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Military Aviation Authority



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Member Nations North Atlantic Treaty Organization STANAG 4703 and STANAG 4746 Custodial Support Team Reference: 20170726 – RPAS Collision Study Release of Results

27 Jul 2017

REMOTELY PILOTED AIR SYSTEMS (RPAS) MID AIR COLLISION (MAC) STUDY RESULTS

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Enclosure:

1. QinetiQ/17/01224/1.0, Small RPAS Collision Study – Final Report, dated 10 Apr 17.

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Small RPAS Collision Study Stakeholder Report Summary

10 April 2017









Enclosure: QinetiQ/17/01224/1.0, Small RPAS Collision Study – Final Report, dated, 10 Apr 2017.

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Report Summary

REMOTELY PILOTED AIR SYSTEMS (RPAS) MID AIR COLLISION (MAC) STUDY

Introduction

1. The Military Aviation Authority (MAA), the British Airline Pilot's Association (BALPA) and the Department for Transport (DfT), hereafter referred to as the Stakeholders, have conducted a 14-month study to better understand the risks that RPAS may pose to manned aviation. Specifically, this study focussed on the severity of a Mid Air Collision (MAC) between small RPAS and manned aircraft components.

Scope

- 2. The Stakeholders undertook this study to address the following issues:
 - a. The Stakeholders regularly receive comments and feedback from aircrew regarding the importance of gaining a better understanding of the MAC risk of RPAS, to determine the most appropriate way forward with regard to enforcement and regulation. In order to make a complete assessment, a quantitative analysis of RPAS MAC severity was required.
 - b. Current MAA regulation for RPAS operation in the UK military¹, establishes the harmless threshold² at 200g; below this threshold RPAS are not subject to any MAA oversight activity. The MAA required investigation as to whether this threshold is set too low, which could allow it to be raised and alleviate some of the regulatory oversight on slightly heavier RPAS types.
 - c. Whilst much is already understood about the degree and type of damage likely to be caused to aircraft structures by a bird strike, little is known about the potential risks presented by RPAS to manned aircraft. The Stakeholders were brought together by a shared interest in gaining a greater understanding as to what extent damage caused by collision with an RPAS can be equated to that caused by a birdstrike.
 - d. The MAA and DfT play a critical role in balancing proportionate and pragmatic safety requirements for the vast number of RPAS types available on the market without hindering emerging RPAS operation and technology. BALPA's first-hand experience, involving an increasing frequency of near-misses with drones, highlights a key concern that airline pilots have for the safety of crew and passengers. BALPA is therefore keen to support the DfT and the MAA in their mandate to assure safety by influencing requirements such as minimum design and operational standards for RPAS. This study serves to inform the Stakeholders whether a significant risk is present, and whether further work should be completed to fully understand how design requirements for RPAS could mitigate against the severity of a MAC should it occur.

¹ RA 1600 - Remotely Piloted Air Systems

² The weight threshold at which damage to property, or injury to people, is highly unlikely.

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- e. Whilst risk is the combination of the probability of the event occurring and the severity of that event, this study served to inform only the hazard severity of an RPAS MAC with a manned aircraft. This will help to inform the overall risk picture of a MAC between an RPAS and a manned aircraft.
- 3. Scoping of this study required consultation with design organisations, international regulators, engineers, operators and industry experts. To consolidate, organise, and scope this project was a significant task which was greatly assisted by the Unmanned Air System Capability Development Centre (UASCDC) within MoD. The UASCDC were instrumental in guiding the tender process, following which they project managed the study to the final delivery of the enclosed report. QinetiQ and Natural Impacts were chosen by the Stakeholders to conduct the study. Both organisations have a wealth of experience in their respective fields, and are highly regarded organisations who conduct studies for Defence, international companies and regulators. They also have first-hand experience with birdstrike testing and impact modelling.

Modelling and Testing

4. In setting the requirements for the study, the Stakeholders analysed the market and took a considered approach in selecting RPAS classifications and manned aviation components to be used. After considering the types and sizes of RPAS in use it was decided that the four different classes of RPAS chosen to reflect the most common RPAS configurations currently in use by leisure and commercial RPAS operators would be;



The selection of manned aircraft components, to model and test, was significantly more challenging. Extensive consultation needed to be undertaken; there was also a need to balance the practicalities of testing, timescales, availability of hardware and available funding. Based upon these considerations, the manned aircraft components selected were:

- a. Rotary Wing non-birdstrike certified windshields (NBCW helicopter)
- b. Rotary Wing birdstrike certified windshields (BCW helicopter)
- c. Rotary Wing tail rotor blades
- d. Fixed Wing birdstrike certified large commercial aircraft windshields (CS-25)

<u>5.</u>	Experimental techniques were developed that enabled projectiles,	
	, to be	launched
over	the full range of typical in-service collision velocities. It is important to not	e that the
	of these representative projectiles was less than the nominal mass of the RI	
type.	As this was believed to be the first time such a comprehensive RPAS mod	elling and
testin	g study had been undertaken, key decisions regarding experimental method	needed to
be ta	iken by the Stakeholders and QinetiQ. One critical decision was to select	only key
comp	onents	
	This decision maximised the opposition of the op	ortunity to

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focus on the RPAS components of most significance in an impact. This led to a simplification of the modelling and the representative test items.

6. Use of impact-modelling software can provide additional insight into the mechanism of
failure, and can enable a wider range of impact conditions to be considered, but to do so
reliably requires that the models be calibrated and validated by experimental tests. This
calibration and validation activity was at the centre of the study's requirements. The scope of
the project included development of equivalent material models
However, there was insufficient scope for detailed calibration of
material and failure models for the windscreens. It was therefore necessary to rely upon data
gained from literature reviews and by conducting a small number of calibration impacts on
windshields.

- Despite the technical challenges associated with calibration, predicting the failure 7. response of glass structures, the complexity of the RPAS configurations and with the dearth of information that was initially available, the modelling activities produced strong correlation with the physical tests of the two helicopter windshields. The results for the large commercial passenger aircraft windshield correlated less strongly for the particular collision conditions examined.
- It should be noted that the velocities modelled and tested represent closing speeds of the aircraft and RPAS. For a Quadcopter RPAS and Fixed-Wing RPAS, a typical true airspeed (TAS) of approximately 20kts and 50kts, respectively, was assumed. Furthermore, when considering practical implications of the results with respect to operational speeds of an aircraft (climb, cruise and approach speed for example) it is important to note that an aircraft is flown by reference to an Indicated Airspeed (IAS) in knots (nautical miles per hour) as shown by the aircraft instruments, rather than the True Airspeed (TAS) i.e. actual speed of the aircraft through the air. The difference between IAS and TAS of an aircraft increases by approximately 2% per 1000ft altitude. For example, an aircraft at 10000ft altitude being

flown at IAS of 250kts will equate to a TAS of approximately 300kts. The speeds referred to the results are therefore equivalent to the TAS of an aircraft.
Results
9. Prior to conducting this research, the resistance of aircraft components (particularly windshields) to an RPAS strike was open to considerable speculation. An important finding from the extensive literature review (which was reinforced throughout this test and modelling study) indicated that the damage created from such a collision is not determined solely by the mass and velocity of the object, but also by the shear properties of the impactor.
For this reason, is not possible to equate the damage caused by a RPAS to the damage caused by the equivalent mass of bird.
10.

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12. The large commercial passenger aircraft windshields (CS-25) were shown to be
13. The modelling results for the NBCW and BCW helicopters proved to be strongly correlated to the test data, The model predictions for the more-complex CS-25
aircraft windshield produced results which tended to predict damage at lower velocities for the types of collision and failure modes observed in testing. Although some discrepancies were likely to be due to the idealisation of the RPAS components, the greatest discrepancies were probably due to the idealisation of the windshield models: particularly the interlaminar failure-models and the material-properties and failure-model for the glass. Further work is recommended to reduce these discrepancies, particularly further calibration of windshield
material and failure models.
14. The helicopter tail rotor model considered a collision between a
It was not possible to conduct any testing of the tail rotor scenario within the scope of the project.
15. This study has resulted in a significant increase in knowledge regarding the severity of a MAC between a manned aircraft and an RPAS. It is therefore helpful to summarise the most important points below:
a. As further described below, a number of factors contributed to the extent and severity of the collision. The design and construction of the RPAS is significant, for example.
absorption, frangibility and separation-of-masses within the RPAS should be further studied
b. The orientation of the projectile and the incidence angle of collision demonstrated that, in some cases, collisions were attenuated
The leading components also absorbed some of the collision energy as they

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•	struck the windshield first and fragmented before the central mass of the RPAS struck the windshield.
C.	A key requirement of this study was to understand whether a comparison could be drawn between birdstrike damage certification criteria and resistance to damage caused by RPAS impact.
•	Birdstrike-certified helicopters at speeds
•	Large commercial aircraft up to typical arrival speeds of
Thus	s, the birdstrike comparison was partially realised.
d.	A non-birdstrike-certified helicopter windshield has a high degree of vulnerability to an RPAS strike.
e.	The birdstrike-certified helicopter windshield shows significant resistance a lt is therefore likely that if a such a windshield was struck by a 1.2kg Class RPAS at less than the windshield would remain largely intact, potentially protecting the pilot from the RPAS penetrating the windshield and entering the cockpit. Collision
f.	
g.	This study, supported by data gathered from similar experiments analysed during the literature review, showed equivalent damage was caused by an RPAS under the same collision conditions.
h.	The component testing showed that the strike had a significant effect on lowering the impulse load during the strike.
i.	

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Conclusions

16.	The	following	conclusions	are	drawn	from	the	RPAS	Collision	Modelling	and	Test
Study		_								_		

a.	Birdstrike	collision	data	does	not	correctly	chara	cterise	collision	with	an	RPAS:
								than	would a	a biro	of	similar
	mass.											

b.	There is	а	diverse	range	of	RPAS	products	on	the	market,	with	numerous
	configura			_								

c. Within the limited scope of this study it was not possible to achieve a higher degree of confidence in the correlation between the modelling and testing of the CS-25 large-aircraft windshields, the modelling delivering apparently more conservative results than when testing. The brittle nature of the windshield materials and the complexity of the interlaminar failure-mechanisms were likely contributing factors. Incomplete calibration of the test components and the reduced mass of the projectile representing the RPAS may have also been contributing factors. When assessing the test results, it is important to recognise that penetrating and non-penetrating impacts generally exhibit very different failure modes and that; the transition between these modes is typically sudden once the critical energy/speed is reached. In non-penetrating impact, the shear-forces around the perimeter of the projectile are insufficient to punch a hole, hence kinetic-energy is transferred to the screen.

This suggests that modelling of penetrating impacts might be less sensitive to uncertainties related to the modelling of the glass and its lamination.

d. Strong correlation was obtained between the model and the test for the NBCW, and the BCW helicopter, which provides a good indication of likely damage at varying speeds. This implies that modelling may be a useful tool for predicting the performance of other impact scenarios for these classes of windshield.



g. Unlike a birdstrike, the aviation industry is only beginning to understand the risks of RPAS. This report considers the severity and nature of damage due to an

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RPAS collision the windshield of manned aircraft. It does not consider the likelihood of collision which would also be needed to fully determine the overall risk. There are currently significantly fewer RPAS than birds; however, it has been shown

h. As a result of this work the operators and designers of both manned aviation and RPAS will have a much better idea of the outcomes of a MAC between the two. This information provides sufficient evidence to allow consideration of potential actions that could be taken to perform an assessment of the risks, and where appropriate make changes in regulation, design or operation of RPAS to reduce the likelihood or severity of any collision.

Recommendations

- 17. The study Stakeholders are considering the following recommendations as a result of this study:
 - a. It is recommended that the results of the current study are used to help inform risk assessments for aircraft operations. In particular, the vulnerabilities in the event of an MAC with an RPAS should be taken into account and appropriate operational mitigation measures should be considered.
 - b. This project does not consider the likelihood of a MAC. In order to understand the full risk picture and develop risk-appropriate mitigations, it is recommended that a better understanding of the likelihood of a collision is developed.
 - c. It is recommended that consideration is given, where complete information was not available on characteristics of some components, to improving this information. This could increase confidence in the results of this study and future work. In particular, improved understanding of the characteristics of windshields and their lamination could help to explain some of the discrepancies between modelling and testing results for non-penetrating impacts (the modelling showed better correlation with testing for penetrating impacts).
 - d. It is recommended that consideration is given to further research into RPAS frangibility and energy absorption with a potential end state being the implementation of a design requirement for civil and military RPAS.



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Small RPAS Collision Study - Final Report

Copy 4 of 5

Bill Austen, Dr Steven Lord, Dr Roger White*, Richard Purver*, Simon Bridges & Kieran Wood * Natural Impacts Limited

QINETIQ/17/01224/1.0

10 April 2017 127 pages

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NATO RPAS Working Group

Federal Aviation Administration (FAA)

Vereinigung Cockpit

Transport Canada

	Rel	ease	Auth	ority
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Name	David Bush	
Post	Project Manager	
Signature	West	

Record of changes

Issue	Date	Detail of changes	
1.0	10 Apr 2017	First Issue	_

Executive Summary

A programme of work has been completed to evaluate, via analysis and full-scale testing, the impact threat posed by small Remotely Piloted Air Systems (RPAS) to manned aircraft. The work was contracted through the Unmanned Air Systems Capability Development Centre (UASCDC) in close collaboration with the Stakeholders: Military Aviation Authority (MAA), the British Airline Pilots Association (BALPA) and the Department for Transport (DfT).

Within this programme, a sequence of research, development, manufacture and test activities have been undertaken to deliver a set of high-value results and develop a capability for the assessment of this emerging and high profile perceived threat to aviation safety.

Prior to this study, the effect of a small RPAS colliding with manned aircraft structures was subject to much speculation and opinion, but very little substantiated evidence existed. The results of this study provide a step change in knowledge and capability that will support the Stakeholders in making informed and balanced decisions/recommendations on future legislation, aircraft operations, operational airspace management, design standards and research requirements.



Despite the technical challenges associated with modelling the failure response of glass structures, the complexity of the RPAS configurations and the dearth of information that was initially available, the modelling activities consistently produced accurate results against the collision tests.

A key factor in the success of this activity was the incremental validation approach, making best use of available testing facilities and aircraft/RPAS hardware assets, to progressively de-risk and guide the model development.

and guide the model development.

The modelling results for rotorcraft windshields proved to be exceptionally accurate

predictions for the thicker, more-complex airliner windshields produced overly-conservative results; this can be attributed, in part, to known simplifications to the RPAS material models and suspected differences in the construction of the windshields from the supplied data. This is an area that is worthy of further exploration, to determine whether the existing analysis methods can be legitimately calibrated for this windshield or whether alternative material models might be required for this class of structural transparency.

List of Contents

	Adm	ninistration Page		. 2
	Exe	cutive Summary		3
	List	of Contents		4
1	Intro	oduction		8
	1.1	Background		8
	1.2	Study requirement		8
	1.3	RPAS class definition		9
	1.4	Manned aircraft		10
	1.5	Approach to the study		11
	1.6	Report structure		13
2	Othe	er relevant studies		14
	2.1	Previous studies in literature		. 14
	2.2	Dstl/Imperial College activities		14
	:			15
	2.4	Outcome of literature review		15
3	RPA	S "projectile" representations		16
	3.1	Introduction		16
	3.2	RPAS mass classes		16
	3.3	Projectile development		16
	3.4	RPAS projectile configurations		17
4	Man	ned aircraft components and representations		23
	4.1	Introduction		23
	4.2	Scope of manned aircraft analysis and test		23
	4.3	Airframes for analysis and test		23
	4.4	Manned aircraft windshield construction		24
				26
5	•	act conditions		28
	5.1	Introduction		28
	5.2	RPAS projectile conditions		28
	5.3	Manned aircraft conditions		30
	5.4	Impact locations		30
		<u></u>		30
6	-	erimental procedures		32
	6.1	Introduction		32
	6.2	Launch capabilities - 6" & 8" calibre guns		32
	6.3	RPAS projectile launch development		32
	6.5	Valenita managara		36
	6.5	Velocity measurement		36 37
	6.6 6.7	Target alignment and impact location		38
_	6.7	High-speed videos	<u>~—</u> .	
Page	e 4 of	12/	QINE	TIQ/17/01224/1.0

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QINETIQ/17/01224/1.0

	6.8 Standard videos		38
	6.9 Dummy pilot		38
7	Collision test results		39
	7.1 Introduction		39
	7.2 Rotorcraft-A windshield tests		40
	7.3 Rotorcraft-B windshield tests		46
	7.4 Airliner-A windshield tests		51
	7.5 Airliner-B windshield tests		58
			61
	7.7 Test summary		64
8	Material definitions		66
	8.1 Introduction		66
	8.2 Glass		66
	8.3 Polyvinyl Butyral (PVB)		68
	8.4 Thermoplastic Polyurethane (TPU)		69
	8.5 Acrylic		69
	8.6 Acrylonitrile Butadiene Styrene (ABS)		69
	8.7 Nylon 66, 30% Glass Fibre		69
	8.8 Aluminium alloy		70
	8.9 E-Glass/MY750 properties		70
	8.10 ROHACELL foam		71
	8.11 NOMEX honeycomb		71
	8.12 Titanium TA10 Alloy		72
	8.13 Testing of individual RPAS components		72
	8.14 Material characterisation of RPAS components		74
9	Model development and validation		75
	9.1 Introduction		75
	9.2 Modelling studies to develop the analysis approach		75
	9.3 Preliminary tests to provide early validation data for model setu	ıp	76
	9.4 Validation against full-scale collision test results		77
10	Collision modelling results		81
	10.1 Introduction		81
	10.2 Rotorcraft-A windshield impacts		82
	10.3 Rotorcraft-B windshield impacts		84
	10.4 Airliner-A windshield impacts		86
			88
	10.6 Summary of collision modelling results		92
11	Conclusions		94
Ē	11.1 Aircraft vulnerability to RPAS threat		94
	11.2 Development and validation of analysis methods		95
12	Recommendations		96
-	12.2 Exploitation of the modelling capability		96
	and the meaning askaramy		

QINETIQ/17/01224/1.0

Page 5 of 127

	12.3 Development and refinement of the	modelling			96
	12.4 Extension of proven modelling appro	oach			97
13	References				98
14	List of Abbreviations				101
15	List of units				102
Α					
				•	
					123
	Initial Distribution List				124
	Report Documentation Page	•			126

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1 Introduction

1.1 Background

1.1.1 The Military Aviation Authority (MAA), the British Airline Pilots Association (BALPA) and the Department for Transport (DfT), share similar concerns regarding the risks and consequences of a collision between a small Remotely Piloted Air System (RPAS) (often referred to as a drone) and a manned aircraft. Figure 1-1 illustrates such a possible collision.

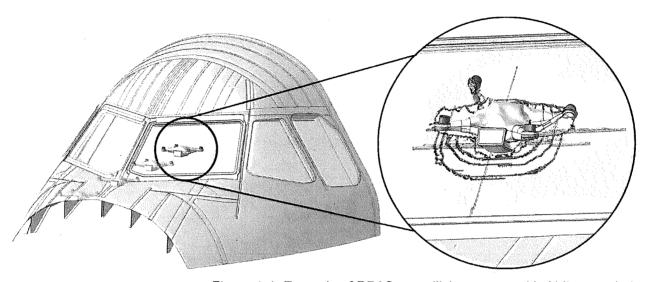


Figure 1-1: Example of RPAS on collision course with Airliner cockpit

- 1.1.2 The Unmanned Air Systems Capability Development Centre (UASCDC) were tasked by the Stakeholders to manage the project and create a Request for Quotation (RFQ) [1] in order to initiate a study to address the concerns. The objectives of this study were to understand the effects of a collision between a range of example RPAS and specific critical sub-systems of manned aircraft, including windshields such that a comparison with Bird-strike collisions can be made by the Stakeholders.
- 1.1.3 This document constitutes Deliverable 'D9' of MAA Contract HOCS1c/0024 and BALPA Purchase Order No 6155G, and contains details of the "Small RPAS Collision Study" test and modelling programme.

1.2 Study requirement

1.2.1 The focus of this work was to assess and evaluate the effect of small RPAS platforms colliding and impacting onto a specific manned aircraft sub-systems such as windshields. Here the primary requirement was to determine the threshold impact velocities at which the Secondary, derived requirements were to identify the extent of damage to the windshields

1.2.2 The specific requirements of this study were to use full-scale, ground-based physical impact testing and computer-based modelling to assess the level of damage/structural

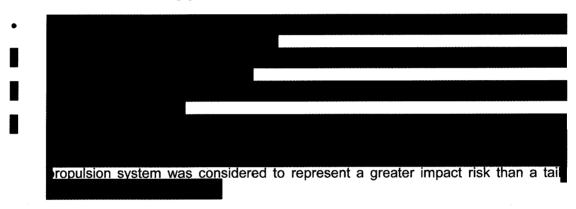
Page 8 of 127

failure that may occur during impacts between various classes of RPAS and specific areas of manned aircraft (i.e. windshields an implicit, enabling requirement to develop and validate new modelling methodologies that could be exploited to:

- Efficiently assess a much wider range of impact scenarios;
- Develop mitigation schemes to reduce the severity of impacts, and;
- Generate data to enable appropriate and proportionate decisions to be made on operational and legislative mitigation measures/controls.

1.3 RPAS class definition

1.3.1 The objective of the study was to assess the effects of impact of RPAS on various manned-aircraft components. The work was intended to be generic, rather than being specific to any particular commercially-available RPAS, and four generic RPAS classes were identified in the RFQ [1]:



1.3.2 The above classes were defined in order to reflect the variation in RPAS masses in service, whilst supporting the definition of particular test articles; termed "projectiles" here. The projectiles were defined by selecting key components that prior work indicated to be dominant in determining the impact response, and which were appropriate to the median MTOW value used to identify each RPAS class. These key components were:



1.3.3 The merit of this approach was that it provided easily comprehensive class definitions for the non-specialist, whilst enabling a scientific approach based on particular components that could be interpreted precisely in any downstream research or policy definition.

1.3.4	It is important to recognise that the projectile masses (stated in Section 3) were less than
	the masses defining the corresponding RPAS classes:
	where abbreviated names of the projectiles are defined
	which may be used, where appropriate, throughout the report.

QINETIQ/17/01224/1.0 Page 9 of 127

RPAS Class	Class projectile components	Abbreviated projectile name
	And the second of the second o	
		1

Table 1-1: Components in the RPAS projectiles

1.4 Manned aircraft

The manned aircraft considered for the studies are given in Table 1-2; this table shows the nomenclature to describe the aircraft throughout this report along with their class description.

1.4.1 In order to ensure that the boundary conditions of the windshields were representative, the screens were mounted to actual airframes, where available. The impact locations chosen conformed, where applicable, to standard bird-strike specifications.

Aircraft name in report	Impact location	Class description
Rotorcraft-A	Windshield	Helicopter with non-birdstrike certified windshield
Rotorcraft-B	Windshield	Helicopter with birdstrike certified windshield
Airliner-A	Windshield	Large Fixed Wing Civil Airliner with CS-25 certified windshield
Airliner-B	Windshield	Fixed Wing Civil Airliner with CS-25 certified windshield

Table 1-2: Manned aircraft considered in study

1.4.2 Applicable velocity ranges for RPAS projectiles and manned aircraft collisions are shown in Table 1-3. The values stated in the table are the impact velocities, which are the relative values of the velocity of the projectile to that of the manned platform. The key colour in the table indicates whether the collision scenarios were: modelled only; physically tested only; or both.

1.4.3	As well as considering the physical impact damage during cobeen expressed about the	ollisions, concerns have also particular, lithium
	above collision tests and report upon any	for all of the

Page 10 of 127

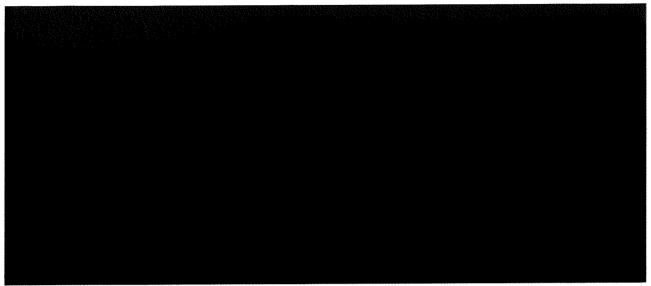


Table 1-3: Collision matrix for RPAS vs manned aircraft

1.5 Approach to the study

- 1.5.1 QinetiQ's programme of work against the Stakeholder requirements included an integrated programme of structural analysis and physical testing.
- 1.5.2 The structure of the programme was as described in the This programme plan is shown diagrammatically in Figure 1-2. Mid-programme enhancements to this plan included additional testing and analysis work to de-risk the technical output, inform technical decisions and to maximise the level of data derived from the available test assets and resources.
- 1.5.3 The computer modelling activities were delivered using Dassault Systemes' Abaqus, finite element (FE) package which is well-suited to complex non-linear and dynamic impact problems. Abaqus is a high-end aerospace industry-standard tool that is commonly used to undertake advanced failure analyses and impact assessments such as composite delamination modelling, bird strikes, crash analyses and in the UK, whole-wing virtual test. The use of this commercially available code has ensured that the demonstrated capability is of direct relevance to the UK aerospace industry.
- 1.5.4 The impact testing was conducted by a specialist sub-contractor, Natural Impacts, who have a wealth of experience designing and conducting certification tests against bird strike, hail, tyre, FOD and blade-off requirements.
- All testing was undertaken using various sizes of gas gun, whereupon compressed gases accelerate the RPAS projectile along a barrel and into the stationary target. In order to meet the needs of this programme, Natural Impacts designed and manufactured a new launcher system to allow the airframe.

Page 11 of 127

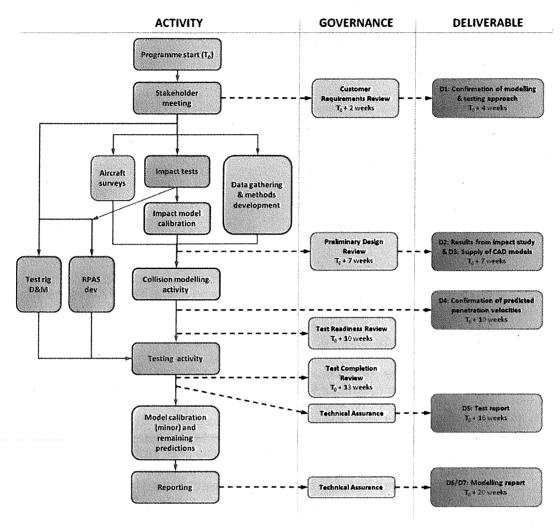


Figure 1-2: QinetiQ's programme of work

- 1.5.6

 It was anticipated that the response of the RPAS components swould be very complex to model using geometry and constituent materials data alone. Therefore, the agreed approach to the modelling was to represent each component as a homogenous material characterised by test. Hence, prior to the full impact tests, Natural Impacts performed static crush tests and dynamic impact tests of the latter tests using high-speed video and instrumented Hopkinson bar targets to record the physical behaviour and force-time response of RPAS threat components. The results from these tests were used to enable characterisation and calibration of material models for the impactor components to be used in the modelling; this process is described in more detail in Sections 8.13 and 8.14.
- 1.5.7 The resulting RPAS models were combined with accurate representations of the manned aircraft and detailed models of the laminated windshields. These whole assembly models were then used extensively to guide the impact testing and refine the approach based upon observations from test. The final models were then run for all of the required impact configurations (as defined in Table 1-3) and reported herein.

Page 12 of 127 QINETIQ/17/01224/1.0

1.6 Report structure

- 1.6.1 Following this introduction, Section 2 of this report contains a brief review of other work on the subject which is, to date, quite limited. The reader is then taken through the configuration and representation of each of the RPAS types under consideration (Section 3), followed by a description of the relevant manned aircraft components being impacted (Section 4). Section 5 describes details of the impact conditions and associated assumptions.
- 1.6.2 Section 6 describes the experimental equipment / setup and the bespoke modifications required to launch the various RPAS. Section 7 presents the results of the testing of the various RPAS against the three different manned aircraft,
- Glass windshields represent the majority of the manned aircraft components being impacted within this programme; hence it has been necessary to investigate the modelling of glass in terms of methods and materials. Section 8 sets out a summary of the materials used, explaining that calibration was required to improve the correlation of some results with test; this was part of the model validation which is detailed in Section 9, along with summary details of the approach developed to modelling this complex and highly dynamic event.
- The developed and calibrated models were then used to predict the effect of collisions between the combination of RPAS and manned aircraft specified in Table 1-3. The results of these predictions are presented in Section 10, with associated images from analysis and test recorded in Appendix A, with Appendix B showing predictions of The report is finalised with conclusions drawn from the study (Section 11) and recommendations (Section 12).

2 Other relevant studies

2.1 Previous studies in literature

- 2.1.1 To date the perceived threats posed by RPAS to aviation safety have been the subject of significant speculation but minimal evidence-based substantiation. This programme is therefore unique in its scope and approach, and is one of only a very small number of studies to directly address the topic of RPAS collisions.
- 2.1.2 While there are many references on the subject of bird-strikes against manned aircraft, where the impacting bird is typically described as a fluid using an 'equation of state', RPAS components such as
- 2.1.3 Due to the compressed timescale of this project and consequential focus on Stakeholder objectives, a detailed survey of all previous relevant studies was not possible. Furthermore, most of the limited work that has been done on this topic appears to be ongoing and/or subject to commercial restrictions. However, the following programmes/reports were identified and where possible, reviewed:
 - Dstl/Imperial College study [2, 3]: Reviewed below.
 - Autonomous Systems Underpinning Research, ASUR [5]: Research and development consortium led by Dstl that aims to advance technology towards new UAS concepts and enhancing current systems. No details of analysis programmes were available in open literature.
 - ASSURE initiative [6]: FAA led consortium to integrate unmanned aircraft into the air space and to identify and develop criteria and standards required for the civil certification and regulations of UAS pilots, equipment and operations. No details of analysis programmes were available in open literature.
 - Monash University final year project [7]: Broad review of collision threats but relatively low-fidelity analysis of specific components.
- 2.1.4 In addition to the above, numerous academic papers and sources of data have been reviewed to provide information on material property data, material models and numerical representations. These are referenced separately within the relevant Sections of this report.

2.2 Dstl/Imperial College activities

2.2.1 Two reports, sponsored by were made available to QinetiQ as GFX. These reports describe modelling (using LS-DYNA) and impact tests that compared the effect of bird-strikes on aircraft with those of nano-UAVs; as represented by The work was undertaken to inform the discussion on whether it was safe to operate nano-UAVs in the vicinity of other aircraft. Important distinctions between the impact characteristics of birds and nano-UAVs were identified. It was found that assessment of RPAS impact requires particular consideration, and cannot be inferred directly from bird-strike response. The levels of damage from the UAS impacts were dependent upon the particular components and impact conditions. In some cases it was found, supported by data from similar experiments within the literature review and determined by stakeholders, that equivalent

Page 14 of 127 QINETIQ/17/01224/1.0

	damage could be caused by an RPAS From the findings, it can be inferred that, in many cases, particular operational limitations (e.g. separation) and/or certification approaches will be required for RPAS impacts.
2.2.2	The modelling included impacts between a representative assembly and various aircraft components: a canopy, a composite leading-edge, a metallic leading-edge, and a fan-blade. UAS' structural components had a negligible effect. The work identified the importance of using accurate material properties within the modelling, and identified a lack of such data in the open literature for were undertaken to calibrate equivalent homogeneous material properties for the and these were used in the impact modelling. Due to health and safety restrictions on testing as a surrogate for the materials, and an material model was calibrated through impact testing. Further work was recommended, including impact testing of and derivation of equivalent material properties.
2.3	
2.3.1	
2.3.2	
	•

2.4 Outcome of literature review

Although some limited work had been done by other parties to assess various classes of RPAS impacting representative aircraft structures, none of the published findings were sufficient to meet the requirements of this programme. It was therefore concluded that the analysis and test activities performed within the current programme should develop data and modelling methods from scratch (albeit based upon QinetiQ's current approach to impact modelling), rather than inheriting assumptions from adjacent activities.

Page 15 of 127

3 RPAS "projectile" representations

3.1 Introduction

3.1.1 This Section gives an overview of the RPAS configurations assessed within this study, and their "projectile" representation for the purpose of modelling and test.

3.2 RPAS mass classes

3.2.1 Four configurations of electrically-propelled RPAS were considered,

3.2.2 The above classes were defined in order to reflect the variation in RPAS masses in service, whilst supporting the definition of the projectile test articles, defined by selecting key components deemed to be dominant in determining the impact response. These key components were:



3.3 Projectile development

Thus, the projectiles did not include such additional components unless it was convenient for their assembly and for their integrity when launched from the gas gun. These simplifications had the additional benefit of reducing the complexity of both the projectiles and the corresponding numerical models, which thereby reduced uncertainty when comparing the numerical models and experimental results.

- The stakeholders developed concepts for the construction of the RPAS classes using key components

 (COTS) sources, together with COTS or representative structural members

 QinetiQ subsequently worked with the stakeholders to refine both the RPAS concepts and the projectiles used to represent them, balancing the representation of the RPAS with the execution of a practicable and scientific programme.
- 3.3.3 The designs of the projectiles were influenced by the practicalities of maintaining their integrity when fired from the gas gun that was used to accelerate them. Analysis and testing indicated that fully assembled successfully, but that the was taken to remove the only components along the longitudinal axis. This eliminated the programmatic and technical risks associated with developing satisfactory techniques to support or reinforce

Page 16 of 127 QINETIQ/17/01224/1.0

during firing. This decision also increased the simplicity of the projectile, the and thereby increased confidence in the testing, modelling, and their comparison. 3.3.4 The mass of each of the four RPAS projectiles are shown in Table 3-1. Also included are the 'Percentage of Class mass', which indicates percentage of the projectile mass to the nominal MTOW. Table 3-1: RPAS projectile masses 3.3.5 Details of the four RPAS representations are included in the following sub-section. The configurations that were modelled were based upon the test projectiles, in order to allow direct comparison of results. 3.4 RPAS projectile configurations 3.4.1 The range of designs, constructions and component mass combinations for most classes 3.4.1.1 of RPAS are great, no exception. There are numerous lowcost toys that fall into this bracket, as well as more advanced systems with lightweight frames and that were specified for this class 3.4.1.2 Figure 3-1 of vehicle, and the basic representation of a airframe. such that an impact event could result in a train of components impacting the same location. 3.4.2 Although the test matrix for this programme (Table 1-3) did not include physical impact and any of the manned aircraft, modelling testing between this class of results were required against all platforms, It was therefore necessary to develop accurate representations of the 3.4.2.1 These components were modelled as primitive geometries but, as described later in Section 8.14, calibrated material models were developed to ensure that when they impact the target structures, the forces that they impart are realistic. 3.4.2.2 The frame is assumed to be a material of This results in a relatively weak and a

QINETIQ/17/01224/1.0 Page 17 of 127

construction that readily fails at the impact velocities of interest. Whilst this

airframe that is designed to withstand only low velocity impacts.

is not based on any particular model of RPAS, it is representative of a

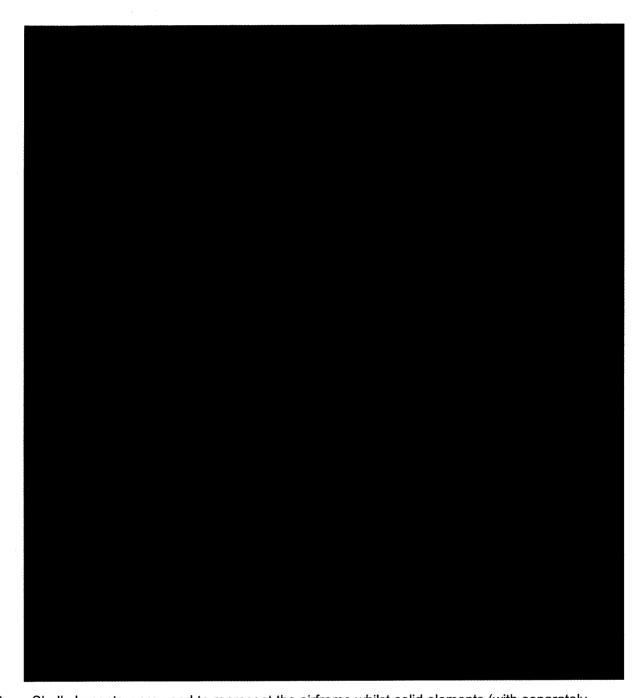


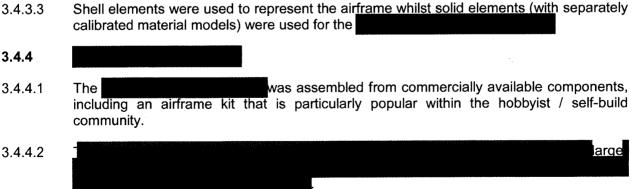
3.4.3 3.4.3.1 The is based upon a On this basis, the projectile configuration is It is recognised that many RPAS of this class include small, 3.4.3.2 . Although these may represent a such systems were not included in the final projectile configuration. Reasons for this include that it would make the projectile very difficult to launch during testing, its complex mechanisms would increase uncertainty in the modelling work,

been prohibitively expensive to procure for all of the test assets.

Figure 3-2 shows the that comprise the projectile, along with the corresponding FE model. The model was developed from scratch, using measurements and photographic projections to create a detailed Computer-Aided-Design (CAD) model. The plastic Acrylonitrile Butadiene Styrene (ABS) airframe was modelled as two separate components (other minor split lines around the were not included) and joints were made at screw and clip locations.

and components would have





QINETIQ/17/01224/1.0

Page 19 of 127

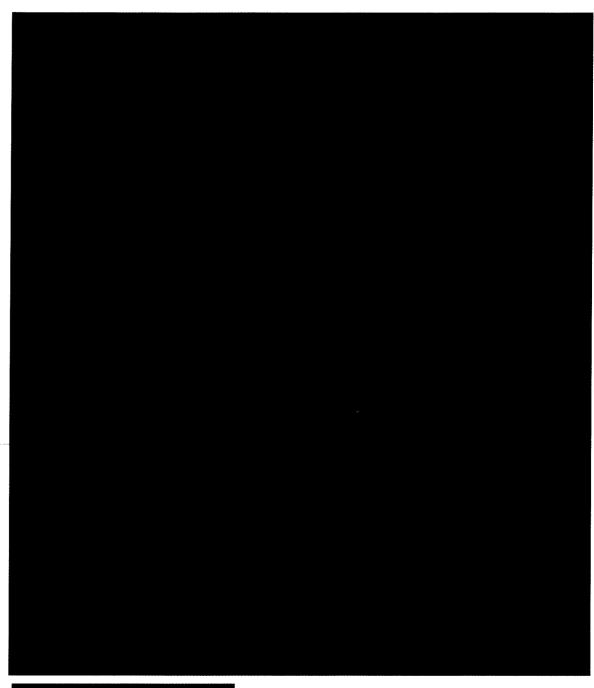
3.4.4.3	Figure 3-3 shows the supplied components and also the FE representation of the fina projectile. Note that some modifications to the components were required in order to achieve a configuration that could be successfully launched via gas gun, at the velocities demanded for the Airliner-A collision tests. These modifications included:
	Only t as the projectile was to be launched from an 8" bore gas gun. This was considered to be an acceptable approximation as the other
	This was a necessary change in order to create an assembly that could withstand the acceleration loads during launch. It
	This was a minor detail and was judged to have minimal effect on the impact case.
3.4.4.4	The model was constructed using a combination of material models were used for the

The current replicate this behaviour so future testing and model development would be required to

is therefore unlikely to

including

refine the modelled

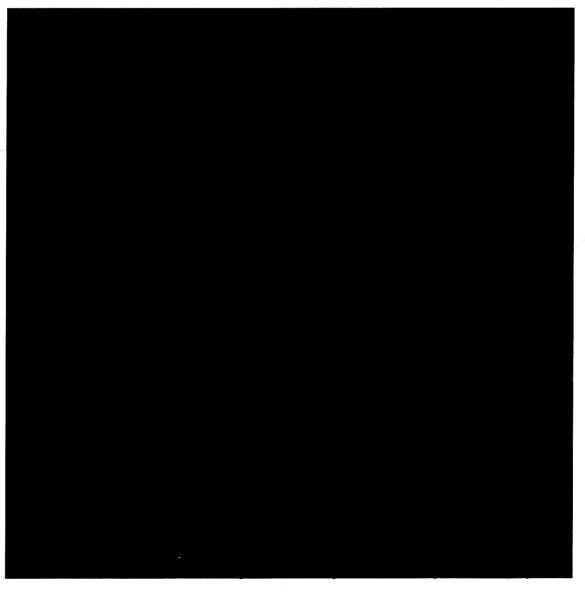


3.4.5.1 A schematic of a representative shown in Figure 3-4; this was simplified greatly for the purpose of creating a test projectile. It was agreed that the components that present the greatest threat in the event of a series of a series of the purpose of creating a test projectile. It was agreed that the components that present the greatest threat in the event of a series of the purpose of creating a test projectile. It was agreed that the components that present the greatest threat in the event of a series of the purpose of creating a test projectile. It was agreed that the components that present the greatest threat in the event of a series of the purpose of creating a test projectile. It was agreed that the components that present the greatest threat in the event of a series of the purpose of creating a test projectile. It was agreed that the components that present the greatest threat in the event of a series of the purpose of creating a test projectile. It was agreed that the components that present the greatest threat in the event of a series of the purpose of creating a test projectile. It was agreed that the components that the purpose of creating a test projectile. It was agreed that the components that the purpose of creating a series of the purpose of crea

QINETIQ/17/01224/1.0

Page 21 of 127

	such as the one used on the	. It was
	therefore agreed with UASCDC and the Stake components shown in Figure 3-4 (no additional	
3.4.5.3	The FE representation of the utilising a calibrated material model for the for the	was constructed from and a semi-calibrated material model
3.4.5.4	projectile assembly to be launched without bre appropriate crush and failure data, this feature possible that this balsa spacer	nodelled); this was necessary to enable the eaking up in the barrel of the gas gun. but in the absence of was not represented in the modelling. It is though it is not
	unreasonable to assume that a at this location.	would have a similar



4 Manned aircraft components and representations

4.1 Introduction

4.1.1 This Section gives an overview of the manned aircraft structures that were analysed and tested within this study. This includes details of the airframes, their representation as CAD models for analysis, the construction of the respective windshields and assumed

4.2 Scope of manned aircraft analysis and test

- 4.2.1 Activities within the programme included the following:
 - Rotorcraft windshields of two aircraft (Rotorcraft-A and Rotorcraft-B) were assessed by both modelling and testing;
 - Large aircraft windshields of a CS-25 class of aircraft (Airliner-A) were assessed by both modelling and testing;
 - Aircraft windshields of a CS-25 class of aircraft (Airliner-B) were assessed by testing only;

4.3 Airframes for analysis and test

- 4.3.1 For the impact analyses and tests to be representative of in-service collisions, it was necessary to ensure that the boundary conditions of the windshields were realistic, so the screens were mounted to actual airframes. The test and modelling activities were therefore undertaken with the windshields installed in genuine fuselage structures. An exception to this was the testing of the Airliner-B windshields; these were redundant windshields obtained by Natural Impacts which were fired into while de-risking projectile launching, and they were only loosely supported at representative angles with laboratory clamps.
- 4.3.2 Sections of the fuselage with cockpit for each of the test aircraft types (Rotorcraft-A, Rotorcraft-B and Airliner-A) were sourced. Each airframe was reviewed and critical structural components around the windshields were identified for inclusion in the CAD models¹.
- 4.3.3 Detailed surveys of the frontal cockpit structures were conducted by specialist contractors, using photogrammetric methods to provide an accurate but simplified CAD representation of each of the airframes. Figure 4-1 shows an example of the output from the survey, prior to being processed into a more-useable CAD format. These CAD models were subsequently converted into shell-element based FE representations for the modelling studies.
- 4.3.4 Photographs of a manned aircraft cockpit and its associated CAD is shown in Figure 4-2.

QINETIQ/17/01224/1.0 Page 23 of 127

The surveyed Rotorcraft-B cockpit (say, airframe 1), used for CAD in the modelling activities, was different from the Rotorcraft-B cockpit (say, airframe 2) that was tested. The reason for this was that the windshields supplied for testing did not fit airframe 1, so the alternative airframe 2 was sourced for the tests. However, the structural configuration of the two airframes was judged sufficiently similar to allow the modelling to proceed using survey data from airframe 1.

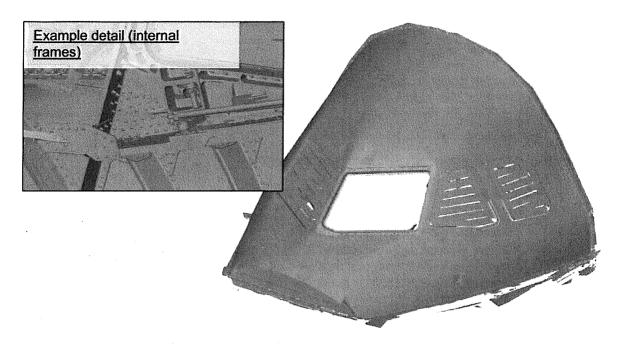


Figure 4-1: Raw data from photogrammetric aircraft survey

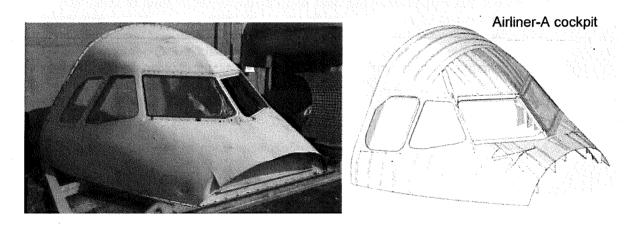


Figure 4-2: Manned aircraft cockpit photos and model representations

4.4 Manned aircraft windshield construction

4.4.1 All of the manned aircraft windshields were laminated glass. The construction of the laminate and their materials are presented below.

4.4.2 Rotorcraft-A windshield

4.4.2.1 The Rotorcraft-A windshield was a laminate, with a total thickness as shown in Figure 4-3. The layer thicknesses are defined on manufacturer's drawings.

Page 24 of 127

QINETIQ/17/01224/1.0

4.4.2.2 Material property data was not available for the glass or interlayer in the Rotorcraft-A windshield, so appropriate values were researched and are presented in Section 8. Engineering judgement was applied, and an assumption made, that the interlayer mechanical properties could be close to those of Polyvinyl Butyral (PVB) (the material suggested to represent the interlayer of the Airliner-A windshield).

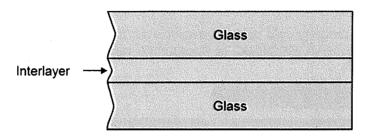
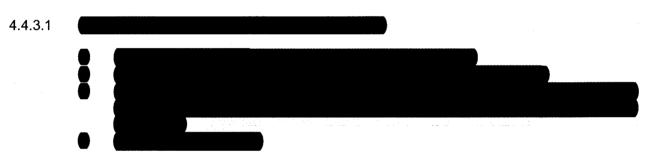


Figure 4-3: Rotorcraft-A windshield laminate

4.4.3 Rotorcraft-B windshield



4.4.3.2 Material property data was not available for the glass or acrylic layers of the Rotorcraft-B windshield, so appropriate values were researched and are presented in Section 8.

4.4.4 Airliner-A windshield

4.4.4.1 The Airliner-A windshield laminate, along with the thicknesses, is shown in Figure 4-4. The total thickness of the laminate was taken to be



QINETIQ/17/01224/1.0

- 4.4.4.2 Initial information suggested that the both of the interlayers were Polyvinyl Butyral (PVB) However, information from the manufacturer's website [12] suggests that the manufacturer has moved away from this design and that the thicker interlayer is now manufactured using Thermoplastic Polyurethane (TPU), whilst PVB is still used to bond the two main glass plies. Although guidance provided to QinetiQ, through UASCDC [11], was to assume that the PVB definition is correct, an initial inspection of a failed Airliner-A windshield suggests that the thicker interlayer is a stiffer material.
- 4.4.4.3 Material property data was not available for the two grades of glass, PVB or TPU layers in the Airliner-A windshield, so appropriate values were researched and are presented in Section 8.



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Page 27 of 127

5 Impact conditions

5.1 Introduction

5.1.1 For a given collision, the possible range of possible impact velocities, locations and orientations are too numerous to fully consider within a practical programme of testing. It was therefore necessary to determine an appropriate set of conditions for each collision scenario to represent a likely worst-case condition.

The maximum impact velocities for collisions between each combination of RPAS and manned aircraft were agreed between UASCDC, the Stakeholders and QinetiQ. These figures, presented in Table 1-3, are based upon the maximum velocities at which each platform could be travelling when an impact might credibly occur. Furthermore, they assume that both the RPAS and manned aircraft are on a direct collision course, and are travelling in opposite directions such that the impact velocity is the sum of their true airspeeds.

5.2	RPAS	projectile	conditions
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- 5.2.1 For calculating the maximum likely impact velocities, the cruise speed of the three classes of
- The yaw orientation of the was initially considered to be such that the manned aircraft was impacted with an in-line train of components as shown in Figure 5-1.

 However, due to launching difficulties in the testing, the orientation of (also shown in the figure)
- 5.2.3 The was tested and modelled as a train of components with zero yaw: Figure 5-1.
- In the testing, the launch of the windshield was intentionally inverted in the gun for the last three of the five shots. This modification to the configuration was implemented following the first two tests, one of which showed that Airliner-A windshield withstood an impact using the nominal projectile configuration. An observation made when reviewing the high-speed video footage of this test was that the

 Although there was no time available to explore alternative RPAS projectile designs (and the associated sabots and launch procedures), it was decided to invert the system in the barrel to represent
- 5.2.5 For most impact tests, the RPAS projectiles were observed to fly approximately straight and level (S&L) i.e. zero pitch and zero roll. However, as an artefact of the launching of the configuration and ~10° downward for the inverted configuration. This was therefore applied to the initial conditions of the projectile in the modelling (shown in Figure 5-1).

Page 28 of 127

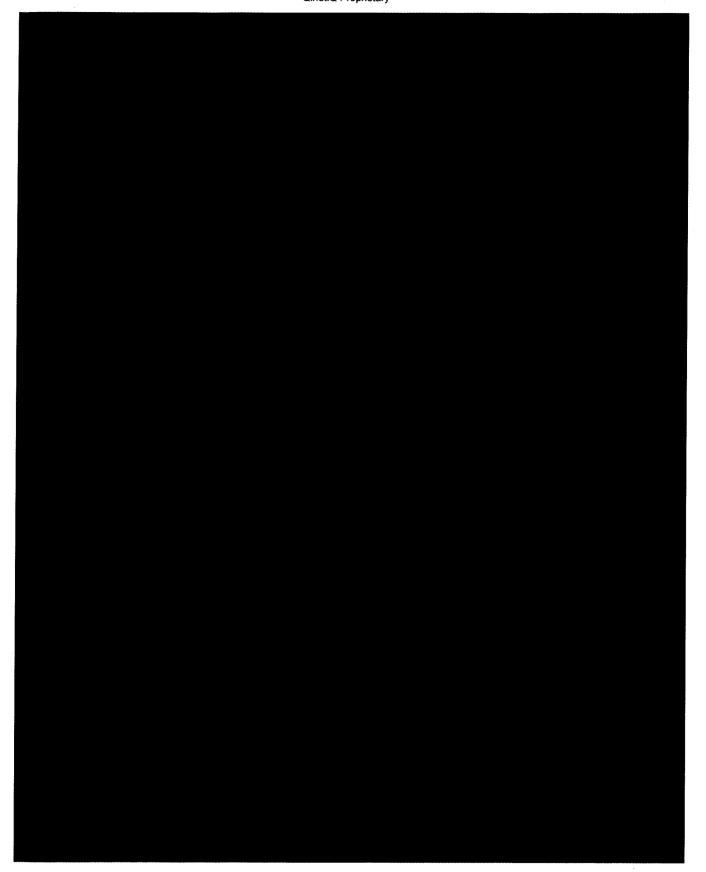


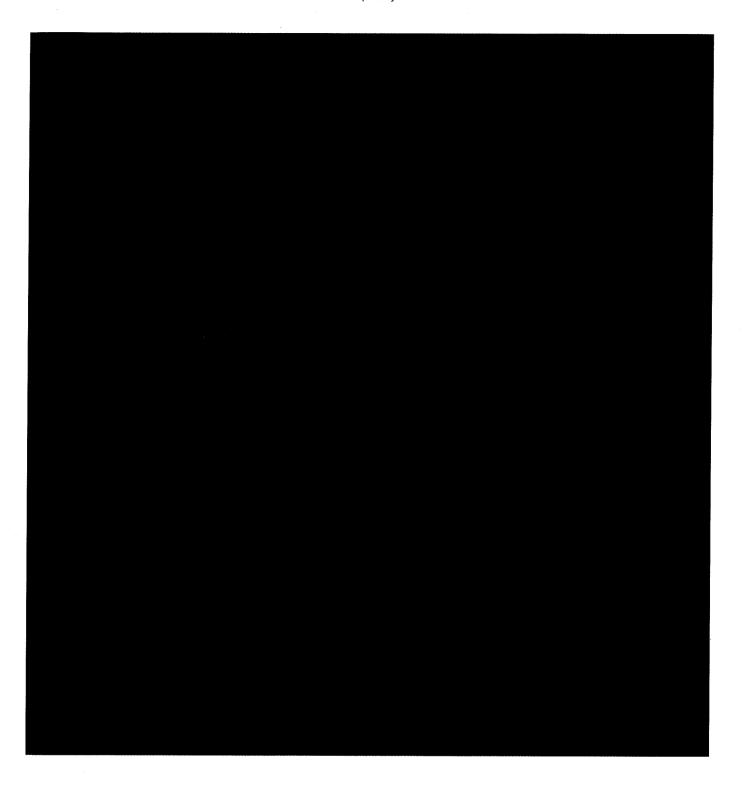
Figure 5-1: RPAS projectile impact orientations and attitudes against windshields

QINETIQ/17/01224/1.0

Page 29 of 127

5.3	Manned aircraft conditions
5.3.1	The maximum velocity of Rotorcraft-A was considered to be whilst Rotorcraft-B was considered to be The attitude of all manned aircraft was considered to be straight and level.
5.4	Impact locations
5.4.1	The location of the RPAS impact relative to the windshield was agreed to be in line with the head of the pilot, which was generally in the central region of each screen. This approach is analogous to that used when testing windshields against bird strike impacts, although bird strike testing can also include impacts in the corner regions (and indeed one test location of the Airliner-A windshield against an inverted
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Experimental procedures

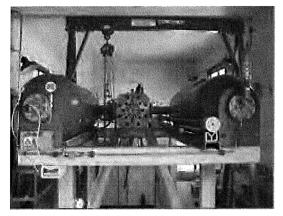
6.1 Introduction

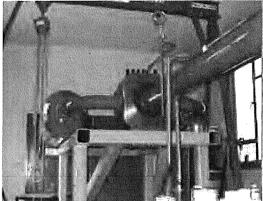
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6.1.1 This Section describes the experimental equipment / setup and the bespoke modifications required to launch the various RPAS projectiles.

6.2 Launch capabilities - 6" & 8" calibre guns

Natural Impacts Ltd has two large gas guns with bores of 6" (152mm) and 8" (203mm) by 18m long, which are capable of launching projectiles up to velocities of 580 knots (300ms⁻¹). The projectiles are accelerated using nitrogen gas stored in two accumulators and emitted via a high-speed valve. The breech and accumulators for the 6" gun are shown in Figure 6-1.





(a) Breach

(b) Barrel

Figure 6-1: Photographs of the 6" calibre gun

6.2.2 Projectiles are fitted into an aluminium alloy 'cup' termed a *sabot* that securely holds and seals the projectile in the gun barrel during launch. At the end of the barrel the *sabot* impacts a steel ring termed a 'stripper' and is arrested allowing the projectile to continue through the 'stripper' ring on to the target.

6.3 RPAS projectile launch development

6.3.1 It was apparent from the outset that launching a complete RPAS would be unlikely due to their dimensions being far greater than the bore of the largest gun.

The situation was further complicated by the fact that RPAS consist of had negative and positive effects; it limited the force that could be applied to accelerate the RPAS but, being weak in comparison to the deceleration forces generated during impact, it was considered acceptable to omit the weak frame components from the test, thus the RPAS was represented through

6.3.3 Due to diversity in the construction and impact velocities, each RPAS type had a bespoke launch solution that enabled representative examples to be launched over the full velocity regimes.

Page 32 of 127 QINETIQ/17/01224/1.0

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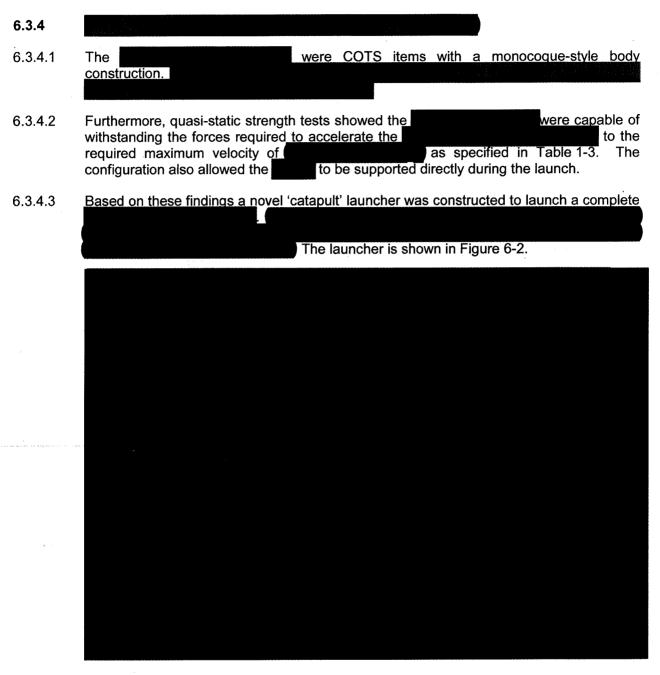


Figure 6-2: Modification to gun barrel for 1.2kg Class QC projectile

6.3.5.1 The was supplied as a number of individual components that could be used in the construction of a (see Figure 3-3).

Guasi-static strength tests showed that due to the required to reach the velocity (see Table 1-3).

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	The assembly is shown in Figure 6-4.
6.3.5.5	In order to directly push the minimise the buckling distances of the axial arms, the QCs were launched in bespoke sabots
6.3.5.4	The combination of both space and strength limitations dictated the components were aligned along the shot-axis.
6.3.5.3	The velocity also meant the projectile would have to be launched using the 8" gun rather than the catapult launcher (Section 6.3.4), as this has the longer 18m barrel enabling lower acceleration loads to be applied.

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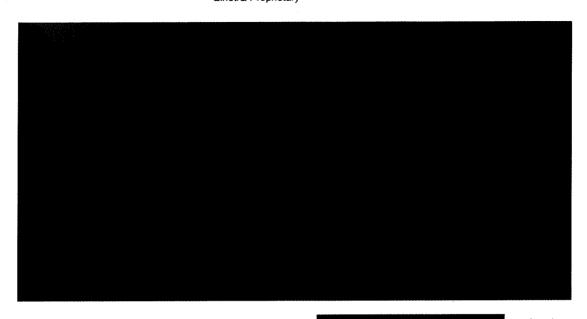
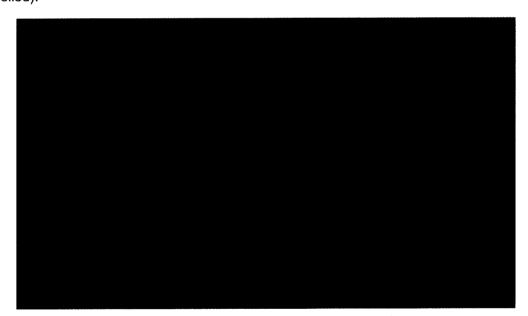


Figure 6-4: and sabot

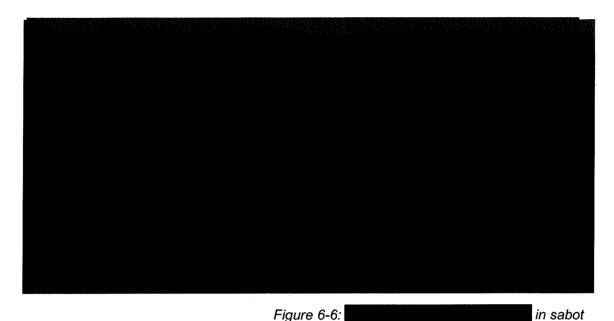
6.3.6

With reference to Figure 3-4, attached directly onto an 6.3.6.1 located immediately in front these were deemed representative as being the key components based on the projectile selection philosophy discussed in Section 3.4. This very significant was replicated as shown in Figure 6-5 with For launching purposes, the test projectile included a balsa wood spacer between (as modelled).



The narrow and symmetrical configuration enabled the assemblies to fit in the 6" sabot 6.3.6.2 with adequate clearance for the sabot to crush without contacting the projectile as it slid out (Figure 6-6).

Page 35 of 127 QINETIQ/17/01224/1.0



6.4.1

6.5 Velocity measurement

6.5.1 Impact velocity

6.4

- 6.5.1.1 The velocity of the projectiles was recorded 1.22m before impacting the windshields by measuring the time taken for it to pass between two IR beams located 50mm apart (see Figure 6-7).
- The velocities of the 200mm before the gun muzzle by measuring the time taken for it to pass between two IR beams located 200mm apart (see Figure 6-6). In all cases the signals were recorded using a Tektronix oscilloscope (Serial No.C040641, Calibration 2179170002).

6.5.2 Residual velocity

6.5.2.1 There was no attempt made to record residual velocities of the projectiles. There was a high-speed camera recording the event from within the cockpit, but this was placed at an angle

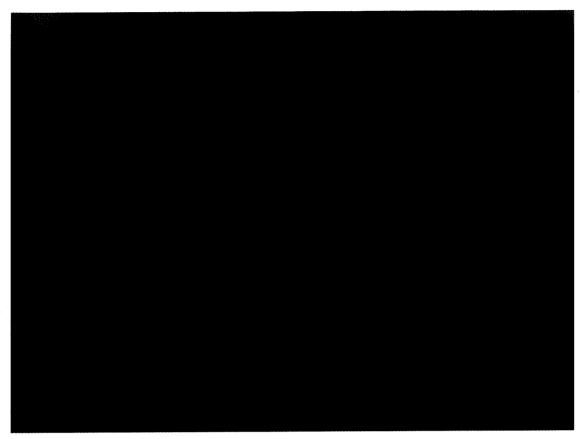


Figure 6-7: Location of IR velocity sensors on guns

Target alignment and impact location 6.6

A laser was inserted down the barrel to identify the gun axis; the airframe was then 6.6.1 moved until the laser beam coincided with the impact point as shown on the windshield in Figure 6-8.

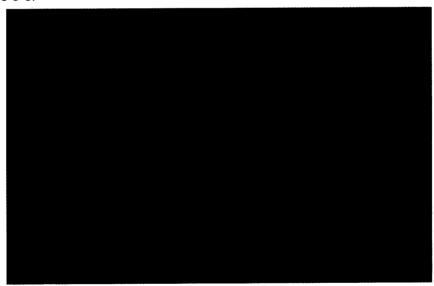


Figure 6-8: The laser beam (pink dot) positioned on windshield

Page 37 of 127

6.6.2 Table 6-1 gives the impact co-ordinates for the three aircraft tested.



Table 6-1: Impact positions for the three aircraft types

6.7 High-speed videos

6.7.1 The free-flight and impact of the RPAS projectiles were optically recorded from outside and inside the aircraft using two NAC GX1 monochrome cameras operating at 5,000fps with a $20\mu s$ shutter speed. Typical outside and inside camera views are shown in Figure 6-9.



Figure 6-9: Snapshot examples from high-speed cameras

6.8 Standard videos

6.8.1 Standard speed (50fps) videos were taken to capture the true speed and intensity of each impact.

6.9 Dummy pilot

6.9.1 In the majority of the tests, a dummy pilot constructed of polystyrene with a gel head was positioned in the cockpit behind the windshield. The pilot appeared in some of the high-speed videos

7 Collision test results

7.1 Introduction

7.1.1 This Section presents the results of the testing of the various RPAS against the three different manned aircraft. A summary of the results is presented in Table 7-1; the colour code of this table indicates damage level definitions given in Table 7-2, which is also used to describe the damage levels in the modelling predictions (Section 10).

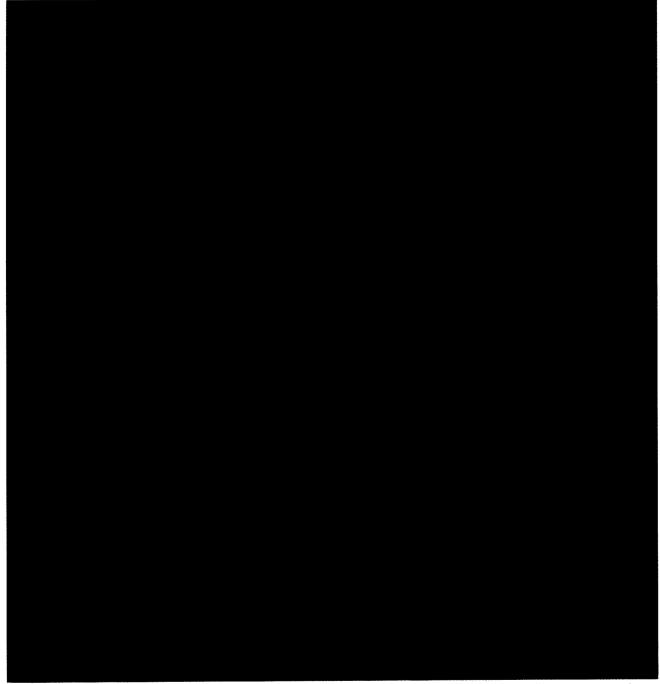


Table 7-1: Summary of the collision test results

Page 39 of 127

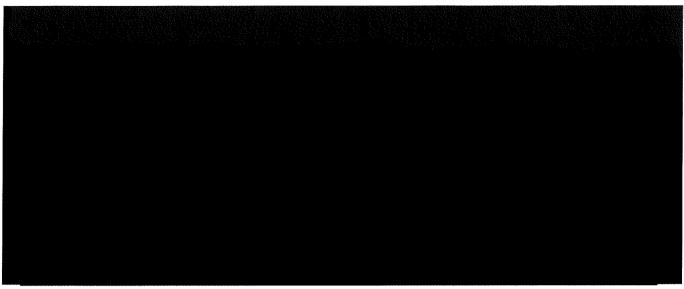


Table 7-2: Damage level definitions by colour

7.1.2 Table 7-3 shows a summary of the test results carried out to de-risk the projectile launching against windshield from Airliner-B, using the same colour damage level definitions given in Table 7-2.



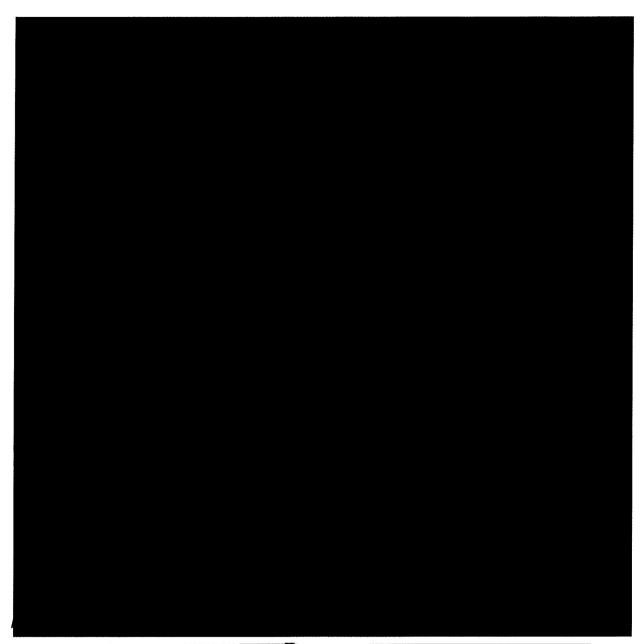
Table 7-3: Summary of the de-risking collision test results

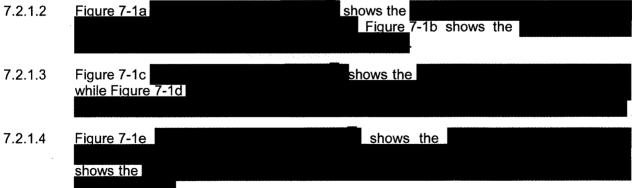
7.2 **Rotorcraft-A windshield tests**

7.2.1

7.2.1.1 High-speed video stills showing the outside and inside views of Tests 1, 2 and 3 respectively are shown in Figure 7-1.

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The front and rear damage to the windshields is shown in Figure 7-2. 7.2.1.5

QINETIQ/17/01224/1.0

Page 41 of 127

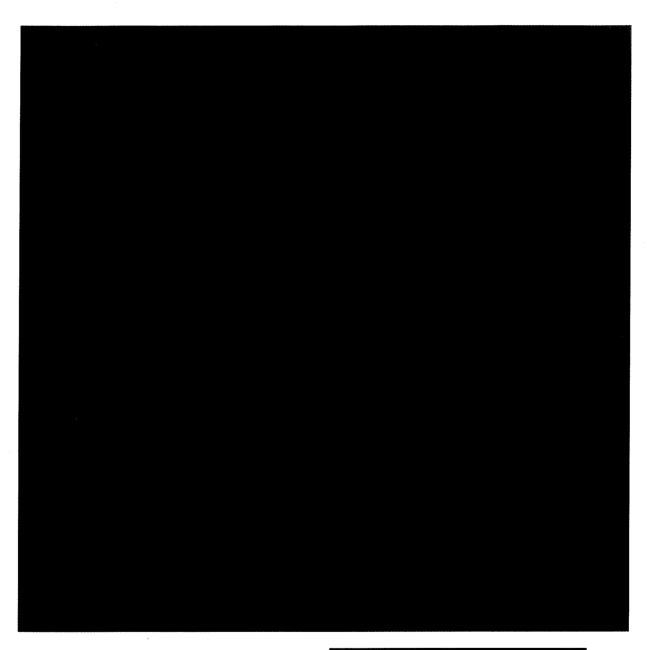


Figure 7-2: Photographs of windshield damage for

The Test 1 windshield shown in Figure 7-2a and Figure 7-2b 7.2.1.6 7.2.2

7.2.2.1 High-speed video stills showing the outside and inside views of Tests 5 to 8 respectively are shown in Figure 7-3.

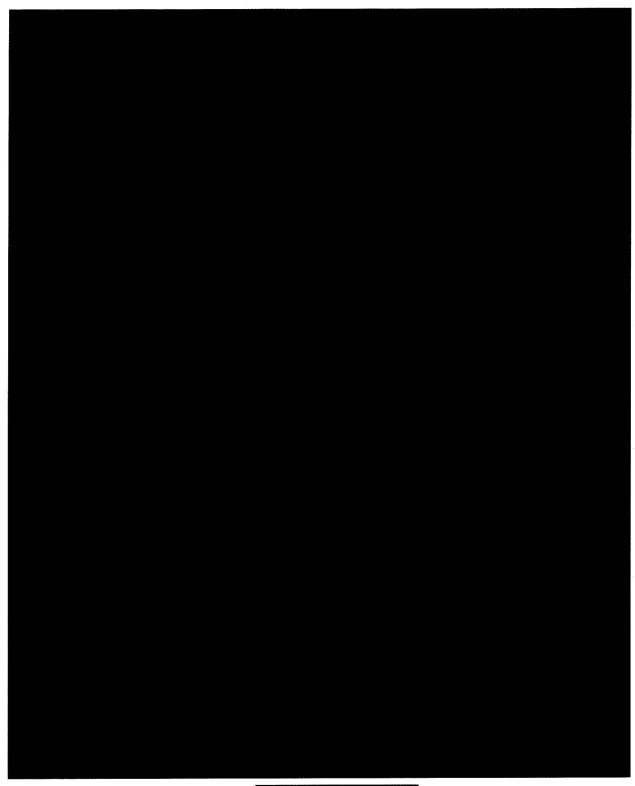
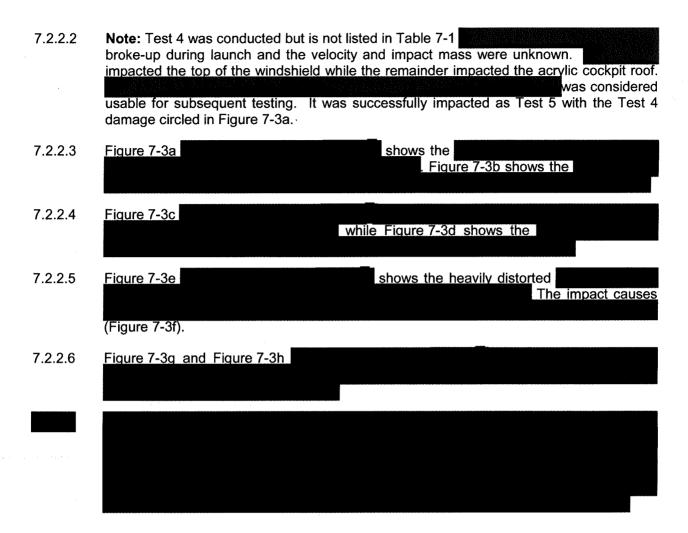


Figure 7-3: High-speed video stills of the

vs Rotorcraft-A windshield

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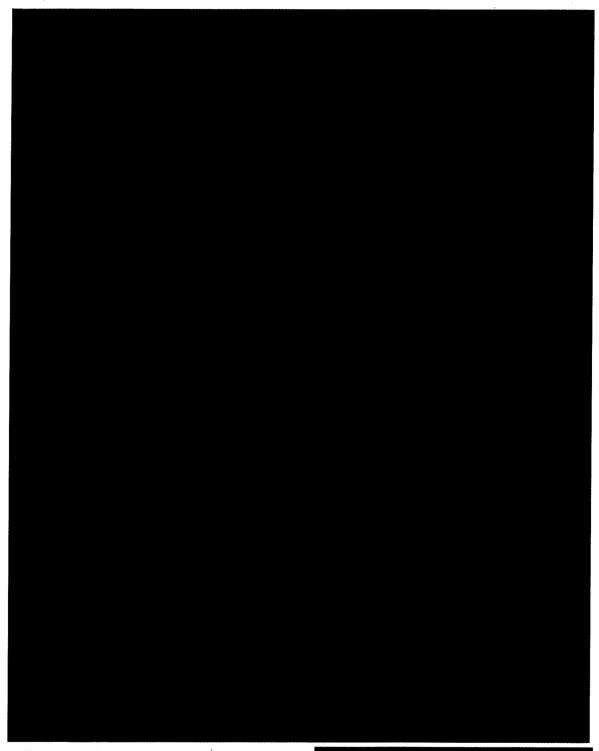
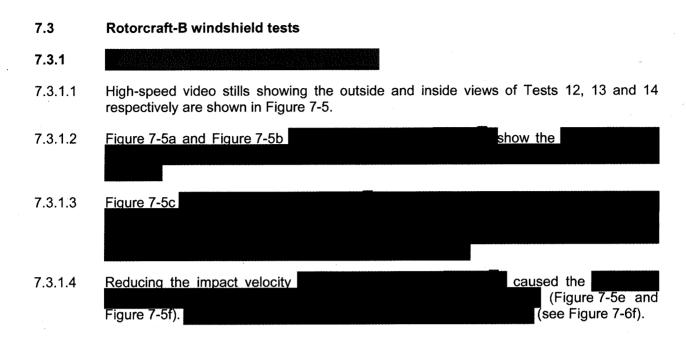


Figure 7-4: Photographs of windshield damage

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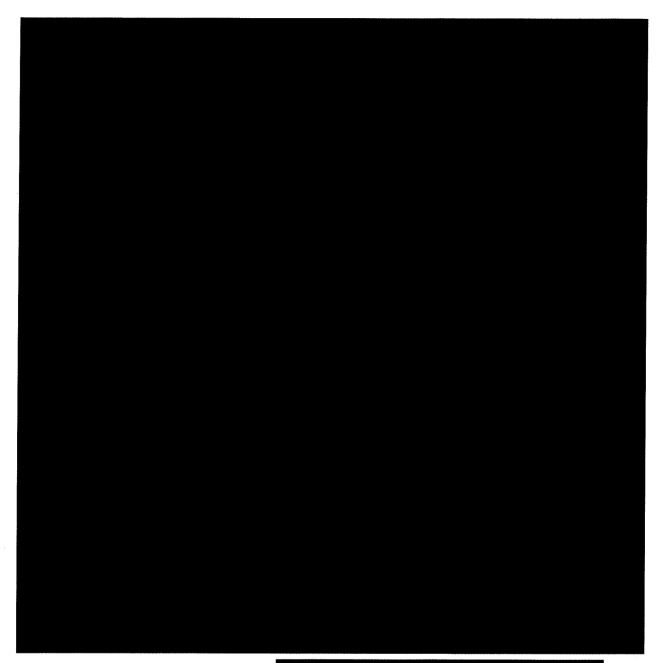


Figure 7-5: High-speed video stills of the

7.3.1.5 The front and rear damage to the windshields is shown in Figure 7-6.

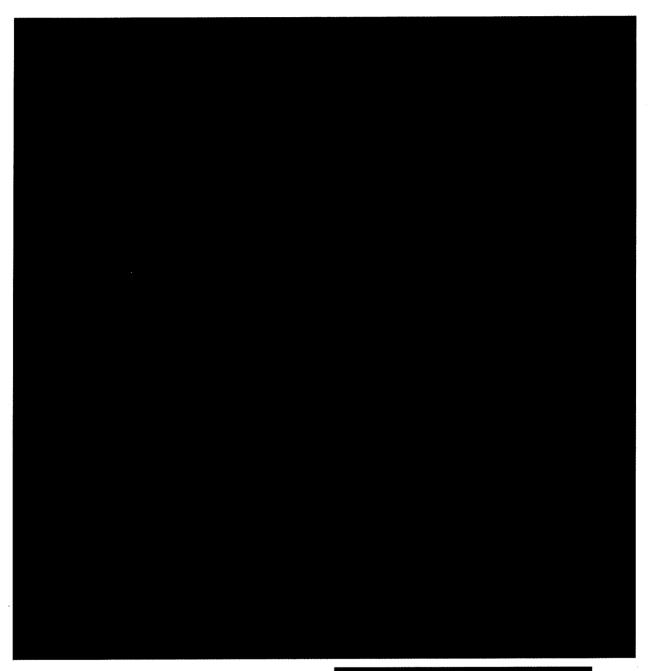
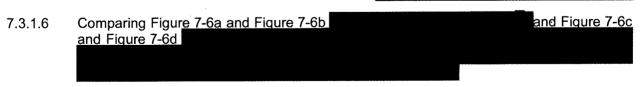


Figure 7-6: Photographs of windshield damage for



7.3.1.7 The Figure 7-6e and Figure 7-6f. The visibility through the screen is good.

7.3.2

7.3.2.1 High-speed video stills showing the outside and inside views of Tests 9 to 11 respectively are shown in Figure 7-7.

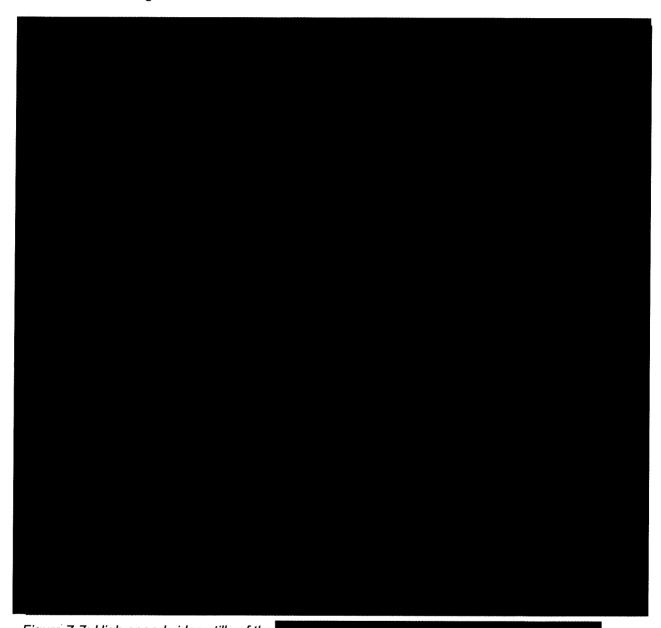


Figure 7-7: High-speed video stills of the

7.3.2.2 Figure 7-7a 7.3.2.3 Figure 7-7c

QINETIQ/17/01224/1.0

7.3.2.4 Figure 7-7e shows the body of the The impact (Figure 7-7f).

7.3.2.5 The front and rear damage to the windshields is shown in Figure 7-8.

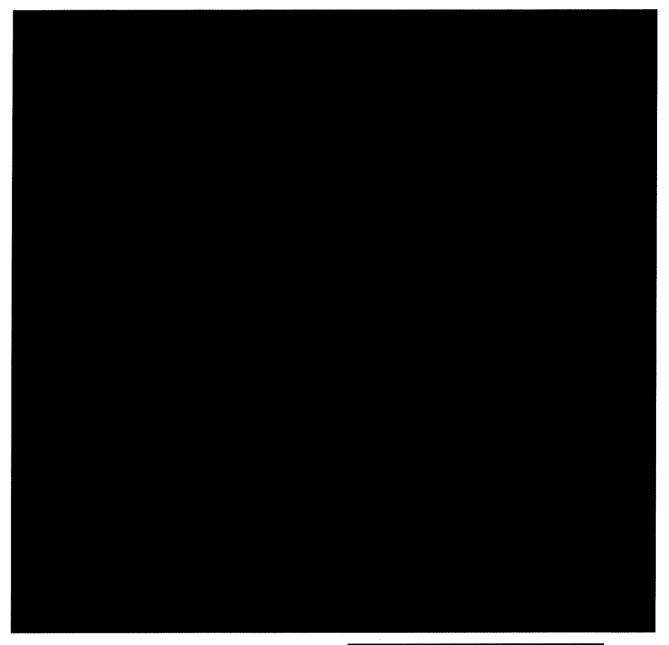


Figure 7-8: Photographs of windshield damage for

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7.3.2.6	The front view of the Test 9 windshield is shown in Figure 7-8a; the inner view was not available.
7.3.2.7	The Test 10 windshield is shown in Figure 7-8c and Figure 7-8d.
7.3.2.8	Figure 7-8e and Figure 7-8f show the Test 11 damage. Figure 7-8e shows the
7.4	Airliner-A windshield tests
7.4.1	
7.4.1.1	High-speed video stills are shown in Figure 7-9 of the impact sequence, from the outside, for a nominal configuration Test 15 Employed as this test was essentially a calibration shot to verify the deployment and free-flight characteristics of the projectile. Note that in many of the high-speed video stills there is evidence of other debris not associated with the RPAS projectile construction;

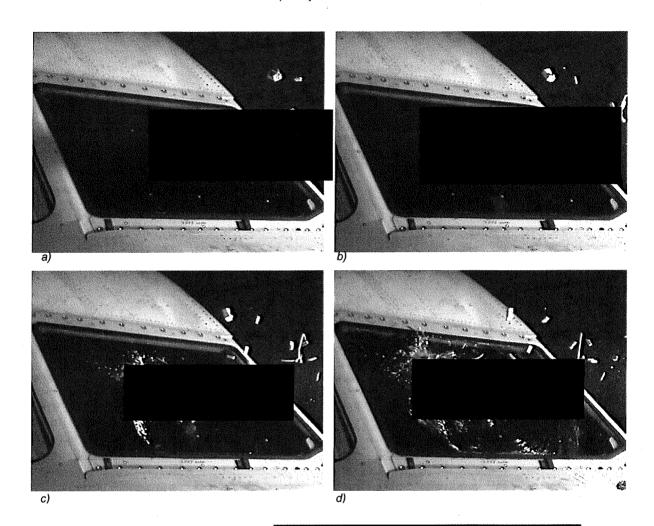


Figure 7-9: High-speed video stills of the

7.4.1.2 Due to the steep compound raked-back angle of the windshield the first item to contact was the circled in Figure 7-9a). It was not until the and started to (Figure 7-9b). Approximately later the

(Figure 7-9d) and did not fully load the windshield. The two main structural plies were undamaged and the damaged windshield is shown in Figure 7-10.



Figure 7-10: Photograph of windshield damage for

7.4.1.3 Test 16 was essentially a repeat of Test 15 but against a different manufactured windshield; subsequent tests were against windshields from the same manufacturer as the Test 16 windshield. Figure 7-11a and b show the point of peak damage in Test 16 from outside and inside the cockpit.

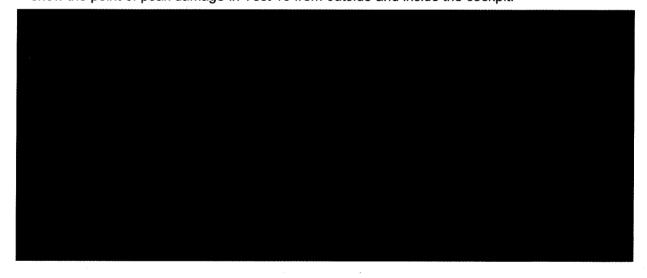


Figure 7-11: High-speed video stills of

7.4.1.4 The impact sequence was virtually identical to that shown in Figure 7-9 with only the outer glass ply failing albeit slightly more than Test 15, possibly due to the higher impact velocity of Figure 7-12.

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Figure 7-12: Photograph of windshield damage

7.4.1.5 Given the variety of it was necessary to evaluate the impact seemed to occur in Test 15 and 16 from without while in the nominal attitude. To achieve this without altering any parameters, the projectile was simply inverted allowing the This also meant that the projectile impacted the windscreen at a less oblique angle than it did whilst in the nominal configuration (see Figure 5-1). This scenario was tested as Test 17 and the impact sequence is shown in Figure 7-13.

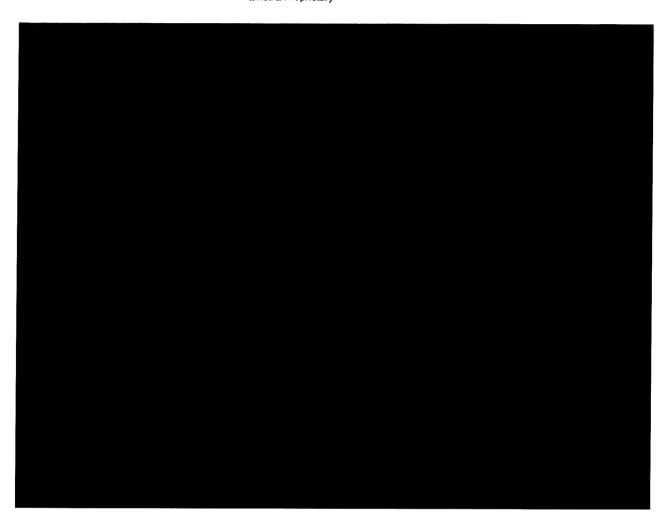


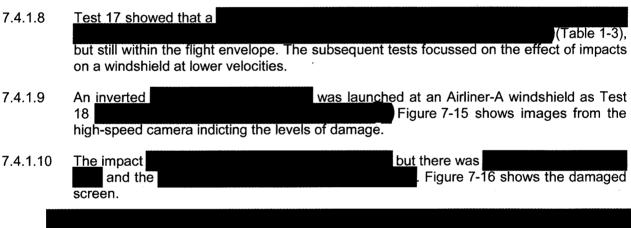
Figure 7-13: High-speed video stills of the

7.4.1.6 It is apparent from Figure 7-13a that the The subsequent impact of the (Figure 7-13b)

7.4.1.7 The loss of allowed the projectile to partly penetrate the layered glass structure (Figure 7-13c) and the impact caused a large amount of glass-spalling from the inside surface, resulting in shards reaching the dummy pilot, as shown in Figure 7-13d. Such a loss of integrity would mean the windshield no longer acted as a pressure seal and, coupled with ram-air, would cause catastrophic failure. Figure 7-14 shows a photograph of the failed screen.



Figure 7-14: Photograph of windshield damage for



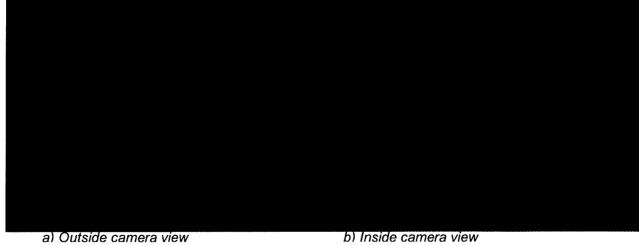


Figure 7-15: High-speed video stills of the

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Figure 7-16: Photograph of windshield damage for

- 7.4.1.11 The rationale for the last test was to run a scenario similar to the velocity of the Test 18, but impacting closer to the frame where the glass ligament was shorter, and to establish if the levels of damage were similar to an impact in the centre of the screen.
- 7.4.1.12 Test 19 impacted the windshield at a point 141mm up and 141mm across from the bottom inboard corner. Figure 7-17 shows images from the high-speed camera showing the levels of damage.

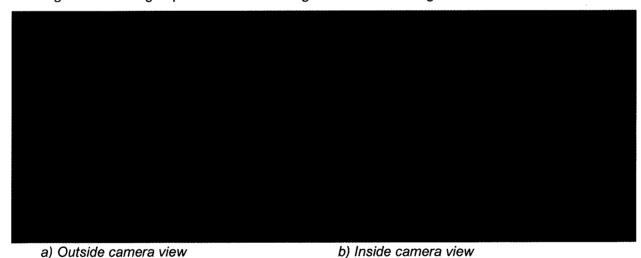


Figure 7-17: High-speed video stills of the

7.4.1.13 Both the generating the dust shown in Figure 7-17a but neither impact damaged the main plies. Figure 7-18 shows the screen post-test.

QINETIQ/17/01224/1.0 Page 57 of 127

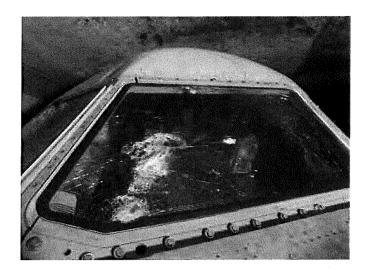


Figure 7-18: Photograph of windshield damage for

7.5 Airliner-B windshield tests

- 7.5.1 In order to de-risk the selection of the components in terms of their ability to damage a CS-25 class windshield, early in the programme, a windshield from Airliner-B was impacted by a was also launched at a second Airliner-B screen to further de-risk the launch process.
- 7.5.2 These tests, where the windshields were only loosely supported at the approximate correct angle, are shown in Table 7-3.
- 7.5.3
- 7.5.3.1 Here the projectile was a reduced version of that defined in Table 3-1, with a

Figure 7-19 shows the projectile fitted in to a 6" sabot.

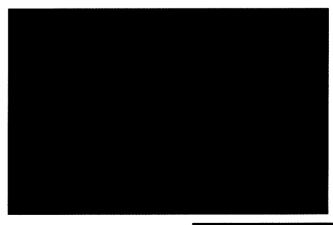


Figure 7-19: The cut-down

7.5.3.2 The projectile was launched as Test A1 and images of the impact are shown in Figure 7-20. shown in Figure 7-20b. b) a) Figure 7-20: High-speed video stills of the cut-down 7.5.3.3 A photograph of the post-test is shown in Figure 7-21a, whilst the is shown in Figure 7-21b. Figure 7-21: Photograph of windshield damage for 7.5.3.4 The windshield from Test A1 was subjected to a second impact by a camera (Test targeted 100mm below the first impact to account for the camera's position under the QC. Figure 7-22a shows the with the but the impact caused as shown in Figure 7-22 b.

Page 59 of 127

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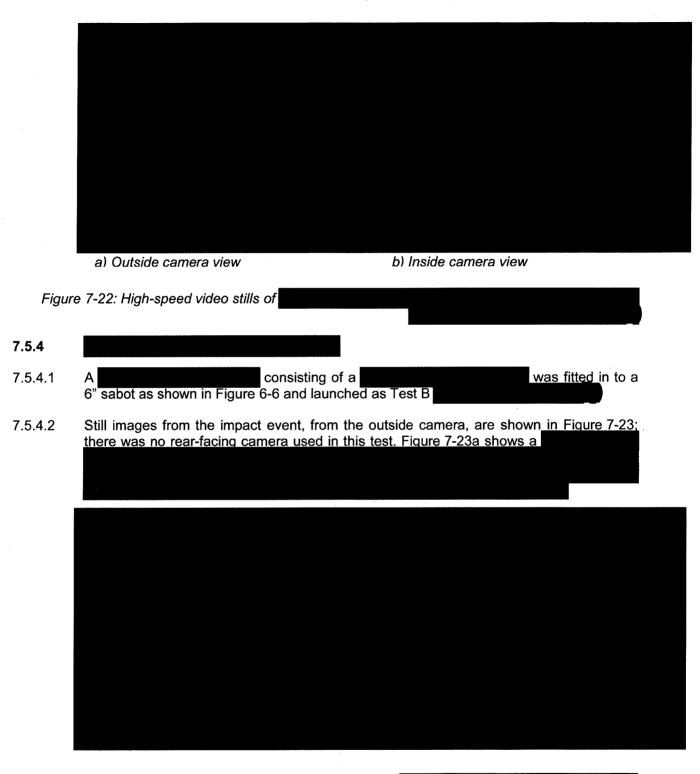
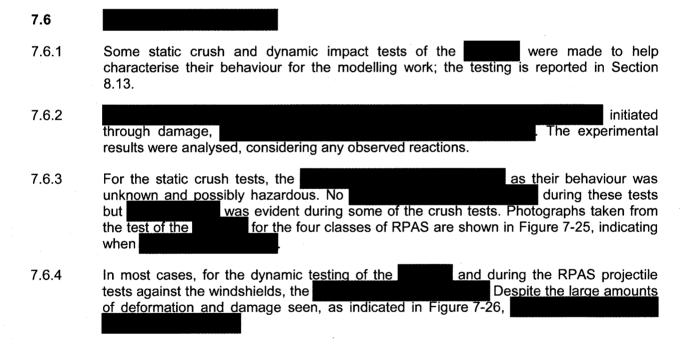


Figure 7-23: High-speed video stills of the cut-down

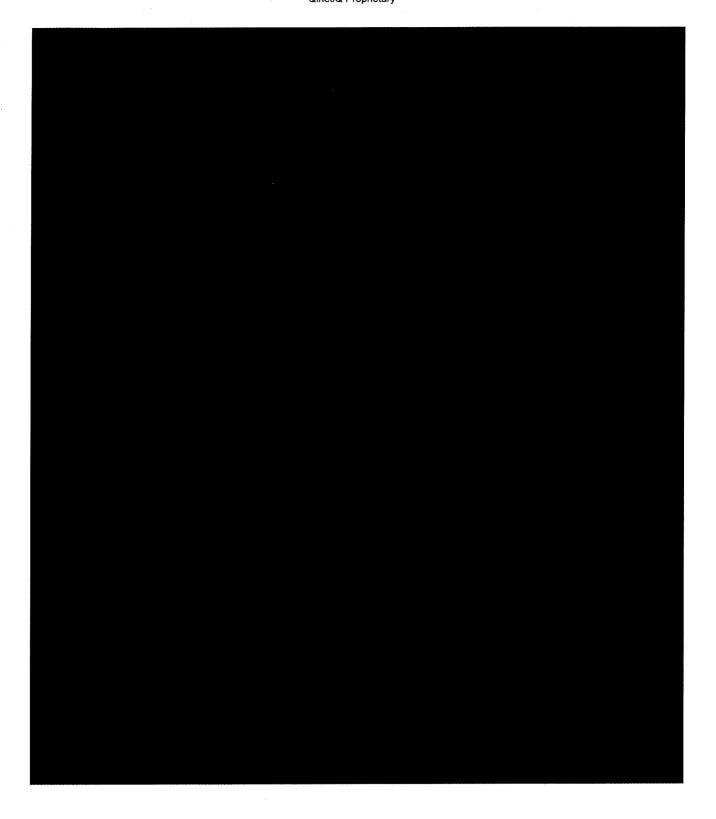
7.5.4.3 A post-impact photograph of the damage is shown in Figure 7-24.

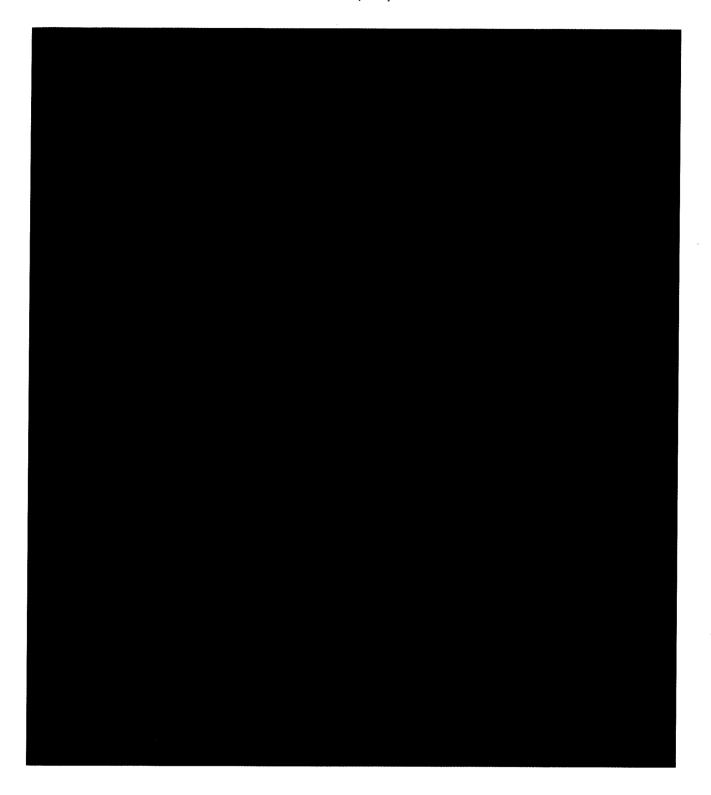


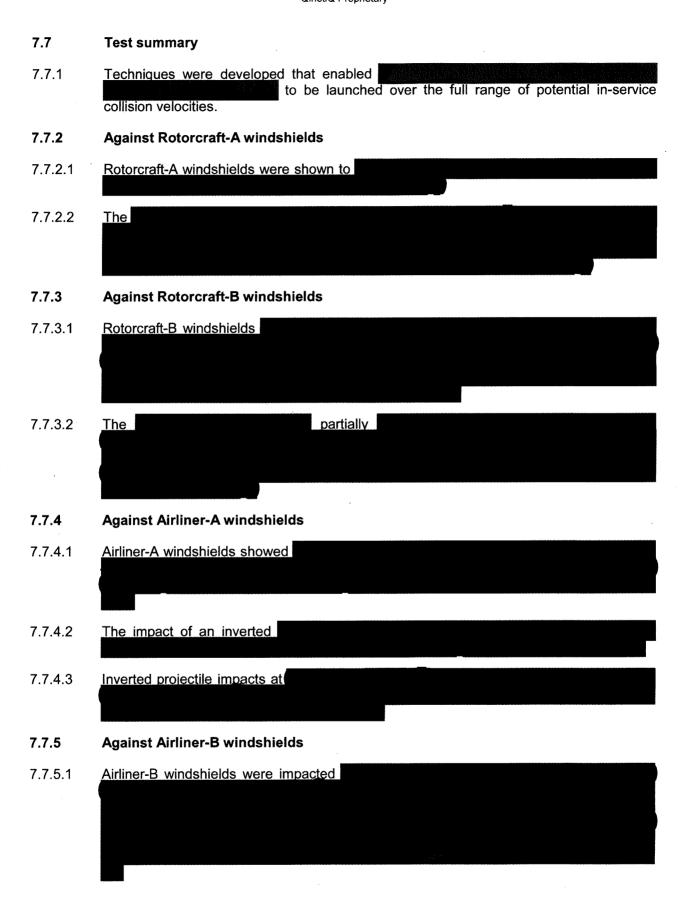
Figure 7-24: Photograph of windshield damage for



QINETIQ/17/01224/1.0







Page 64 of 127



8 Material definitions

8.1 Introduction

- 8.1.1 Both the manned aircraft and the RPAS consist of a variety of materials which, in some cases, are specified by name and grade, but in others are more generically defined. A major part of being able to accurately model any real-world scenario, especially with damage and failure, is to have accurate mechanical properties of the materials and appropriate failure models in the FE code, along with the knowledge and expertise to be able to populate appropriate models.
- 8.1.2 In many cases, the exact specification of material will be unknown and some judgement has to be made based on the range of values found for a material property (e.g. yield strength), through literature surveys. In the absence of any supplied material data for the specific RPAS and target aircraft components, this was the approach taken here. Within a representative range of material property values, it was possible to calibrate model material parameters against available test data.
- 8.1.3 Within this programme, the material modelling of items such as were derived from tests. These articles are themselves complex and are composed of different materials. To model such a compound item would be onerous and numerically inefficient as the desired outcome is the effect on the manned aircraft and not the state of the RPAS post-impact. For this reason, each of these parts were considered as a homogeneous material and characterised by static crush and dynamic impact tests (Sections 8.13 and 8.14).
- 8.1.4 This section summarises the selection of appropriate material models and the utilised material data in order to accurately model the manned aircraft and RPAS airframes. The method used to produce representative models of RPAS components is also covered along with details of the physical testing completed by Natural Impacts to support this modelling activity.

8.2 Glass

- 8.2.1 Glass generally behaves as a brittle material when loaded to failure. However, common (soda-lime) glass may be strengthened via thermal tempering heat treatments and chemical toughening processes. This can lead to a wide range of values for its strength and fracture toughness. Although some glass types have been defined for the manned aircraft windshields (Section 4.4), the exact properties of these materials are proprietary and not openly published. In the absence of specific data it was necessary to carry out a search of relevant literature to establish the possible range of values and the probable values for the windshield types tested in this programme.
- 8.2.2 A further challenge was the selection of an appropriate material model for use in the FE code Abaqus. Consideration was first made to the desired purpose of the material model. The focus of this study was to identify relative collision velocities at which a threat would either penetrate, cause extensive damage or rebound from a windshield. Therefore the use of a macroscopic brittle material model that performed elastically to failure in tension but not in compression was desired. During a literature study of method to model glass, multiple methods were investigated as to their applicability to this study; two of these showed the greatest promise and were subject to further investigation.

Page 66 of 127 QINETIQ/17/01224/1.0



- 8.2.5 With a material model selected, it was necessary to define relevant material properties. Unlike other engineering materials, documents detailing the difference between the behaviour of different glasses were not readily accessible, either due to the information being proprietary or too difficult to measure reliably.
- 8.2.6 As the failure of glass occurs rapidly and can be altered significantly by a number of factors (for example, the variation and location of microcracks), tests to define a specific failure strength and toughness provide a wide range of values. This is highlighted in the first two rows of Table 8-1 which show the minimum and maximum values identified from a review of published experimental data [14], [15], [16], [18], [19], [20], [21], [22], [23], [24].
- 8.2.7 Parametric studies were carried out to determine the effect of the variation in material properties to aid with later calibration studies. The results from these studies, coupled with some initial tests on Rotorcraft-A windshields (Section 9.3), allowed the selection of data deemed appropriate for airframe windshields. The values identified via this exercise were used in modelling of the RPAS impact with Rotorcraft-A and Rotorcraft-B windshields (Section 10) without further calibration. Whilst the outside layer of the Airliner-A windshield used these same properties, the two main thicker layers were treated as having the maximum identified strength and fracture toughness; Table 8-1 details the material property values used for each windshield.

Page 67 of 127



Table 8-1: Glass material properties: range and selected data

8.3 Polyvinyl Butyral (PVB)

- 8.3.1 Polyvinyl Butyral (PVB) is a 'rubbery' material used to bond layers of glass into a laminate and provides the ability to make such laminates 'shatter-proof' when impact by foreign objects. This bond layer acts as a membrane and has no appreciable bending stiffness.
- 8.3.2 Many different methods are available to model PVB, each tailored towards different problems. The driving factors of the selection process were for a model which would be simple to calibrate and allow easy implementation of failure behaviour, whilst still being representative of the material at high strain rates.
- 8.3.3 Several PVB material models were identified in the literature review and considered for use within this study:

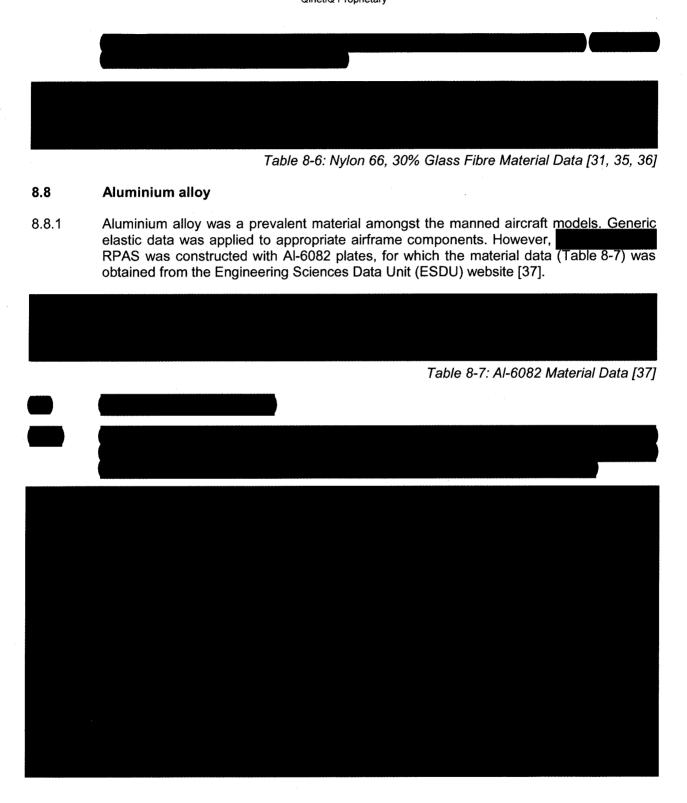


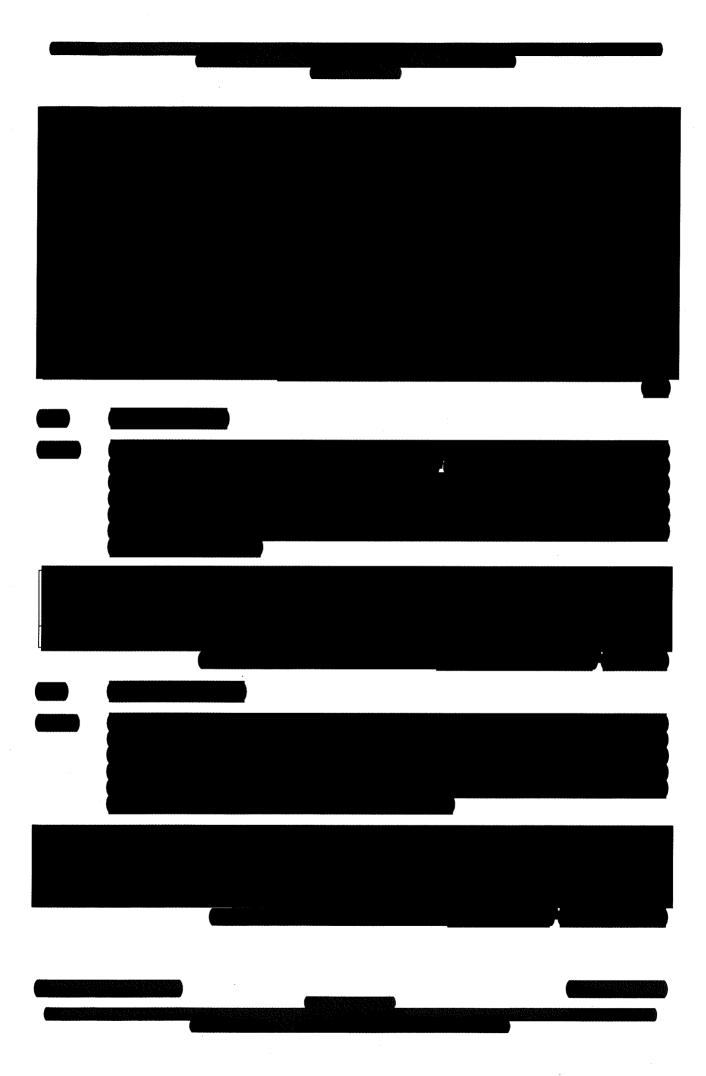
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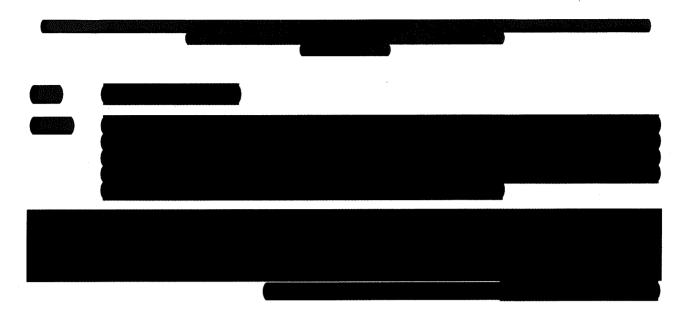
8.4	Thermoplastic Polyurethane (TPU)
8.4.1	For the Airliner-A windshield, it was understood from the manufacturer's website [12] that the thick interlayer between the outer glass ply and the middle glass plies was a Thermoplastic Polyurethane (TPU). Data for this was taken from a website [29] and detailed in Table 8-3.
	Table 8-3: Thermoplastic Polyurethane material properties
8.5	Acrylic
8.5.1	Acrylic forms the inner layer of the Rotorcraft-B windshield laminate.
	Table 8-4: Acrylic material properties
8.6	Acrylonitrile Butadiene Styrene (ABS)
8.6.1	ABS was selected as a representative material for the Table 8-5 details the mechanical data implemented for this material.
	Table 8-5: ABS Material Data [33, 34]
8.7	Nylon 66, 30% Glass Fibre
8.7.1	

QINETIQ/17/01224/1.0

Page 69 of 127







8.13 Testing of individual RPAS components

- 8.13.2 Crush tests were initially carried out to classify the compressive behaviour of the components; force-displacement curves were obtained. All component types were crushed, except for the procurement of these items; Table 8-15 shows the items tested.

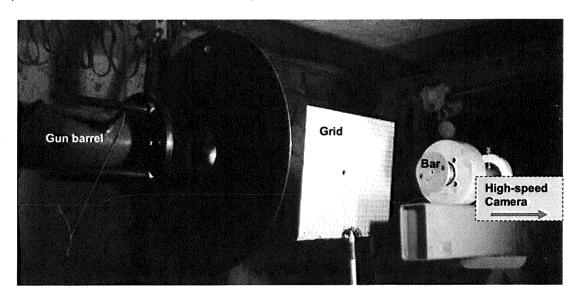


Figure 8-1: Natural Impacts' large Hopkinson bar test setup

8.13.3 Following this, impact tests against a Hopkinson bar (Figure 8-1) documented the dynamic response of the component; force-time histories were obtained. These were impacted along the same axis as the static crush tests, with the exception of the

which was impacted longitudinally. An example of a crush and impact test on a motor within its frame is shown in Figure 8-2.



Table 8-15: Natural Impacts RPAS component testing matrix



QINETIQ/17/01224/1.0

The crush direction was aligned with the anticipated direction of impact during collision testing. The exception to this was the which was tested laterally to avoid premature on-set of localised which was tested laterally to avoid premature on-set of localised which was tested laterally to avoid premature on-set of localised which was tested laterally to avoid premature on-set of localised which was tested laterally to avoid premature in the impact tests, where the true behaviour of the successfully characterised. The subsequently derived material properties were considered to homogeneous isotropic since there was only test data in one direction.

8.14 Material characterisation of RPAS components

- 8.14.1 An approach was developed by QinetiQ to produce representative material models of the supplied RPAS components using test data (Section 8.13). The force-displacement data from the crush tests was converted to elastic-plastic stress-strain data, which was then used in Abaqus to simulate the crush test to validate the stress-strain data.
- 8.14.2 This material model was then used to model the impact event of the same component at the same velocity as the physical test; the predicted force-time response was compared to that of the test.





8.14.4

9 Model development and validation

9.1 Introduction

9.1.1 This Section describes the approach taken to the development and incremental validation of the modelling work.

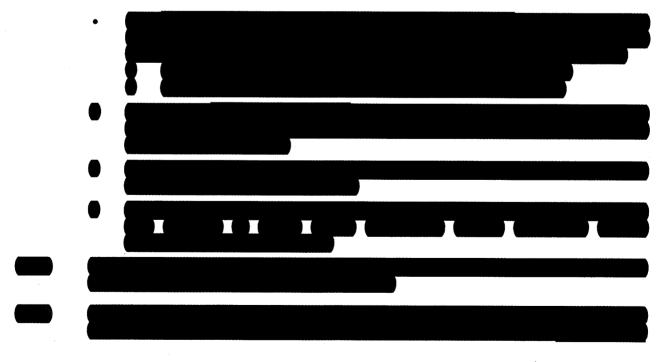
In addition to the RPAS component model calibration described in Sections 8.13 and 8.14, various additional studies and test activities were undertaken to inform and de-risk the development of methods prior to the final modelling runs against the threat matrix shown in Table 1-3.

9.1.2 These activities included:

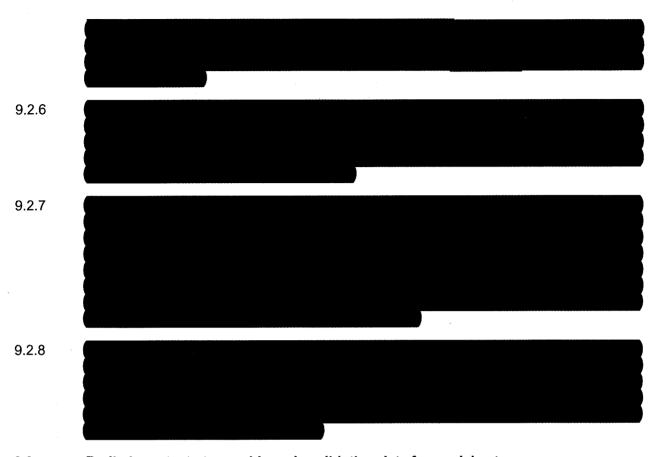
- 1. Modelling studies to develop the analysis approach (Section 9.2);
- 2. Preliminary tests to provide early validation data of the models (Section 9.3), and;
- 3. Validation against the full-scale collision test results (Section 9.4).

9.2 Modelling studies to develop the analysis approach

- 9.2.1 As described in Section 8.1, the requirement to predict the failure of laminated glass structures introduced a great number of challenges to the modelling exercise. In addition to investigating suitable material models, it was necessary to determine an appropriate 'meshing scheme' for the windshields.
- 9.2.2 Preliminary studies included tens of thousands of simulations, run as parameter studies with a simple windshield being impacted with a simple projectile. These studies provided useful information that enabled decisions to be made on the setup of the model, element type, mesh density and contact properties.
- 9.2.3 Observations and conclusions from these early modelling studies included:



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9.3 Preliminary tests to provide early validation data for model setup

9.3.1 To aid model development, in terms of approach and material models, additional impact tests were carried out using various components, fired against spare/damaged Rotorcraft-A windshields that were clamped to a test bench (not installed in the airframe). As the windshield material models and overall modelling approach had not been validated against experimental data, this was a significant step towards de-risking the technical delivery of the programme.

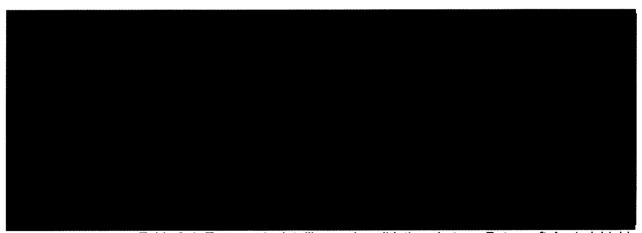


Table 9-1: Test matrix detailing early validation shots vs Rotorcraft-A windshields

9.3.2	The additional impact tests conducted against Rotorcraft-A screens are summarised in Table 9-1. Note that in order to maximise the benefits of the data being generated, these tests were carried out at velocities in the same velocity range as the planned full-scale collision tests.	
9.3.3	These tests were very valuable, not just for early calibration efforts, but they also provided confidence in the material models and modelling method at the time.	
9.4	Validation against full-scale collision test results	
9.4.1	The complete schedule of full-scale collision tests have been completed using the developed RPAS projectiles against windshields installed in the acquired manned aircraft structures. These tests are reported Section 7 and a summary of the test matrix with the measured impact velocities are presented in Table 7-1.	
9.4.2	Rotorcraft-A results	
9.4.2.1	Tests were carried out against the Rotorcraft-A windshield using the the The Rotorcraft-A windshield is a Early tests on loosely-held screens (Section 9.3) demonstrated that	
9.4.2.2	The Finite Element Model (FEM) of the Rotorcraft-A cockpit and windshield, which consisted of around elements elements degrees of freedom), was run using the same velocities at the tests ³ .	
9.4.2.3	The material models were calibrated using the test results, as follows:	
	 No changes to the glass properties Simplification of the PVB model to prevent excessive failure strengths due to high strain rates, as described in Section 8.3. 	
9.4.2.4	Figures in Appendix A.1 and A.2 provide a visual comparison of the test and predicted windshield condition post-impact; the comparison is excellent in terms of the extent of damage caused. Furthermore, comparisons of predicted damage and penetration thresholds against test results are illustrated in Section 10.	
3	The explicit dynamic time-stepping simulations of the RPAS projectiles vs manned aircraft scenarios (of Rotorcraft-A, Rotorcraft-B, Airliner-A and simulation time of greater than (depending on the initial impact velocity) in order to progress the damage (should there be any). This would typically take between 50 and 150 CPU hours with an average of 90 CPU hours on 64-bit Dell workstations with 128GB RAM using Intel® Xeon® CPUE5-2697v3 2.6GHz processors.	

QINETIQ/17/01224/1.0 Page 77 of 127

9.4.3	Rotorcraft-B results		
9.4.3.1	Tests were carried out against the Rotorcraft-B windshield using the . The windshield is a		
9.4.3.2	The FEM of the Rotorcraft-B cockpit and windshield, which consisted of around elements degrees of freedom), was run for the same velocities as the tests.		
9.4.3.3	The material models were calibrated using the test results, as follows:		
	 No changes to the glass properties 10% increase to the acrylic strength from the values that were originally assumed Note that this increase is relatively modest and the strength remains within the range of values identified within QinetiQ's literature review. 		
9.4.3.4	Figures in Appendix A.3 and A.4 provide a visual comparison of the test and predicted windshield condition post-impact; the comparison is excellent in terms of the extent of damage caused. Furthermore, comparisons of predicted damage and penetration thresholds against test results are illustrated in Section 10.		
9.4.4	Airliner-A results		
9.4.4.1	Tests were carried out against the Airliner-A windshield using the The windshield is a		
9.4.4.2	The FEM of the Airliner-A cockpit and windshield, which consisted of around elements degrees of freedom), was run at the same velocities as the tests. This included impacts with the the first two tests and also the inverted case, which was used for the remaining three impact tests. To better reflect the test conditions, the nominal configuration was run with 10° pitch up and the inverted configuration was run with 10° of downward pitch.		
9.4.4.3	The first two collision tests on the Airliner-A windshields were conducted with the projectile in its nominal orientation (see Figure 5-1) and at a velocity of		
9.4.4.4	Inspection of the high-speed video footage showed that the windshield, with its toughened outer glass ply, Furthermore, from inspection of the part of the that the screens. For example, The appearance of the part of the		
4	It was judged that the and associated sabot were very close to the limit of what they could withstand during launch. Given that there were it was not considered to be a good use of the available shots to attempt to increase the launch velocity to		

Page 78 of 127

compared with the available test results. A range of steps were therefore taken to try to

The initial modelling results suggested

9.4.4.5

of the Airliner-A screen, when

5	Whilst it might be possible to adjust the model by simply increasing the strength of the glass
9.4.4.7	The subsequent models which employed the inverted projectile configuration (C4.0QC-I), had the from the projectile model as it was considered that the material behaviour of the was not representative of the tests.
	and the interest of the state o
	this is unlikely to be significant as the material model was developed from this data
•	than the However,
	 applied toughening treatments. The was tested statically in the rather
	and/or the strength of the laminate is greater than expected, possibly due to the
	over-predicted, the load transfer within the laminate not being correctly modelled,
	• This implies that the impact forces are being
	utilised within the analysis code, or differences in support provided by the interlayer.
	This could be due to many factors including (but not limited to) the material degradation and erosion laws
	with the whereas the
	so this might lead to conservative estimates of failure velocities.
	speed video footage suggested the
	material was only calibrated against crush test data and so the resulting
	and are likely to significantly over-estimate the contact forces. This is because the
	Analysis cases where the directly impacts the windshield (i.e. do not capture the failure response of the correctly)
	excellent correlation observed for the other four collision test combinations. Key differences between the predicted and tested response include:
9.4.4.6	The above changes did improve the response but were not sufficient to achieve the
	•
	following changes were made to the models:
	refine the models and calibrate the material properties to better-capture the subtle interactions that were revealed in the high-speed video footage. In particular, the

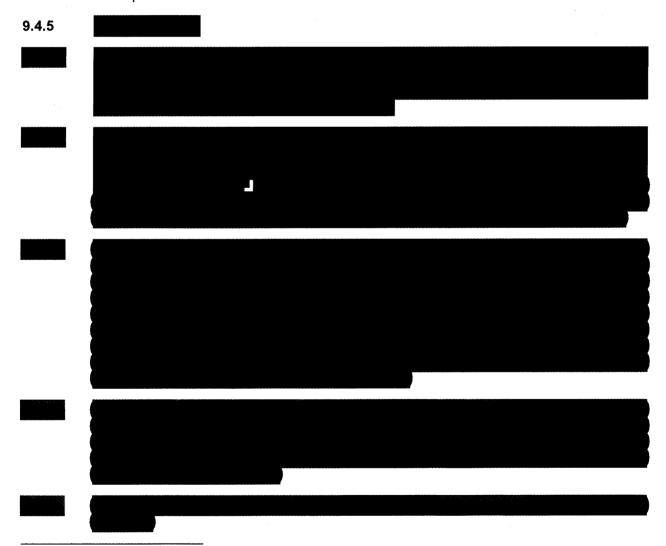
QINETIQ/17/01224/1.0 Page 79 of 127

justification.

without consideration of physical limits, this would not be good practice. Instead, modifications have been limited to those that are compatible with available evidence and have a clear physical

- 9.4.4.8 Figures in Appendix A.5 and A.6 provide a visual comparison of the test and predicted windshield condition post-impact. Furthermore, comparisons of predicted damage and penetration thresholds against test results are illustrated in Section 10.
- 9.4.4.9 It can be seen from these results that:
 - a. The current Airliner-A model gives conservative results.
 - b. The extent of damage predicted in the outer ply is broadly comparable with that observed in test, but the model fails in a less complex manner.
 - c.

 is consistent with the inverted RPAS test results°, even if the models
- 9.4.4.10 Further possible refinements to the models have been identified but are not within the scope or available timescales of this programme. Recommendations for future work on this topic are included in Section 12.



⁶ No collapse result was recorded for the nominal configuration.

Page 80 of 127 QINETIQ/17/01224/1.0

A continuum shell behaves largely like a conventional shell element, but it is a three-dimensional cell with its thickness being defined by geometry and a surface normal.

10 Collision modelling results

10.1 Introduction

- 10.1.1 Previous sections of this report have documented the development and validation of modelling methods to predict the effect of impacts between small RPAS and manned aircraft. The final part in this programme was to exercise these methods against the full analysis matrix defined in Table 1-3.
- There is a high level of confidence in the results of the Rotorcraft-A and Rotorcraft-B windshield analyses due to the predictions showing good comparison with the testing (Section 9.4). However, the comparison of the Airliner-A predictions with the limited tests has been less favourable, with a trend towards more conservative predictions of impact velocities causing damage.
- 10.1.3 Generation of analysis results to determine damage and failure thresholds for each of the collision scenarios was carried out by running each case at different initial impact velocities and making an assessment of the predicted outcome. This required approximately 100 model simulations, totalling approximately 9,000 CPU hours of computational effort. The result have been plotted on bar charts (shown in later figures) using the green-amber-red colour damage level definitions defined in Table 7-2.
- 10.1.4 The collision test results are also marked on the bar-charts⁸. These are displayed as discrete points and are also coloured in accordance with the damage level definitions in Table 7-2. Further, for comparison, photographs of the resulting damage of the test windshields are shown against the predicted damage of the modelling in Appendix A.

10.1.5

Charts for Airliner-B have not been produced because no modelling activity was undertaken for this configuration. Note that the test activities on Airliner-B, presented within this report, were not planned within the contract. Furthermore, it should be noted that these tests were conducted with the screens not installed in their parent airframe.

Rotorcraft-A windshield impacts 10.2

. Results for all collision scenarios are shown	
Frames from an example impact analysis against Rotorcraft-A are shown below in Figure 10-1	in Figure 10-2.
0.2.1	

QINETIQ/17/01224/1.0 Page 82 of 127

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QINETIQ/17/01224/1.0

Page 83 of 127

10.3 Rotorcraft-B windshield impacts

Frames from an example impact analysis against Rotorcraft-B are shown below in Figure 10-3. Results for all collision scenarios are shown in Figure 10-4. 10.3.1

Page 84 of 127

QINETIQ/17/01224/1.0

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Page 87 of 127

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Page 89 of 127

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Summary of collision modelling results 10.6

collisions against the Table 10-1 provided a summary of the different manned aircraft. 10.6.1

Page 92 of 127

QinetiQ Proprietary

QINETIQ/17/01224/1.0

Page 93 of 127

Conclusions 11

11.1 Aircraft vulnerability to RPAS threat

11.1.1 Prior to this study, the effect of small RPAS colliding with manned aircraft structures was subject to much speculation and opinion, but very little evidence. The results of this study provide a step change in knowledge and will support the Stakeholders in making informed and balanced decisions or recommendations on future legislation, aircraft operations, operational airspace management, design standards and research requirements.



11.1.3 Table 11-1 shows the predicted damage

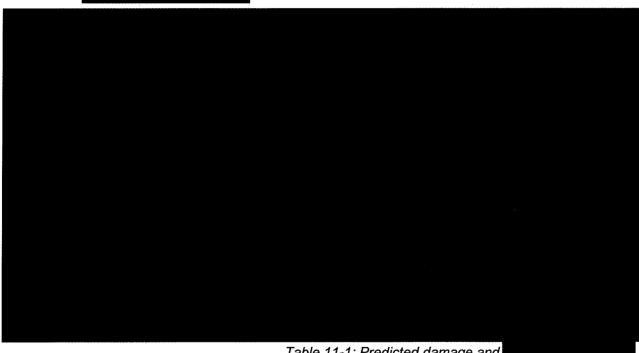


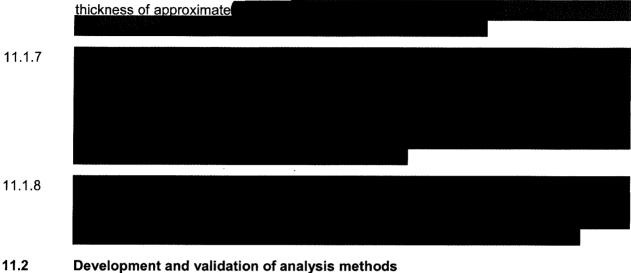
Table 11-1: Predicted damage and

- 11.1.4
- It is worthy of note that the Rotorcraft-B windshield is certified against bird strike 11.1.5 requirements, whereas the Rotorcraft-A screen is not;
- The Airliner-A windshield is significantly more substantial than that of the rotorcraft 11.1.6 windshields, and comprises multiple layers of glass and interlayer materials up to a

Page 94 of 127

QINETIQ/17/01224/1.0

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- Development and validation of analysis methods
- 11.2.1 Despite the technical challenges associated with modelling the failure response of glass structures, the complexity of the RPAS configurations and the dearth of information that was initially available, the modelling activities generally produced accurate predictions, particularly against the rotorcraft tests.
- 11.2.2 A key factor in the success of this activity was the incremental validation approach, making best use of available testing facilities and aircraft/RPAS hardware assets, to progressively de-risk and guide the model development.
- 11.2.3 The modelling results for Rotorcraft-A and Rotorcraft-B proved to be accurate This is evident from the comparison of test and modelling results presented in Section 10 and Appendix A. The predictions for the more-complex Airliner-A windshields did not achieve the same level of accuracy but this can, in part, but attributed to known simplifications to the RPAS material models and suspected differences in the construction of the screens from the supplied data. Attempts were made to refine and calibrate the Airliner-A windshield model but there remains a discrepancy that appears to result in overly-conservative failure predictions. This is an area that is worthy of further exploration, to determine whether the existing analysis methods can be legitimately calibrated for this thicker, more-complex screen or whether alternative
- 11.2.4 The modelling work has created a capability that can be used to explore additional impact scenarios and possible mitigation measures for embodiment in future design guidelines.

material models might be required for this class of structural transparency.

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12 Recommendations

The test evidence and methods developed and validated within this programme provide a high-value and unique capability that can be exploited in many ways. The application and development of the information and capability will depend upon Stakeholder, industry and wider government requirements, but the following section provides QinetiQ's summary of recommendations from the work. This includes aspects where QinetiQ feel development should continue, and ideas and recommendations for further exploitation of the work completed to date.

12.2 Exploitation of the modelling capability

- 12.2.1 The modelling work has created a capability that can be used to explore additional impact scenarios and possible mitigation measures for embodiment in future design guidelines. In particular, further activities could include:
 - Assessing the effect of impacts against other areas of the aircraft, including leading edges, nose cones, main rotors and control surfaces.
 - Assessing alternative platforms e.g. Fast Jets, or alternative RPAS representations.
 - Assessing the effect of glancing impacts and different impact scenarios/locations to provide data that could be used when quantifying the risk, as well as the severity of impact.

12.3 Development and refinement of the modelling

The analysis activity developed methods that produced accurate results for the majority of the collision scenarios. However further development of the Airliner-A windshield impact cases is recommended in order to improve the level of confidence in the screen configuration/materials and the accuracy of the modelling predictions. Initial modifications to the Airliner-A windshield and representation during the post-test calibration activity improved the correlation with test (including behaviour at different stages of the impact as well as the headline red-amber-green criteria) but it was not possible to explore all of the identified options. There are many activities that could be undertaken to support this including small experimental studies, forensic evaluation of the screens and pure model development. Examples include:

- Development/application of a to better reflect its response under impact, including the observed to have on the nominal configuration to better tests.
- Inspection/test of the Airliner-A windshield interlayer to determine its material type and generate better material property data.
- Testing of Airliner-A glass samples to determine realistic performance data for the material.
- Investigation of alternative material models for thick glass structures, such as the Airliner-A screens.

Page 96 of 127 QINETIQ/17/01224/1.0

Additional testing against Airliner-A screens, using well-defined projectiles such as ball bearings or individual components.
 Component testing against instrumented wedges to improve failure models
 Consideration of secondary impacts between RPAS debris and

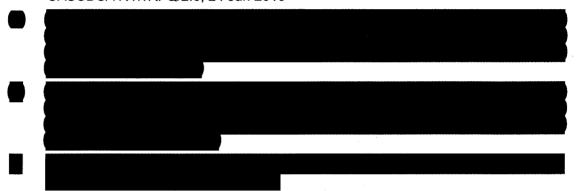
12.4 Extension of proven modelling approach

12.4.1 The methodology developed by QinetiQ to deliver this programme of work could be applied to other complex impact modelling problems. This might include development of test evidence and modelling capability to assess the consequences of RPAS impacting other critical structures such as fan blades.

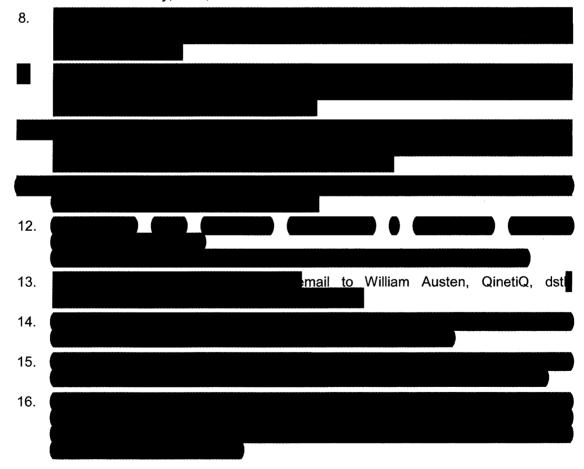
Page 97 of 127

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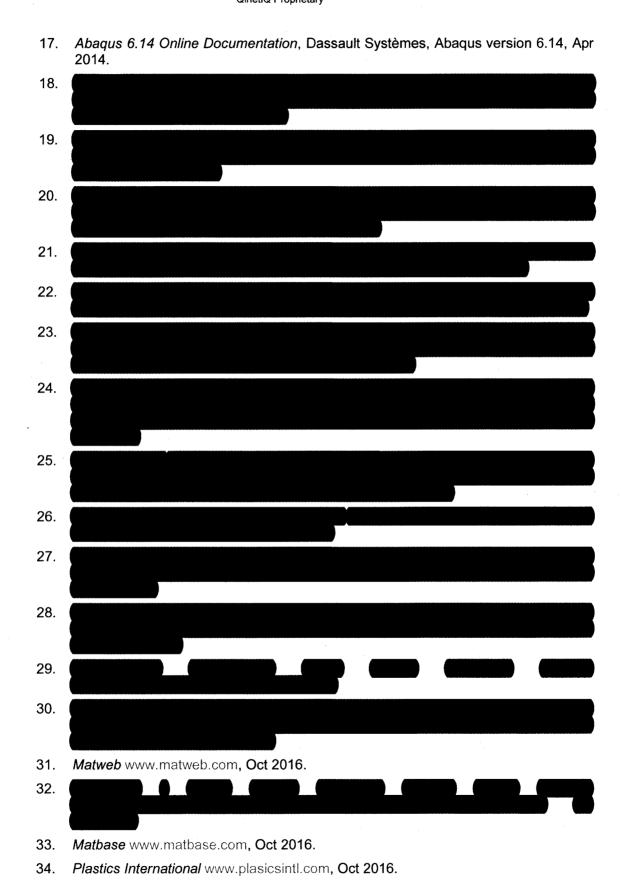


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Page 98 of 127

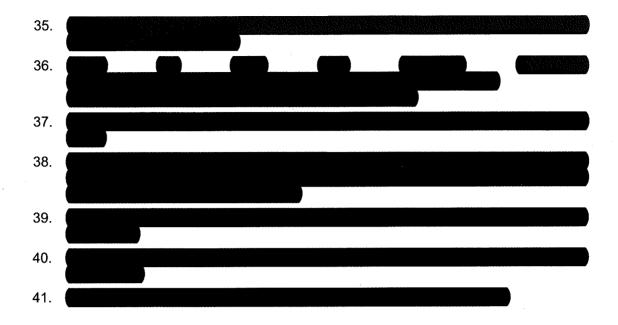
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Page 99 of 127

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List of Abbreviations 14

Acrylonitrile Butadiene Styrene **ABS**

BALPA British Airline Pilots Association

CAA Civil Aviation Authority CAD

Computer-Aided-Design COTS Commercial Off-The-Shelf

DfT Department for Transport

Def Stan Defence Standard (UK)

FEA Finite Element Analysis

FEM Finite Element Model

fps Frames per second

FW Fixed-Wing

GFX **Government Furnished Supplies**

HDPE High-density polyethylene

IR Infra-Red Li-Fe Lithium-iron

Li-Po Lithium-polymer

MAA Military Aviation Authority

MTOW Maximum Take-Off Weight

Ni Natural Impacts **PVB** Polyvinyl Butyral

QC Quadcopter

RPAS Remotely Piloted Air System

S&L Straight and Level

TPU Thermoplastic Polyurethane

UK United Kingdom

UAS Unmanned Air System

UASCDC Unmanned Air Systems Capability Development Centre

List of units 15

inch gram kilogram metre millimetre mm millisecond ms ms⁻¹ metre per second

Pictorial comparison of windshield damage	Rotorcraft-A vs				
⋖	A .1				

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Page 103 of 127

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.2	2 Rotorcraft-A vs	

Page 107 of 127

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Page 108 of 127

Page 109 of 127

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Page 112 of 127

Rotorcraft-B vs

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Page 113 of 127

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Airliner-A vs

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Page 117 of 127

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Airliner-B vs

A.7

Page 120 of 127

Airliner-B vs

A.8

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Page 122 of 127

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Abstract A programme of work has been successfully completed to evaluate, via state-of-the-art analysis and full-scale testing, the impact threat posed by various small Remotely Piloted Air Systems (RPAS) to different classes of manned aircraft. Results have demonstrated that the study provides a step change in knowledge and capability that will support the UK military and aviation authorities in making informed and balanced decisions/recommendations on future legislation, aircraft operations, operational airspace management, design standards and research requirements.						
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Last page

Page 127 of 127