criticality levels with the frequency of occurrence levels. A seriousness grade is obtained with the multiplication. Table 2.12 shows the 'Seriousness' matrix with Table 2.11 representing the seriousness levels and colour coding.

Seriousness Level	Grade
Low seriousness	1
Medium seriousness	2 - 4
High seriousness	6 - 8
Very high seriousness	9 - 16

Table 2.11: Seriousness Colour Coding

Seriousness Matrix		Criticality level →			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level ↓	0% Low (1)	1	2	3	4
	0 - 5% Medium (2)	2	4	6	8
	5 - 10% High (3)	3	6	9	12
	>10% Very high (4)	4	8	12	16

Table 2.12: Seriousness Matrix

3 Results and Discussion

At the start of this study it is decided to choose a fuselage section with the highest amount of damages, a section with the lowest amount of damages and another section with an amount of damages relatively close to the lowest in order to study the difference in risks levels of damages with variating occurrences. The chosen fuselage section with highest amount of damages was Section 47 and the section with the lowest amount of damages was Section 46. Section 41 turned out to be the third section with the amount of damages in between that of fuselage Section 46 and fuselage Section 47.

Conventional Risk Analysis

As stated in Section 2 of this paper there is not one approach to perform a risk analysis. The level of severity of the damage can depend on several factors which is up to the assessor to determine. In this study the level of severity of the damages is defined based on the size of the damage only. Defining the level of frequency is also up to the assessor. As defined in Section 2 zero percent frequency is defined as low and above ten percent is defined as very high frequency.

Figures 3.1 - 3.6 show an overview of the frequencies of occurrence of damages for each severity level is presented for each section.

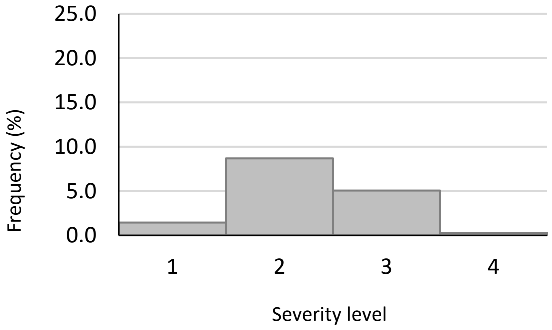


Figure 3.1: Section 41, Impactor Type 1

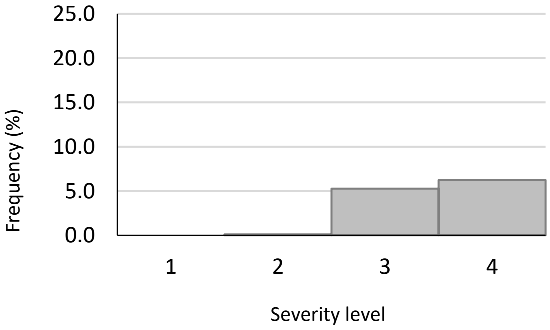


Figure 3.2: Section 41, Impactor Type 2

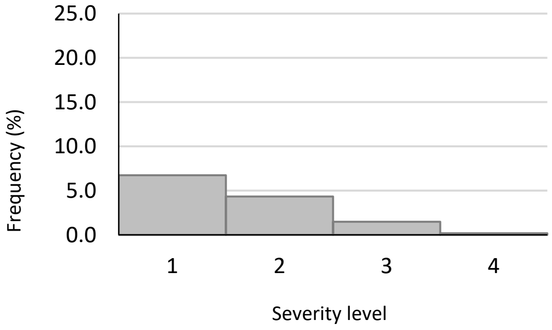


Figure 3.3: Section 46, Impactor Type 1

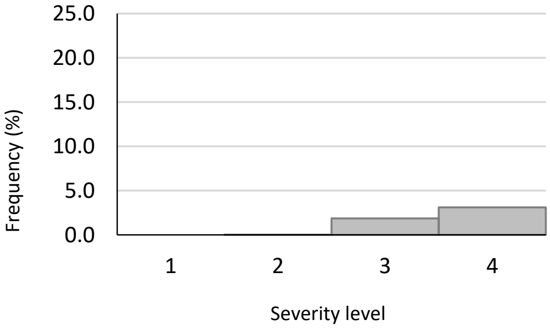


Figure 3.4: Section 46, Impactor Type 2

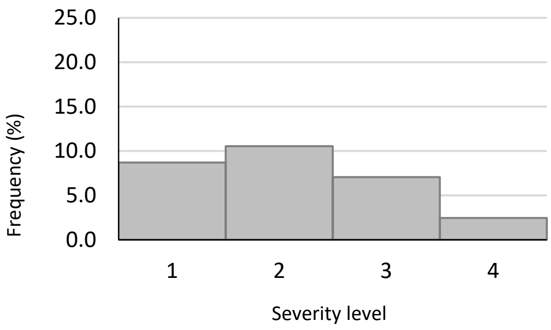


Figure 3.5: Section 47, Impactor Type 1

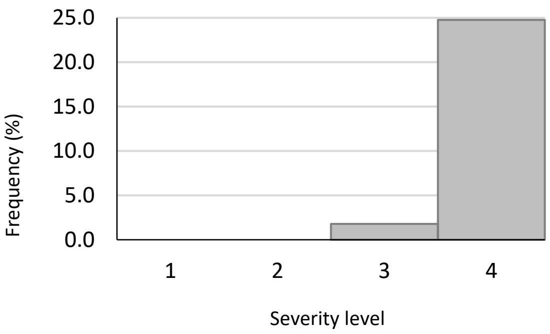
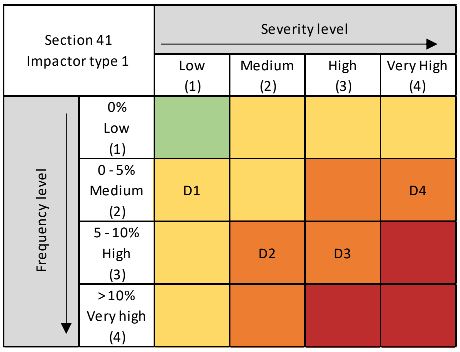


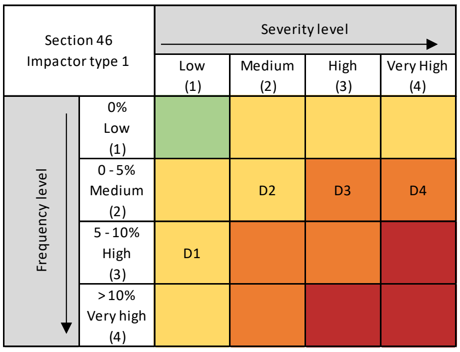
Figure 3.6: Section 47, Impactor Type 2

Performing the conventional DRMA analysis resulted in the risk matrices as shown in Figures 3.7 - 3.12. D_i represents the damage of level i.



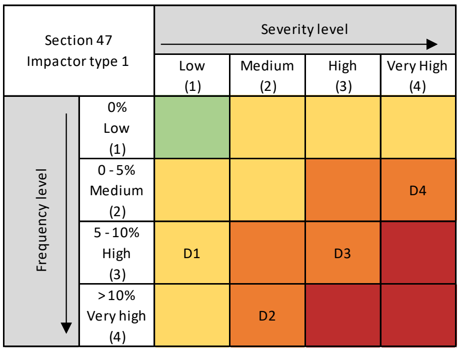
Section 41 Impactor type 1		Severity level →			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level ↓	0% Low (1)	🟩	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨 D1	🟨	🟧	🟧 D4
	5 - 10% High (3)	🟨	🟧 D2	🟧 D3	🟥
	> 10% Very high (4)	🟨	🟧	🟥	🟥

Figure 3.7: Risk Matrix Section 41, Impactor type 1



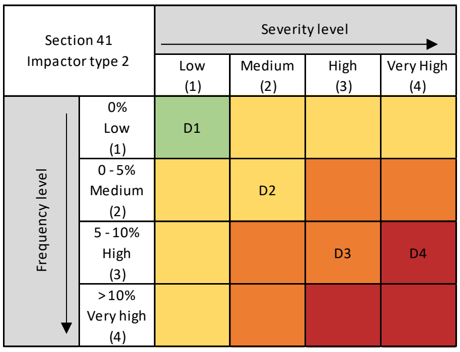
Section 46 Impactor type 1		Severity level →			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level ↓	0% Low (1)	🟩	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨	🟨 D2	🟧 D3	🟧 D4
	5 - 10% High (3)	🟨 D1	🟧	🟧	🟥
	> 10% Very high (4)	🟨	🟧	🟥	🟥

Figure 3.8: Risk Matrix Section 46, Impactor type 1



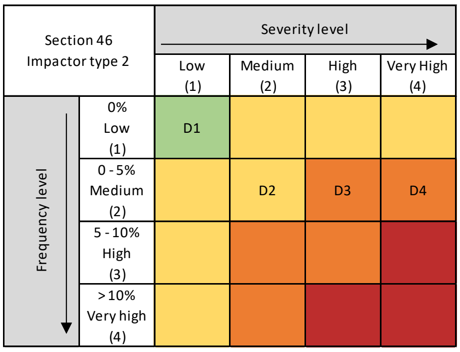
Section 47 Impactor type 1		Severity level →			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level ↓	0% Low (1)	🟩	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨	🟨	🟧	🟧 D4
	5 - 10% High (3)	🟨 D1	🟧	🟧 D3	🟥
	> 10% Very high (4)	🟨	🟧 D2	🟥	🟥

Figure 3.9: Risk Matrix Section 47, Impactor type 1



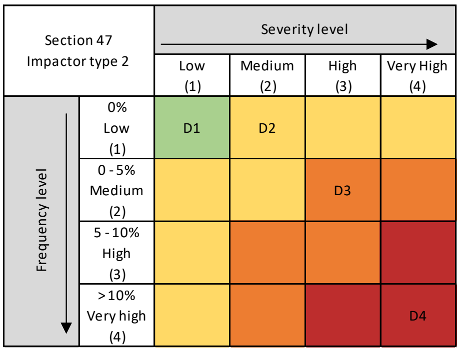
Section 41 Impactor type 2		Severity level →			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level ↓	0% Low (1)	🟩 D1	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨	🟨 D2	🟧	🟧
	5 - 10% High (3)	🟨	🟧	🟧 D3	🟥 D4
	> 10% Very high (4)	🟨	🟧	🟥	🟥

Figure 3.10: Risk Matrix Section 41, Impactor type 2



Section 46 Impactor type 2		Severity level →			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level ↓	0% Low (1)	🟩 D1	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨	🟨 D2	🟧 D3	🟧 D4
	5 - 10% High (3)	🟨	🟧	🟧	🟥
	> 10% Very high (4)	🟨	🟧	🟥	🟥

Figure 3.11: Risk Matrix Section 46, Impactor type 2



Section 47 Impactor type 2		Severity level →			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level ↓	0% Low (1)	🟩 D1	🟨 D2	🟨	🟨
	0 - 5% Medium (2)	🟨	🟨	🟧 D3	🟧
	5 - 10% High (3)	🟨	🟧	🟧	🟥
	> 10% Very high (4)	🟨	🟧	🟥	🟥 D4

Figure 3.12: Risk Matrix Section 47, Impactor type 2

As noticed from Figures 3.7 - 3.12 and looking at the overall risk score from Table 3.1 fuselage Section 47 scores the highest with a difference of 1.9% from Section 41 and a difference of 9.9% from Section 46. This corresponds to Section 47 having the largest amount of impacts. The ratio of amount of damages between Section 47 and Section 46 is 3.1, the ratio of amount of damages between Section 47 and Section 41 is 2.0 and the ratio of amount of damages between Section 41 and Section 46 is 1.5. It makes sense that the section with the largest amount of impacts results in the highest risk section.

Comparison between the matrices of Section 41 and Section 47 show similarity in risk level. For Impactor Type 1 D_1 and D_2 of Section 47 show a higher frequency, however D_1 and D_2 remain in the yellow and orange area respectively. This results in the same risk levels 'Medium Risk' and 'High Risk'. The same holds for the damages caused by Impactor Type 2. Damage types D_3 and

D_4 have different frequencies of occurrence for Section 41 and Section 47, however these damage types are located in the same risk level area 'High Risk' and 'Very High Risk'. Hence the risk levels for Section 41 and Section 47 are similar.

It is noticed from the risk matrix that the larger impactor size, Impactor Type 2, results in a low risk level for small damage type D_1. It would be alluring to say that these impactors causing small damages have very low risk. However the risk of these small damages is low due to no occurrence of these damages caused by Impactor Type 2. Impacts by this type of impactor results in larger damages as the contact area of the impactor is above a minimum size. Hence these impactors cause larger damages resulting in higher severity, hence higher risks.

Adding up the risk levels for each section shows that Section 47 scores the highest. This was expected for performing a conventional risk analysis as Section 47 has the largest amount of damages. It may be concluded that the section with the highest frequency of damages has the highest level of risk.

Overall Risk Score	Section 41	Section 46	Section 47
Impactor type 1	25	21	**28**
Impactor type 2	**26**	19	25
Total	51	40	**53**

Table 3.1: Overall Risk Score

The results of the conventional risk analysis are not sufficient regarding damages on composite structures. With the damage severity and risk levels of these damages known it is crucial to include the detectability of these damages. As stated in Section 2.4 this study scopes only the probability of detection of damages by Visual Inspection. An overview of the amount of detectable damages as a result of including the POD model as described in Section 2.4 is shown in Table 3.2 where ND stands for non-detectable and D stand for detectable. The percentages shown are based on the total number of damages within each section.

Section 41	%	Section 46	%	Section 47	%
ND	85.4		93.9		85.9
Impactor 1	%	Impactor 1	%	Impactor 1	%
ND	77.8	ND	91.5	ND	80.2
D	22.2	D	8.5	D	19.8
Impactor 2	%	Impactor 2	%	Impactor 2	%
ND	95.6	ND	100.0	ND	92.2
D	4.4	D	0.0	D	7.8

Table 3.2: Non-Detectability of each separate Section

The result of the POD model shows that for each section the amount of detectable damages is very low. For each section more than 85% of the damages are undetectable. From the POD results it is also observed that damages caused by Impactor Type 2 have a significant lower detectability compared to damages caused by Impactor Type 1, which was the smaller size impactor. However from the risk matrix above it is clear that large very severe subsurface damages caused by Impactor Type 2 are present. This is in coherence with what is found in literature. Literature says that large impactors leave very small to no dents however they leave large subsurface damage [2]. This demonstrates that small surface dents can contain very severe delamination on the subsurface which is not detectible by visual inspection. Furthermore, the comparison for each level of severity for delamination size shows that the amount of undetectable surface dents is much higher than that of the detectable dents. Even for the larger size delamination which also include larger size surface dents, the dents are undetectable.

To compare the three sections with each other another overview of the percentages of the non-detectable damages is shown in Table 3.3. Note that these percentages are based on the total number of damages on all three fuselage sections.

Section 41	%	Section 46	%	Section 47	%
ND	23.1		16.6		47.5
Impactor 1	**%**	**Impactor 1**	**%**	**Impactor 1**	**%**
ND	12.0	ND	11.6	ND	23.0
D	3.4	D	1.1	D	5.7
Impactor 2	**%**	**Impactor 2**	**%**	**Impactor 2**	**%**
ND	11.1	ND	5.0	ND	24.5
D	0.5	D	0.0	D	2.1

Table 3.3: Non-Detectability Comparison of all Three Sections

As can be seen from Table 3.3 the results of the POD analysis shows that the section with the largest amount of damages which is Section 47 results in the one with the highest amount of non-detectable damages. Section 47 and Section 46 show a large difference which results from Section 47 having three times more damages than Section 46. The result of the POD analysis shows similarity with the conventional risk analysis. Both methods show that the section with the larger amount of impacts leads to the section with the highest risk.

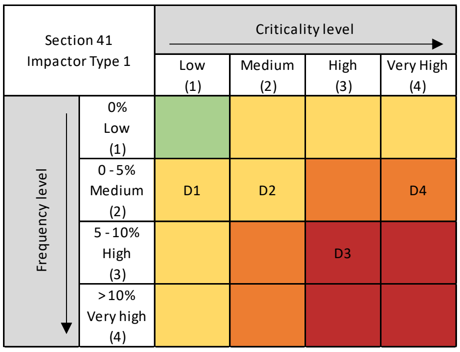
As stated in Section 2.4 the conventional DRMA method and the POD method are combined as damages on composite structures behave differently than damages on metal structures. It is crucial to assess the risks of composite damages by including the probability of detection of the damages to the conventional risk analysis. Performing the combined methods resulted in the seriousness scores represented in Table 3.4. the seriousness score is obtained by multiplying the criticality level by the frequency level.

Section 41 Impactor 1					Section 46 Impactor 1					Section 47 Impactor 1				
Grade	Crit Level	Freq %	Freq Level	Score	Grade	Crit Level	Freq %	Freq Level	Score	Grade	Crit Level	Freq %	Freq Level	Score
2 - 3	1	1.3	2	2	2 - 3	1	0.4	2	2	2 - 3	1	0.9	2	2
4 - 5	2	2.1	2	4	4 - 5	2	0.7	2	4	4 - 5	2	4.8	2	4
6 - 7	3	8.8	3	9	6 - 7	3	10.6	4	12	6 - 7	3	18.4	4	12
8 - 9	4	3.2	2	8	8 - 9	4	1.0	2	8	8 - 9	4	4.7	2	8
				23					**26**					**26**

Section 41 Impactor 2					Section 46 Impactor 2					Section 47 Impactor 2				
Grade	Crit Level	Freq %	Freq Level	Score	Grade	Crit Level	Freq %	Freq Level	Score	Grade	Crit Level	Freq %	Freq Level	Score
2 - 3	1	0.0	1	1	2 - 3	1	0.0	1	1	2 - 3	1	0.0	1	1
4 - 5	2	0.5	2	4	4 - 5	2	0.0	1	2	4 - 5	2	2.1	2	4
6 - 7	3	0.1	2	6	6 - 7	3	0.02	2	6	6 - 7	3	0.0	1	3
8 - 9	4	11.0	4	16	8 - 9	4	5.0	3	12	8 - 9	4	24.5	4	16
				27					**21**					**24**
				50					47					50

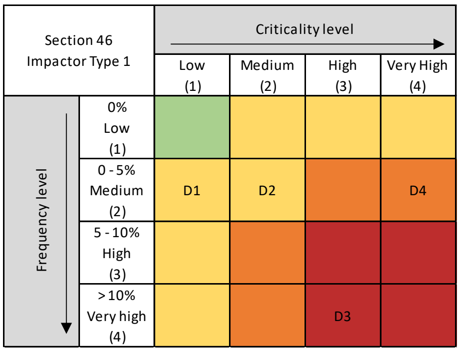
Table 3.4: Seriousness score

The seriousness matrices as a result of the combined risk assessment with the Probability of Detection as explained in Section 2.4 is presented in Figures 3.13 - 3.18. From the seriousness matrices it can be noticed that there is no significant difference between the three sections. Looking at the seriousness scores Section 41 and Section 47 have similar overall scores. Damages caused by Impactor Type 1 result in the same seriousness score for Section 46 and Section 47. Section 41 scores the highest for damages caused by Impactor Type 1. It is essential to remark that Section 47 had the highest amount of impacts. This indicates that the fuselage section with highest number of impacts does not result in the highest seriousness section. Comparing the combined methods with the DRMA method shows that including the POD method holds an important role in assessing the risks of damages on composite structures. From Figures 3.13 - 3.18 can be seen that the non-detectable high severe damage type D_4 has a relatively high frequency of occurrence compared to the other damage types. This holds true for all three sections and impactor types, except for Section 41 Impactor Type 1. Inspection of these type of damages by Visual Inspection seems not to be sufficient.



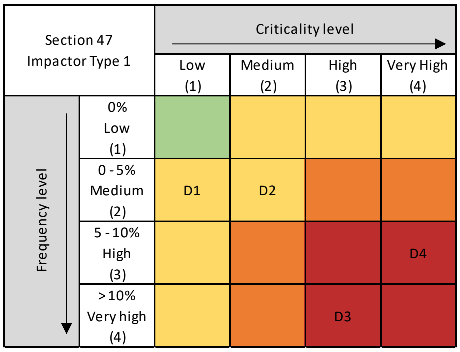
Section 41 Impactor Type 1		Criticality level			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level	0% Low (1)	🟩	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨 D1	🟨 D2	🟧	🟧 D4
	5 - 10% High (3)	🟨	🟧	🟥 D3	🟥
	> 10% Very high (4)	🟨	🟧	🟥	🟥

Figure 3.13: Seriousness Matrix Section 41, Impactor type 1



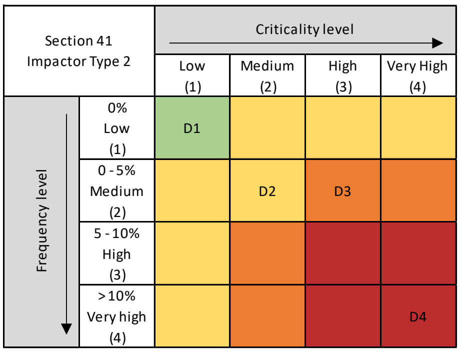
Section 46 Impactor Type 1		Criticality level			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level	0% Low (1)	🟩	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨 D1	🟨 D2	🟧	🟧 D4
	5 - 10% High (3)	🟨	🟧	🟥	🟥
	> 10% Very high (4)	🟨	🟧	🟥 D3	🟥

Figure 3.14: Seriousness Matrix Section 46, Impactor type 1



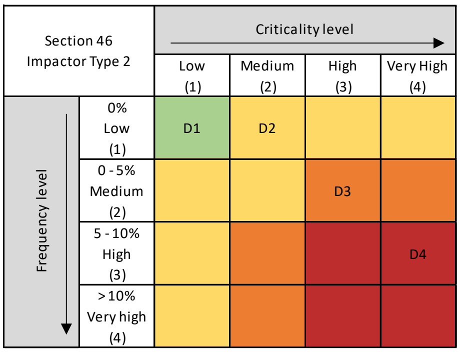
Section 47 Impactor Type 1		Criticality level			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level	0% Low (1)	🟩	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨 D1	🟨 D2	🟧	🟧
	5 - 10% High (3)	🟨	🟧	🟥	🟥 D4
	> 10% Very high (4)	🟨	🟧	🟥 D3	🟥

Figure 3.15: Seriousness Matrix Section 47, Impactor type 1



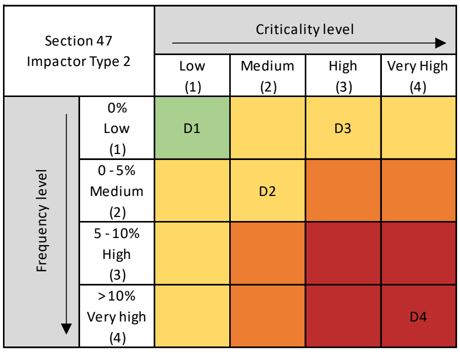
Section 41 Impactor Type 2		Criticality level			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level	0% Low (1)	🟩 D1	🟨	🟨	🟨
	0 - 5% Medium (2)	🟨	🟨 D2	🟧 D3	🟧
	5 - 10% High (3)	🟨	🟧	🟥	🟥
	> 10% Very high (4)	🟨	🟧	🟥	🟥 D4

Figure 3.16: Seriousness Matrix Section 41, Impactor type 2



Section 46 Impactor Type 2		Criticality level			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level	0% Low (1)	🟩 D1	🟨 D2	🟨	🟨
	0 - 5% Medium (2)	🟨	🟨	🟧 D3	🟧
	5 - 10% High (3)	🟨	🟧	🟥	🟥 D4
	> 10% Very high (4)	🟨	🟧	🟥	🟥

Figure 3.17: Seriousness Matrix Section 46, Impactor type 2



Section 47 Impactor Type 2		Criticality level			
		Low (1)	Medium (2)	High (3)	Very High (4)
Frequency level	0% Low (1)	🟩 D1	🟨	🟨 D3	🟨
	0 - 5% Medium (2)	🟨	🟨 D2	🟧	🟧
	5 - 10% High (3)	🟨	🟧	🟥	🟥
	> 10% Very high (4)	🟨	🟧	🟥	🟥 D4

Figure 3.18: Seriousness Matrix Section 47, Impactor type 2

4 Conclusion and recommendations

Due to their light weight, high resistance against corrosion, high strength and high resistance against fatigue, composite materials are increasingly used in new generation aircraft in lieu of metal. However low velocity impact on these materials result in minor indentation on the surface while larger damage, delamination, is present on the subsurface. This subsurface damage is difficult to detect with the most widely used Non Destructive Technique named Visual Inspection. Due to the short in-service operation of the new generation composite aircraft, maintenance organisations have limited experience with damages on these aircraft compared to older generation metal aircraft. Hence these organisations have a lack of data of composite damages. Due to this lack of composite data, metal damage data of a Boeing 777 fleet over the past 20 years was used in this research to estimate the impactors which caused these damages. With the estimated impactors the impact damages on composite aircraft were predicted. For the estimation of impactors and prediction of composite damages a model developed at Delft University of Technology, named MIDAS, was utilized. To have a better understanding of the risk of damages on composite structures the risks of impact damages are assessed by combining a conventional method named Decision Risk Matrix Analysis with the POD of the damages. As Visual Inspection is the primary used technique for inspecting damages on composite structures. Thus the probability of detection of damages in this research only involved visual inspection. Determining the probability of detection of the composite damages is based on a logistic regression model. In this model external factors such as detection type, detection distance and angle, personnel qualifications, gender and age and the colour of the fuselage were kept constant. Internal factors such as impact damage dent depth and radius were used to determine the probability of detection of these damages.

The selection of damages caused by impact and a selection of three fuselage sections led to 181 useable metal impact damage data. 181 impactors were estimated based on the metal impact damage data. For a more accurate risk analysis the impactor data was augmented to approximately 10.000.

For the risk analysis the levels of severity of the composite damages was used as input. The severity was classified in four levels using the Jenks Natural Breaks Optimization algorithm. For the conventional risk analysis the severity of the damage consisting of delamination size and the frequency of occurrence were incorporated. A larger damage size resulted in higher severity. The results of the conventional risk showed predictable results. The fuselage section with the largest number of damages resulted in the section with the highest risk. This was due to the highest amount of damages on that fuselage section.

For determining the probability of detection of the damages the surface damage properties such as dent depth and radius were incorporated. Looking at each fuselage section separately, more than 85% of the damages were undetectable by Visual Inspection. Comparing the three sections by including a weighting factor for each section, the results show that again the fuselage section with largest number of damages resulted in the section with the highest risk regarding number of non-detectable damages.

Basing the inspection strategies only on these methods separately was assumed to be inadequate. It does not give representative results of the risk. It was decided to combine the conventional Decision Risk Matrix Analysis method and the Probability of Detection of damages. Combining the two methods provided different and revealing results. The section with the largest amount of damages was not automatically the section with the highest risk. The section with half the amount of damages and the section with the largest amount of damages scored similar risk. The risk score of the section with three times less damages compared to the section with the largest amount of damages was 3% less than the score of the section with the largest amount of damages. This proves the hypothesis that for composite structures the area with the largest number of damages is not necessarily the one with the highest risk. From the results which show similar risks for the chosen fuselage sections neither section can be prioritized. As there is high frequency of occurrence of non-detectable high severe damages, visual inspection seems not to be sufficient for detecting these damages.

With this information maintenance organisations have a better understanding of the actual risks of low velocity impact damages on composite structures and have an inducement to take the current inspection strategies into consideration.

Although the process started with a small set of data, the method of combining the conventional risks analysis with the Probability of Detection model proved to be a novel approach for determining the risks of composite structures.

In this study several methods and theories of different fields were incorporated, however each step and each method can be varied, optimized and improved to evaluate the outcome of the risk assessment. The influence of other factors such as direct and indirect repair costs could also be included in further research.

This research was limited to impact damages caused by metal impactors. Aircraft encounter many other hazards such as lighting strikes, bird and hail strikes. Damages of these impactors behave differently and should be included to have better knowledge of the overall risks.

This study incorporated only one Probability of Detection model where dent depth was the pivotal factor for detectability. Other models can be developed based on test set-ups which might result in both depth and diameter being equally pivotal for detectability.

Lastly, comparing the risks of damages on metal aircraft structures with the risks of damages on composite aircraft structures, can give a better understanding of the differences between the risk analysis, which can result in better inspection strategies.

References

1. Chen, J. and Z. Fu. *Influence of Grounding Modes on the Damage of Carbon Fiber Reinforced Plastics subjected to Lightning Strikes*. in *2019 11th Asia-Pacific International Conference on Lightning (APL)*. 2019. IEEE.
2. Cantwell, W.J. and J. Morton, *The impact resistance of composite materials—a review.* composites, 1991. **22**(5): p. 347-362.
3. Rice, M., et al. *Automating the visual inspection of aircraft*. in *Aerospace Technology and Engineering Conference*. 2018.
4. Wronkowicz-Katunin, A., A. Katunin, and K. Dragan, *Reconstruction of barely visible impact damage in composite structures based on non-destructive evaluation results.* Sensors, 2019. **19**(21): p. 4629.
5. Rhead, A.T., S. Hua, and R. Butler, *Damage resistance and damage tolerance of hybrid carbon-glass laminates.* Composites Part A: Applied Science and Manufacturing, 2015. **76**: p. 224-232.
6. Dhanisetty, V., *Impact damage repair decision-making for composite structures: Predicting impact damage on composite aircraft using aluminium data*. 2019, Delft University of Technology.
7. Massart, P., *Modelling Impact Damage on Aircraft Structures (MIDAS): Predicting impact damage on (composite) aircraft based on maintenance data of (metal) aircraft.* 2018.
8. Marhavilas, P.-K., D. Koulouriotis, and V. Gemeni, *Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000–2009*. Journal of Loss Prevention in the Process Industries, 2011. **24**(5): p. 477-523.
9. Shivakumar, K., W. Elber, and W. Illg, *Prediction of impact force and duration due to low-velocity impact on circular composite laminates*. 1985.
10. Abrate, S., *Modeling of impacts on composite structures.* Composite structures, 2001. **51**(2): p. 129-138.
11. Simonsen, B.C. and L.P. Lauridsen, *Energy absorption and ductile failure in metal sheets under lateral indentation by a sphere.* International Journal of Impact Engineering, 2000. **24**(10): p. 1017-1039.
12. Lee, Y.-W., J.C. Woertz, and T. Wierzbicki, *Fracture prediction of thin plates under hemi-spherical punch with calibration and experimental verification.* International Journal of Mechanical Sciences, 2004. **46**(5): p. 751-781.
13. Cairns, D., *A simple, elasto-plastic contact law for composites.* Journal of reinforced plastics and composites, 1991. **10**(4): p. 423-433.
14. Olsson, R. and T.B. Block, *Criteria for skin rupture and core shear cracking induced by impact on sandwich panels.* Composite Structures, 2015. **125**: p. 81-87.
15. Omran, M.G., A.P. Engelbrecht, and A. Salman, *An overview of clustering methods.* Intelligent Data Analysis, 2007. **11**(6): p. 583-605.
16. Rausand, M., *Risk assessment: theory, methods, and applications.* Vol. 115. 2013: John Wiley & Sons.
17. Baaran, J., *Visual inspection of composite structures.* 2009.
18. Heida, J.H. and D.J. Platenkamp. *Evaluation of non-destructive inspection methods for composite aerospace structures*. in *International Workshop of NDT Experts*. 2011.
19. Capriotti, M., et al., *Non-Destructive inspection of impact damage in composite aircraft panels by ultrasonic guided waves and statistical processing.* Materials, 2017. **10**(6): p. 616.
20. Cook, L., *Visual inspection reliability for composite aircraft structures.* 2009.
21. Jiang, F., et al., *A method of predicting visual detectability of low-velocity impact damage in composite structures based on logistic regression model.* Chinese Journal of Aeronautics, 2021. **34**(1): p. 296-308.
22. Tropis, A., et al., *Certification of the composite outer wing of the ATR72.* Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 1995. **209**(4): p. 327-339.

23. Morteau, E. and C. Fualdes. *Composites@ Airbus Damage tolerance methodology*. in *Composite Damage Tolerance & Maintenance Workshop*. 2006.
24. Fawcett, A.J. and G.D. Oakes. *Boeing composite airframe damage tolerance and service experience*. in *Composite damage tolerance & maintenance workshop*. 2006.

II

Literature Study

previously graded under AE4020

Risk Assessment of Impact Damage on Composite Structures

Literature Review

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A report presented in preparation of a
Master's thesis research project

Air Transport & Operations
Delft University of Technology
The Netherlands
August 25th, 2020

Executive Summary

Aircraft maintenance organisations are dealing with unexpected impact damages on composite aircraft. Due to limited experience of these aircraft in operations a complete understanding of types of impact damage expected over a long operational lifetime is lacking. To make up for the absence of damage data a damage model has been developed which predicts impact damage threats and impact damage properties on composite aircraft. However, the effect these impact threats and impact damages on composite aircraft have on maintenance strategies are unknown. This motivates to execute a research on the risks of impact threats and types of damages on composite aircraft whis led to following research question:

How can the risks of the predicted damages and damage threats influence the inspection, maintenance and repair strategies of new generation composite aircraft?

In order to be able to execute the research and answer the research question a literature review has been done on three different subjects namely: impact damage and impact damage modelling, maintenance strategies and risk assessment methods.

In order to understand the cause of impact damages literature on impact damage threats have been reviewed. In literature typical damage threats on aircraft are lightning strike, bird strike, tool drops, Ground Service Equipment (GSE), hail and runway debris. Lightning strikes on aircraft depend on the geographic area the aircraft operates and the number of times the aircraft pass through take-off and landing altitudes. Hail is sub-categorized in in-flight impact which occurs on front surfaces of aircraft and ground impact which occurs on horizontal surfaces. Both lightning and hail are season dependent. Runway debris are subcategorized in large debris such as large pieces of pavement and small debris such as gravel. Tool drops are threats during maintenance activities and GSE are threats during ground operations at airports. Impact on composite structures can result in minor indentation or non-visible damage while significant subsurface damage is present. This is because composite material show brittle behaviour which only allows strains up to 0.5% - 1.0% before failure. Impact energy is dissipated by initiation and damage growth which result in matrix crack, delamination and fibre breakage [1, 2]. Matrix crack can as well grow into delamination and fibre breakage.

In the thesis assignment an existing model [3] will be used to estimate impact threats and predict damage properties on composite aircraft based on impact damage properties on metal aircraft. The impact threats on aircraft are the same for both metal and composite aircraft however the types of damage differ. The existing model MIDAS (Model Impact Damage on Aircraft Structures) consists of two variations, the deductive solution MIDAS-M and the inductive solution MIDAS-C [3]. The deductive solution uses impact damage properties on metal aircraft to deduce the impactor properties. The inductive solution, uses these impactor properties to predict the damage dimensions and properties. MIDAS supports the use of real life data consisting of damage properties on metal aircraft. With decades of metal aircraft in operation a large amount of damage data in terms of damage properties can be used to predict damage properties on composite aircraft. However MIDAS also has some limitations. Aircraft structures are assumed to be flat plates whereas most plates are curved. This influences the behaviour of the plate during and after impact. Secondly it is assumed that the impact event occurs at the center of the plate, because the practical restriction is that the locations of the impacts are not always known. Furthermore, the impact event assumes to be boundary dependent and approximated as a quasi-static event leading to neglecting the effect of mass and

velocity of impactor. These drawbacks will be taken into account during the analysis of the output of MIDAS and the risk assessment.

To know how the risks of the types of impact damages can influence the maintenance strategies literature review of the state-of-the-art of maintenance strategies is necessary. In literature maintenance strategies are divided in: scheduled and unscheduled maintenance. Scheduled maintenance is executed after a defined number of hours or cycles. Unscheduled maintenance is dependent on unusual conditions such as the impact threats discussed above. There are three types of maintenance categories: aggressive maintenance, proactive maintenance and reactive maintenance of which reactive maintenance is applicable to impact damage and damage due to lightning strike. This type of maintenance is executed after report of malfunction and unusual events. Aggressive maintenance involves modification in design for prevention of maintenance and proactive maintenance strategies involve maintenance tasks before actual failure or degradation happens. This strategy is applicable for wear-out or fatigue of structures. Hence aggressive and proactive maintenance strategies do not correspond to the impact damage threats above. Maintenance processes are divided up into tasks such as inspection and repair. With inspection being the first task performed within maintenance and affecting the consecutive tasks, inspection is further reviewed. As matrix crack, delamination and fibre breakage are barely visible and non-visible damage, special inspection techniques have been developed and are addressed in literature. These inspection techniques are defined as Non Destructive Testing (NDT). NDT techniques such as Visual Inspection, Eddy Current Testing, Shearography, Ultrasonic Testing and Thermography are frequent techniques evaluated in literature. Visual Inspection might not be the best technique for such damages on composite structures as only the naked eye is used. The other NDT techniques use electromagnetic waves, lasers, ultrasound and heat to detect delamination, fibre breakage and matrix crack. In the research to be executed these techniques can be prioritized depending on the type of threat and type of damage.

Another area of research related to this thesis assignment is risk assessment. Risk assessments are build up from what the hazardous event is, the probability of the event happening and what the consequences are on assets if not controlled [4]. To determine the likelihood of an event happening probability theory needs to be used. Rausand [4] identifies three main approaches to probability: the Classical approach, the Frequentist approach and the Bayesian or Subjective approach. The Classical approach is only applicable for experiments with a finite number outcomes with the same likelihood of occurring. The Frequentist approach is applicable when the experiments can be repeated many times with nearly identical conditions. The Bayesian approach is suitable for outcomes without having the same probability. The risk approaches can be categorized into qualitative and quantitative of which the quantitative method is the better option for the research because it gives a more accurate representation. In literature several quantitative techniques are described. The Proportional Risk Assessment Technique quantifies the risk by multiplying the probability factor, the severity factor and the frequency factor. The Decision Matrix Risk Assessment quantifies the risk by taking the product of severity and probability which are used to set up a risk matrix. The risk matrix gives an illustration of the low to high risk events. The Quantitative Risk Assessment Tool is another quantitative technique where the frequencies of occurrence of events are first defined. The risk is defined as the probability of the event happening. Not a single but more than one risk technique can be applied. In the research this will be done in an iterative manner.

Contents

Introduction

Aircraft maintenance organisations are dealing with unexpected impact damages on aircraft on a daily basis. In contrast with metal aircraft, a complete understanding of types of impact damage on composite aircraft expected over a long operational lifetime is lacking. This lack of data is due to limited experience with new generation composite aircraft in operation. Damage models have been developed to predict impact damage threats and impact damage properties on composite aircraft. However, the effect these impact threats and impact damages on composite aircraft have on maintenance strategies are unknown. Moreover the risks of these damage threats are unknown in a maintenance context. As a consequence maintenance strategies and planning are not accommodated to composite aircraft but to older generation metal aircraft only. The question is how the risks of impact threats on composite aircraft and impact damages can influence maintenance strategies. Therefore the motivation to execute the research is to quantify the risks of these damage threats and impact damages by performing a risk analysis. Knowing the risks makes it possible to evaluate the maintenance strategies and to adapt or optimize the maintenance tasks. The research will assess the risks of damage threats and types of impact damage on composite structures. Before initiating the research literature study on state-of-the-art damage modelling, impact threats on aircraft and impact damages on composite aircraft is performed in order to have an understanding of the damages affecting these type of aircraft. In addition risk assessment theories and current maintenance strategies are studied in order to know how maintenance strategies on composite aircraft can possibly be improved.

In the first chapter literature on impact threats on aircraft and the resulting type of damages on composite structures is being reviewed. Also an existing model, MIDAS (Modelling Impact Damages on Aircraft Structures) which predicts impact damages on composite structures is discussed. This model will be used during the thesis research for predicting impact damages on composite aircraft. A literature review on maintenance strategies applied in maintenance organisations is described in Chapter 2. The third chapter describes a variety of risk methods most relevant for the research to be executed. In Chapter 4 risk methods which will possibly be used and that are related to the type of threats and damages will be discussed. Chapter 5 will present the methodology of the research to be executed including the research objective and research question.

Chapter 1 | Damage Modelling

The thesis project to be executed will consist of a risk assessment on damage threats and impact damages on composite structures. Therefore, to be able to execute the thesis assignment it is fundamental to know what literature says about impact damage threats to aircraft, impact damages on composite structures and modelling these damages. A review of literature on impact threats and damages on composite aircraft structures is presented in the first section. In the second section the model, MIDAS (Modelling Impact Damages on Aircraft Structures) which predicts impact damages on composite structures based on metal damage data is discussed.

1.1 Impact Threats and Impact Damages

During flight, taxiing and ground operations such as freight and baggage loading and unloading and passengers embarking and disembarking, aircraft encounter impact damages of varying severity. These damages are caused by impact threats. Impact threats are the same for both metal and composite aircraft. For the thesis project composite aircraft will be the research object. As the impact threat can cause damage, it is one of the important parameters in the research.

1.1.1 Impact threats

Impact threats are defined by Massart [3] as impactors with an initial velocity, mass, shape and material. There is a large amount of debris and objects which can potentially cause damage. These are defined as Foreign Object Damage (FOD). The FOD are generally divided into hail, bird strikes, runway debris, tool drops and Ground Service Equipment (GSE). To use appropriate modelling techniques Massart [3] characterized the FOD categories by their impact locations, velocities and material properties of both impactor and aircraft.

Hail is sub categorized depending on location and velocity of impact. The first sub-category is in-flight impact which occurs on front surfaces such as nose and wing leading edge with a velocity of around 200 m/s [5],[6]. The second sub category is when the aircraft is located on the ground named ground impact. This impact occurs on horizontal surfaces for example top skin fuselage with velocities up to 30 m/s [6]. Research of Kim [7] has shown that during ascend an descend the normal component of the inclined impact is dominant. This type of impact damages the horizontal surfaces as well.

Bird strikes occur during flight, take-off and landing [8-10]. While hail is season and weather dependent, the threat of bird-strikes is continuous. With the threat of bird strikes being continuous the damage depends on the size of the bird. This type of damage occurs at forward facing surfaces such as leading edges, aircraft nose and front window and engine blades.

Runway debris can cause damage such as torn or punctuated tires, impact on airframes, engine blades [3]. Runway debris is subcategorized into large debris and small debris. Aircraft parts or large pieces of pavement are considered as large debris which lead to safety issues of aircraft operation. Small debris such as gravel, rivets, bolts, nuts and tire fragment only lead to high operational cost[3].

Tool drops are referred to impact damage threats during all maintenance activities. The characteristics of this category are low-velocity ranging between 4 and 8 m/s [1] and large mass impact with masses and height up to 1 kg and 1.5 m respectively. Kassapoglou [11] differentiates the impacts into smaller objects with an impact energy of approximately 5 J and larger objects with impact energy of 25 J.

The Ground Service Equipment (GSE) category is the largest impactor type in size. GSE is used for ground operations such as refuelling, baggage handling, passenger disembarking and embarking, catering loading, etc. GSE accounts for 50% and 60% of major and minor damage of commercial aircraft. Research done by the University of California San Diego (UCSD) [12-16] showed that the velocities of ground handling operations are in the range of 0.5 -1.0 m/s within 0.1 – 1.0 m distance from the aircraft. GSE vehicles have a mass range of 500 to 1000 kg resulting with an impact energy of 1000 J depending on mass and velocity. The contact area of impact is larger compared to the other FOD categories but typical damage is not found on the skin but at the support structures [3].

The damage threats hold true for both metal and composite aircraft. However the damages on composite aircraft differ from damage on metal aircraft. In the research to be executed the type of damage and the severity of damage to composite aircraft will be assessed and the relation between damage threats and types of damage will be examined.

1.1.2 Damages

Impact on composite structures can result in minor indentation or even damage not being visible while significant subsurface damage is present [2]. The brittle behaviour of composite material allows strains up to only 0.5% - 1.0% before failure. The impact energy is dissipated by initiation and damage growth [1, 2]. This results in non-visible delamination and fiber breakage extending beyond the dent region and significant reduction in residual strength [12, 17]. The picture below shows an example of subsurface damage.

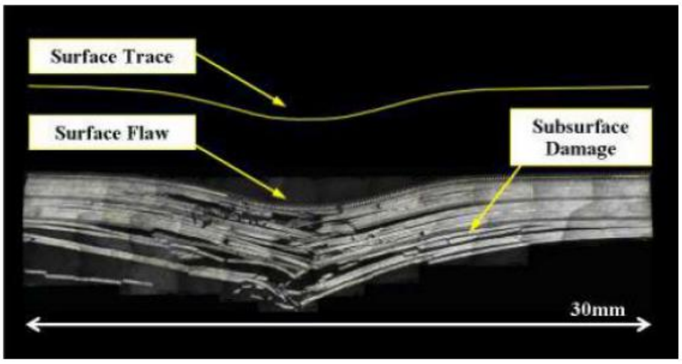

Figure 1: Cross section impact damage on CFRP laminate [18]

Massart [3] made a distinction between surface and sub-surface damage where indentation and surface cracks are forms of surface damage. Sub-surface impact damages consist of delamination, fiber breakage and matrix cracks [19]. Massart [3] divided the impacted structures in three types: thick, thin and reinforced structures. Thick composite parts have limited flexibility where damage is primarily found close to the impact center [2, 19, 20]. The surface damage is described as a hole rather than a surface dent [20]. Kim *et al* [12] point out that GSE cause limited damage to aircraft skin but severe damage to the substructure. Hail and runway debris primarily affect the thin structural components [5]. However Kim *et al* [12] argue that hail damages internal components as well. Bird strikes can damage internal components as well.

Sjoblom, Hartness and Cordell [21] have found that matrix crack results from low energy impacts up to 1.0J. Matrix crack is difficult to detect and does not significantly reduce the stiffness of the laminate. However matrix crack can initiate delamination and fibre breakage.

A study has been executed by Delaney [22] where tests have been done to find the relation between the visibility of surface dent size and delamination damage. Impactors of radii ranging between 12.7mm and 76.2mm have been used on specimens of carbon/epoxy panels. For the examination of the visibility impact damage aerospace quality paint was applied on the panels. By this the test panels were representative to aircraft outer skin. Delaney's [22] study shows that the extend of internal damage and visibility were related, but that the radius of the contact area of the impactor has a strong effect on this relation. Damage by small impactor tip radii were clearly visible with increasing depth correlating to increasing area of internal delamination. Furthermore, small radii impactor tips can leave a surface dent without any internal damage. Larger radii of impactor tips (blunt tips) can create large-area internal delamination without leaving any visual surface damage or low visibility surface damage. Low velocity high radius impactors such as GSE are therefore dangerous impactors as they leave barely-visible to non-visible impact damage.

The threshold of visibility depends on human factors as well, which is not included in the scope of the this literature review.

The damages on composite structures caused by impact are minor residual indentation which result in subsurface damage such as delamination and fibre breakage [2].

1.1.3 Lightning

According to the definition of an impactor lightning is not considered an impactor. However lightning is a common damage threat to aircraft and is therefore included in the research.

Carbon Fiber Reinforced Plastic (CFRP) composites have been introduced to aircraft structures to reduce overall weight in order to improve fuel efficiency and reduce costs. They have high specific strength, high specific modulus, lightweight, high fatigue and corrosion resistance [23]. However, when lightning strikes low electrical conductivity of CFRP is a disadvantage compared to metal airframes. Low electrical conductivity, low thermal conductivity and anisotropy of CFRP cause more damage when lightning strikes compared to metal aircraft; electromagnetic force cannot be prevented sufficiently from destroying the structure [23]. Sweers [24] argues that the severity and type of damage lightning strikes can vary greatly, depending on factors such as the energy level of the strike, the attachment and exit locations, and the duration of the strike. Damages such as melting or burning at lightning attachment points [25] result in delamination, fiber and matrix breakage [23].

Furthermore, Sweers [24] found that the frequency of lightning strikes on aircraft depends on the geographic area the aircraft operates and the number of times the aircraft pass through take-off and landing altitudes. At these altitudes the lightning activity is most prevalent. Lightning activity varies greatly by geographic location; lightning tends to occur most near the equator due to higher temperatures. Concluding that lightning activity is lowest over oceanic and polar areas and highest over warm continental areas. Therefore for the research to be executed damages on long-haul composite aircraft will be predicted assuming operation over oceanic areas. Gathered data from airlines with 881 strikes reported Sweers [24] concluded that more lightning strikes occur when aircraft fly through the clouds, during climb and descent phase. Sweers [24] argues that the reason for this is because lightning activity is more prevalent between 5000 and 15000 ft (1524 – 4572 m) altitude. This means that short haul flights operating at these altitudes are more likely to have a higher frequency of lightning strikes compared to aircraft operating long haul flight over oceanic areas and higher altitudes. Sweers [24] points out that the aircraft locations with the highest probability of lightning attachment are the outer extremities, such as wing tips, nose, or rudder.

Protection against lightning

To prevent or reduce damage on composite aircraft due to lightning strikes Lightning Strike Protection (LSP) has been introduced. The protection principle used in LSP is the increase of electrical surface conductivity where a continuous conductive path of low resistance over almost the entire aircraft surface is provided. The conductive path, typically expanded metal foil, is assembled on top of the upper composite ply. This path reduces heating and prevents electrical flow inside the composite material. However, this tends to negate the benefits of composite structures as metal is used for conductivity. For the past few years there has been an increase in research for high performance, multifunctional nano-reinforced composite structures [26].

Modelling lightning strikes

To predict lightning strike damages to CFRP Fu [27] developed a numerical lightning strike model. They have simulated lightning strikes on CRFP with and without LSP systems. Their study showed that the shape and depth of damage predicted by their model were comparable to experimental data. Although lightning strike damage have been modelled the scope of this review will not include the use of lightning strike models, but is solely for background information and reference for further analysis of lightning strikes on composites.

The model which will be reviewed and used for further research of impact damages is an impact damage model developed by Massart [3] which is limited to impact damage only. This model will be reviewed in the following section.

1.2 MIDAS

When aircraft are inspected damages are found by maintenance personnel. However the properties such as size, velocity, mass and material of the impactors are unknown. To estimate the impact threats on the aircraft an impact damage model MIDAS has been developed by Massart [3]. This model uses metal damage properties to deduce the impactor properties. These impactor properties are then used to predict composite impact damage. The model is based on combinations of elements of modelling methods proposed by Shivakumar [28], Abrate [29], Simonson and Lauridson [30].

1.2.1 Modelling Impact Event

Literature categorizes a wide variety of impact events such as velocity, damage formation or deformation response of the structure [1, 2, 19, 31, 32]. Velocity is most common and is distinguished in low, high and hyper velocities where thresholds of low, high and hyper high varies per study. Impactor stiffness and mass, plate size and stiffness and boundary conditions influence the variation in thresholds. Olsson [33] points out that besides impactor energy or velocity, the impact duration is also important to classify the impact event. Impact duration depends on the impactor inertias. High and hyper velocity impact events relate to very short impact times and low velocity impact relate to short and long impact times [1]. This means that low velocity impact corresponds to a large mass impactor and high velocity impact corresponds to small mass impactor. Impact event with low and high velocity are simulated by researchers using a pendulum drop weight test, gas gun impact test and hydraulic test machines.

1.2.2 Development of MIDAS

Massart [3] developed an analytical model, Model Impact Damage on Aircraft Structures (MIDAS), which enables to predict impact damages on composite aircraft structures based on damages of metal aircraft structures. The model consists of two variations, MIDAS-M referred to as the deductive solution and MIDAS-C referred to as the inductive solution. There are several models developed based on theory and experiments to model impactor, damage impact and damage due to impact. However MIDAS is able to estimate impact scenarios and use the impact scenarios to predict impact damage on composite structures.

MIDAS is useful for the prediction of impact damage on composite structures within the research to be executed. The output of MIDAS allows to assess the risk of the damage threats. MIDAS provides damage estimates over a wide range of impact scenarios within a short time. As mentioned before MIDAS can use industry’s metal damage data consisting of dent depth and radius to estimate the damages on composite structures. Being able to use industry’s data will give a sufficient approximation of expected damages on composite structures which can thereafter be used to adapt maintenance planning.

MIDAS-M

The deductive solution uses impact damage dimensions such as dent depth and size/radius of the dent on metal aircraft structures as input. Impactor properties such as mass, velocity, size/radius and material are deduced by MIDAS-M from the metal damage properties. With these impactor properties impact scenarios are estimated. The development of MIDAS-M uses modelling methods of Shivakumar [28], Abrate [29], Simonsen and Lauridsen [30] and Lee [34]. For metal damage Massart [3] implemented a transition region between the local and global deformation modes based on penetration limits. Literature describes a procedure which approximates the deformation state of the entire plate close to penetration whereas Massart's model [3] approximates the entire impact event, which includes deformation such as bending strains further away from penetration area.

MIDAS-C

The inductive solution, uses the impactor properties deduced in MIDAS-M as input for MIDAS-C to induce composite damage properties such as dent depth, size/radius of the dent, delamination and fibre breakage. The development of MIDAS-C builds upon Cairns [35] and Olsson and Block [36]. Composite materials behave differently; there is no transition region between local and global deformation but only local and global deformation occur. However, Massart [3] argues that MIDAS-C provides an approach for permanent indentation in the post fibre breakage region. The loading phase of an impact event on composite structures consists of elasto-plastic stage, delamination initiation and growth, and fibre breakage. In MIDAS-C delamination and fibre breakage modify the base behaviour in the elasto-plastic stage. The development of MIDAS-C is based on the elasto-plastic contact law of Cairns [35].

Drawbacks and Limitations

As described in Section 1.1.2 matrix cracks, delamination and fiber breakage are impact responses in composite structures. It is noted that matrix crack is not included during the development of MIDAS-C. However, from literature matrix cracks appear regularly after impact which develop into delamination and fibre breakage. Including matrix crack in the modelling process will give a more elaborate representation of damage on composite structures which can be used for further analysis of composite damages.

Besides the excluded matrix crack in the model it has some limitations due to primary assumptions at the start of the development. Impact threat is assumed to be rigid. However impactors such as hail and rubber bumpers from GSE deform during impact. This can result in a larger contact area of impactor than assumed. Moreover the impactors are characterized as spherical objects but bird strikes and tool drops can have sharp areas which can result in another type of damage or severity of damage.

The target structure is assumed to be a flat plate which is clamped or simply supported. The aircraft structures to be assessed are mostly curved plates which have smaller contact area during impact.

Due to the boundary condition assumptions the plate absorbs the impact energy. However in aircraft structures, stringers and frames take up part of the energy. Studying the effect of energy absorption of stringers and frames may result in a better understanding of these damages.

Impact events are assumed to be boundary dependent and approximated as quasi static event, therefore the effect of mass and impact velocity with respect to type of impact response is neglected. However the effect of impact energy with respect to type of damage can be determined.

Perpendicular and centrally located impacts are assumed. For non-perpendicular impact the perpendicular component of the impact is the dominant one which is smaller in intensity compared to the assumed perpendicular impact. However this is a good approximation of intensity of damage. Central impact is assumed due to unknown exact location of impact. This may result in different damage characteristics. The damages due to off-center impacts can therefore not be analysed using MIDAS.

A limitation of Massart's [3] work is that modelling of damage on composite structures due to lightning strikes is not included as lightning strikes make up a large amount of impact damages.

Chapter 2 | Maintenance Strategies

The amount of composite materials used in commercial aircraft has increased. With the use of more of these materials in new generation aircraft composite material structures have to be maintained in a safe and economical manner, as is for metal structures. Maintenance of aircraft has to be performed regularly according to regulation standards set by the Maintenance Steering Group-3 (MSG-3). As described in Chapter 1 composite materials are susceptible to impact damage with damage modes difficult to detect. Inspection is the first step within the maintenance process to detect damages before the right repair method can be applied. Special inspection techniques are necessary to detect these type of damages. First the state-of-the-art literature of applied maintenance processes is discussed in Section 2.1 after which inspection techniques relevant to the before mentioned type of damages are reviewed.

2.1 Maintenance Processes

Aircraft maintenance is a process which ensures that the aircraft parts can continually perform at its intended level of reliability and safety. Inspection, overhaul, repair, preservation and replacement of parts are typical maintenance activities. There are two types of maintenance: scheduled and unscheduled maintenance. Scheduled maintenance activities are divided in: en-route service, pre-flight checks, service checks, daily and weekly checks, A-check also known as ‘hangar maintenance’, C-check and D-check known as ‘heavy maintenance’ [37]. The A, C and D-checks are performed after a defined number of flight cycles and flight hours. Unscheduled maintenance is not related to number of flight cycles or flight hours. This type of maintenance is dependent on unusual conditions such as hard landing, bird hit, lightning strike, etc. The type of maintenance depends on the type of flaw or damage.

Scheduled maintenance tasks and intervals for aircraft structural items are determined by the Maintenance Steering Group (MSG-3). However, MSG-3 largely depends on engineering experience. Chen [38] claims that the defined tasks and intervals are inappropriate for new generation composite aircraft. However these defined tasks and intervals are a foundation for further research and evaluation of the effect of damages on composite structures on the maintenance process.

As impact damages and lightning strike damages are the scope of this review and cause unscheduled maintenance, this type of maintenance will be further reviewed.
MSG-3 defined three types of unscheduled maintenance strategies [39]:

Redundancy
During the design phase aircraft parts and components are designed with redundancy. These parts are allowed to fail without affecting the aircraft’s airworthiness. When such parts or components fail the redundancy parts are able to take over the function. For structures redundancy components are able to carry the loads. Apart from structural components, this strategy also applies to radio, radar, etc.

Line Replaceable Units (LRU)
Failure of LRU's such as engine parts and avionics does not affect the aircraft's airworthiness due to the ability of quickly replacing these units during ground operation of the aircraft. The faulty unit is repaired or discarded.

Minimum Equipment List (MEL)
A MEL is a list of equipment which must remain in service in order to keep the aircraft airworthy. It includes the items which may be inoperable while maintaining airworthiness. Defective items on this list may be scheduled for later repair. This strategy provides flexibility to the maintenance planning and execution.

From the above strategies redundancy is the only one applicable for impact damage and lightning strike on composite wing and fuselage skin structures. When aircraft are subjected to impact damage or lightning strike during operation at a location where there are no maintenance facilities for composite repair these aircraft should be able to fly to the nearest maintenance facility at least with adapted control.

Maintenance categories

Maintenance is categorized in reactive, proactive and aggressive maintenance [40]. These categories are again subcategorized as shown in Figure 2.1.

Aggressive maintenance strategies aim at improving the equipment of the system by modifications in the design for prevention of failures.

Proactive maintenance strategies are developed to prevent system breakdowns. Maintenance performed before actual failure happens or degradation below a certain level appears.

Reactive maintenance is done after report of malfunction or report of unusual events, such as hard landing, bird strike, etc. Reactive maintenance is divided into corrective and detective maintenance. Where corrective maintenance, is characterized by fixing and/or replacing components when failed or detected when failing. Detective maintenance only applies to hidden or unrevealed failures of items such as protective devices of which the failure may have occurred long before revealed by a periodic test.

Inspection and detection of impact damage and lightning strikes are tasks that are part of reactive maintenance. For the research to be executed it can be said that these types of damages occur randomly and unexpected/unforeseen. In this case proactive maintenance cannot be done. However, analysing the impact damage data for the thesis assignment may result in proactive maintenance in the sense of equipment, tools and facility preparation and incorporating maintenance time for impact damage within the maintenance schedule and prioritize inspection locations. Obviously proactive maintenance in the sense of replacement before failure is not possible for impact and lightning strike.

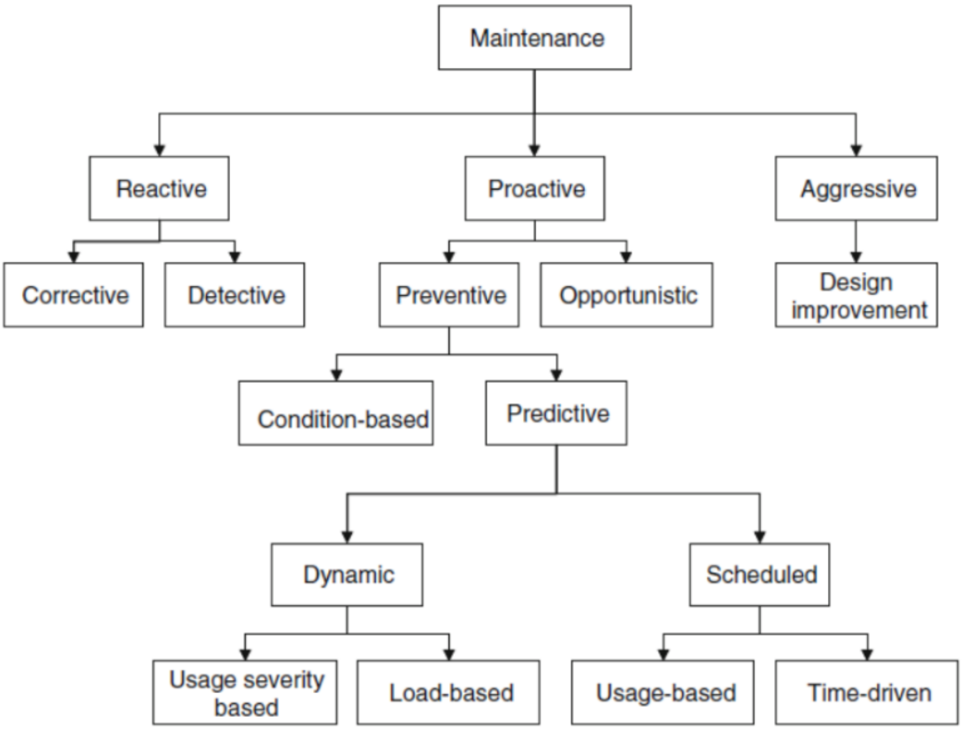

Figure 2.1: Maintenance Categorization [40]

There is earlier research done on causes of delays during A-check maintenance which show several factors leading to delay found by the researchers:

- inadequate logistic process which lead to unavailability of spares when needed [41, 42],
- long time to find solutions for reported defects due to poor troubleshooting [43, 44],
- defects found during maintenance inspections at the time of A-check [45],
- uncertainty of required spares for maintenance [46-49],
- poor communication [37].

Although these researchers focused on line maintenance, the delay factors may also count for reactive maintenance due to impact and lightning strike damages.

Studies have shown that one half of the overall maintenance workload within heavy maintenance consists of planned activities [50]. Concluding that the other half of heavy maintenance comes from unscheduled maintenance activities arising from inspections or pilot reports. These unplanned activities could lead to delay and complications in scheduled maintenance. Therefore the thesis will focus on impact damages which are the cause of unscheduled maintenance activities.

Assessing the impact damages from Chapter 1 on composite structures and finding the relative inspection technique and repair method can contribute to the knowledge for preventing the delay factors and consider the maintenance tasks in heavy maintenance scheduling.

2.2 Inspection

2.2.1 Inspection Process

Visual search for damage is a major sub task within inspection of aircraft structures. For studying visual inspection of damage and to present ways in which inspection strategies can be assessed a multi-level framework is provided in literature. A generic task analysis for inspection of aircraft structures is presented by [51] consisting of: ‘Initiation’ - prepare equipment, ‘Access’ - reach the to be inspected part of aircraft, ‘Search’ - examine specified area for specified indications, ‘Decision’ - determine action required, ‘Action’ - mark damage and document, ‘Repair’ - complete repair, ‘Buy-back’ - inspect repair for airworthiness. The scope of this review limits to the task ‘Search’.

Search Hierarchy

It is common that the component or item to be examined is larger than the visual field of the person examining or the device. This results in movement of the ‘field of view’ (FOV) over the component. The ‘visual lobe’ (VL) should only be moved within the ‘field of view’. Within the visual lobe information can only be extracted at a certain rate [book’s ref: Eriksen]. Hence, the ‘attention area’ (AA) within the visual lobe should be chosen as starting point in the read-out process [51]. Figure 2.2 gives a representation of the search hierarchy.

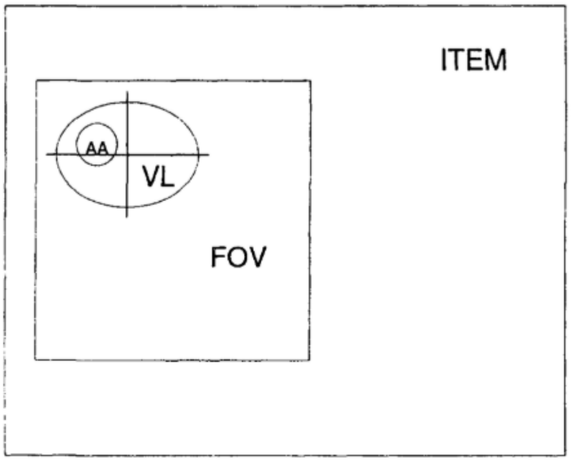

Figure 2.2: Hierarchy of areas in search [51]

Search Process

Information read-out from the attention area can be damage found or no damage found. The process stops when damage is found and when no damage found the search over the item continues. The information can redirect towards the location of damage as well. The search is terminated when no damage found over the entire component.

2.2.2 Inspection Methods – Non Destructive Techniques

Non Destructive Techniques (NDT) make it possible to detect, localize and determine the size of barely visible damages and flaws of composite structures. Furthermore, these NDT techniques should allow for possibly early damage detection. There is a wide variety of NDT methods which play major roles in testing of composite materials.

Non-destructive testing involves the identification and characterization of damages of materials without destroying or altering the material [52]. The Encyclopaedia [53] describes the state of the art NDT techniques. These NDT techniques include effectiveness in detection, early localization and identification of damage. The main techniques that are evaluated their applicability to detect damage on composite structures, are visual inspection, optical methods, eddy-current (electro-magnetic testing), ultrasonic inspection, laser ultrasonic, acoustic emission, vibration analysis, radiography, thermography and Lamb waves.

For *Visual Inspection* only the 'naked eye' is conducted without the use of any tools. Sufficient illumination of the surface to be tested is required. This technique is limited to near surface inspection [54].

Optical methods use optical fibre sensors which detect material changes based on variations in transmission intensities and phase changes. This technique is used in Structural health Monitoring (SHM) during the aircraft's life cycle by offering strain and temperature readings. SHM techniques have high costs.

Shearography is an optical method for testing which monitors surface displacement gradients using a laser [55]. Flaws are identified from strain concentration induced in the region around the defect. The purpose of Shearography is to detect delamination of composite materials.

Eddy Current Testing is an electromagnetic inspection method most used for in-service inspections. This technique is widely used to identify flaws or damages in electrically conducting materials by correlating the measured impedance with calibrated defect dimension [54]. Eddy current is used for inspection for surface and sub-surface cracks, corrosion, delamination and other structural defects. The scanning probe needs to be perpendicular and as close as possible to the test material. In some cases the component needs to be removed in order to inspect the part underneath.

Ultrasonic Testing is a very accurate (in mm) measurement technique which uses ultrasound to inspect. Concentrated high energy acoustic waves are generated with frequencies ranging from 1 to 50 MHz. The sound can be damped or reflected of which the information is analysed. This testing method is applicable to detect flaw existence and dimensions, characterize material properties, measurements of the location and size of damage, delamination, corrosion and cracks [56]. Ultrasonic inspection can be done with immersion in water. This technique requires component removal which causes disruption in operation. Another ultrasonic technique does not require component removal and uses air-coupling. However this technique gives less accurate results.

As an alternative for the water required ultrasonic testing laser-generated ultrasound is developed [57]. This is a highly sensitive technique and allows testing of complex curvature structures. However the high cost of laser techniques is a limitation for extensive use.
Acoustic emission is generated by stress waves produced by movements of defects in solids such as fibre breakage, fibre pull-out, matrix cracking and delamination in laminated composite plates [58]. This technique is applicable for the inspection of impact damage of composite material. A requirement for this technique is that the structure needs to be stressed during inspection and the environment should be free of noise.

Coin-tap is a vibration based method where the change of sound between defected and non-defected regions indicates the presence of damage [54]. This inspection technique was found to be promising for quality control of production of fibre reinforced plastic tubes.

X-radiography uses electromagnetic waves with short wave length (< 10-8m of Angstrom) to penetrate through materials after which an image is formed on a digital medium. The application of conventional X-radiography to inspection of composite material is limited due to low absorption of X-rays [54]. Furthermore X-radiography brings safety issues; personnel has to be trained for radiation safety.

Thermography Testing monitors heat distribution. Energy heat is propagated through the cross section of a structure from the exposed surface to the opposite surface of the test object. For homogeneous material without defects the heat passes through uniformly whereas defects in the material create high thermal impedance to the passage of heat [54]. The accuracy of the method is limited to the surface of the object. Thermal wave propagation methods such as lock-in thermography and pulse thermography have been used to detect delamination, corrosion, surface cracks and voids. Detection of microcracks are done by combining elastic wave propagation with thermal wave propagation [59].

Lamb Waves are elastic waves generated in a solid plate. Using lamb waves for NDT can be used in line scan rather of large panels rather than point scan in most other NDT techniques. Furthermore greater propagation distances can be achieved [54]. Lamb waves used in NDT are used for fault or damage detection.

For the thesis assignment the results of the risk analysis will be evaluated together with the above inspection techniques derived from literature to conclude which technique fits best for each type of damage.

2.2.3 Detection of Damage

In this section the work of two researchers is reviewed. Katunin [60] thoroughly evaluated NDT techniques on Glass Fiber Reinforced Plastics while Gaudenzi [61] evaluated three NDI techniques on Carbon Fiber Reinforced Plastic.

Katunin [60] evaluated the applicability of non-destructive testing techniques based on the following categories: effectiveness in detection, localization and identification of damage in early phase of development and the application of the technique. PZT sensing, ultrasonic,

thermography and vibration-based inspection are the NDT techniques evaluated. Katunin [60] used glass fibre-reinforced plastic (GFRP) plate and a multi-layered Al-GFRP-Al plate consisting of GFRP core and aluminium alloy on top and bottom with typical damage of 0J, 3J, 6J and 9J.
As mentioned in Chapter 1 composite structures are vulnerable to impacts and even low velocity impact. Damages such as matrix cracking and delamination inside the composite are in most cases not visible on the surface during visual inspection, named Barely Visible Impact Damage (BVID).

Piezoelectric Transducers (PZT) are used in some ultrasonic testing techniques. The PZT are embedded in the structure and are used as transducers or receivers of elastic waves. This method is a form of inspection and called Structural Health Monitoring. PZT transducers continuously monitor the health of the structure. For the analysis of the results Katunin [60] used Damages Indices (DI). The results showed a higher change in Averaged Damage Indices (ADI) which is caused by a higher impact damage of 9J. the DI depend on the size of the damage however, they can also be adjusted by the properties of the transducer or measuring device, or coupling with the ambient medium. Katunin [60] states that this technique cannot be used for exact characterization of damage. Still, the use of PZT in Ultrasonic Testing can indicate that damage occurred in an early stage detection stage.

Katunin's [60] experiment of inspection of the GFRP and Al-GFRP-Al specimens using ultrasonic testing exposed all barely visible damages (BVID) with size and depth. Here the amount of impact energy and type of inspected structure did not have an influence on the detection. Katunin [60] found that not only the damage is visible on C-scans but also the PZT transducers (embedded during production) and the Al-GFRP-Al coatings. It can be seen that the aluminium sheets are plastically deformed due to impact and it is possible to distinguish between the plastic deformation and delamination.

For the evaluation of thermography inspection Katunin [60] used and Echo Therm System camera. It appeared that the damage of the lowest impact energy of the GFRP structure was not detected. For the Al-GFRP-Al structure all damages were detected. However with this technique it is more difficult to differentiate between delamination and plastic deformation of the aluminium sheets. Katunin [60] concluded that this technique is faster to be performed compared to UT which is validated by in-service experience of Aircraft Force Institute of Technology in testing composite elements of aircraft.

Gaudenzi [61] performed an evaluation of impact damage on composite structures by comparing different NDI techniques as well. In this experiment carbon fibre reinforced plastics (CFRP) are used as test specimens. the performances of ultrasonic testing, (optical) thermography and sonic infrared for inspection of barely visible impact damage were evaluated. Gaudenzi [61] related low velocity impact with an energy range of 5 -25J. The selected energy levels to impact the specimens were 8J, 12J and 20J.

For the *Optical Thermographic* testing the operating frequency was varied from 0.1 Hz down to 0.04 Hz. Gaudenzi [61] found that depending on the material's thermal diffusivity, the shallowest defects and the deepest defects in the CFRP test piece were identified.

Gaudenzi [61] operated the *Sonic Infrared Thermography* with a modulated excitation to produce heat in order to identify the areas with failures. Discontinuities of physical properties are detected. The result presents a typical multi-delaminated pine-tree formation.

Ultrasonic Testing using PZT was used to complement the infrared thermography in order to refine the depth profiling of composite delamination, the morphology and propagation of impact damage throughout the whole thickness of the specimen.

Chapter 3 | Risk Analysis

Risk analysis also known as probabilistic analysis is the analysis of frequencies and consequences of accidents or hazardous events. To prioritize aircraft inspection and maintenance strategies risk assessment performs an important role. The goal of risk analysis is to inform decision-makers about the probability that certain (hazardous) events occur and what the consequences are on assets or environment. The effectiveness of the prioritized strategy depends on the extend of the risk assessment and the risk assessment method. Literature shows a wide variety of risk assessments of which the most relevant are described in this chapter.

3.1 Risk Assessment Process

In literature there are many different definitions for risks. Words such as chance, possibility, hazard and danger are often used, however they are all related to an event which can happen in the future. Within this review a future event which can happen is considered a risk when this event can cause harm or damage. These risks are analysed by identifying the causes of the harmful events (risks), determining the probability of occurring and identifying the consequences if the event happens. When assessing these risks the severity of the consequences are analysed to determine if the risks are tolerable or not. Determining mitigation options is part of a risk assessment in order to decrease the probability of occurring and decrease the severity of the harmful event [4, 62]. However this review will not scope mitigation.

Before explaining the risk assessment process the general terminology used in risk assessments is described first. Before a risk assessment can be executed the events and type of events should be defined. An event can be divided into initiating event (or initiator) and hazardous event where the initiating event is defined as an event that upsets the normal operations of the system and may require a response to avoid undesirable outcomes [4]. The hazardous event is defined as the first event in a sequence of events that, if not controlled, will lead to undesired consequences [4]. An accident scenario is defined as a specific sequence of events from initiating event to an undesired consequence. The initiating event may even represent the hazardous event [4]. A hazardous event may lead to consequences. Consequences often refer to damage or harm to people, assets or environment. The probability of occurrence of the consequence depends on the physical situation. According to the theory stated above a specific operation, situation or weather condition can be defined as the initiator and an object striking another object or asset the hazardous event with damage or harm being the consequence. However Rausand [4] states that it is up to the risk analyst to choose what the initiating event is.

Risk Assessment Process

The ISO Guide 73/ANSI Z690.1-2011 [62] defines a risk assessment process consisting of three steps: risk identification, risk analysis an risk evaluation. In the risk identification step potential hazards are found, recognized and recorded. Risk analysis includes determining the probabilities of occurrence of the hazardous events and relative consequences. Furthermore the severity of the consequences is classified to determine the risk levels. Risk Evaluation contains comparing the levels of risks and considering additional controls in order to reduce the risk. ICAO (International Civil Aviation Organisation) describes the 5-step Risk Management Process consisting of Hazard Identification, Hazard Probability, Hazard Consequence, Risk Assessment, Risk Control/Mitigation. In the risk management process ICAO describes Hazard Identification includes the same tasks as risk identification. Hazard Probability and Hazard Consequence are both included in the Risk Analysis step of the ISO guide and Risk Control contains the same tasks as Risk Evaluation. This concludes that both approaches describe the same process order with the same tasks. Furthermore both approaches include the same key factors of the risk assessment: probability, frequency and severity. For the risk assessment to be executed the ISO guide will be used as presented in Chapter 4

3.1.1 Key Risk Factors

Probability
Probability or likelihood is a measure of chance of the occurrence of an event. In literature likelihood and probability are used interchangeably. However Popov [62] defines likelihood as the chance of an event happening expressed qualitatively and probability as a quantitative measure of the chance of something happening. Historical data, predictive techniques and expert experience are three methods used to determine the future likelihood or probability of occurrence.

The probability of occurrence of the hazardous event knows three main approaches: the classical approach, the frequentist approach and the Bayesian approach [4].

The classical approach is only applicable for events with a finite number of possible outcomes with each the same likelihood of occurring. The classical approach should be able to be repeated a large number of times under nearly the same conditions. The probability of the event is determined by the following equation [4]:

$$\Pr(E) = \frac{number\ of\ favourable\ outcomes}{total\ number\ of\ possible\ outcomes} = \frac{n_E}{n} \tag{3.1}$$

Where the favourable outcomes are the outcomes that belong to event E.

For the research to be executed the outcome is defined as the consequence of the hazardous event namely the damage. During the research bird strikes can be modelled as a classical approach if assuming the strikes occur under the same conditions.

The frequentist approach involves events which are repeatable with essentially the same conditions for each experiment. It is assumed that each repetition may or may not result in the same hazard. If the experiment is repeated n times the relative frequency [4] can be defined by:

$$f_n(E) = \frac{n_E}{n} \tag{3.2}$$

Since the conditions are nearly the same for all experiments, the relative frequency will approach a limit when $n \to \infty$. This limit is called the probability of E and is denoted by the following relation [4]:

$$\Pr(E) = \lim_{n \to \infty} \frac{n_E}{n} \tag{3.3}$$

This means that if the experiment is repeated several times, the relative frequency will fluctuate. For large n the fluctuation of the frequency will decrease.

For the research to be executed most damage threats can be modelled as the frequentist approach as they are repeatable with same conditions e.g. ground operations are the same for each aircraft on the ground. However the hazard can be different and so does the consequence.

The Bayesian approach is useful for low-frequency scenario's and when the outcomes do not occur with the same probability [4]. This approach is able to incorporate non-empirical data. The Bernoulli process and the Poisson process are widely used stochastic models which apply to the Bayesian approach [63]. A Bernoulli process is used when there are only two possible outcomes. A Poisson process is used to determine the number of events within a defined time frame. Within the scope of the research the Poisson process is most likely the most applicable technique for the damage threats. Instead of a defined time frame, flight cycles or flight hours will be defined.

Frequency

Frequency plays an important role in the research to be executed. It is looked how often event E occurs within some time interval. This is determined by the frequency relation below [63]:

$$f_t(E) = \frac{n_E(t)}{t} \tag{3.4}$$

In risk analysis the probability of occurrence is categorized where the most common categories are: improbable/very unlikely, remote/seldom/rare, occasional/possible, probable/likely, frequent/very likely[Popov]. With each category defined by the probability of occurrence intervals. Determining the intervals of the categories is dependent on the specific case to be assessed.

In risk assessments it is sufficient to categorize the frequencies in different groups varying from 'no occurrence' to 'often occurrence', however these types are not fixed and depend on the assessor's decision which will be done during the to be executed research.

Severity

Severity indicates the seriousness of the consequence of the event. In risk assessments the event is classified based on the severity of the consequence in order to determine if and how the events should be mitigated or as an aid in decision-making. The most common severity classification consists of: catastrophic, critical, marginal and negligible which can be used for the research to be executed. The levels of severity are dependent on the specific situation where historical data can be significant for defining these severity levels [62]. Severity levels are the primary risk factors which determine the level of risk of an possible hazardous event. This can be expressed qualitatively and quantitatively.

Most often in risk assessments frequency and severity both are represented in a Risk Matrix. This tabular representation gives a clear overview of the levels of the risk events. There are no accepted standards related to the design of the matrix. One is free to choose what to put on the axis and to determine the matrix size.

3.2 Risk Categories and Methodologies

In literature a wide variety of risk assessment methods are discussed. There are many appropriate risk techniques found for different events. P.K. Marhavilas [64] classified the main risk methodologies in three main categories: the qualitative, the quantitative and the hybrid techniques. Each of these three categories consist of different risk assessment techniques of which the most relevant are discussed.

3.2.1 Qualitative Technique

In qualitative risk analysis words and descriptive scales are used to describe the frequency of the hazardous event and the severity of the consequence. In the qualitative risk assessment the risks are classified based on expert knowledge and documentation reviews. This method only provides qualitative information such as low, medium and high risks and no quantitative estimation of risks. Below the most common techniques used within a qualitive risk assessment are presented.

Checklist are lists with generic hazardous events based on experience and document reviews and is used for hazard identification. Most checklist review result in qualitative estimated results [64].

Failure Modes, Effects, and Critically Analysis (FMECA) is used to identify all potential failure modes of a system, identify the causes and assess the results of each failure mode on the entire system [4].

What-if analysis is an approach where a set of questions are asked by a experts about the potential hazardous events.

The Hazard and Operability (HAZOP) Study was developed to identify possible deviations from normal operations and document hazards [64]. It involves examination of design documents. A variant of HAZOP can be used to identify hazards in complex work procedures such as inspection and maintenance strategies.

3.2.2 Quantitative Technique

The quantitative risk method considers risk as a quantity which can be estimated and expressed by a mathematical relation with the help of recorded data. It uses numerical values for frequency and severity of consequence.

The proportional risk-assessment (PRAT) technique
For the proportional risk-assessment technique the risk is quantified by the severity factor, the probability factor and frequency factor which is given as followed [64]:

$$R = P * S * F \tag{3.5}$$

where: R is the Risk, P is the Probability Factor, S is the Severity of Harm Factor and F is the Frequency (or the Exposure) Factor. Each factor takes values in the scale of 1 – 10 so that the quantity R can be expressed in the scale of 1 – 1000. The risk values can be categorized into urgency level of required action.

The decision matrix risk-assessment (DMRA) technique
The decision matrix risk-assessment technique is very common. Due to the graphical representation (risk matrix) high risks and lower risk are clearly represented in one table. Risks are estimated and categorized based on probability of occurrence and severity of consequence. The measure of the identified risks are determined by taking the product of severity and likelihood expressed as followed [64]:

$$R = S * P \tag{3.6}$$

Where S is the severity and P the likelihood. The severity of the consequence and the likelihood of the hazard are used to set up a risk matrix. The values of the risks are divided in groups from low to high risks. Risk measuring and graphical representation can help the risk managers to prioritize and manage key risks.

The QRA (Quantitative Risk-Assessment) tool
A QRA tool has been developed by Van der Voort [65] for the external safety of industrial plants with a dust explosion hazard. In this assessment the explosion scenarios and their frequencies of occurrence are defined first. The risk is defined as the probability (frequency) of accidents within the area of the hazardous location. Afterwards the consequences and the scenario frequency are then combined to the individual risk, which can be compared to the relevant regulations. Although this tool is developed for assessing explosion hazards to the environment, it is applicable to assess objects impacting aircraft resulting in damages. This tool can be used as a basis for the assessment of impact damage threats of composite aircraft where frequencies of different types of impactors and damages play an important role.

The weighted risk analysis (WRA)

The weighted risk analysis methodology is applicable for balancing safety measures with aspects such as the environment, quality and economics. Different risks, such as investments, economical losses and the loss of human lives are compared in one-dimension. In the aircraft maintenance industry the quality as well as the economic aspect play important role. Maintenance organizations want to keep performing high quality maintenance to ensure airworthiness/safety. However these organizations and airlines aim for lower costs as well. Weighing the risks with the quality of performance and the costs can result in optimization of the operations. Weighing factors for all risk dimensions can be used in order to make them comparable to each other and to relate them to the measures that must be taken for possible risk reduction. In aircraft maintenance the inspection and maintenance strategies should have a higher weight compared to the economics as safety plays a crucial role. A “one-dimensional” weighted risk Rw, e.g. in terms of money, as followed [66, 67]:

$$R_w = \sum_{j=1} a_j \sum_{i=1} R_{ij} \tag{3.7}$$

Where R_w is the weighted risk (cost unit per year); a_j is the (monetary) value per considered loss (cost unit). It has to be noted that the weighted risk R_w may consist of cost unities, which can be financial, but not necessarily. The weighted risk R_w an easily be extended into multiple decision-making elements, depending on the origin of the decision-maker. The previous formula can be specified into particular risk components:

$$R_w = a_1 \sum_{i=1} R_{human,i} + a_2 \sum_{j=1} R_{ieconomic,j} + a_3 \sum_{k=1} R_{environment,k} + a_4 \sum_{l=1} R_{quality,l} + \cdots \tag{3.8}$$

in which a_1 is the (monetary) value per fatality or injury (cost unit); a_2 is the (monetary) value per environmental risk (cost unit); a_3 is the (monetary) value per economical risk (cost unit) a_4 is the (monetary) value per quality risk (cost unit), and so on.

3.2.3 Hybrid Technique

The hybrid techniques is a combination of the qualitative and the quantitative techniques. Qualitative scales are given to values which do not have to have any accurate relationship to the actual magnitude of the frequency and severity. In case of no available data hybrid forecast methods such as Fault Tree Analysis or Event Tree Analysis can be used to estimate probabilities which are often used with the Bayesian method [Popov].

Fault Tree Analysis

Fault tree analysis (FTA) is a deductive technique which provides a method to determine causes to one individual event. Fault trees are created using events and gates. The gates represent several events which can cause failure. AND gates are gates which both need to occur to cause failure where for OR gates only one of the events needs to occur to cause failure [64].

The Event Tree Analysis

The Event Tree Analysis (ETA) consists of decision trees of quantified possible outcomes of an initiating event. In this method the initiating event which can cause failure is used as the starting point. ETA is a system with initiating events, probable subsequent events and final result (failure). Subsequent events are only dependent on the relative initial event. Probabilities of one path consisting of initial event and subsequent events can be multiplied. With ETA all events and possible failures are represented graphically (advantage). Usually ETA is used in the design stage of a system, however it is applicable for change of operations. ETA generates quantitative estimates of event frequencies or likelihoods.

Discussion

Researchers have presented damage modelling techniques which are focused on inducing impact damages from impact threats. However MIDAS (Modelling Impact Damage on Aircraft Structures) deduces impact threats from damage properties as well. This ensures that MIDAS makes it possible to predict impact damages on composite structures based on damage data of metal structures. Usually predictions are based on stochastic simulations using a small amount of historical data. However MIDAS allows to predict future damages based on large amount of data of metal damage. The damage data MIDAS uses as input are damage dimensions such as dent depth and radius. Moreover MIDAS can give an indication of the expected types of impact threats. For the risk assessment to be executed the impact threats and damages to be expected are of great importance to evaluate the high risks for maintenance strategies. Furthermore, MIDAS ensures the analysis of a wide variety of impact scenarios. Although MIDAS has some limitations due to assumptions which had to be made the results give a sufficient estimate of composite damage dimensions which can be used as a first order approximation of the risk assessment.

The assessment of impact threats and predicted impact damages on composite structures will generate knowledge about the influence these predicted damages have on maintenance strategies. The generated knowledge includes the high probability impact events, the severity of the damage and which locations on the aircraft have high probabilities in terms of damage. Inspection is the first task within the maintenance process and determines the consecutive tasks to be executed. Therefore a further look into the influence of the predicted damages on inspection strategies will be performed in the thesis. The influence contains prioritizing inspection of certain locations on aircraft and inspection techniques.

Literature divides an event into initiating and hazardous event. This leads to undesired consequences such as damage or harm to people, assets or the environment. In the risk assessment to be executed ground operations, presence of birds and bad weather conditions can be prescribed as the ‘initiating events’. Ground operations and the presence of birds do not upset the normal operations as they are considered to be the normal operation at airports. However these initiating events can cause ‘hazardous events’ such as impacting the aircraft. The damage caused by ground operation equipment and vehicles and the presence of birds nearby is then prescribed as the ‘undesired consequence’. In the case of lightning, bad weather conditions are prescribed as the ‘initiating event’ as it upsets the normal weather condition which can lead to an ‘hazardous event’ such as lightning striking the aircraft which causes damage on aircraft structure being the ‘undesired consequence’. In the thesis the damages due to impact and lightning strike will be the consequence, as these consequences (damages) will be analysed in terms of frequency and severity. The relevant severity levels of the damages are prescribed as ‘no damage’, ‘minor damage’, ‘major damage’ or ‘not visible’, ‘barely visible’ and ‘visible’ damage depending on the composite damage results of MIDAS. The results of these analysis will be used to determine which locations on the aircraft and which inspection strategies need to be prioritized.

Literature shows a wide variety of types of risk analysis. Only the most relevant methods for the behaviour of impact and damage in aircraft operations is reviewed. Different types and combinations of methods can be chosen together for each stage of the risk assessment. It depends on the types of impact behaviour which (hybrid) methods are applicable. It will become more clear which methods will be used when the data for the research is provided. The research will be an iterative process. However a first assumption of relevant methods for the different types of impactor behaviours is presented below.

To determine the probability of damage the Bernoulli process is assumed. The possible outcomes are ‘damage’ and ‘no damage’. For the research to be executed it is assumed that the probability of ‘damage’ is 1 and ‘no damage’ is 0. This is because damage data will be analysed where only the occurred damages are being assessed.

Using the provided data makes it possible to perform a quantitative risk assessment as the key risk factors such as probability and frequency can be calculated. The classification of severity can be expressed quantitatively by giving each level a grade; a low grade for low severity and a high grade for high severity. The calculated frequency and probability leads to the Proportional Risk-Assessment Technique (PRAT) and the Decision Matrix Risk-Assessment technique (DMRA), both being the most suitable methods for the research. In some cases the frequency will be the probability, in that case DMRA is suitable. The quantitative risk assessment (QRA) tool is relevant for the assessment of damages at different locations on the aircraft such as wing tip, root and forward facing areas.

Hail

Hail is seasonal and locally dependent. To determine the probability of occurrence a Poisson process is assumed. Time frames will be defined to determine the number of hail events within each time frame.

Bird strikes

The type of birds present near and at airports depend on the geographical location of the airport and the season at that location. Within the location it is assumed that for bird strikes the classical approach is used. Bird strike events are able to be repeated a large number times under nearly the same conditions. However the assumption is not necessary as it is unknown from the damage data at which location the strike occurred.

Runway debris

Runway debris is independent from the location of the airport as it is assumed that all airports and airlines comply to safety regulations. This implies that the conditions at all airports are the same. The most suitable approach is the frequentist approach as it is assumed that the conditions for each event are nearly the same of which the impact may or may not be the same.

Tool drops

For tool drops the same assumptions hold true as for runway debris. It is also assumed that maintenance personnel comply with safety regulations resulting in the same work conditions. The situation for each event is nearly the same but the result may or may not be the same for each event.

Ground Service Equipment (GSE)
Due to unknown geographical locations of damage can be assumed that at all airports the same GSE are used. However damage as a result of GSE impacting the aircraft is not the same for all events. Hence the frequentist approach would be applicable.

Lightning strikes
As found in literature lightning strikes mostly occur during take-off and landing altitudes and depend on the geographical location the aircraft operates. As the data is based on long-haul aircraft it can be said that the operation is at high altitude. The conditions for each flight cycle are the same and the damage depends on the intensity of the strike. Again the frequentist approach would be applicable.

As mentioned before the methods will be definite when the data is provided and the first analysis are performed.

Methodology

There is an absence of data about impact damage on new generation composite structure aircraft such as B787 and A350 over a long operational life due to limited operations of these aircraft. Therefore a thorough understanding of the types of damages and the expected risks these damage threats pose on inspection and maintenance strategies are deficient. To combat the lack of data, the damage model MIDAS developed by Massart [3] is able to predict impact damage threats in terms of impact energy, projectile size, damage type and size based on data from previous generation aircraft such as B777.

The research to be done aims to acquire knowledge from these predicted future damages. Therefore the research objective is:

To know if maintenance strategies can be improved in terms of prioritizing locations on aircraft and/or type of inspection and repair techniques by analysing the risks of predicted damage impact on composite aircraft structures based on impact damage data of metal aircraft structures using an existing damage model.

The research addresses the following research question:
How can the risks of the predicted damages and damage threats influence the maintenance strategies of new generation composite aircraft?

To address the research question the outputs of the model MIDAS will be used as input for a risk assessment. Damage properties such as dent depth and radius will be used as input for the model (MIDAS-M). The model outputs an estimation of the impact scenarios such as size and energy. With the output data the frequency and location of the estimated impactors will analysed in a risk assessment. The output data of MIDAS-M will be used as input for MIDAS-C to predict the damage properties such as dent depth, radius and delamination on composite structures. This damage data will be analysed and used for risk assessment. The results of the risk assessment will be in the form of heat maps presenting the probability of occurrence and the frequencies. The frequencies of impact threats on different fuselage locations will be presented. These results will be used to conclude the influence of the impact risk on inspection strategies. Quantifying the risks is beneficial for maintenance planning and prioritization of inspections areas and procedures. The procedure of the risk assessment is illustrated in Table 1.

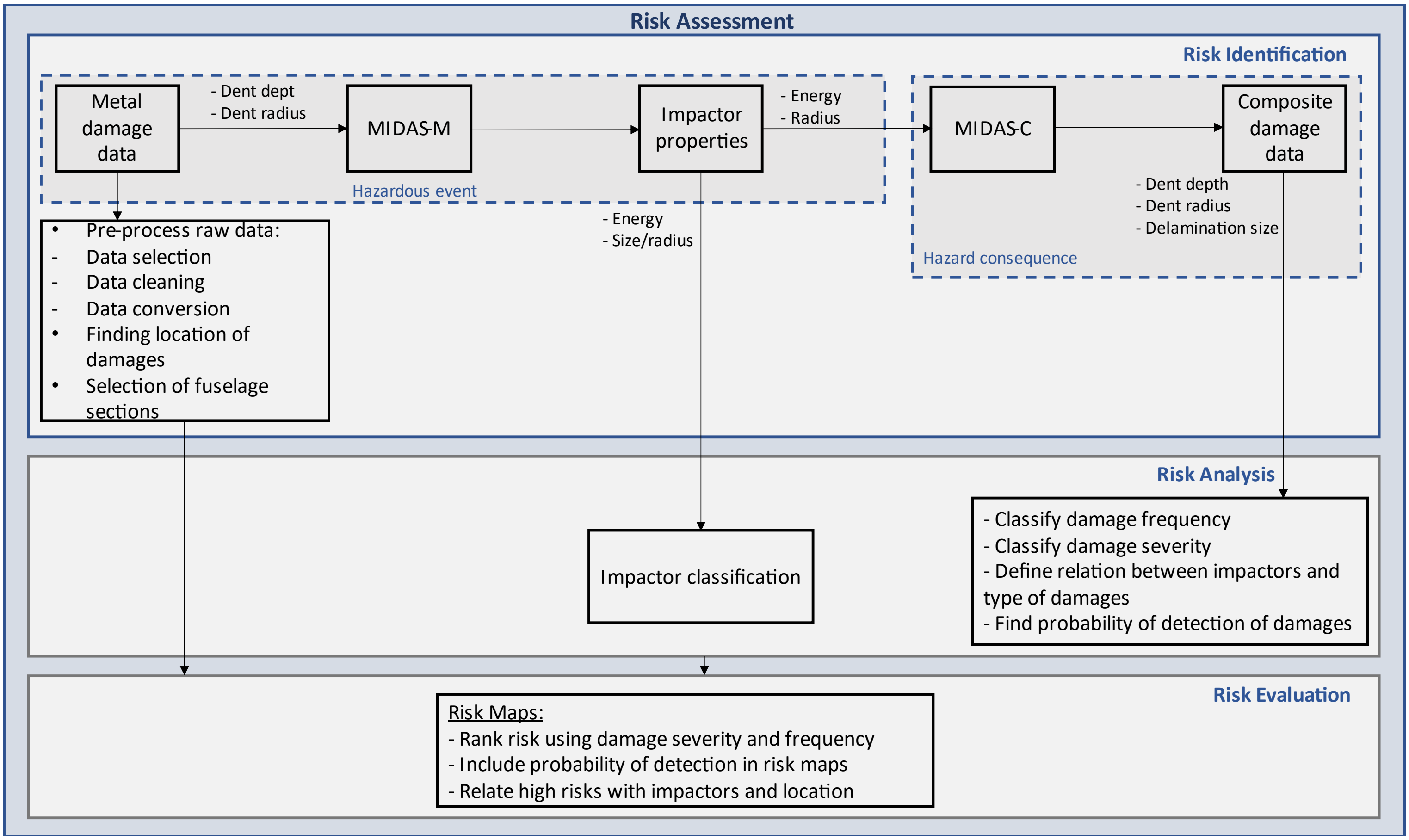

Table 1: Risk Assessment

Conclusion

As there is limited experience with impact threats and damages on composite structures maintenance strategies are not adapted to these threats. Therefore literature study has been done on impact damage threats on aircraft, impact damages on composite structures, damage modelling, maintenance strategies and risk assessment methods. These five subjects are intertwined and will shape the backbone of the thesis research.

Typical damage threats on aircraft discussed in literature are lightning strike, bird strike, tool drops, Ground Service Equipment, hail and runway debris. Impact by these threats result in no visible to barely visible damages such as matrix crack, delamination and fibre breakage. According to literature matrix cracks in composite structures are difficult to detect and also lead to delamination and fibre breakage if no action is taken. The 'no-visible' and 'barely visible' damages require special inspection techniques. In literature various inspection techniques were found, each of them specifically developed to detect a certain type of damage. These techniques are defined as Non Destructive Testing (NDT) where the tested part is not being damaged during testing. The most common NDT techniques are Visual Inspection, Eddy Current, Shearography, Ultrasonic Testing and Thermography. During the research NDT techniques will be evaluated in order to adapt the maintenance tasks according to the expected type of impact damages.

An existing model called MIDAS (Modelling Impact Damage on Aircraft Structures) is beneficial for the thesis project to predict the impact damages on composite structures. MIDAS consists of two parts namely the deductive solution and the inductive solution. The deductive solution converts damage properties on metal aircraft to properties of damage threats. The inductive solution converts damage threat properties to damage dimensions on composite aircraft. It can be concluded that literature only focuses on the inductive solution. However MIDAS has been developed to include the deductive solution as well which makes it possible to predict damages on composite structures based on data metal damage properties. This makes MIDAS a suitable model for the thesis project.

Many researchers have described various risk assessment methods in literature. In this review two of them have been selected because of the elaborate explanation of most of the methods found. Furthermore, these researchers indicate that the methods are valid for maintenance engineering and the aviation industry. A selection of the most applicable methods for the thesis project is described in this review. It can be concluded that a quantitative risk method gives a more accurate indication of the risks. Furthermore not a single but several of the quantitative risk techniques can be applied to the research in an iterative manner. However the Poisson Process seems most suitable to start with for all types of impact threats and impact damages as described in the literature study.

References

1. Davies, G. and R. Olsson, *Impact on composite structures.* The Aeronautical Journal, 2004. **108**(1089): p. 541-563.
2. Cantwell, W.J. and J. Morton, *The impact resistance of composite materials—a review.* composites, 1991. **22**(5): p. 347-362.
3. Massart, P., *Modelling Impact Damage on Aircraft Structures (MIDAS): Predicting impact damage on (composite) aircraft based on maintenance data of (metal) aircraft.* 2018.
4. Rausand, M., *Risk assessment: theory, methods, and applications*. Vol. 115. 2013: John Wiley & Sons.
5. Rhymer, J., H. Kim, and D. Roach, *The damage resistance of quasi-isotropic carbon/epoxy composite tape laminates impacted by high velocity ice.* Composites Part A: Applied Science and Manufacturing, 2012. **43**(7): p. 1134-1144.
6. Kim, H. and K.T. Kedward, *Modeling hail ice impacts and predicting impact damage initiation in composite structures.* AIAA journal, 2000. **38**(7): p. 1278-1288.
7. Kim, H., D.A. Welch, and K.T. Kedward, *Experimental investigation of high velocity ice impacts on woven carbon/epoxy composite panels.* Composites Part A: applied science and manufacturing, 2003. **34**(1): p. 25-41.
8. SRI, I., *The economic cost of FOD to airlines.* 2008.
9. Heimbs, S., *Computational methods for bird strike simulations: A review.* Computers & Structures, 2011. **89**(23-24): p. 2093-2112.
10. Georgiadis, S., et al., *Bird-strike simulation for certification of the Boeing 787 composite moveable trailing edge.* Composite Structures, 2008. **86**(1-3): p. 258-268.
11. Kassapoglou, C., *Modeling the effect of damage in composite structures: Simplified approaches*. 2015: John Wiley & Sons.
12. Kim, H., G.K. DeFrancisci, and Z.M. Chen, *Ground vehicle blunt impact damage formation to composite aircraft structures.* Advanced Composite Materials, 2014. **23**(1): p. 53-71.
13. Kim, H., et al. *Impact damage formation on composite aircraft structures*. in *UCSD FAA JAMS Paper, Technical Review Meeting*. 2012.
14. DeFrancisci, G., Z. Chen, and H. Kim. *Blunt impact damage formation in frame and stringer stiffened composite panels*. in *18th International Conference on Composite Materials, Jeju ICC, Korea*. 2011.
15. DeFrancisci, G.K., *High energy wide area blunt impact on composite aircraft structures*. 2013: University of California, San Diego.
16. Chen, Z.M., *Experimental and Numerical Investigation of Wide Area Blunt Impact Damage to Composite Aircraft Structures*. 2015, UC San Diego.
17. Polimeno, U. and M. Meo, *Detecting barely visible impact damage detection on aircraft composites structures.* Composite structures, 2009. **91**(4): p. 398-402.
18. Cook, L., *Visual inspection reliability for composite aircraft structures.* 2009.
19. Abrate, S., *Impact on laminated composites: recent advances.* 1994.
20. Heida, J. and J. Müller, *In-service inspection and monitoring of composite aerospace structures.* 2013.
21. Sjoblom, P.O., J.T. Hartness, and T.M. Cordell, *On low-velocity impact testing of composite materials.* Journal of composite materials, 1988. **22**(1): p. 30-52.
22. Delaney, M.P., S.Y. Fung, and H. Kim, *Dent depth visibility versus delamination damage for impact of composite panels by tips of varying radius.* Journal of Composite Materials, 2018. **52**(19): p. 2691-2705.

23. Chen, J. and Z. Fu. *Influence of Grounding Modes on the Damage of Carbon Fiber Reinforced Plastics subjected to Lightning Strikes*. in *2019 11th Asia-Pacific International Conference on Lightning (APL)*. 2019. IEEE.
24. Sweers, G., B. Birch, and J. Gokcen, *Lightning strikes: protection, inspection, and repair.* Aero Magazine, 2012. **4**: p. 19-28.
25. Hearley, B., K. Peters, and M. Pankow, *Development of a New Testing Method to Capture Progressive Damage in Carbon Fiber Reinforced Polymers Subject to a Simulated Lightning Strike*, in *Dynamic Behavior of Materials, Volume 1*. 2020, Springer. p. 137-142.
26. Karch, C. and C. Metzner. *Lightning protection of carbon fibre reinforced plastics—An overview*. in *2016 33rd International Conference on Lightning Protection (ICLP)*. 2016. IEEE.
27. Fu, K., et al., *Modelling of lightning strike damage to CFRP composites with an advanced protection system. Part I: Thermal–electrical transition.* Composite Structures, 2017. **165**: p. 83-90.
28. Shivakumar, K., W. Elber, and W. Illg, *Prediction of impact force and duration due to low-velocity impact on circular composite laminates.* 1985.
29. Abrate, S., *Modeling of impacts on composite structures.* Composite structures, 2001. **51**(2): p. 129-138.
30. Simonsen, B.C. and L.P. Lauridsen, *Energy absorption and ductile failure in metal sheets under lateral indentation by a sphere.* International Journal of Impact Engineering, 2000. **24**(10): p. 1017-1039.
31. Richardson, M. and M. Wisheart, *Review of low-velocity impact properties of composite materials.* Composites Part A: Applied Science and Manufacturing, 1996. **27**(12): p. 1123-1131.
32. Razali, N., et al., *Impact damage on composite structures–a review.* The International Journal of Engineering and Science, 2014. **3**(7): p. 08-20.
33. Olsson, R., *Mass criterion for wave controlled impact response of composite plates.* Composites Part A: Applied Science and Manufacturing, 2000. **31**(8): p. 879-887.
34. Lee, Y.-W., J.C. Woertz, and T. Wierzbicki, *Fracture prediction of thin plates under hemi-spherical punch with calibration and experimental verification.* International Journal of Mechanical Sciences, 2004. **46**(5): p. 751-781.
35. Cairns, D., *A simple, elasto-plastic contact law for composites.* Journal of reinforced plastics and composites, 1991. **10**(4): p. 423-433.
36. Olsson, R. and T.B. Block, *Criteria for skin rupture and core shear cracking induced by impact on sandwich panels.* Composite Structures, 2015. **125**: p. 81-87.
37. Mofokeng, T.J. and A. Marnewick. *Factors contributing to delays regarding aircraft during A-check maintenance*. IEEE.
38. Chen, X., H. Ren, and C. Bil, *Inspection intervals optimization for aircraft composite structures considering dent damage.* Journal of Aircraft, 2014. **51**(1): p. 303-309.
39. Sahay, A., *Leveraging information technology for optimal aircraft maintenance, repair and overhaul (MRO)*. 2012: Elsevier.
40. Tinga, T., *Principles of loads and failure mechanisms: applications in maintenance, reliability and design*. 2013: Springer Science & Business Media.
41. Knotts, R.M., *Civil aircraft maintenance and support Fault diagnosis from a business perspective.* Journal of quality in maintenance engineering, 1999.
42. Yang, T.-H., S. Yan, and H.-H. Chen, *An airline maintenance manpower planning model with flexible strategies.* Journal of Air Transport Management, 2003. **9**(4): p. 233-239.

43. Ward, M., et al., *A performance improvement case study in aircraft maintenance and its implications for hazard identification.* Ergonomics, 2010. **53**(2): p. 247-267.
44. Ahmadi, A., P. Söderholm, and U. Kumar, *On aircraft scheduled maintenance program development.* Journal of Quality in Maintenance Engineering, 2010.
45. Alves, V.A. and A.A. Ghobbar. *A predictive model to evaluate and improve punctuality of fleet of wide-body aircraft maintenance and reliability*. in *Air Transport and Operations: Proceedings of the First International Air Transport and Operations Symposium 2010*. 2010. IOS Press.
46. Lowas III, A.F. and F.W. Ciarallo, *Reliability and operations: Keys to lumpy aircraft spare parts demands.* Journal of Air Transport Management, 2016. **50**: p. 30-40.
47. Julka, N., et al., *Making use of prognostics health management information for aerospace spare components logistics network optimisation.* Computers in industry, 2011. **62**(6): p. 613-622.
48. Regattieri, A., et al., *Managing lumpy demand for aircraft spare parts.* Journal of Air Transport Management, 2005. **11**(6): p. 426-431.
49. Ayeni, P., et al., *State-of-the-art of 'Lean'in the aviation maintenance, repair, and overhaul industry.* Proceedings of the Institution of Mechanical Engineers, Part B: journal of engineering manufacture, 2011. **225**(11): p. 2108-2123.
50. Samaranayake, P. and S. Kiridena, *Aircraft maintenance planning and scheduling: an integrated framework.* Journal of Quality in Maintenance Engineering, 2012. **18**(4): p. 432-453.
51. Brogan, D., A. Gale, and K. Carr, *Visual search 2*. 1993: Taylor & Francis, Inc.
52. Lockard, C.D., *Anomaly detection in radiographic images of composite materials via crosshatch regression*. 2015, Mills College.
53. Boller, C., F.-K. Chang, and Y. Fujino, *Encyclopedia of structural health monitoring*. 2009: Wiley.
54. Diamanti, K. and C. Soutis, *Structural health monitoring techniques for aircraft composite structures.* Progress in Aerospace Sciences, 2010. **46**(8): p. 342-352.
55. Hung, Y., *Shearography: a new optical method for strain measurement and nondestructive testing.* Optical engineering, 1982. **21**(3): p. 213391.
56. Rose, J.L., *Ultrasonic guided waves in solid media*. 2014: Cambridge university press.
57. Bhardwaj, M. *Evolution of piezoelectric transducers to full scale non-contact ultrasonic analysis mode*. in *16 th World Conference on Nondestructive testing*. 2004. Citeseer.
58. Pollock, A.A., *Acoustic emission inspection.* Metals handbook, 1989.
59. Meola, C. and G.M. Carlomagno, *Recent advances in the use of infrared thermography.* Measurement science and technology, 2004. **15**(9): p. R27.
60. Katunin, A., K. Dragan, and M. Dziendzikowski, *Damage identification in aircraft composite structures: A case study using various non-destructive testing techniques.* Composite Structures, 2015. **127**: p. 1-9.
61. Gaudenzi, P., et al., *On the evaluation of impact damage on composite materials by comparing different NDI techniques.* Composite Structures, 2014. **118**: p. 257-266.
62. Popov, G., B.K. Lyon, and B. Hollcroft, *Risk assessment : a practical guide to assessing operational risks*. 2016, John Wiley & Sons, Inc.: Hoboken.
63. Kelly, D. and C. Smith, *Bayesian inference for probabilistic risk assessment a practitioner's guidebook*. 2011, Springer: London.
64. Marhavilas, P.-K., D. Koulouriotis, and V. Gemeni, *Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000–2009.* Journal of Loss Prevention in the Process Industries, 2011. **24**(5): p. 477-523.

65. Van der Voort, M.M., et al., *A quantitative risk assessment tool for the external safety of industrial plants with a dust explosion hazard.* Journal of Loss Prevention in the Process Industries, 2007. **20**(4-6): p. 375-386.
66. Suddle, S. and P. Waarts, *The safety of risk or the risk of safety?* 2003: Lisse [etc.]: AA Balkema Publishers; Swets & Zeitlinger.
67. Suddle, S., *The weighted risk analysis.* Safety Science, 2009. **47**(5): p. 668-679.

III

Supporting Work

A. MIDAS & Data Pre-Processing

A schematic representation of how Modelling Impact Damage on Aircraft Structures (MIDAS) works is shown in Figure A1. When aircraft are inspected damages are found by maintenance personnel. The size of these damages are registered in a maintenance database. The deductive solution, MIDAS-M, estimates the impactor properties such as size, velocity, mass and material which are caused the damages. The velocity, mass and material determines the energy of the impactor. For each damage registered MIDAS-M gives an estimation of the impactor properties. Afterwards the impactor properties are used to induce the damages these same impactors can cause on composite aircraft structures. MIDAS-C gives as output the composite damage properties dent depth, dent radius and delamination.

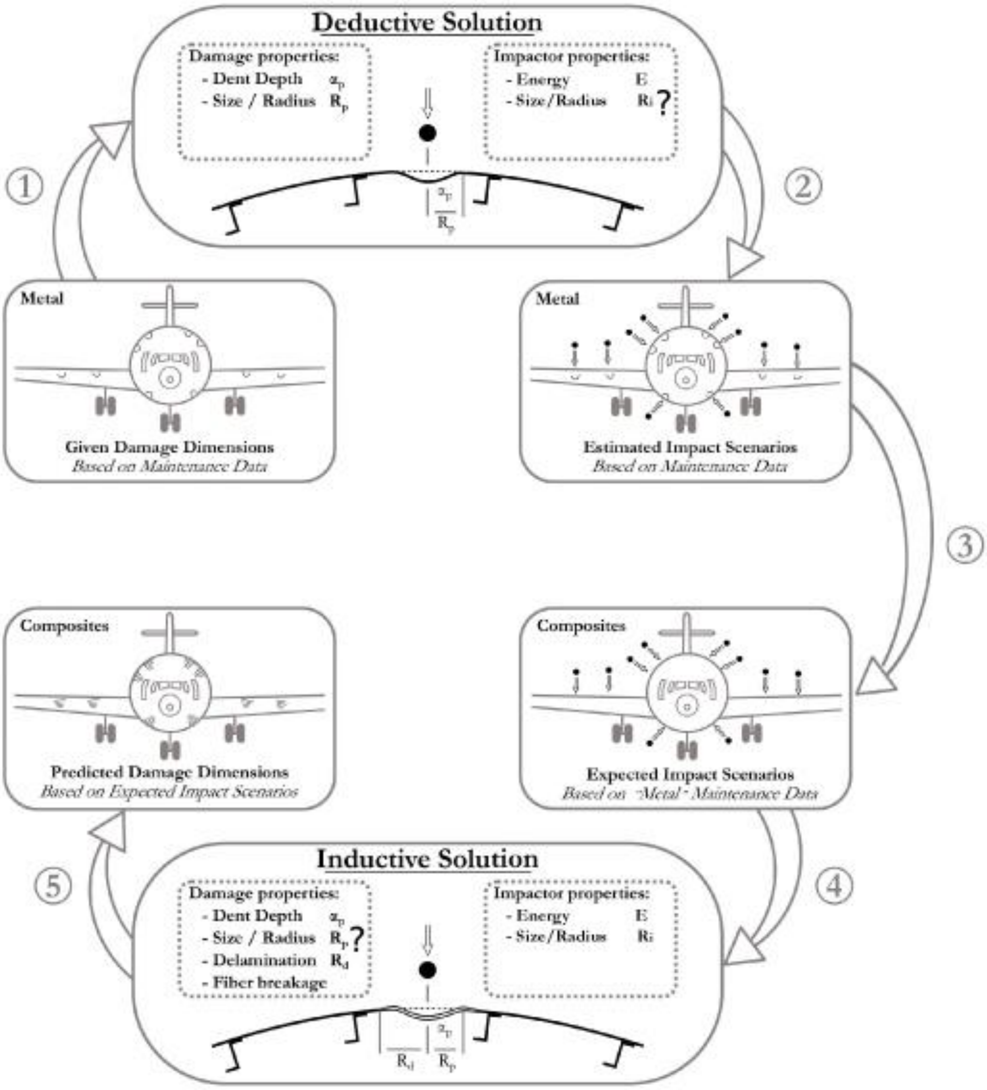

Figure A1: Integration of inductive and deductive procedure to predict impact damage on aircraft structures [9]

Matrix cracks and delamination are impact responses in composite structures. It is noted that matrix crack is not included during the development of MIDAS-C. However, from literature delamination is preceded by matrix cracks [10]. Therefor it can be said that if delamination is present, matrix crack is present and that these types of damages do not occur separately.

Data pre-processing

A database consisting of damages from 20 years operation of the Boeing 777 fleet was provided by a Maintenance and Overhaul Organisation (MRO). The Structural Repair Manual (SRM) of the Boeing 777 was provided as well. The database consisting of approximately 10.000 damages included different types of damages such as lightning strikes, hail, bird strikes, impacts by Foreign Object Debris (FOD), but damages due to wear were registered in the database as well. However there were many other damages reported without knowing the impactor source. In many cases the location of the damage was registered as well and the registration number of the aircraft, Flight Cycles (FC), Flight Hours (FH) and date of damage detection were registered. These variables were used to find the data necessary for the further research.

To be able to use the right data in order to be used as input for MIDAS the data needed to be pre-processed. However, the database included many incomplete data and many spelling mistakes and synonyms, which was led to pre-processing the data manually. The following pre-processing steps were followed:

- Data cleaning
- Data editing
- Data selection
- Data conversion

In Figure A2 an indication of the data pre-processing is shown.

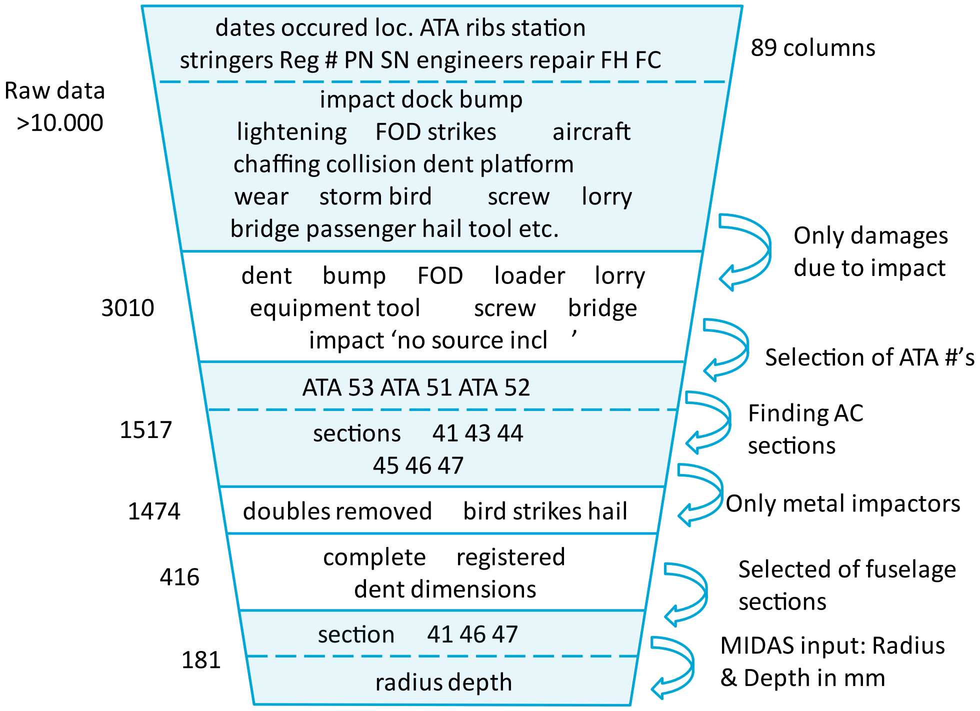

Figure A2: Pre-processing steps

First every row was given a damage ID in order to verify the pre-processing steps. As MIDAS is limited to only impact damages caused by blunt metal impactors a selection from the data was made. This was done by eliminating all bird strikes, lightning strikes, impact by hail, wear and so on. In some cases the raw data gave a description of the damage such as scratch, hole and burn. These types of damages were eliminated as well.

From the left over data a selection was made of the damages which included 'dent' in the description.

The data cleaning step consisted of eliminating incomplete data and data with missing dent dimensions. Using the registration numbers, FC, FH and date of detected damage double entries were able to be found. All double entries were eliminated.

The raw data consisted of frame numbers and ATA numbers of the aircraft. Using this data and the SRM the section location of the damages on the aircraft was found. An overview is given in Figure A3 and Table A1.

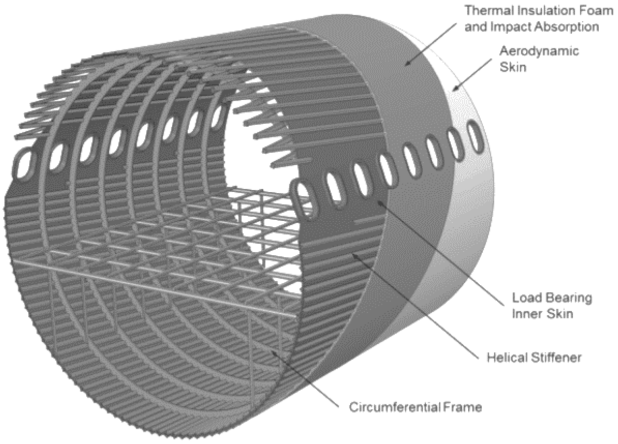

Figure A3: Fuselage section with circumferential frames [11]

ATA Number	Name
ATA 51	General
ATA 52	Doors
ATA 53	Fuselage
ATA 54	Nacelles/Pylons
ATA 55	Stabilizers
ATA 56	Windows
ATA 57	Wings

Table A1: ATA Numbering

As MIDAS is modelled such that the input should consist of dent radius and depth in mm the dimensions of the selected data needed to be converted. Most of the dent dimensions were registered as width, depth and length in inches. These dimensions were converted into radius and depth in mm.

B. Data Augmentation

For data augmentation an approximation of the best fit distributions of the impactor radius and energy of each section were determined. To find the best fit distributions the Sum-Squared-Error (SSE) method was used. A lower SSE indicated the best fit. Table B1 gives the SSE results of the distributions. However there is no large difference between the SSEs of the different distributions. Iteratively all five distributions were used for augmentation until the most fit augmentation results were found. The plots of the top five best fit distributions are presented in Figures B1 – B12 . E_1 and E_2 stand for energy of impactor type one and type two respectively and R_1 and R_2 stand for radius of impactor type one and type two respectively.

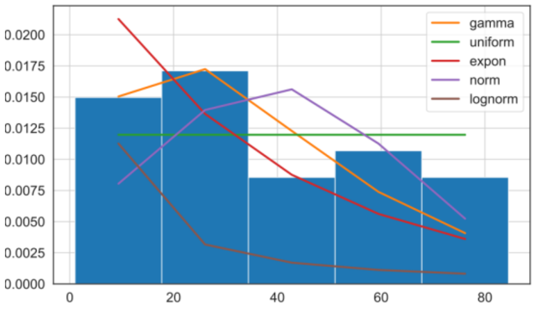

Figure B1: Section 41 R_1

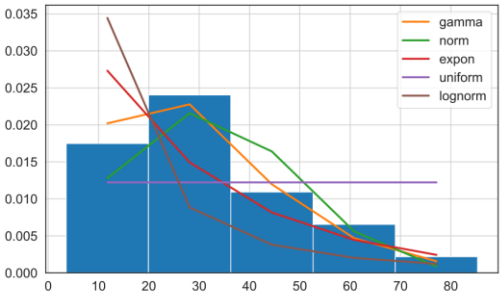

Figure B2: Section 41 E_1

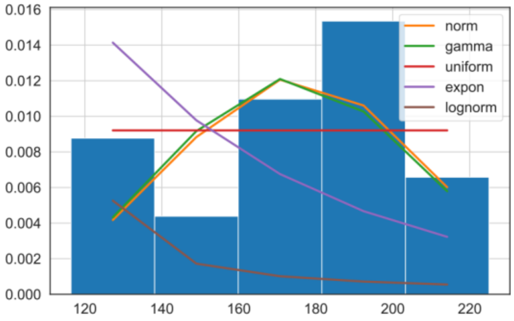

Figure B3: Section 41 R_2

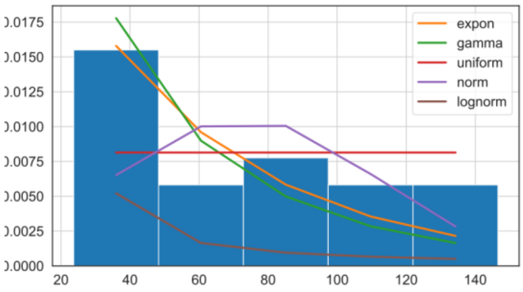

Figure B4: Section 41 E_2

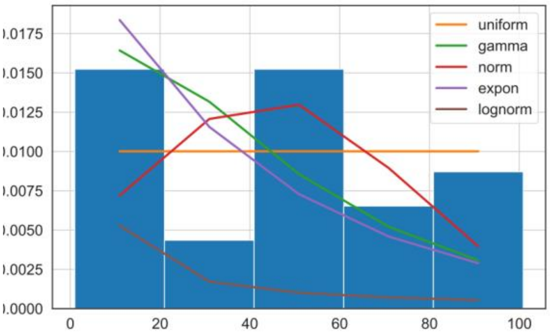

Figure B5: Section 46 R_1

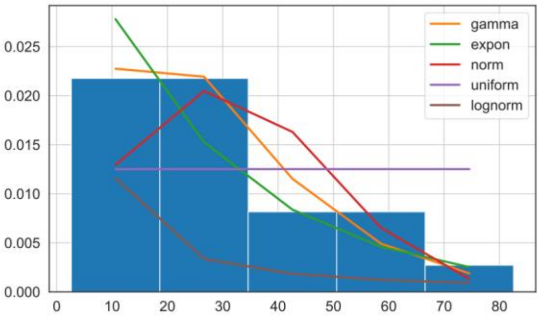

Figure B6: Section 46 E_1

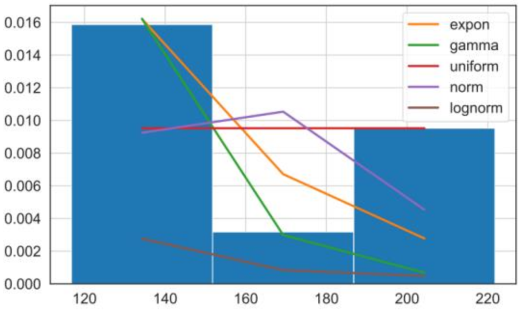

Figure B7: Section 46 R_2

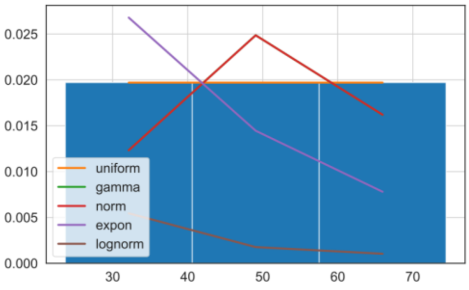

Figure B8: Section 46 E_2

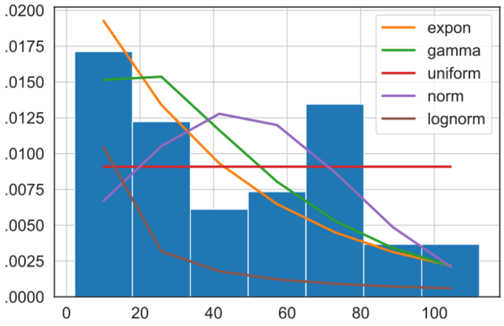

Figure B9: Section 47 R_1

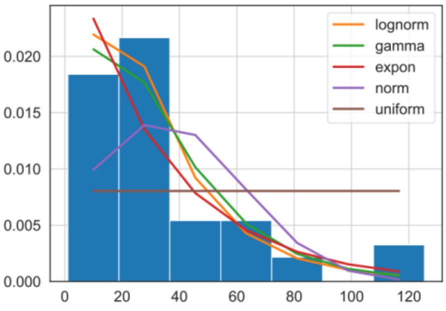

Figure B10: Section 47 E_1

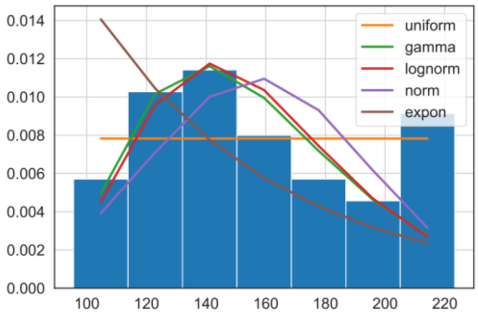

Figure B11: Section 47 R_2

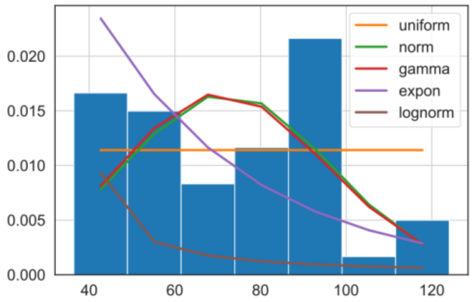

Figure B12: Section 47 E_2

Section 41		Section 46		Section 47	
R1		R1		R1	
Gamma	0.000045	Uniform	0.000100	Exponential	0.000100
Uniform	0.000060	Gamma	0.000157	Gamma	0.000113
Exponential	0.000102	Normal	0.000158	Uniform	0.000164
Normal	0.000119	Exponential	0.000163	Normal	0.000204
Lognormal	0.000406	Lognormal	0.000409	Lognormal	0.000358
E1		E1		E1	
Gamma	0.000014	Gamma	0.000024	Lognormal	0.000043
Normal	0.000061	Exponential	0.000091	Gamma	0.000052
Exponential	0.000192	Normal	0.000150	Exponential	0.000105
Uniform	0.000302	Uniform	0.000305	Normal	0.000209
Lognormal	0.000590	Lognormal	0.000534	Uniform	0.000429
R2		R2		R2	
Normal	0.000065	Exponential	0.000058	Uniform	0.000040
Gamma	0.000070	Gamma	0.000078	Gamma	0.000047
Uniform	0.000071	Uniform	0.000081	Lognormal	0.000052
Exponential	0.000201	Normal	0.000123	Normal	0.000138
Lognormal	0.000369	Lognormal	0.000259	Exponential	0.000203
E2		E2		E2	
Exponential	0.000037	Uniform	0.000000	Uniform	0.000290
Gamma	0.000049	Gamma	0.000093	Normal	0.000292
Uniform	0.000071	Normal	0.000093	Gamma	0.000293
Normal	0.000113	Exponential	0.000200	Exponential	0.000333
Lognormal	0.000224	Lognormal	0.000873	Lognormal	0.000795

Table B1: SSE values of best five distributions

Plots of the cumulative distributions for the best fit distribution for augmentation are given in Figures B13 – B24.

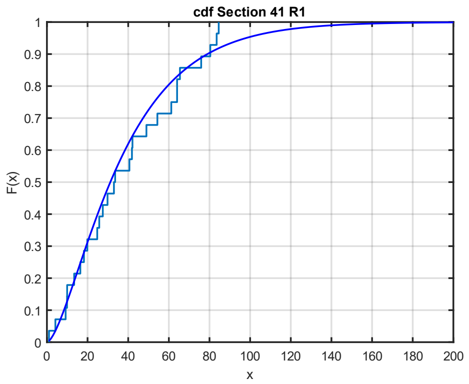

Figure B13: Section 41 R1

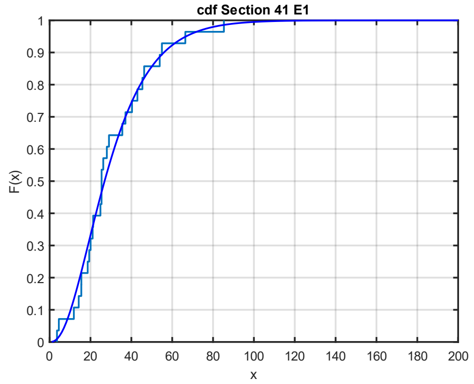

Figure B14: Section 41 E1

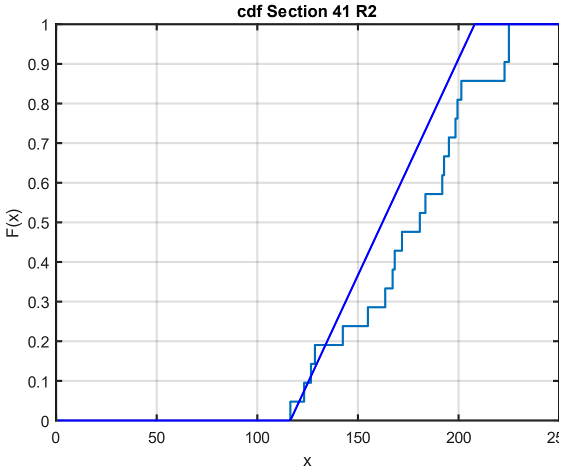

Figure B15: Section 41 R2

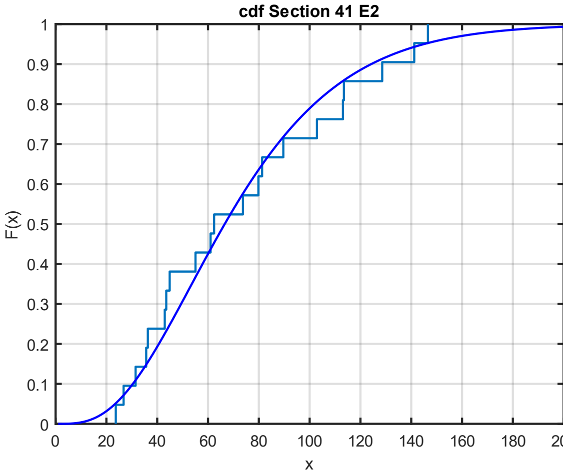

Figure B16: Section 41 E2

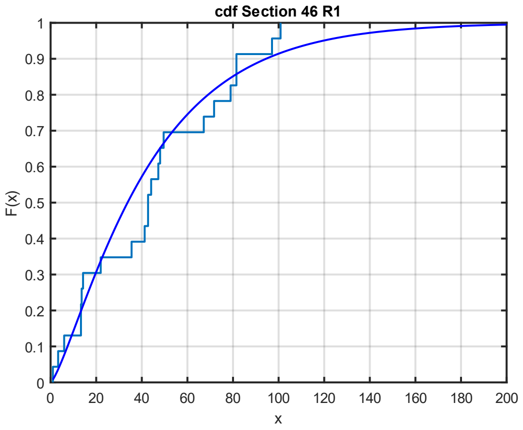

Figure B17: Section 46 R1

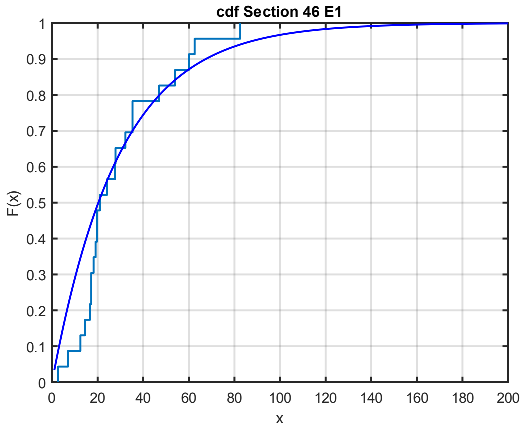

Figure B18: Section 46 E1

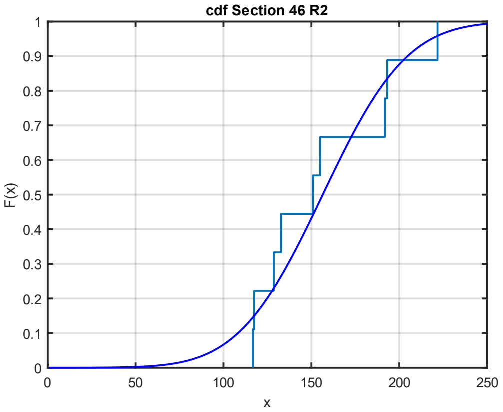

Figure B19: Section 46 R2

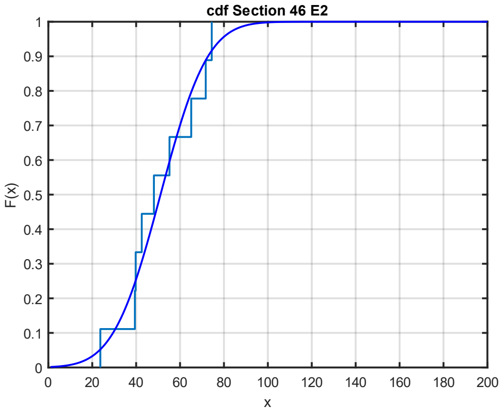

Figure B20: Section 46 E2

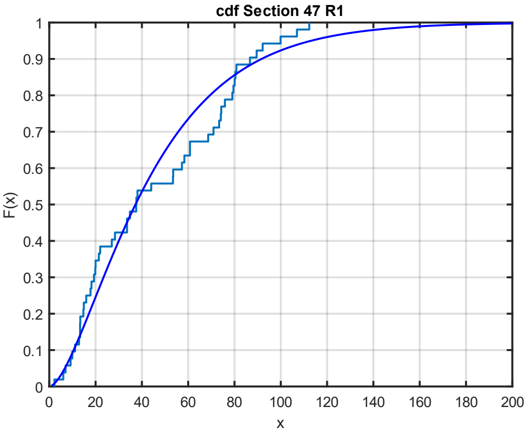

Figure B21: Section 47 R1

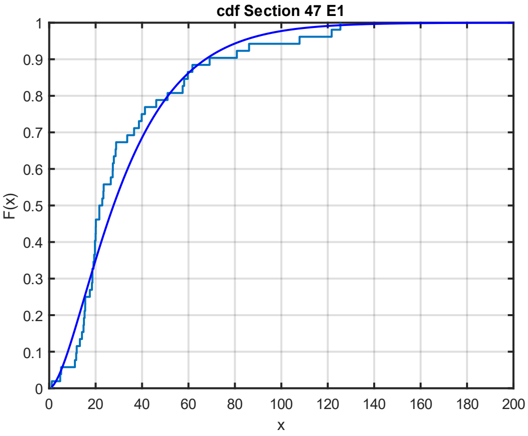

Figure B22: Section 47 E1

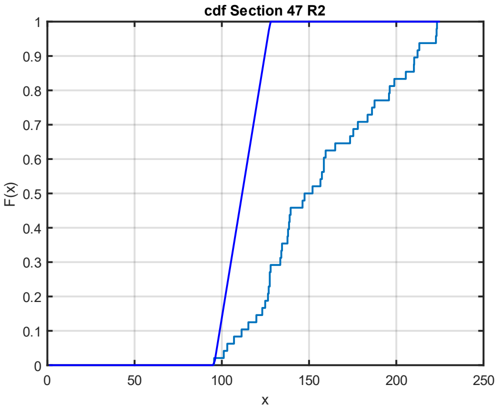

Figure B23: Section 47 R2

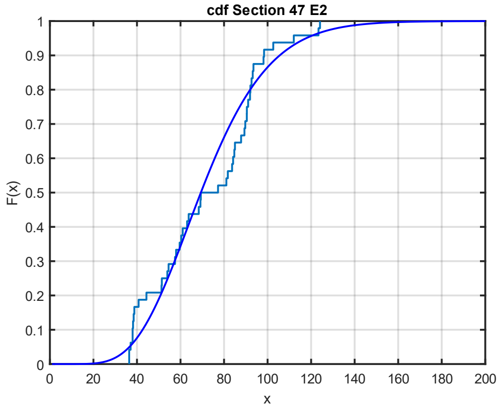

Figure B24: Section 47 E2

The plots for the original and augmented data are given in Figures B25 – B36.

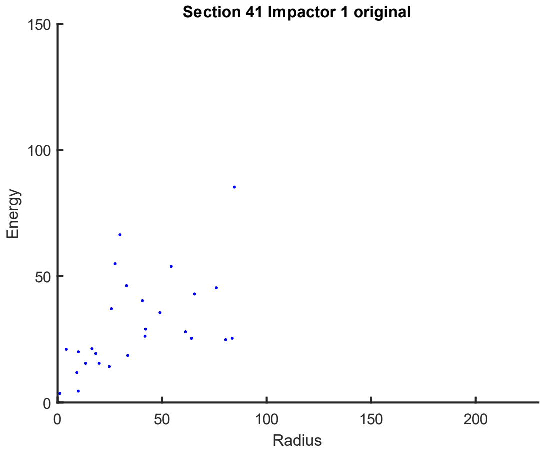

Figure B25: Section 41 Original

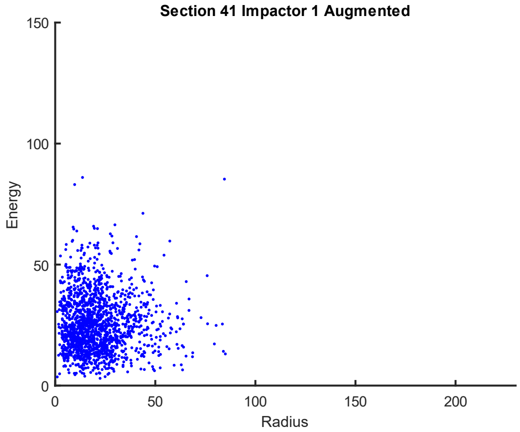

Figure B26: Section 41 Augmented

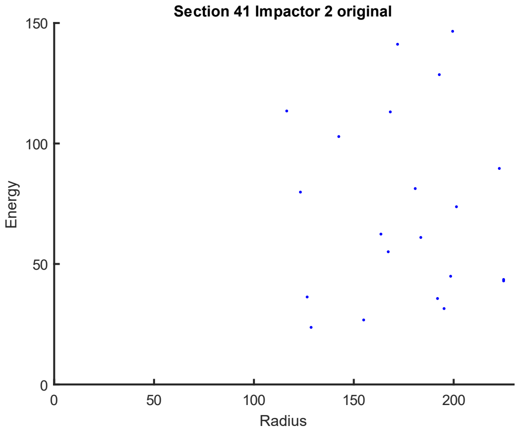

Figure B27: Section 41 Original

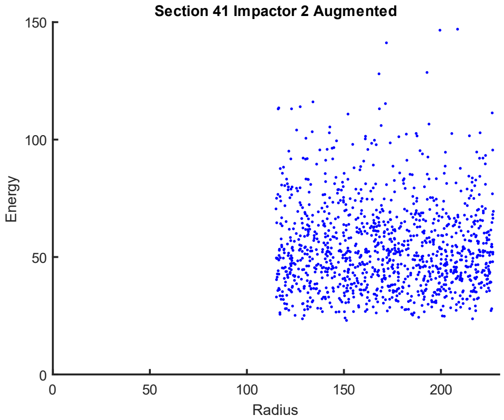

Figure B28: Section 41 Augmented

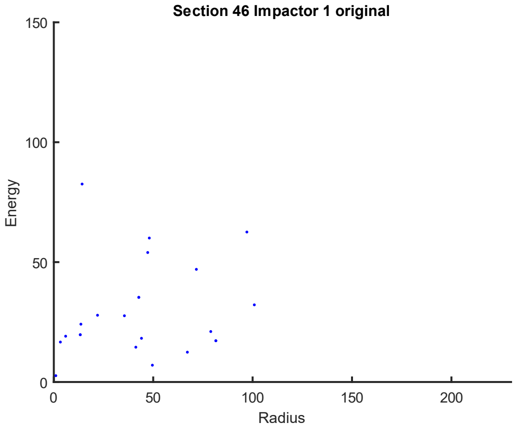

Figure B29: Section 46 Original

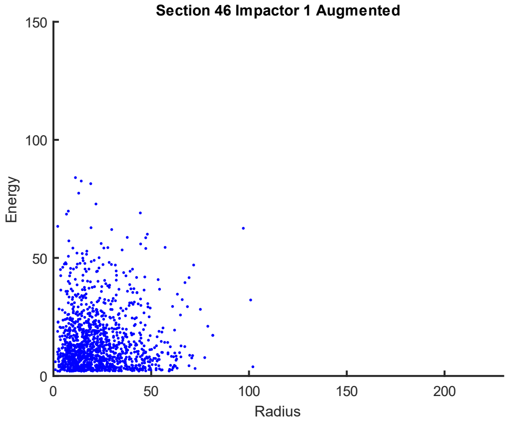

Figure B30: Section 46 Augmented

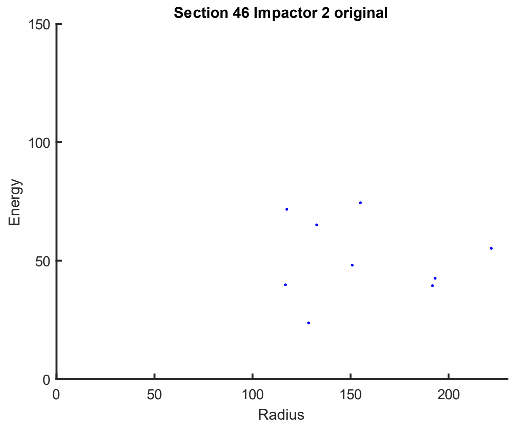

Figure B31: Section 46 Original

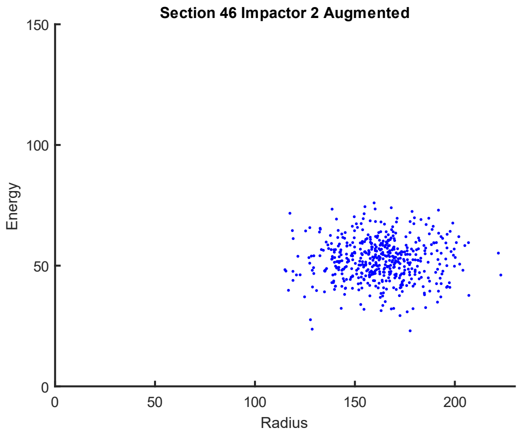

Figure B32: Section 46 Augmented

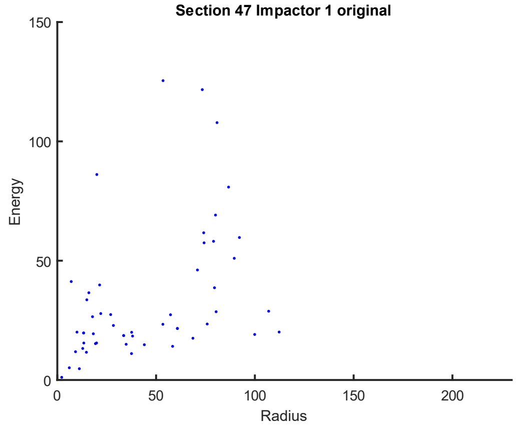

Figure B33: Section 47 Original

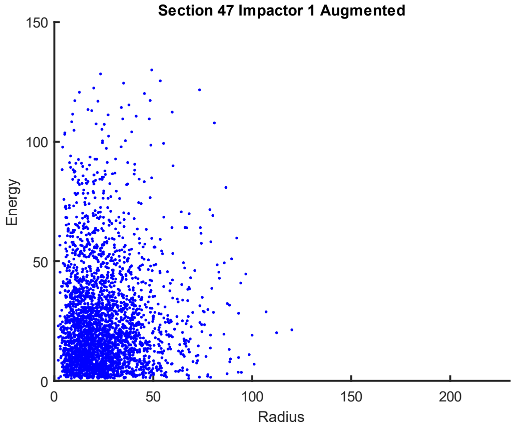

Figure B34: Section 47 Augmented

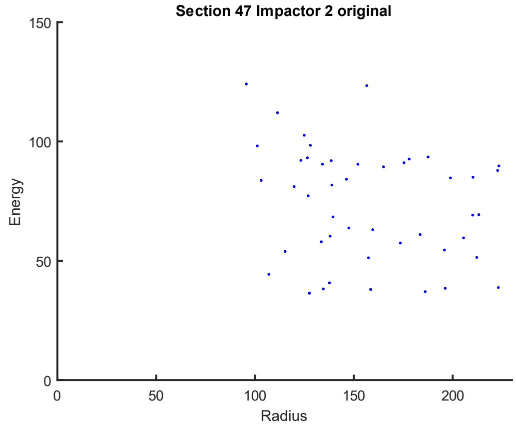

Figure B35: Section 47 Original

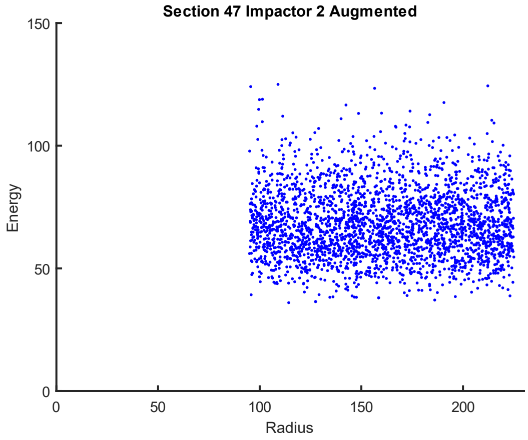

Figure B36: Section 47 Augmented

C. Jenks Natural Breaks Optimization

For classifying the severity levels the Jenks Natural Breaks Optimization algorithm was used. First, the number of classes was chosen to be four. The results of the classification are given in Table C1. The first two levels turned out to have small ranges with a relatively small size compared to the other levels. Afterwards the number of classes was chosen to be three. The results as shown in Table C2 show that level one consisted of the data of level one and level two for when the class number was four. It was then chosen to keep level one and two as indicated in Table C2 and to split level three in two classes as shown in Table C3.

Cluster	output_1	output_2		output_853	output_854	output_855	output_2397	output_6022
level 1	0	0	…	6.861				
level 2	6.947	6.956	…	…	…	16.631		
level 3	16.640	16.659	…	…	…	…	35.039	
level 4	35.0	35.06	…	…	…	…	…	77.973

Table C1: Severity Classification 4

Cluster	output_1	output_2		output_853	output_854	output_855	output_2397	output_6022
level 1	0	0	…	6.861	6.947	6.956		
level 2	16.640	16.659	…	…	…	…	35.039	
level 3	35.0	35.06	…	…	…	…	…	77.973

Table C2: Severity Classification 3

Size	Delamination length
1	< 16.64 mm
2	16.64 mm - 35 mm
3	35 mm - 50 mm
4	> 50 mm

Table C3: Severity Classification Levels

D. Data Summary Sheets

Table D1 shows the MIDAS conversion of impactor data to composite damage data.

Impactor size (mm)	Energy (J)	Dent depth (mm)	Dent radius (mm)	Delamination radius (mm)
64.053	25.414	0.051	3.461	34.26
61.196	27.999	0.061	3.653	36.334
32.98	46.271	0.226	4.725	46.818
54.356	53.886	0.147	5.034	50.947
75.911	45.417	0	4.588	47.313
41.841	26.245	0.093	3.621	34.705
…	…	…	…	…
…	…	…	…	…
48.962	35.579	0.107	4.163	41.454
24.755	14.227	0.093	2.785	21.622
84.538	85.312	0.139	6.126	62.541
18.225	19.376	0.185	3.213	27.473
42.094	29.047	0	3.801	36.883

Table D1: Impact damage summary sheet

Table D2 represents a summary of the input data for the risk and seriousness matrices.

ID	Fuselage section	Dent depth (mm)	Dent diameter (mm)	Delamination radius (mm)	Severity level	POD	D/ND	POD grade	Criticality level
0001	41	0.01	3.392	7.988	1	0.26	ND	5	3
0002	41	0.073	5.076	17.471	2	0.44	ND	5	3
…		…	…	…	…	…	…	…	…
0100	41	0.516	8.514	40.553	3	0.93	D	1	2
…		…	…	…	…	…	…	…	…
…		…	…	…	…	…	…	…	…
9998	47	0.096	11.918	61.818	4	0.89	ND	5	4
…		…	…	…	…	…	…	…	…
10127	47	0.084	12.061	63.045	4	0.90	D	1	2

Table D2: Data input for risk and seriousness matrices

References

1. Rana, S. and R. Fangueiro, *Advanced composite materials for aerospace engineering: Processing, properties and applications*. 2016: Woodhead Publishing.
2. Safety, A., *Status of FAA's actions to oversee the safety of composite airplanes.* Aviation Safety, 2011.
3. Giurgiutiu, V., *Structural health monitoring (SHM) of aerospace composites*, in *Polymer composites in the aerospace industry*. 2020, Elsevier. p. 491-558.
4. Chen, J. and Z. Fu. *Influence of Grounding Modes on the Damage of Carbon Fiber Reinforced Plastics subjected to Lightning Strikes*. in *2019 11th Asia-Pacific International Conference on Lightning (APL)*. 2019. IEEE.
5. Dhanisetty, V., *Impact damage repair decision-making for composite structures: Predicting impact damage on composite aircraft using aluminium data*. 2019, Delft University of Technology.
6. Chen, X., H. Ren, and C. Bil, *Inspection intervals optimization for aircraft composite structures considering dent damage.* Journal of Aircraft, 2014. **51**(1): p. 303-309.
7. Cook, L., *Visual inspection reliability for composite aircraft structures.* 2009.
8. Mohotti, D., et al., *Out-of-plane impact resistance of aluminium plates subjected to low velocity impacts.* Materials & Design, 2013. **50**: p. 413-426.
9. Massart, P., *Modelling Impact Damage on Aircraft Structures (MIDAS): Predicting impact damage on (composite) aircraft based on maintenance data of (metal) aircraft.* 2018.
10. Schoeppner, G.A. and S. Abrate, *Delamination threshold loads for low velocity impact on composite laminates.* Composites Part A: applied science and manufacturing, 2000. **31**(9): p. 903-915.
11. miei articoli Wire, I., *Advanced Lattice Structures for Composite Airframes Rendicontazione.*