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Analysis of the state-of-the-art (D1.3), and Research Cooperation (D1.4)

QinetiQ is the prime lead in this 'Horizon 2020' research framework which is sponsored by the European Commission contracted through EASA. The programme will also be supported by other subcontractors.

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Summary

Problem area

Recent technological developments have led to the emergence of affordable and increasingly capable remotely-piloted aircraft or 'drones' within the global marketplace. These drones present significant opportunities to consumers, businesses, research organisations and governments but – if used improperly – they also represent a potential threat to the safety of manned aviation.

This study aims to: deepen the understanding — through experimental testing and simulation techniques — regarding the effects of a potential collision of drones in the consumer / prosumer market segment ('threat') with manned aircraft ('target'); identify drone design strategies aimed at containing the risk that drone-aircraft collision may induce on the aircraft and its occupants, and; draft design requirements and test standards for future drones to be put on the market within the EU open category (CE marking) addressing the containment of the above risk. The programme of work, undertaken by QinetiQ, is spilt into nine tasks, relating to research planning, development and validation, exploitation and mitigation, whilst remaining engaged with Stakeholders.

Description of work

The work presented here is part of 'Task 1' which aims to identify the state-of-the-art in drone collision modelling, explore opportunities to cooperate with other studies, and gather data, methods and conclusions that would benefit the ongoing programme.

Outcome

A report has been produced which includes a review of worldwide literature relating to the assessment of drone strikes by analysis or test, and a review of confirmed mid-air collisions. A summary of the state-of-the-art in both drone collision testing and modelling has been provided, and research cooperation opportunities are proposed. Supporting data to aid in future tasks has been extracted from the identified studies and reported.

The literature has shown that – with suitable levels of supporting testing – dynamic finite element (FE) analysis methods provide a credible approach to modelling drone collisions. The range of drone masses considered across all of the reviewed literature show the lowest to be the DJI Spark (0.3kg) up to the DJI Inspire (3.4kg). The range of drones identified fits within the requirements of this programme and so most, if not all, results can be exploited in future tasks. The focus in the literature has been mainly on leading edge impacts and, secondary to that, windshields and engine ingestions. Furthermore, data in the literature is mostly associated with collisions against fixed wing manned aircraft. Hence a number of gaps, notably the lack on collisions against rotorcraft, have been identified which will help direct future efforts within the programme.

If any readers are involved with new or existing drone collision studies that have not been referenced in this document then comments and enquiries can be directed to the technical points of contact for the project, provided on EASA website [1].

Contents

Abbreviations

Acronym	Description
ASN	Aviation Safety Network
ASSURE	Alliance for System Safety of UAS through Research Excellence (USA)
ATMRI	Air Traffic Management Research Institute (Singapore)
BALPA	British Airline Pilot Association (UK)
CAAC	Civil Aviation Administration of China
CASA	Civil Aviation Safety Authority (Australia)
CFRP	Carbon Fibre Reinforced Plastic
CRASH	CRashworthiness for Aerospace Structure and Hybrids (USA)
DLR	Deutsches Zentrum für Luft- und Raumfahrt or German Aerospace Centre (Germany)
DfT	Department for Transport (UK)
EASA	European Union Aviation Safety Agency (EASA)
FAA	Federal Aviation Administration (USA)
FE	Finite Element
KAIST	Korea Advanced Institute of Science and Technology (South Korea)
LE	Leading Edge
Li-Po	Lithium-Polymer (battery)
MAA	Military Aviation Authority (UK)
NIAR	National Institute for Aviation Research (USA)
OSU MAE	Ohio State University Mechanical and Aerospace Engineering (USA)
RPAS	Remotely Piloted Aircraft System(s)
TU Delft	Delft University of Technology (Netherlands)
UAS	Unmanned Aerial System
UASCDC	Unmanned Air Systems Capability Development Centre
UAV	Unmanned Aerial Vehicle
UDRI	University of Dayton Research Institute (USA)
UFMG	Federal University of Minas Gerais (Brazil)
USA	United States of America

1. Introduction

1.1 Background

Recent technological developments have led to the emergence of affordable and increasingly capable remotely-piloted aircraft or 'drones' within the global marketplace. These drones present significant opportunities to consumers, businesses, research organisations and governments but – if used improperly – they also represent a potential threat to the safety of manned aviation.

EASA has been active in monitoring the risks and threats associated with mid-air drone collisions, including forming a Drone Collision Task Force in 2016 to identify research requirements with input from a broad group of industry stakeholders. Recommendations from the Task Force report [4] were developed further by QinetiQ in EASA's 2017 'Research project on collision with drones' (EASA.2016.LVP.50); In this short programme, methodologies were defined and an outline programme of research was proposed to assess the severity of collisions between a broad range of drone configurations and manned aircraft classes [5, 6].

The current programme, 'Vulnerability of Manned Aircraft to Drone Strikes' (EASA.2020.C04) [1] is funded via the European Commission's 'Horizon 2020' research framework and has been contracted to QinetiQ. The programme is based upon the previous research and has three main objectives:

- to deepen the understanding — through experimental testing and simulation techniques — regarding the effects of a potential collision of drones in the consumer / prosumer market segment ('threat') with manned aircraft ('target');
- to identify drone design strategies aimed at containing the risk that drone-aircraft collision may induce on the aircraft and its occupants, and;
- to draft design requirements and test standards for future drones to be put on the market within the EU open category (CE marking) addressing the containment of the above risk.

The programme of work [3] is split into nine tasks, as depicted in Figure 1.

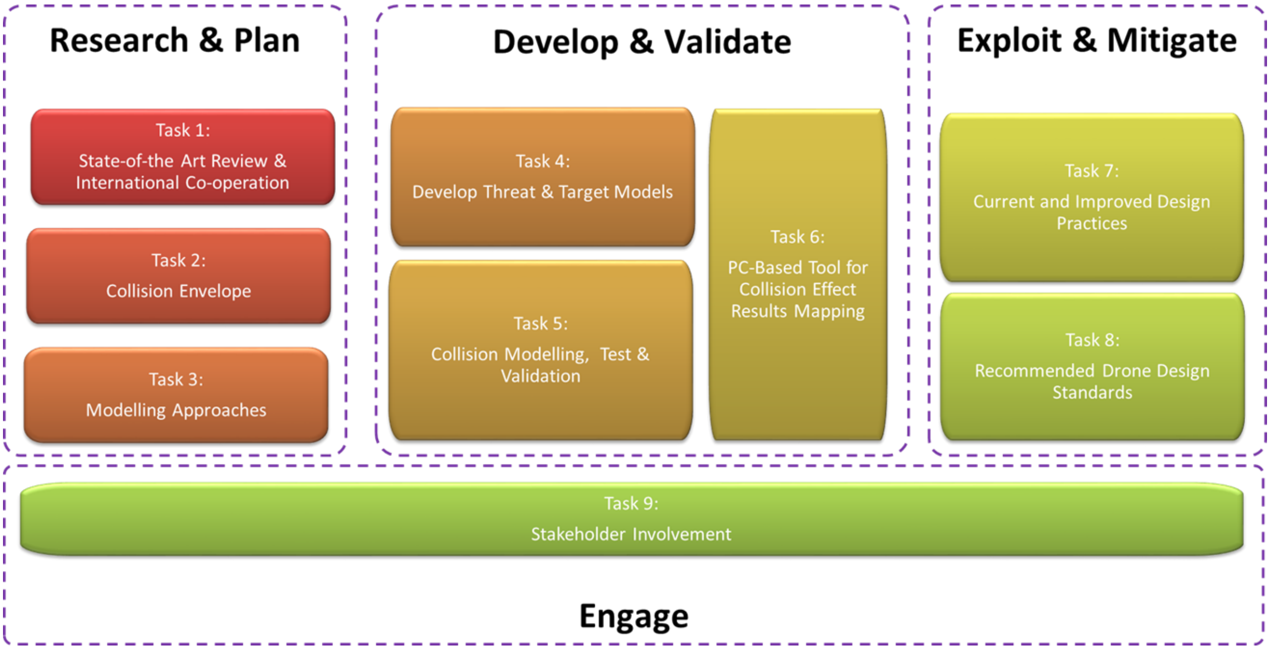

Figure 1 Programme structure

1.2 Scope of report

This report represents deliverables 'D1.3' and 'D1.4' of the Vulnerability of Manned Aircraft to Drone Strikes research programme (EASA.2020.C04). The work presented is part of 'Task 1', which aims to identify the state-of-the-art in drone collision modelling, explore opportunities to cooperate with other studies, and gather data, methods and conclusions (lessons learned) that would benefit the ongoing programme.

This report includes a review of worldwide literature relating to the assessment of drone strikes by analysis or test (Section 2), and review of confirmed mid-air collisions (Section 3). A summary of the state-of-the-art in drone collision modelling is provided in Section 4 and research cooperation opportunities are discussed in Section 5. Supporting data extracted from other studies is included in Appendix A .

2. Analysis of literature

2.1 Introduction

A worldwide literature review of research into the severity of mid-air collision drone strikes has been completed. This has focussed on studies that seek to evaluate the consequence of mid-air collisions with drones and not the myriad papers investigating tangential topics such as sense and avoid, control and autonomy, low speed collisions with obstacles, drone tracking, energy absorbing materials etc.

Fourteen distinct programmes have been identified and 19 published papers/reports/theses/articles have been reviewed. The programmes and groups are identified in Table 2-1, in approximate chronological order, along with their titles/subjects and the date published. Also included in the table are studies which relate to drone ground collisions and potential for human injury; these are shown in grey text and are only presented here for bibliographical interest.

Table 2-1 Drone collision studies sourced

Originator	Title	Date Published
CASA	Potential damage assessment of a mid-air collision with a small UAV [24]	06 Dec 2013
Aero Kinetics	The real consequences of flying toy drones in the national airspace system [29]	2015
DLR	Full-Scale Testing of Structures under Hard and Soft Body Impact [28]	26 Feb 2016
CRASH Lab	Investigation of UAS Ingestion into High-Bypass Engines, Part I: Bird vs. Drone [25]	09 Jan 2017
CRASH Lab	Investigation of UAS Ingestion into High-Bypass Engines, Part II: Drone Parametric Study [26]	09 Jan 2017
ASSURE	A4: UAS Ground Collision Severity Evaluation	28 Apr 2017
QinetiQ	Small Remotely Piloted Aircraft Systems (drones) Mid-Air Collision Study [7]	22 Jul 2017
ASSURE	A3: UAS Airborne Collision Severity Evaluation [8, 9, 10, 11]	Jul 2017
Aalborg University	Mass threshold for “harmless” drones	2017
ATMRI	Experimental and Simulation Weight Threshold Study for Safe Drone Operations	08 Jan 2018
ATMRI	Weight threshold estimation of falling UAVs (Unmanned Aerial Vehicles) based on impact energy	13 Jun 2018
UDRI	Risk in the Sky? [42]	13 Sep 2018
CAAC	Dynamic response of the horizontal stabilizer during UAS airborne collisions [16]	28 Nov 2018
OSU MAE	Parametric study of a Unmanned Aerial Vehicle ingestion into a business jet size fan assembly model [27]	10 Jan 2019
TU Delft	Multibody system modelling of unmanned aircraft system collisions with the human head	27 Jul 2019

Originator	Title	Date Published
KAIST	Unmanned Aerial Vehicle Impacts on Heat-Strengthened Glass [20]	13 Aug 2019
UFMG	Evaluation of Increase Weight in a Wing Fixed Leading Edge Design to Support UAS Impact [15]	08 Oct 2019
CAAC	Simulations of airborne collisions between drones and an aircraft windshield [22]	22 Jan 2020
THI	Analytical approach to predicting small UAS impact forces	25 Feb 2020
Hungarian Hub in Aviation, Légtér.hu	First drone vs Plane crash in slow motion (video available only) [43, 44]	01 Jun 2020
TU Delft	Predicting helicopter damage caused by a collision with an Unmanned Aerial System using explicit Finite Element Analysis (Draft) [21]	Draft, Review: 21 Aug 2020
ASSURE	A14: UAS Ground Collision Severity Evaluation 2017-2019	Ongoing

Each aircraft collision study has been reviewed to understand its scope, methods, conclusions, credibility and relevance to the current programme. In particular, the following was sought from the literature:

- Conclusions, methodologies and input data e.g. material failure models, which can be used to inform or validate QinetiQ's planned modelling approach in Task 3;
- Physical test or predictive results that can be used to develop or validate:
  - Drone threat models in Task 4
  - Local aircraft target models in Task 4
  - Collision models in Task 5
- Physical test or predictive results that can populate the database of the software tool in Task 6
- Data to facilitate Impact Effect Assessment (IEA), as defined by the EASA Drone Task Force [4], within Task 5.

To-date, most of the published studies have concentrated upon impacts against leading edges, impacts against windshields, or ingestion into the fan stage of aero engines. The following sub-sections provide an overview of the work undertaken on these focus areas, before providing a summary of other relevant publications and on-line content. Results have been extracted from each of these studies and are summarised in tabular form in Appendix A .

2.2 Studies on LE impacts

2.2.1 ASSURE studies (USA)

The Alliance for System Safety of UAS through Research Excellence (ASSURE) is a collaboration comprising of multiple universities, industries and governments and is part of the United States of America's Federal Aviation Administration (FAA) Center of Excellence.

ASSURE is a broad-reaching programme with a mission to provide the FAA with the research that they need to quickly, safely and efficiently integrate unmanned aerial systems into the North American National Airspace System with minimal changes to their current system. The ASSURE vision is to help the Unmanned Aerial System market grow into its multi-billion dollar market potential by conducting research that quickly, safely and effectively get UAS flying alongside manned aircraft around the world. Through these objectives, the programme is embracing the potential of drone technologies whilst also seeking to understand the consequences of their misuse so that appropriate mitigations and safeguards can be developed.

To date, airborne collision-related activities within ASSURE have been funded with an estimated $4.7m (with $2.6m spent up to 2019) and has publicised significant advances in the area of drone collision modelling. Principal activities include:

- Down selection of drone projectiles and aircraft targets [8].
  - Selected drones were a DJI Phantom 3 quadcopter and a Precision Hawk fixed wing aircraft.
  - Manned aircraft targets were Boeing 737 as the typical commercial transport target (CS-25) and a Lear 31A business jet (CS-23).
- Development and validation of a quadcopter drone Finite Element (FE) model [9] and the fixed-wing drone FE model [10].
  - Detailed airframe finite element models of the two aircraft targets had previously been developed the National Institute for Aviation Research (NIAR).
- FE analysis of multiple collisions scenarios between the aircraft and drones [9, 10, 11].
- Development of damage evaluation criteria to quantify aircraft damage to different impact scenarios.

The ASSURE assessment methodology uses physics-based dynamic-explicit FE modelling techniques based on the Building Block Approach [8, 13]. The ASSURE reports give no details of physical testing of whole RPAS against targets, although it is noted that an ASSURE presentation [14] does show images from a physical test of a DJI Phantom being fired at a metallic wing leading edge (LE). Relevant notes on the modelling method can be found in Appendix A.1. Appendix A.3 and A.4 show useful material data for drones and target aircraft, respectively, found in the ASSURE studies.

In the impact studies, using LS-DYNA, local targets on a CS-25 Boeing 737 (CS-25/FAR-25) and Learjet 31A (CS-23/FAR-23) manned aircraft were selected (listed below). Multiple impact sites and conditions were modelled on each local target area to investigate their effect on the structural response (the number of variations on each local target area is shown in brackets):

- The horizontal stabiliser (CS-25: 5-off; CS-23: 3-off);
- The vertical stabiliser (CS-25: 4-off; CS-23: 3-off);
- The main wing LE (CS-25: 4-off; CS-23: 3-off);

For each of these cases, the projectile was a 1.2kg quadcopter or a 1.8kg fixed-wing drone.

In the baseline study a single closing velocity of 250 knots (128.6 ms^{-1}), representative of the aircraft holding velocity, was assessed. Details of each scenario and the predicted damage outcome are summarised in Appendix A.6.

'Damage level categories', from 1 to 4, were assigned to each collision result to describe the level of damage sustained. This approach is analogous to EASA's proposed 'Impact Effect Assessment' (IEA) which is then used to determine the severity of the outcome in the context of the continued safe flight of the aircraft via a 'Hazard Effect Classification'. Appendix A.1, Table A-1 shows an example of the ASSURE and EASA classification systems and illustrates how the two systems could be crudely mapped to allow comparison of results on Leading Edge structures. The ASSURE damage level categories will be considered further in Task 5, when determining the metrics to be used for the IEA and HEC classifications.

In addition to the above local impact studies, ASSURE used their collision methodology to investigate the effect of mass and velocity in a kinetic energy study. This involved up-scaling the masses of the drones (the quadcopter from 1.2kg to 1.8kg and the fixed-wing from 1.8kg to 3.6kg), and considering two additional velocities representing a lower-bound landing velocity and cruise velocity for each of the two target aircraft. The cruise velocity for both aircraft was defined as 365 knots (187.8 ms^{-1}) and the lower-bound landing velocity was 110 knots (56.7 ms^{-1}) for the CS-25 airliner and 87 knots (44.8 ms^{-1}) for the CS-23 business jet. The results of this study were as expected, with damage level categories increasing (or remaining the same) against the baseline for heavier and/or faster collisions and reducing (or staying the same) for slower collisions. These results are summarised in Appendix A.6 and the data points will be fed into Task 5 studies and the Task 6 results database.

ASSURE also conducted parallel comparisons with bird strikes of the same mass, concluding that RPAS impacts are likely to cause more damage. This was attributed to the behaviour of dense, stiff components within a drone rather than soft tissue in a bird, which behaves as a fluid in a high velocity impact.

Within the ASSURE reports, there was no evidence that full-scale tests were carried out to validate the modelling. However, as evident in the ASSURE presentation [14], there may be one (or possibly more) physical tests of a DJI Phantom against a leading edge. This will be further investigated to ascertain whether more details are available for validation use and thus be more cost effective when carrying out test activities in Tasks 3 and 4.

2.2.2 CAAC collaboration (China)

A collaboration between China's Northwestern Polytechnical University and the Civil Aviation Administration of China (CAAC) investigated the effect of an 'Inspire I' professional drone (3.428 kg), supplied by SZ DJI Technology Co., Ltd. against a leading edge segment typical of a commercial airliner horizontal stabilizer [16]. Their motivation was to investigate the effectiveness of a LE reinforcement scheme to survive a drone impact.

The drone components were treated as homogeneous entities to simplify the simulation model, and mesh studies were carried out to obtain the optimum balance between accuracy and computational efficiency using the commercial FE code PAM-CRASH.

The paper is a good source of materials data and the involvement of SZ DJI Technology Co. provides increased confidence that the data for the plastics used in the Inspire I (Polycarbonate shell body and Polyamide 6 joint parts) are appropriate.

A single horizontal stabiliser was manufactured from 2024-T3 skin with 7075-T6 ribs and front spar and was ~1m long. However, this was an unconventional LE as it also included, in front of the ribs, some 7075-T3 triangular reinforcement which is the collaboration group's novel anti-bird strike design from previous studies.

A test was carried out in which a section of airliner cockpit was mounted on a rocket sled and accelerated towards the suspended stationary drone, impacting at 152.8 ms-1. The stabiliser concept was also included in the same test arrangement, installed in front of the cockpit but aligned so that it impacted a second drone; this allowed both test items to be impacted for each run of the sled. Details of this test are included in Appendix A.5 for future use in Task 5 and Task 6. Note a preliminary test was performed on the windshield of the cockpit with a 0.3 kg drone in order to test the camera and strain gauge equipment. The comparison between the test and model for the single LE case was considered acceptable but the group concluded they needed to improve their model.

They then utilised their model to create a longer stabiliser model to investigate different impact locations and impact velocities (120 ms^{-1}, 151 ms^{-1} and 180 ms^{-1}). Although the paper shows some useful results, as previously stated, the LE structure used was not conventional having an additional layer of reinforcement, which they ultimately showed to be ineffective against the drone collisions considered. Regardless, the data points created by this work are include in Appendix A.6 for the Task 6 database.

2.2.3 Federal University of Minas Gerais (Brazil)

The Federal University of Minas Gerais (UFMG), Brazil, carried out a study on the comparison of drone impact versus bird strike against the leading edge of an unspecified metallic fixed-wing commercial aircraft [15]. The RPAS projectile considered was a DJI Phantom 3 quadcopter, scaled up from 1.2kg to 1.8kg (via factoring material densities) in order to make comparisons with a 1.8kg bird. The motivation for their work, like the CAAC group, was to investigate strengthening the aircraft to withstand the drone impact at 250 knots (128.6 ms^{-1}). This was done via thickening the skin from 3mm to 5mm and modifying the spar web. Skin thickening was shown to be ineffective for the cases considered but the spar web thickening and spar stiffening did prevent rupture, albeit with a significant mass increase. This paper draws on previous ASSURE work, in particular their individual component testing and material models for the Phantom 3. Some of the simulation results involving skins and spar with different thicknesses could add to the database of IEA, hence these are synthesised for use in Tasks 5 and 6, and are presented in Appendix A.6.

2.3 Studies on windshield impacts

2.3.1 QinetiQ studies (UK)

QinetiQ has developed capabilities to assess of drone collisions with validated numerical modelling methods and on-site facilities to test whole drones and drone sub-assemblies impacting against real aircraft structures. A variety of drone types and manned aircraft targets have been considered though relatively little has been published in open literature. To date, QinetiQ has:

- A library of experimentally-validated drone threat models, including the DJI Inspire 2 drone with gimballed camera.
- Completed hundreds of validated collision simulations, using dynamic finite element analysis to efficiently evaluate complex failure events.
- Test capabilities to launch whole drones, drone sub-assemblies and drone components, at collision speeds appropriate for rotorcraft, airliners and fast jets. This includes bespoke facilities to launch complete DJI Inspire 2 drones at speeds of up to 300 km/hr.
- Invested in this capability to deliver high quality, independent results on matters of aviation safety.

QinetiQ has developed and validated drone models of DJI Phantom 3 and DJI Inspire 2, as well as other bespoke and generic configurations. The material representations for these were achieved through physical testing of components (both quasi-statically and dynamically) and ensuring models gave accurate results at a component level; components were generally simplified and the material assumed homogenous and isotropic. The testing was expanded to sub-assemblies, followed by full drone testing to validate the associated models.

The majority of QinetiQ’s targets have been windshields from large commercial aircraft (CS-25 [17]), small rotorcraft (CS-27 [18]) and large rotorcraft (CS-29 [19]). Many of these were laminated transparencies of various materials and thicknesses. In addition to full-scale validation testing, QinetiQ has also undertaken lower-level static and dynamic materials characterisation activities to develop appropriate material models.

QinetiQ has carried out many hundreds of collision simulations using the Abaqus FE code, for various programmes, simulating different drones and targets to understand damage levels that occur during collisions; QinetiQ’s damage level definitions for windshields are shown in Appendix A.1, Table A-2 alongside other group’s damage definitions. Very few of QinetiQ’s reports are available in the open literature. The only data in the public domain relates to an overview of a programme for the UK’s Unmanned Air Systems Capability Development Centre (UASCDC) which was conducted in collaboration with the UK Military Aviation Authority (MAA), British Airline Pilot Association (BALPA) and the UK’s Department for Transport (DfT) [7].

2.3.2 ASSURE studies (USA)

Alongside their predictive studies on LE impacts, the ASSURE group also considered the impact of their developed quadcopter drone FE model [9] and the fixed-wing drone FE model [10] against models of aircraft windshields.

Again, there were no details of any physical testing of whole RPAS against targets and it is presumed there were no such tests. Both the CS-25 and CS-23 manned aircraft were considered and were impacted in three different locations on their respective windshields: centre and corner of windshield and centre frame. For each of these the baseline cases were the 1.2kg quadcopter or a 1.8kg fixed-wing RPAS at a closing velocity representative of the aircraft holding velocity, 250 knots (128.6 ms^{-1}).

Similar to the LE studies, further velocities and masses were considered in a parameter study. This involved up-scaling the masses of the drones (the quadcopter from 1.2kg to 1.8kg and the fixed-wing from 1.8kg to 3.6kg), and considering two additional velocities representing a lower-bound landing velocity and cruise velocity for each of the two target aircraft. The cruise velocity for both aircraft was defined as 365 knots (187.8 ms^{-1}) and the lower-bound landing velocity was 110 knots (56.7 ms^{-1}) for the CS-25 airliner and 87 knots (44.8 ms^{-1}) for the CS-23 business jet. The results of this study were as expected, with damage level categories increasing (or remaining the same) against the baseline for heavier and/or faster collisions and reducing (or staying the same) for slower collisions. These results are summarised in Appendix A.6 and the data points will be fed into Task 5 studies and the Task 6 results database.

The ASSURE windshield "damage level categories" are rated from 1 to 4 using their LE damage level definition. An interpretation of this has been included in Appendix A.1, Table A-2 which shows the ASSURE damage level classification (modified to reference windshield rather than LE structures) and compared to the damage levels of other groups including the EASA IEA levels for a windshield.

2.3.3 CAAC collaboration (China)

The Chinese collaborative group from Section 2.2.2 – now including Nanjing University of Aeronautics & Astronautics – continued their work to investigate drone impact against a commercial airliner windshield [22] using physical testing and the FE modelling techniques developed in [16].

In this study, five DJI-provided drones were considered. These were: Spark (0.3kg); Mavic (0.7kg); Phantom 4 Pro (1.36kg), Phantom 4 Pro with two batteries (1.82kg) and Inspire I (3.33kg). As per the LE study, the drone models were treated as homogeneous entities and the paper provides data on the material models used. This approach included many simplifying assumptions such as representing the camera and motors as a single 6061-T6 aluminium alloy material (with Johnson–Cook elastic-plastic material model), and representing the lithum-polymer (Li-Po) batteries as crushable foams. The materials data used has been compiled in Appendix A.3.

The target structure was a commercial airliner windshield. The model was not dissimilar to the QinetiQ CS-25 windshield assessments as it also included a representative section of the cockpit to provide realistic boundary conditions for the windshield. Also similar was the sandwich construction of the windshield itself, though the configuration used in the CAAC study was 22.5mm thick whereas the CS-25 airliner assessed by QinetiQ had a screen thickness of approximately 30mm.

There were four physical tests carried out by accelerating the cockpit along a rocket-sled test track and impacting the stationary drones with the windshield. In each test, two impacts were achieved with a drone against both the port and starboard windshields. Simulations were made for some of the tests and the results are compared in Table 2-2. The results show that the modelling agrees well with the test results. Also, in this table the collaboration define three levels of damage which are shown against the EASA IEA and the ASSURE and QinetiQ damage levels in Appendix A.1, Table A-2.

The test windshields were also strain gauged providing an additional level of validation and predicted strains were generally in good agreement. Test data is recorded in Appendix A.5 for possible use in Task 5.

The validated model set-up was used to carry out a parametric study considering a Phantom 4 Pro impacting the windshield at 154.8 ms^{-1} at various yaw/pitch angles and at 152.7 ms^{-1} looking at 9 different impact positions on the windshield.

This paper includes physical test data and simulation results which would be useful when validating new DJI RPAS models and providing data points in the database relating to IEA damage levels (Task5/6). The simulation prediction results are recorded in Appendix A.6.

Table 2-2 Results of tests and simulations for CAAC windshield impacts [22]

	Condition	Type	Weight	Location	Yaw	Pitch	Expected velocity	Measured velocity	Test result	Simulation result
1st test		Spark	300 g	corner	0°	0°	142 m/s	140.0 m/s	used for calibration mainly	–
		Spark	300 g	center	0°	0°	142 m/s	136.0 m/s		
2nd test	1	Phantom 4 Pro	1360 g	center	0°	3.6°	151 m/s	150.7 m/s	only outermost glass broken	only outermost glass broken
	2	Phantom 4 Pro	1360 g	corner	0°	8.5°	151 m/s	150.7 m/s	only outermost glass broken	only outermost glass broken
3rd test	3	Mavic	700 g	center	24.4°	45°	151 m/s	158.6 m/s	only outermost glass broken	only outermost glass broken
	4	Phantom 4 Pro	1360 g	center	−24.4°	45°	151 m/s	154.8 m/s	the outermost glass broken the middle glass cracks PVb panel broken the innermost glass broken	the outermost glass broken the middle glass cracks PVb panel broken the innermost glass broken
4th test	5	Phantom 4 Pro (two batteries)	1819 g	center	0°	0°	151 m/s	153.4 m/s	the outermost glass broken the middle glass cracks	the outermost glass broken the middle glass cracks
	6	Inspire I	3330 g	center	0°	0°	116 m/s	118.5 m/s	only outermost glass broken	only outermost glass broken

Note: ■ safe ■ dangerous ■ already unairworthy.

2.3.4 Korea Advanced Institute of Science and Technology (South Korea)

In 2017, the Department of Civil and Environmental Engineering of the Korea Advanced Institute of Science and Technology (KAIST) carried out a study on drone collision with heat-strengthened glass of a type that is widely used in buildings [20]. Their studies included both physical test and modelling using LS-DYNA on monolithic glass of varying thickness against a DJI kit drone of 903g. These were low speed impacts in which the drones were flown into the test specimens at velocities of approximately 12.7ms^{-1}.

The paper provides some information on homogenised material properties of the drone parts, recorded in Appendix A.3, but the provenance of the data is not described. The glass strength was assumed to be 80 MPa, which represents the maximum failure strength of typical commercially-available construction glass rather than a stronger aerospace specification.

Simulations were in good agreement with the physical tests in terms of impact forces and predicted damage, but the results are not considered to be directly applicable to aerospace applications.

2.3.5 Delft University of Technology (Netherlands)

A recent MSc. Thesis from the Delft University of Technology (TU Delft) investigated – via modelling only – collisions between a 1.211kg DJI Phantom 3 drone and the windshield of a bird-strike certified (CS-29) AW-109 helicopter [21]. The selection of a rotorcraft windshield was, in part, due to the perceived lack of published data on this class of windshields as most drone collisions in the literature are against fixed-wing manned aircraft.

The geometry of the drone was taken from an online CAD library and the material models mainly referenced the ASSURE and CAAC literature. The individual component models e.g. motors and batteries, were then validated against the results of the ASSURE component physical tests.

The windshield geometry was taken from free online CAD of a whole AW-109 aircraft but only the windshield was modelled, with boundary conditions applied to the edges of the screen. The work states that the windshields of the AW-109 are made out of acrylic as reported as indicated by two sources; the data has been recorded within Appendix A.4. It appeared that the thickness of the windshield was unknown, so a series of simulations were initially carried out to determine the minimum thickness at which the windshield would comply with the Part 29 certification requirements for bird strike analysis; this was shown to be at least 9.3 mm thick if the edges of the screen are rigidly held in the frame (fully-clamped boundary conditions).

Using LS-DYNA with the windshield modelled as 2D shells, collisions were simulated at a closing velocity of $80ms^{-1}$ (maximum cruise speed). The predicted result for the 9.3mm thick windshield showed significant damage with penetration of drone components into the cockpit. Further simulations were carried out where the windshield was thickened and it was concluded that a screen thickness of 16mm would be required to maintain structural integrity, assuming fully-clamped boundary conditions.

It was identified that the boundary conditions of the screen can influence its damage response, and impact performance was shown to improve when the boundary conditions were relaxed in some degrees of freedom. This illustrates the need to include some representation of the supporting fuselage when undertaking collision assessments against windshield structures.

The collision model was used to investigate the effect of various impact orientation and mass down-scaling of the drone to a half and a quarter of its original volume and mass.

Although the windshield did not represent the likely thickness of the AW-109 windshield, the results are presented in Appendix A.6. However, the sensitivity of the results to the simplified boundary conditions and the absence of validation tests means that it would not be prudent to accept these as verified results without further investigation.

Among a number of conclusions, the main one was that the CS-29 AW-109 rotorcraft windshield would be severely damaged when impacted with a 1.2kg drone at a closing velocity of $80ms^{-1}$.

2.4 Studies on engine ingestion

2.4.1 ASSURE studies (USA)

In further numerical and predictive studies, ASSURE developed generic engine models for a mid-sized business jet with approximations of solid titanium fan blades [11].

The engine ingestion studies [11] also considered the same two RPAS projectiles as the LE and windshield studies: a 1.2kg DJI Phantom 3 quadcopter and a 1.8kg Precision Hawk fixed wing aircraft. For this work, as well as the representative aircraft holding velocity of 250 knots (128.6 ms^{-1}), an additional take-off velocity of 180 knots (92.6 ms^{-1}) was considered along with three different fan speeds. Furthermore, predictive simulations were carried out using a variety of impact locations, fan blade thicknesses, impact orientations and the study considered the effect of individual RPAS component impacts.

The study concluded that damage to an engine during an ingestion of a drone is dependent on these variables and damage evaluations were made. Again ASSURE have their own damage level categorisation and these are shown next to the EASA IEA for engine ingestion in Appendix A.1, Table A-3. Further details on the scenarios and damage outcome can be found in Appendix A.6.

Aside from producing some preliminary results, this study demonstrated the feasibility of modelling engine ingestion events using explicit finite element methods. However, further work is required (and is currently ongoing [12]) to validate the models against this mode of impact and refine the engine representation before reaching definitive conclusions about the effect of ingesting different classes of drone.

2.4.2 CRASH Lab (USA)

The CRashworthiness for Aerospace Structure and Hybrids (CRASH) Lab at Virginia Tech, USA have presented two papers on the investigation of UAS ingestion into high-bypass engines [25, 26].

In their work, they created a virtual 2.5kg drone for comparison with a bird model of the same mass being ingested into a composite fan. There is scant detail on the how the models were created (i.e. no materials data, mesh information) or even the analysis code used to obtain results. There is no evidence that the material models are validated and it is assumed that mass plays the biggest part in creating damage, although the engine model is stated to comply with FAA engine regulations for analysis.

In the first part [25], their models were used to investigate the effect of drone ingestion at different locations on the engine. The fans were set to rotate at 2200 RPM, in order to represent the stress of the engine during maximum thrust generation at take-off, and the impacts occur at halfway along the length of a blade with an ingestion speed is 92 ms^{-1}. They concluded that, although the drone would cause more damage than the bird, the size of drone was not enough to cause catastrophic damage.

In the second part [26], they consider similar impact conditions with a 4-motor “hobby” drone of 1.43kg and a 6-motor “professional” drone of 7kg. This study also considered titanium alloy and carbon composite fan blades.

They concluded that the hobby class drone may not present a significant threat to either titanium or composite modern high bypass propulsion system. However, the professional class drone, which was constructed from aerospace grade carbon-fibre, was predicted to permanently deform both titanium and CFRP fan blades. In the case of CFRP blades, the damage was extensive enough to cause significant material failure, damage propagation, and casing contact, which could potentially evolve into a more serious blade-off and fragment containment scenario.

Note that any use of these results should be used with caution, considering the assumptions made in the studies and the limited data pertaining to setup and validation of the drone models. These studies compare the relative severity of a bird and drone strike to engine structural integrity, whilst also assessing the relative impact severity between typical small consumer drones and professional style drones. However, the published results do not provide sufficient evidence to be used in this programme.

2.4.3 Gas Turbine Laboratory, Ohio (USA)

The Gas Turbine Laboratory of Ohio State University Mechanical and Aerospace Engineering (OSU MAE) completed a parametric study of drone ingestion into a fan assembly of a size comparable to a business jet [27]. The drone model was the 1.2kg DJI Phantom 3 from the ASSURE programme. The full fan assembly model was derived from a previously developed fan blade model but the specific material properties used were not provided in the report.

A number of parameters were varied, such as the fan thickness, drone velocity, fan RPM and impact location and damage levels are reported. One scenario was similar to that of the CRASH Lab baseline study [25], confirming their conclusion that the impact would not be catastrophic. Although no damage levels are suggested here, some of the conclusions are worthy of note:

- Highest rotational velocity of the fan (take-off) results in the greatest damage to the fan blades.
- Impacts farthest from the centre of the fan, radially, result in more damage.
- Thicker fan blades experience significantly less damage when impacted.

2.5 Other studies of note

In this sub-section, other studies are identified that may be relevant but contain too little information to be of use to this study, in terms of data points and verification.

2.5.1 Civil Aviation Safety Authority / Monash University (Australia)

The Australian Civil Aviation Safety Authority (CASA) and Monash University carried out a desktop study considering literature and empirical equations (FAA penetration equation) to approximate V50 velocities[1] of RPAS components versus representative manned aircraft targets [24].

They considered scenarios of the ingestion of UAV components by engines and impacts into fuselages and cockpit windscreens. The methods used in the study leads to very conservative results.

The study gave consideration to only the impact of dense/heavy components from a drone (and not the whole vehicle). A range of drone components were used, representing a small quadcopter (67g motor, 160g battery, 190g camera), a large quadcopter (154g motor, 583g battery, 820g camera), as well as a 2.73kg engine. The penetration equation was used to find the V50 of these components against:

- Representative fuselage and wing skin (3.175mm (1/8”) and 1.5875mm (1/16”) thicknesses)
- Representative Lexan windshields (12.7mm (1/2”) and 3.175mm (1/8”) thicknesses)

No calculations were carried out regarding engine ingestion.

2.5.2 DLR (Germany)

The German Aerospace Centre, DLR are well known for their extensive testing facilities. In a presentation to InnoTesting in 2016 [28], they presented a variety of work on soft and hard body impacts against full-scale structures. However, it is a high level overview and little can be gleaned for this work from this document.

2.5.3 Aero Kinetics (USA)

The Aero Kinetics Aviation group carried out a study in 2015 [29], whereby the calculation of typical impact energies (and momentums) were compared to FAA requirements for collisions between commercial RPAS and aircraft to judge potential outcomes. This work is entirely analytical with no material modelling involved, and the outcomes are somewhat speculative. It is deemed that this work has no immediate use for this programme.

2.5.4 THI (Germany)

Technische Hochschule Ingolstadt (THI) in Germany presented a paper at the Aerospace Europe Conference on analytical methods for predicting impact forces from small UAS. The paper proposes an approach that would allow the imparted on a rigid or elastic target structure to be predicted based upon simplified representations of their airframe and major systems. Whilst this work is in its early stages, it could provide a useful method for supplementing test data and numerical modelling results. It may also be useful in exploring the potential benefits of alternative drone configurations or providing an acceptable means of compliance for a future design standard.

[1] The V50 velocity is the velocity at which 50% of impacts would be expected to results in penetration of the structure. This approach respects the probabilistic nature of dynamic events and the performance of real-world structures.

2.6 Studies with online content only

Two studies have been identified which are only referenced on websites or video-sharing platforms.

2.6.1 Hungarian Hub in Aviation Légtér.hu

In 2020, the Hungarian Hub in Aviation (https://legter.hu/en/) commissioned physical tests of a manned low-flying Antonov AN-2 (a Soviet produced single-engine biplane) impacting a hovering drone. Four tests were carried out at a target speed of 54 knots (27.8 ms^{-1}):

- Leading Edge (between the ribs) vs DJI Phantom 3;
- Leading Edge (glancing lower surface) vs DJI Phantom 3;
- Wing Strut vs Syma X8S
- Propeller (mid section) vs Syma X8S (RPM unknown)

The set-up and tests were recorded on video, which is available in [43].

A presentation given by the Hungarian Hub in Aviation in January 2020 [44], discusses airspace organization, the current regulatory system in Hungary, how to reserve airspace for drone use, how pilots visually detect UAVs and further discussion of the AN-2 impact studies.

In all four tests, the results showed little damage to the AN-2, but showed the drones to be largely damaged and unserviceable post-impact. Although the primary material and thicknesses of the impacted parts is currently unknown, these physical tests have the potential to be useful in Task 5, and so have been included in Appendix A.5, Table A-17.

2.6.2 University of Dayton Research Institute

The University of Dayton Research Institute (UDRI) Ohio, USA carried out a physical test in 2018 of firing a 953g DJI Phantom 2 (missing half the legs and without camera/gimbal) into the wing of a Mooney M20 aircraft at 206.8 knots (106.4ms^{-1}). The main web page for the article and video of the test is available in [42].

There is additional video footage of the test in the Hungarian presentation (starting at around 31 minutes) available in [44].

This test has been criticised by drone users and in particular, DJI [45]; the Mooney M20 EASA certification stated the never exceed velocity to be 195 KIAS [52]. However, this remains a data point and so has been included in Appendix A.5, Table A-17 for possible use in Task 5.

2.7 Studies on battery hazards

Modern lithium-ion batteries (including lithium-polymer (Li-Po) and lithium-ion phosphate ($LiFePO_4$) variants) are commonly used in consumer drones. They have high energy-densities and are capable of high discharge rates to meet the needs of multi-rotor and fixed wing drones. However they are also susceptible to damage which, in some circumstances, may cause them to self-ignite.

It has been postured that this behaviour could present a secondary threat to the safety of the aircraft if the battery (or cells) ignite after becoming lodged within the airframe. This scenario has the potential to greatly-increase the severity of the threat as fire on an aircraft can be catastrophic.

An exhaustive literature review has not been conducted on the behaviour of lithium-ion batteries, but some observations have been made which may be relevant when considering the consequences of collisions at an aircraft level; these are discussed below.

The use of lithium-ion battery technologies is commonplace within modern consumer electronics and is also a significant enabling technology for high-power applications in the automotive sector. Whilst the technologies are considered to be safe enough for widespread adoption, the hazards associated with them are also recognised. For example, the Federal Aviation Authority recorded 290 in-flight or in-airport incidents involving lithium batteries carried as cargo or baggage between January 2006 and August 2020 in the United States [46]; this excludes three major incidents where battery shipments were implicated but not proven to be the cause. As a result of these hazards, EASA classes lithium-ion batteries as Dangerous Goods [47] and provides guidance on how they should be transported as well as limiting the energy capacity of batteries that may be carried.

There are examples of lithium-ion batteries self-igniting that have been published on media-sharing platforms such as Youtube [48]. Some of these examples show footage of fires starting during charging but many appear to be initiated deliberately, typically by someone driving a conductor through them e.g. a nail, shorting unprotected terminals or violently impacting them.

More-rigorous studies have been undertaken, such as “A review of lithium ion battery failure mechanisms and fire prevention strategies” [49] in which battery failure modes, the chemistry of thermal runaway conditions, and fire suppression techniques are explored.

Other published studies have investigated the mechanical behaviours of cells and batteries under static, impact and ballistic conditions [50, 51]. These studies include experimental characterisation of cells and batteries of different types (though none which are specifically aligned with small drones) and accompanying finite element-based analysis.

The potential for battery-related fires is commented upon in the ASSURE activities and a separate ‘Fire Risk’ classification was applied to some results. A positive fire risk was flagged when the UAS battery penetrates the airframe and sustains only minor deformations. It is stated in the ASSURE Volume II report [9] that “physical tests showed that partly-damaged batteries create heat and sparks” which could therefore lead to fire. Conversely, collisions in which the battery sustains great damage is not considered to present a fire hazard because “physical tests showed that completely damaged batteries did not create sparks and heat”. Also, scenarios in which the battery is deflected are assumed to present no additional fire hazard to the aircraft.

QinetiQ has also undertaken a variety of tests on lithium-ion batteries for other customers, including subjecting charged batteries to crush, impact and sustained vibration loads. The details of these tests have not been published but observations are broadly in-line with the findings of the ASSURE programme i.e. that completely destroyed batteries do not ignite but that there is a possibility of fire in damaged cells.

QinetiQ is also aware of programmes undertaken by UK universities to assess the threat posed by drone batteries. However, these activities were sponsored by third-parties and are subject to commercial restrictions.

It is anticipated that additional battery testing will occur within this programme and so observations on the behaviour of batteries upon impact will be recorded.

3. Mid-air collisions

3.1 Summary of reported drone collisions

A review has been undertaken of reported mid-air collisions between drones and manned aircraft.

The data available on drone collisions has been presented in two tables, with confirmed drone collisions in Table 3-1 and suspected drone collisions in Table 3-2. Confirmed drone collisions are defined as those which a drone was sighted prior to the impact; suspected drone collisions are defined as those where no intact drone was sighted prior to the impact, but inspected damage is conducive with damaged caused by drone strike (i.e. no organic matter about the site of impact).

In addition to these, over 11,000 near misses or suspected sightings from aircraft have been compiled by the 'Aviation Safety Network' (ASN) [53]. These are too numerous to present here and – due to the nature of the source data – are of variable reliability and detail. QinetiQ has acquired a copy of the ASN Drone Database and analysis of near misses shall be undertaken to inform the 'Collision Envelope' in Task 2.

Table 3-1 Summary of confirmed drone collisions with aircraft

Date	Location	Aircraft Model	Drone	Altitude [ft]	Impact Location	Outcome/Extent of Damage	Ref
03/08/1997	Schopfheim, Germany	Grob G109B	Dingo (10kg)	650	Unknown	Aircraft destroyed, two fatalities	[54]
14/08/2010	Van-Aire Estates Airport (CO12), CO, USA	Stolp SA 750	AJ Slick model airplane	50	Lower left wing	Lower wing crushed aft to the main spar, tear of wing skin and damage to leading edge of wing aileron	[55]
15/08/2011	Afghanistan	Lockheed C-130	AAI RQ-7 Shadow		Left wing between engines	Wing fuel tank ruptured, wing spar and wing box damaged	[56]
05/04/2015 12:40	Upton-upon-Severn, UK	Alpi Aviation Pioneer 300	Model glider (1.8kg)	630	Left wing leading edge	Hole in left wing leading edge and surface damage	[57]
30/04/2015	Shoreham, UK	Robin DR400-180	Model glider (0.615kg)	600-800	Right wing leading edge	Scuffing and scraping damage to the right wing leading edge	[58]
30/08/2015	USA	Grumman American AA-1B	Unidentified	2500	Undercarriage	No damage to aircraft	[4]
22/09/2017 00:30	Staten Island, New York, NY, USA	Sikorsky UH-60 Black Hawk	DJI Phantom 4	300	Main rotor blade	Minor damage: 1.5" dent in main rotor blade leading edge, cracked composite fairing and window frame	[59]
12/10/2017 22:02	Québec City, QC, Canada	Beech A100 King Air	Unidentified	1500	Left wing tip	Minor damage including scratches to left wing, returned to service	[60]
11/11/2017 12:17	Buenos Aires, Argentina	Boeing 737-800	Unidentified	Landing	Forward side of fuselage	Minor damage, grounded for inspections	[61]
25/05/2018 08:20	Locarno, Switzerland	Guimbal Cabri G2	Drone in excess 0.5kg	3000	Main rotor blade	Damage to the main rotor blade (extent unknown)	[62]
10/08/2018	Driggs, ID, USA	Hot Air Balloon (LBL-105)	Unidentified	Unknown	Fabric and load lines	Force landing, no damage to balloon	[63]
14/08/2018	Petah Tiqwa, Israel	Robinson R44	DJI Phantom 4	100	Lower left side fuselage	Drone jammed and broken into spray equipment	[64]

Date	Location	Aircraft Model	Drone	Altitude [ft]	Impact Location	Outcome/Extent of Damage	Ref
06/02/2020 22:00	Houston, BC, Canada	Eurocopter AS 350B3	FLIR SkyRanger R60 (2.4kg)	>300	Rotor blade and stabiliser	Precautionary landing, primary damage to main rotor blades, superficial damage to tail boom and tail rotor	[65]

Table 3-2 Summary of suspected drone collisions with aircraft

Date	Location	Aircraft Model	Drone	Altitude [ft]	Impact Location	Outcome	Ref
27/04/2015 15:40	Livermore, CA, USA	Cessna 206	Suspected	4500	Propeller and nose cowling	Gouges to the lower portion of the nose cowl (approx. 3" long), scratch marks at propeller root	[66]
02/01/2016 14:00	Modesto, CA, USA	Cessna 188	Suspected	1400	Landing gear tyre	No damage to aircraft	[67]
11/06/2016	Farmingdale, NY, USA	Piper PA-28	Suspected		Left wingtip	Minor damage to aircraft: dent in left wingtip	[68]
18/08/2016	San Jose, CA, USA	Cessna 172	Suspected	1100	Left wing leading edge	Minor scratches to the left wing	[69]
20/01/2017 23:00	Santiago, Chile	Kamov KA-32A	Suspected	Low alt	Avionics door	Minor damage to front avionics door, tear in skin and damage to door lower hinge	[70]
13/02/2017	Sedona, AZ, USA	Piper PA-28	Suspected	6000	Propeller	Damage to propeller (extent unknown)	[71]
03/08/2017	Punta Gorda, FL, USA	Cessna 172	Suspected	2500	Left wing	No visible damage reported	[72]
25/08/2017	New York, NY, USA	CRJ-700	Suspected	1800	Unknown	No damage reported	[72]
28/10/2017 14:01	Zandvoort, Netherlands	Lange Antares 20E	Suspected	150	Right winglet	20cm tear of the right winglet	[73]
22/12/2017 14:10	Buenos Aires, Argentina	Boeing 737-800	Suspected	Landing	Engine ingestion	Damage to fan blades (unconfirmed incident)	[61]
04/12/2019	Burbank, CA, USA	Eurocopter AS 350B-2	Suspected	1100	Unknown	Extent of damage unknown	[74]

4. State-of-the-art

4.1 Modelling methods

It is worthy of note that all of the modelling activities reviewed used specialist dynamic-explicit FE methods to simulate the collision event. This has been achieved via a variety of different software packages, though the underlying theory remains consistent.

Different approaches have been taken in the development of the drone threat models. In some studies (such as those by KAIST, CRASH Lab and, to a lesser extent, CAAC) the drones were constructed using assumed standard homogeneous material properties to represent complex assemblies without further validation. However, the more-credible approaches that were used by ASSURE and QinetiQ involve incrementally developing and validating the drone models using a series of material-level, sub-component, sub-assembly and full-scale tests. Other studies (such as UFMG, OSU MAE and TU Delft) utilised published model and/or test data from ASSURE to develop their threat models. It is encouraging that both UFMG and TU Delft used ASSURE's public domain component test results to validate their respective FE models of individual components, such as the battery and motors, suggesting that this is viewed as the most promising approach to developing a validated model.

The ASSURE and QinetiQ approach to modelling the drone threats is very similar. The main difference was the higher fidelity of some component models e.g. motors, in ASSURE, whereas QinetiQ's preferred approach has been to develop custom homogenised material properties to represent complex assemblies in a more computationally-efficient way. This may be revisited in Task 4 if it is considered necessary to achieve a good fit with component test data and does not have a significant effect on model solution times.

Other differences in QinetiQ and ASSURE's methods have been in the final validation of results. QinetiQ have traditionally validated the whole RPAS models using tests against target aircraft component (or other targets), whilst work within ASSURE has placed a greater emphasis on refining the models against slower-speed impacts e.g. drop testing.

Although much of QinetiQ's work is unpublished, it includes a combination of simplified and detailed models for a variety of multi-rotor and fixed wing drone models. In contrast, the ASSURE work has concentrated on detailed models of DJI Phantom 3 and Precision Hawk.

There is a consensus across all of the modelling in the literature that thin sections such as drone shells and casings should be represented with conventional Mindlin-type 3D shell elements which have a flexural theory that includes transverse shear. Other thicker components, such as batteries and motors, should be represented by 3D solid elements. Furthermore, all authors generally consider non-linear material properties with failure and damage methods to better represent the behaviour of the drone on impact.

A similar ideology is used when representing thin and thick parts of the manned aircraft targets. For example, leading edge structures, engine cone and engine containment structures have been modelled with shells, whilst components such a windshields and engine fan blades have utilised solid elements in most studies.

4.2 Test methods

The level of full-scale testing (and therefore final validation) varies between studies and is not directly correlated with the size and scope of the programme. For example, the ASSURE activity included a significant amount of low-level testing and a broad range of simulations, but no full-scale collision tests have been officially reported.

Where full scale testing has been carried out, the most common method, and likely the most cost-effective carried out under laboratory conditions, is where the target is stationary and the drone is fired via a gas gun into the target. The CAAC approach was to run a whole cockpit on the rails of a long-test track, powered by a rocket sled, into suspended stationary drones. This is more realistic of the mid-air collision scenario and allows the most accurate positioning of drones with respect to impact location and orientation, although it is evident that the set-up is significant and requires access to expensive facilities. The Hungarian Hub in Aviation achieved the most realistic approach of actually flying a manned aircraft into hovering drones. Although they did achieve some successful impacts, the impact position could not be accurately controlled and the closing velocity was relatively low.

Many low level drone component tests have been carried out and are reported in the literature. ASSURE has reported much of this and other groups have used this data to validate their own FE component models. Using this method, and despite very little full-scale testing, the ASSURE LE work has been well developed and is considered to be a credible source of results.

There has been little in the way of material tests reported for manned aircraft components. This may be because the alloys typically used in aircraft structures are often well characterised. However, for the windshield components, such as glass, acrylic and the PVB interlayers, the data in the literature can give quite a broad range of values for mechanical properties. In QinetiQ's past work much has been accomplished on using small-scale tests to help characterise various windshield materials which has been an important element in making the work successful.

4.3 Conclusions

The data in the literature includes a range of diligent, well thought through pieces of work. The approaches, using dynamic FE analysis, are based upon some common methodologies and in the cases where validation work has been done, it has shown a reasonable degree of accuracy.

Drones considered across all of literature range from the DJI Spark (0.3kg) up to the DJI Inspire (3.4kg). Within this range, the following have been considered: Syma X85 (0.68kg); DJI Mavic (0.7kg); DJI Phantom 2 (0.95kg); DJI Phantom 3 (1.2kg); DJI Phantom 4 Pro (1.36kg), and; Precision Hawk (1.8kg). The range of drones fits within the requirements of this programme and so most, if not all, results can be exploited in future tasks.

It has been seen that the focus in the literature has been mainly on leading edge impacts and, secondary to that, windshields and engine ingestion. Most studies have considered collisions with fixed wing manned aircraft, the exception being the TU Delft work on a rotorcraft windshield and QinetiQ's unpublished work on rotorcraft windshields.

Although much simulation work has been carried out investigating LE collisions, there is no documented results of such physical tests, aside from some video evidence presented in Section 2.6. For this reason, it is anticipated that further testing work will be required within this programme, though this will be reviewed in greater detail within Task 3.

The reviewed studies concentrated upon the local damage caused to the aircraft structures rather than exploring the effect it would have on the continuous airworthiness and safety of the aircraft post-impact. However, in many cases, the damage classifications used to grade the severity of the local damage were implicitly linked to the aircraft-level threat. For example, windshield damage is graded from minor scratches to penetration into the cockpit, engine damage ranges from denting/deformation of components to containment failure, and leading edge damage ranges from minor deformation to penetration and failure of primary structure. In all of these cases, the relevant aircraft-level hazard(s) may be retrospectively evaluated to build-upon these published results.

It is also noted that many of the local target areas that are referenced in EASA's statement of work [1] have not yet been assessed within the literature. In particular:

- Fixed wing:
    - LE impacts (with drone configurations not addressed in literature)
    - Frontal fuselage and nose cones;
    - Radomes;
    - Propellers.
- Rotorcraft:
    - Windshields;
    - Frontal fuselage and nose cones;
    - Fairings and fuel tanks;
    - Main rotor hub
    - Tail rotor

The review of the state-of-the-art presented herein is a stake in the ground at the time of writing. Obviously, research moves forward and is ever changing – QinetiQ will continually look for new research with the opportunity to add further data points.

5. Research Cooperation

5.1 Introduction

The aims and objectives of this research programme are broad and ambitious, and it is recognised that the collision scenarios that are considered via modelling and/or test will need to be prioritised to make best use of the project budget.

QinetiQ's proposal document [3] described a technical plan that was based upon experience of delivering drone collision programmes and assumptions about what impact conditions should be prioritised to fill critical knowledge gaps. However, it was intended that these provisional plans should be revisited and – if necessary – modified in Task 3 (Modelling Methods) based upon the outputs of Tasks 1 (State-of-the-art review and International Cooperation) and 2 (Collision Envelope).

A critical component of this re-evaluation process is to identify opportunities for cooperation with similar ongoing activities being undertaken within the international community.

This section of the report summarises the opportunities that have been explored and includes proposals for how to proceed.

5.2 Scope of Cooperation

The level and type of cooperation that have been considered for this project include the following:

- **Passive cooperation:** Review and use of published outputs from relevant studies. This is considered to be the minimum baseline level of cooperation for this programme and the findings of this approach are included within earlier sections of this report and Appendix A .
- **Co-ordination:** Active dialogue between programmes to manage the prioritisation of tasks between studies and avoid undesirable levels of overlap/repetition. This level could be highly effective in managing global research efforts with minimal administrative overhead and without the need for negotiated commercial arrangements.
- **Collaborative data sharing:** Data sharing between programmes, which may include providing privileged access to results, methods or models, e.g. drone or target models. This level of cooperation would have significant benefits in reducing the time and resources required to research and develop models or conduct tests but would require agreement of commercial terms between single/multiple third-parties.
- **Collaborative task sharing:** Co-working on analysis or test activities with third-party studies, or pooling of budgets to deliver agreed activities. One implementation of this would be an extension of the programme via third-party investment, where the third-party customer has a mutual interest in the results of an activity and an appropriate commercial agreement can be reached. This would enable the scope of the programme to be increased, providing gearing from current and new research funding.
- **Contribution or support:** Other forms of support or contribution to the project that may assist in its delivery.

The most appropriate level will depend upon many factors including the nature of the ongoing/past work, feasibility of collaborative working between organisations, commercial and intellectual property limitations, and agreement of the mutual benefits.

5.3 Cooperation with other studies

The studies discussed in earlier sections of this report are of varying scope, fidelity and rigour. Whilst all may have advanced knowledge in this technical area or meet the specific needs of their authors/stakeholder, only a few are considered to be suitable for higher levels of co-operation.

QinetiQ has reviewed each of the published studies and has identified the following opportunities.

5.3.1 ASSURE

The ASSURE programme is an obvious candidate for cooperation as it includes large-scale, ongoing drone collision activities that share many of the same knowledge generation objectives of this programme. Furthermore the model development and simulation methods are highly comparable with QinetiQ's approach to collision assessments, which would aid the sharing of ideas and data.

Much information has already been obtained from early phases of the programme via the good-quality reports that have been published. This flow of publically-available information is expected to continue, with annual reports on relevant topics being due for publication early 2021 (structural impacts) and Summer 2021 (engine ingestion). Although all output needs to be considered within the bounds of its original assumptions, ASSURE represents a good, reliable source of data.

Meetings have been held with the Technical Lead of the ASSURE aircraft collision studies, to discuss planned activities and potential cooperation. In this forum it was agreed that there would be mutual benefit in developing links between the two studies and a range of options were discussed.

5.3.1.1 Co-ordination of activities

It was agreed that some degree of co-ordination should be achieved to ensure that global resources are directed to maximise the value of the research.

As an example, it was confirmed that the ASSURE programme has initiated a dedicated activity to evaluate the effect of small drones being ingested into the fan of a generic representation of a modern high bypass ratio aero engine. This builds-upon a previous proof of concept simulation activity undertaken in 2017 [11] and is being delivered in collaboration with engine manufacturers. In addition to developing more-accurate representations of a large engine, it will also involve additional development and validation of the drone threat models to account for the 'chopping modes' associated with ingestion into the fan stage.

The engine ingestion task is a major activity with a total budget of approximately $1.5m (€1.27m)[2] [30]. It is therefore proposed that engine ingestion should not be assessed by modelling or test within the current programme and that evaluation of this scenario should be based upon the output from the ASSURE study, which is due summer 2021. This would enable programme budgets to be directed towards other critical features that address EASA's specific objectives i.e. to gain broad understanding of collisions between different mass-market drones and multiple classes of manned aircraft, for the purpose of informing legislation and developing new design standards. Whilst there is a risk associated with relying upon outputs from external organisations this is judged to be low due to the focussed, well-funded nature of the ASSURE programme activities and their track record in this field. The timeline for completion of the work is compatible with this programme, though significant delays due to technical difficulties or other factors could result in a knowledge gap in the interim. If major delays are experienced then QinetiQ shall consider other possible approaches which might include referencing current published data (Section 2.4) or additional analysis/testing, though this will also be constrained by budgets and a value-for-money assessment.

[2] At an exchange rate of €0.85 on 13th August, 2020

A parallel 'Airborne Collision Severity – Structural Impact' activity under ASSURE is focussing on collisions between small UAS and both rotorcraft and General Aviation classes. It is likely that there will be some overlap in activities conducted on the EASA/H2020 programme and ASSURE, but this will allow comparison of results and conclusions. However, it is proposed that discussions should continue between the technical teams to ensure that any overlap is understood and opportunities for further co-ordination of activities is explored.

It should be noted that the drone threat models that have been (or are being) developed do not all fit within the scope of the EASA/H2020 programme i.e. mass-market consumer/prosumer drones. For example, of the two threat models developed in ASSURE's initial programme, one was a commercial-oriented Precision Hawk fixed wing surveying aircraft.

5.3.1.2 Co-ordination of metrics

EASA have developed an Impact Effect Assessment (IEA) classification scheme to describe the level of damage sustained by different local structural features. A similar system has been adopted within the ASSURE programme, although it has four Levels rather than the Low, Medium and High of EASA's IEA classifications; see for example Appendix A.1, Table A-1 showing the ASSURE damage level classification and the EASA IEA levels for a wing LE.

Other studies such as the Chinese CAAC collaboration [16, 22] and QinetiQ's windshield assessments also use comparable, but differently-defined classifications. However, the significant body of published work under ASSURE, and the ongoing studies provide an argument to consider harmonisation of metrics so that results from the work can be readily compared and assimilated. Ideally this would involve the establishment or adoption of an agreed set of damage metrics, but an alternative approach would be to attempt to equate the IEA definitions with the ASSURE Levels on a feature-by-feature basis to enable approximate translation of results. Appendix A.1, Table A-2 which shows the ASSURE and CAAC damage level classification against the EASA IEA levels for a windshield.

5.3.1.3 Formal collaboration

The possibility of data sharing has been discussed and although it may be possible in-principle, it would require commercial agreement from all parties including customer and contributing stakeholder organisations. This may be complicated because many of the models and data used within the ASSURE programme have been supplied by third-party organisations with strict limitations of use. Furthermore, current intellectual property rights arrangements and publication schedules would need to be agreed.

Actions have been taken to discuss this with ASSURE's management and EASA, to determine whether the benefits of a more-formal collaboration agreement is possible and desirable.

However, for the purpose of planning, it is currently assumed that co-operation between the two programmes will be based upon coordination of activities and establishing communications to discuss progress. Opportunities to expand this relationship will be sought throughout the programme, taking opportunities to share data and results where possible, or provide mutual input to reviews.

5.3.2 QinetiQ's customers

QinetiQ has delivered multiple drone collision assessments under other commercial contracts. These programmes included detailed modelling activities and full-scale validation tests, launching drones against fixed wing and rotorcraft windshield structures. Additional data from these programmes include observations of battery behaviours under impact loads. Furthermore, these programmes (with co-investment from QinetiQ) were responsible for developing the analysis and test capabilities that shall be exploited to EASA's advantage. It would therefore be of great benefit to the programme to have access to these results and/or conclusions so that programme budgets can be directed towards other collision assessments rather than repeating work unnecessarily.

Although QinetiQ holds this data, its release into the EASA programme and/or the public domain is not possible without permission from third-parties.

It is therefore proposed that discussions be held between QinetiQ, EASA and QinetiQ's primary customers to discuss mutual data sharing to the benefit of all parties. If agreed, this may require commercial agreements to be established.

5.4 Other forms of cooperation

In addition to forming links between other programmes, opportunities exist to improve the quality and scope of technical output through cooperation with other relevant parties.

5.4.1 Stakeholder groups

A Stakeholder Group has been formed, including representatives from drone manufacturers, aircraft OEMs and standards organisations.

Engagement with these organisations is essential to the success of this programme. Their input will be required to validate key programme decisions and assumptions e.g. selection of drones and prioritisation of impact regions, and to ensure that proposals for drone design standards are both feasible and effective.

5.4.2 EASA Working Groups

EASA organise or are present on working groups that discuss relevant or tangential topics, such as counter-UAS approaches. Links are forming with these groups via the programme technical leads within QinetiQ and EASA, and are expected to enable productive flow of information and advice between relevant stakeholders.

5.4.3 Software vendors

Various calibration and validation impact tests are planned within this research programme, but most results will be generated by simulation. The specialist dynamic finite element codes that will be used to model collision events are expensive and although QinetiQ invests heavily in software, throughput of simulations will be limited by available licenses rather than computational hardware.

Initial contact has been made with one of QinetiQ's software vendors to explore whether there could be mutual benefit in sponsoring the project with additional licenses or cloud computing facilities during periods of peak demand. If agreed, this would increase the volume of work delivered and would provide good publicity and case-studies for the software supplier.

This option shall be discussed with EASA and – if agreed – shall continue to be pursued with the software vendor.

5.5 Conclusions

In addition to the benefits derived from the review of open literature, a range of different options have been identified that will add value to the programme through co-operation and collaboration with other parties. In particular, ongoing work within the ASSURE programme is expected to be highly-relevant to the objectives of this programme and a productive dialogue has been established. There are also opportunities to gain gearing from the outputs from other programmes, to avoid unnecessarily repeating work that has been done elsewhere.

The Stakeholder Group provides an essential link between this study and the drone and manned aircraft industries. Engagement with this group of experts shall continue through the course of the programme and will be essential in ensuring that the outputs of the work lead to demonstrable improvements in aviation safety whilst also being compatible with the continued development and application of drone technologies.

Opportunities to engage and collaborate with other relevant studies will continue to be reviewed through the course of the programme. Notifications of ongoing or recently published work on this subject are welcomed and can be directed to the points of contact provided on the project web page on EASA's website [1].

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Appendix A Data from literature

A.1 Damage classifications

Most research groups have applied a classification system to describe the levels of damage recorded/predicted as a result of drone collisions. For this programme, EASA have already proposed Impact Effect Assessment (IEA), which is a series of damage levels related to the impact of different component zones; these levels are defined Appendix VIII of the EASA Task Force report [4].

In this section of the Appendix, the descriptions of the various damage levels from research groups are presented alongside the EASA IEA definitions. The definition and mapping of damage metrics will be developed further within Task 5 with input from the stakeholder group.

Table A-1 shows the damage classification for LE impacts developed by ASSURE and the current equivalent EASA IEA definitions.

Table A-2 shows the damage classification for windshield impacts as defined by ASSURE, CAAC and QinetiQ, along with the EASA IEA definition. Note that the ASSURE definition for the windshield impacts were as for the LE impact, so QinetiQ have made a degree of interpretation in these definition (highlighted by *italics* in the table). QinetiQ have two entries in the table: one relates to laminated airliner windshields and the other to rotorcraft windshields which may be either monolithic or simple sandwich construction.

Table A-3 shows the damage classification for gas turbine engines developed by ASSURE and the related EASA IEA definitions.

Table A-1 Definitions of ASSURE and EASA damage classification for wing LE

Damage identification method	Classification of damage			
ASSURE damage	Level 1	Level 2	Level 3	Level 4
	Airframe undamaged. Small deformations	Extensive permanent deformation on external surfaces. Some deformation in internal structure. No failure of skin	Skin fracture. Penetration of at least one component into the airframe.	Penetration of UAS into airframe. Failure of primary structure.
EASA IEA	Low	Medium	High	
	Only dents or scratches	No penetration but limited deformation	Penetration, major deformation, part detachment	

Table A-2 Definition of ASSURE, CAAC, QinetiQ and EASA damage classification for windshields

Damage identification method	**Classification of damage**			
ASSURE damage for windshield (interpreted by QinetiQ - *changed parts in italics*)	Level 1	Level 2	Level 3	Level 4
	Windshield undamaged. Small *scratches*	Extensive permanent *damage* on external surfaces. Some *damage* in internal structure. No failure of *windshield*	*Windshield* fracture. Penetration of at least one component into the *cockpit*.	Penetration of UAS into *cockpit*. Failure of *windshield* structure.
CAAC damage	"Safe"	"Dangerous"	"Already unairworthy"	
	Only outermost windshield glass suffered damage	Outermost glass and the middle glass suffered damage	All three layers of glass broken or penetration	
QinetiQ damage (airliner)	Green	Amber	Red	
	No damage or damage to the outer glass lamina of windshield. Visibility likely to be retained.	One or both of (inner) main glass plies cracked. Windshield Certification failure (using bird strike criteria).	Penetration of RPAS into cockpit, or: Major structural damage/cave-in of the two main structural glass plies.	
QinetiQ damage (rotorcraft)	Green	Amber	Red	
	Little or no damage to the windshield. Visibility likely to be retained.	Extensive damage to one or more transparent plies. Visibility compromised.	Penetration of major RPAS components into the cockpit.	
EASA IEA	Low	Medium	High	
	No or limited damage. Non-significant loss of external visibility	No Penetration, partial loss of visibility.	Penetration or total loss of visibility	

Table A-3 Definition of ASSURE and EASA damage classification for engines (gas turbine)

Damage identification method	**Classification of damage**			
ASSURE damage	Level 1	Level 2	Level 3	Level 4
	Deformation of fan blades. Minor material loss from fan blades. Dent in nose cone. No containment failure.	Significant material loss from one or multiple blades. Loss of up to one full fan blade. Crack in nosecone. No containment failure.	Loss of multiple fan blades. UAV penetration of the nosecone. No containment failure.	Containment failure due to UAV ingestion.
EASA IEA	Low	Medium	High	
	No or acceptable damage	Non-significant mechanical damage. Reduction of Engine performance. Deterioration of Engine handling characteristics and possible increase of Engine operating temperatures.	Significant mechanical damage or detachment of parts. Immediate or ultimate reduction of Engine performance. Significant deterioration of Engine handling characteristics.	

A.2 Modelling methodologies

This sub-section summarises details of the methods and assumptions used to model drones, targets and collisions, as described in the literature. The aim of this section is to identify data and methods which will aid the progress of Task 3.

A.2.1 Analysis software

Review of the literature has identified a range of analysis codes which were utilised to undertake previous drone collision studies. Although the prevalence of a specific analysis code will not dictate the selection of the analysis code for this study, the distribution of analysis code use is of interest when considering model and result compatibility for future collaboration agreements.

Note that the studies undertaken by the CRASH Lab is not included as the analysis code was not stated in the assessed report, as discussed in Section 2.4.2.

Table A-4 Overview of analysis software used

Analysis Code	Studies	Reference
Abaqus	QinetiQ: Small Remotely Piloted Aircraft Systems (drones) Mid-Air Collision Study	[7]
LS-DYNA	ASSURE: A3: UAS Airborne Collision Severity Evaluation KAIST: Unmanned Aerial Vehicle Impacts on Heat-Strengthened Glass OSU MAE: Parametric study of a Unmanned Aerial Vehicle ingestion into a business jet size fan assembly model TU Delft: Predicting helicopter damage caused by a collision with an Unmanned Aerial System using explicit Finite Element Analysis	[9,10,11] [20] [27] [21]
NASTRAN	UFMG: Evaluation of Increase Weight in a Wing Fixed Leading Edge Design to Support UAS Impact	[15]
PAM-CRASH	CAAC: Dynamic response of the horizontal stabilizer during UAS airborne collisions CAAC: Simulations of airborne collisions between drones and an aircraft windshield	[16] [22]

A.2.2 Model validation

The extent of model validation encountered in the assessed literature is summarised in Table A-5. This highlights that – in many studies – drone and/or target validation exercises are limited (or have not been reported) and that most of the studies did not include full-scale testing. In all of these cases, considerable faith is being placed in the analysis software to capture the complex damage and failure responses accurately based upon basic source data.

Table A-5 Overview of model validation exercises reported in the assessed literature

Study Reference	Drone Model Validation	Target Model Validation
ASSURE airframe [9,10]	Basic coupon level testing verification for material systems. Component level testing of critical drone components. Full drone assembly drop test validation (quadcopter only).	Materials characterised at the "coupon level" and some component impacts against flat panels.
ASSURE engine ingestion [11]		No specific target validation reported.
CAAC [16, 22]	No specific drone validation reported prior to full scale test. Model validated against full scale test.	No specific target validation reported. Model validated against full scale test.
CRASH Lab [25, 26]	No specific drone validation exercises were reported.	Fan assembly compared with analytical blade root stresses.
KAIST [20]	No specific drone validation reported prior to full scale test.	No specific target validation reported.
TU Delft [21]	Drone components validated against published literature [9].	Validation defined as "not achievable" due to limited availability of data.
UFMG [15]	Drone components validated against published literature [9].	No specific target validation exercises reported.
QinetiQ [unpublished]	Basic coupon level testing of material systems. Static and dynamic component and sub-assembly level testing of critical drone components and features. Impact tests into panels or aircraft components.	Static and dynamic testing of target materials. Full-scale collision testing with drones launched at speeds predicted to fail the structure (up to credible mid-air collision speed for platforms).

A.2.3 Impact velocities

An overview of the closing velocities used for the assessed literature, and reasoning behind the selections (where known), is shown in Table A-6.

Table A-6 Overview selected closing velocities in assessed literature

Study Reference	Velocity	Comment
ASSURE [9,10]	**Aircraft (General)** 208 knots (Holding Velocity) **Aircraft (Airliner)** 110 knots (Landing) 365 knots (Cruise) **Aircraft (Business Jet)** 87 knots (Landing) 325 knots (Cruise) **Drone (DJI Phantom 3)** 32 knots	The selected baseline velocity represents a holding speed of 200 KIAS at an altitude of 2,500ft, selected as the most probable high velocity impact scenario. Velocities were sourced from the FAA General Operating and Flight Rules Airworthiness Requirements and the Aeronautical Information Manual. Cruise and landing velocities were selected depending on the aircraft type (airliner/business jet). The maximum velocity of the drone was identified as 16 $m \cdot s^{-1}$, however it was noted that "newer" UAS of a similar type had maximum speeds of up to 20 $m \cdot s^{-1}$.
ASSURE [11]	**Air Speed / Blade Tip Speed** Takeoff: 180KIAS / 1422$ft \cdot s^{-1}$ Below 10,000ft: 250KIAS / 955$ft \cdot s^{-1}$ Approach: 180KIAS / 355$ft \cdot s^{-1}$	These conditions were based the FAA General Operating and Flight Rules and further FAA published material relating to UAV ingestion hazards.
CAAC [16]	**Aircraft** 126$m \cdot s^{-1}$ **Drone (DJI Inspire)** 25$m \cdot s^{-1}$	The aircraft speed is stated to correspond to its flight envelope at an altitude of 500m. The drone's velocity is stated to correspond to the maximum velocity of the selected drone.
CAAC [22]	**Aircraft** 131$m \cdot s^{-1}$, 122$m \cdot s^{-1}$, 96$m \cdot s^{-1}$ **Drone** 20$m \cdot s^{-1}$	The three aircraft speeds were selected based upon the flight parameters of the aircraft and the following points: 1. FAR 91.117 which states that the maximum airspeed of an aircraft must not exceed 250knots at an altitude of less than 10,000ft 2. The maximum flight altitude of the assessed drones is 500m 3. Thirdly FAR Part 107 states that small drones are not permitted to operate above 400ft Drone speed stated as "average speed of the drone".
CRASH Lab [25, 26]	**Fan Speed** 2200 RPM **Ingestion Speed** 92$m \cdot s^{-1}$	Stated as worst case scenario, representing maximum thrust generation at take-off.
TU Delft [21]	**Aircraft (AW-109)** 80 $m \cdot s^{-1}$ (Cruise)	This velocity was selected as it represents the maximum velocity of the selected rotorcraft, no further drone velocity was added to the closing speed.

A.3 Material data (drones)

This section of the appendix presents material data found in the literature on the make-up of common drone components. This is relevant to drone threat model development activities in Task 4.

Material data presented herein includes values which are explicitly published in the assessed literature and does not include data from secondary references. Note that in some cases, the materials data quoted within the literature represents 'starting values' which are later adjusted during a test-based calibration exercise. Calibrated materials data is typically not quoted in the published reports.

A.3.1 Battery Cells

Review of the literature has identified that drone battery cells are predominately represented by crushable foam models, outlined in studies [31, 32]. This material model's use is not unique for a specific drone and has been used to represent battery cells for DJI Phantom 3, DJI Spark, DJI Mavic and DJI Inspire drones across multiple studies. The KAIST study opted for a different methodology however, generating a bi-linear elastic-plastic model to represent the component. The identified material data is summarised in Table A-7.

Table A-7 Published battery cell material data

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Failure Strain	Source data Reference
ASSURE [9]	Crushable Foam	1755	0.5	0.01		[31, 32]
CAAC [16]	Crushable Foam	1750	0.5	0.01		[31, 32]
CAAC [22]	Crushable Foam	1750	0.5	0.01		[31, 32]
UFMG [15]	Crushable Foam	1750	0.5	0.01	0.16	[31]

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Compressive Failure [MPa]	Failure Strain	Tensile Cut Off [MPa]	Source Reference
TU Delft [21]	Crushable Foam	1750	0.5	0.01	$276\ \varepsilon^{1.8}$	0.16	30	[31]

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Ref
KAIST [20]	Bi-linear	3406	0.5	0.30	0.30	[20]

A.3.2 Circuit Boards

Several different methodologies to represent drone circuit boards have been highlighted. The most common method is to use a composite model analogous to G-10 glass epoxy, which has been used in both the ASSURE and CAAC studies. Conversely the KAIST study opted to use a bi-linear elastic-plastic material model. Where applicable, circuit board components are typically represented as an additional parasitic mass applied to the modelled circuit board. The identified material data is summarised in Table A-8.

Table A-8 Published circuit board material data

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]		Compressive Strength [MPa]		Tensile Strength [MPa]		Shear Modulus [GPa]	Shear Strength [MPa]	Poisson's Ratio		Source Ref
			X	Y	X	Y	X	Y			XY	XZ/YZ	
ASSURE [9]	Composite (G-10 Glass Epoxy)	1850	18.83	19.26	365	300	233	310	8.275	152	0.136	0.118	[33]
CAAC [22]	Composite (Glass-Epoxy)	1850	18.83	19.26	365	300	233	310	8.275	152	0.136	0.118	[9, 33]

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Source Ref
KAIST [20]	PCB Bi-linear	2700	68.9	0.33	276	[20]

A.3.3 Propellers

Drone propellers are typically not assigned bespoke material models; instead basic material properties for the appropriate class of material are used (a range of polymer materials are included in Table A-11). However the KAIST study did publish a bespoke bi-linear elastic-plastic material model, which was generated specifically for the assessed DJI propeller blades; this are summarised in Table A-9.

Table A-9 Published bespoke propeller material data

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Source Reference
KAIST [20]	Bi-linear	1520	1.7	0.35	39	[20]

A.3.4 Composites

Composite materials were identified as being used in some of the larger drones, such as the DJI Inspire and Precision Hawk. These are typically used in structures such as wing spars and quadcopter 'arms' though it is noted that they are also used in some other, more generic drone configuration. Published material data is limited to the two CAAC studies, which define different properties (Table A-10) for the carbon fibre reinforced plastic (CFRP) materials used in the Inspire I quadcopter. The CAAC windshield study [22] used ply values to define a laminate with a $[0/90/45/-45/-90/0]_4$ layup, though it is noted that the ply stiffness values are unusually low and the density is twice what would normally be expected for a CFRP material. The CAAC stabilizer study also defined a single unidirectional CFRP ply, though the lay-up is not included.

Table A-10 Published composite material data utilised in drone threat models

Study Reference	Model Type	CPT [mm]	Modulus [GPa]		Shear Modulus [GPa]	Poisson's Ratio	X_T [GPa]	X_C [GPa]	Y_T [GPa]	Y_C [GPa]	Density [kg·m^{-3}]	Ref
			E_{11}	$E_{22}=E_{33}$	$G_{12}=G_{13}=G_{23}$	$\nu_{12}=\nu_{13}=\nu_{23}$						
CAAC [22]	CFRP Unidirectional ply	0.02	42.2	1.1	3.81	0.278	1.548	1.226	0.056	0.218	3220	[22]

Study Reference	Model Type	Young's Modulus [GPa]		Poisson's Ratio	Shear Modulus [GPa]	Longitudinal fibre tensile damage strain factors			Source Reference
		E1	E2	v12		Initial threshold	Ultimate	Allowed damage	
CAAC [16]	CFRP Unidirectional ply	191	9.9	0.33	63	0.019	0.023	0.99	[34]

A.3.5 Polymers

Different drones utilise a variety of polymers, accounting for a significant proportion of components such as outer shells, airframes and propellers. The ASSURE study references multiple polymers including expanded polystyrene but not all property data is reported. Material data published in the collision reports is summarised in Table A-11.

Table A-11 Published polymer material data utilised in drone threat models

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Failure Strain	Source Reference
CAAC [22]	Nylon 6 PA6 *Not Stated*	1350	6.2	0.3	70		
CAAC [16]	Polyamide (PA6) Ideal Plasticity	1350	6.2	0.3	70	0.2	*
CAAC [22]	Polycarbonate (PC2200) *Not Stated*	1180	2.35	0.3	62		
CAAC [16]	Polycarbonate Ideal Plasticity	1180	2.35	0.3	62	0.2	*
TU Delft [21]	Polycarbonate Ideal Plasticity	1180	2.35	0.3	62	0.2	[16]
UFMG [15]	Polycarbonate Ideal Plasticity	1180	2.35	0.3	62	0.2	[9]
KAIST [20]	PA66-GF Bi-Linear	1370	10	0.35	190		

**CAAC Polyamide and Polycarbonate mechanical properties were "supported by SZ DJI Technology Co., Ltd"*

Study Ref.	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Shear Modulus [GPa]	A [MPa]	B [MPa]	C	m	n	C_v [KJ·kg^{-1}·K^{-1}]	Melt Temp [K]	Ref
ASSURE [9]	Polycarbonate Johnson-Cook	1197.8	2.59	0.93	80	75	0.052	0.548	2	1.3	562	[35]

A.3.6 Aluminium alloys

Studies identify aluminium alloys in components such as motor casings and camera casings. The ASSURE study also identified the use of an aluminium foil cell pouch for the DJI Phantom 3 battery cell. However material data published in the assessed literature is limited to those presented in Table A-12.

Table A-12 Published aluminium material data utilised in drone threat models

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Tangent Modulus [MPa]	Failure Strain	Source Reference
UFMG [15]	Al520.0-F Bi-linear	2600	66	0.33	170	1164		[36]
TU Delft [21]	Al520.0-F Bi-linear	2600	66	0.33	170	1164	0.14	[37]

A.3.7 Steel alloys

Steel components in drones are limited to small components such as fasteners, mounting brackets and motor stators; however, only two of the assessed studies modelled drone components in such fidelity to include any of these components. The materials data used to represent the DJI Phantom 3 motor core stator is summarised in Table A-13. Similar materials and level of detail is used in the ASSURE study, however material data is not quoted.

Table A-13 Published steel material data utilised in drone threat models

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Tangent Modulus [MPa]	Failure Strain	Source Reference
UFMG [15]	AISI 4130 Bi-linear	7850	200	0.32	483	1174		[37]
TU Delft [21]	AISI 4130 Bi-linear	7850	200	0.32	483	1174	0.12	[37]

A.4 Material data (targets)

This section of the Appendix presents material data found in the literature on the target components. This may be of relevance to the target modelling activities in Task 4.

Material data presented herein includes values which are explicitly published in the assessed literature and does not include data from secondary references. Note that in some cases, the materials data quoted within the literature represents 'starting values' which are later adjusted during a test-based calibration exercise. Calibrated materials data is typically not quoted in the published reports.

A.4.1 Aluminium alloys

Aluminium alloys are commonplace in traditional airframe structures. Although a range of alloys were assessed in the ASSURE program, the material data used is not explicitly published within the study and so is not included here. The assessed literature suggests that a Johnson-Cook material model is the preferred method of representing this class of material. Available material data, including parameters used for different Johnson-Cook material models (A, B, C, m, n, D_x), is summarised in Table A-14.

Table A-14 Published aluminium material data utilised in target models

Study Reference	Model Type	A [MPa]	B [MPa]	n	C	Failure Strain	Source Reference
CAAC [16]	Al 2024-T3 Johnson-Cook	280	400	0.2	0.015	0.2	
CAAC [16]	Al 7075-T6 Johnson-Cook	480	400	0.42	-0.001	0.12	
CAAC [16]	Al 6061-T6 Johnson-Cook	324	114	0.42	0.002	0.12	

Study Reference	Model Type	A [MPa]	B [MPa]	C	m	n	Melt Temperature [K]	Source Reference
CAAC [22]	Al 6061-T6 Johnson-Cook	324	114	0.002	1.34	0.42	855	[38]

Study Reference	Model Type	A [MPa]	B [MPa]	C	m	n	D_1	D_2	D_3	D_4	D_5	Source Reference
UFMG [15]	Al 2024-T3 Johnson-Cook	369	684	0.0083	1.7	0.73	0.112	0.123	1.5	0.007	0	[39]

Study Reference		Model Type	Density [$kg \cdot m^{-3}$]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Tangent Modulus [MPa]	Source Reference
UFMG [15]		Al 7075-T7451 Bi-linear	2770	71	0.33	462	663	[37]

A.4.2 Glass

Windshields represent a critical component of the airframe and have been the subject of several previous collision studies. Aircraft windshield construction can vary significantly between platforms, utilising various materials and layups. The assessed literature covers analysis of acrylic based windshields (ASSURE and TU Delft studies) and inorganic glass based windshields (CAAC study), however the material data values used in the ASSURE study is not explicitly stated. Glass data summarised in Table A-15.

Note that a simple elastic-plastic bi-linear material model was utilised to represent the glass in the CAAC study, but a small failure strain was chosen to represent brittle failure.

Table A-15 Published glass material models data in target models

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Failure Strain	Source Reference
CAAC [22]	Inorganic Glass Bi-linear with strain hardening	2450	71.48	0.22	370	0.001	[40]
TU Delft [21]	Stretch Acrylic Ideal plasticity with strain hardening	1180	330	0.4	600	0.025	[41]

A.4.3 Windshield Interlayers

As stated in Appendix A.4.2, the windshield represents a critical component of the airframe and can vary significantly in construction between platforms. Laminated windshields incorporate highly-elastic interlayers which provide numerous performance advantages to the overall windshield. Several interlayer materials are summarised in Table A-16 which were modelled using a simple elastic-plastic bi-linear model. Note the low failure strain used to limit deformation in the plastic region. The ASSURE study also included a PVB interlayer in their windshield collision analysis, however their material data was not published.

Table A-16 Published windshield interlayer material data utilised in target models

Study Reference	Model Type	Density [kg·m^{-3}]	Young's Modulus [GPa]	Poisson's Ratio	Yield Stress [MPa]	Failure Strain	Source Reference
CAAC [22]	PU Bi-linear with strain hardening	1000	0.499	0.30	150	0.001	[40]
CAAC [22]	PVB Bi-linear with strain hardening	1000	1.293	0.38	150	0.001	[40]

A.5 Collision data – Physical test

This section of the Appendix provides summary details and the outcome of published physical impact tests between drones and various aircraft structures. The aim of this Appendix is to identify data which can be used to validate other models (Task 5) and/or provide data points for the database (Task 6).

A.5.1 Full scale testing

As discussed in Sections 2.2.2 and 2.3.3 the CAAC used a rocket sled to replicate collisions between drones and aircraft structures. With this arrangement, they tested a representative airliner windshield against various DJI quadcopters and a novel bird strike designed leading edge against a DJI Inspire quadcopter.

As discussed in Section 2.6, the University of Dayton's Research Institute undertook a high speed impact in September 2018 between a CS-23 leading edge and a DJI Phantom 2 using a gas gun. It is noted that the closing velocity selected represented worse case conditions, equalling a combination of the maximum airspeed of both the quadcopter and aircraft.

The Hungarian based Légtér.hu also undertook live testing between several quadcopters and an Antonov AN-2 in September 2019. Although damage to the airframe was limited, it is noted that the closing speed was much lower than other mid-air collision studies.

Results of all published tests against aircraft structures are summarised in the Table A-17. Note, the results presented in the KAIST study were not included in this summary table as it was determined that the velocity range and materials were not sufficiently relevant to this study. The colour coding used in the 'Outcome' column relates to the severity of the result, as defined in the relevant programme.

Table A-17 Published physical drone collision test results

Study Reference	Impact Data		Threat Data		Target Data				Outcome
	Closing Velocity [m·s⁻¹]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
CAAC [16]	152.8	Direct	DJI Inspire	3.428	Airliner leading edge (novel anti-birdstrike design)	Between ribs	Al 2024-T6	1.2 - 2.0	Penetration of the entire drone
CAAC [22]	140.0	Direct	DJI Spark	0.300	Airliner windshield	Corner	Laminated windshield	22.5	Calibration - not reported
	136.0	Direct	DJI Spark	0.300		Corner			Calibration - not reported
	150.7	Y = 0° P = 3.6°	DJI Phantom 4 Pro	1.360		Centre			Outer ply damage
	150.7	Y = 0° P = 8.5°	DJI Phantom 4 Pro	1.360		Corner			Outer ply damage
	158.6	Y = 24.4° P = 45°	DJI Mavic	0.700		Centre			Outer ply damage
	154.8	Y = -24.4° P = 45°	DJI Phantom 4 Pro	1.360		Centre			All glass plies and PVB damage
	153.4	Direct	DJI Phantom 4 Pro (Two batteries)	1.819		Centre			Outer and mid glass ply damage
CAAC [22]	118.5	Direct	DJI Inspire	3.330		Centre			Outer ply damage
UDRI [42]	106.4	Direct	DJI Phantom 2	0.953	Mooney M20 Wing Leading Edge	Between ribs	Unknown	Unknown	Penetration (entire drone) main spar damage
Légtér.hu [43]	27.8 (target speed)**	Direct	DJI Phantom 3	1.236*	Antonov AN-2 Leading Edge	Between ribs, glancing lower surface	Unknown	Unknown	Skin deformation
		Direct	DJI Phantom 3*	1.236*					Localised skin rupture, skin deformation
		Direct	Syma X8S*	0.680*	Antonov AN-2 Wing Strut	Lower section	Unknown	Unknown	Surface scratches, external cable damaged
	Unknown RPM	Direct	Syma X8S	0.680*	Antonov AN-2 Propeller	Mid blade	Unknown	Unknown	Leading edge scratches

**Model/Mass indicative, not reported, **Target airspeed, collision speed not reported*

A.6 Collision data – Predicted

This section of the Appendix provides summary details and the outcome of simulated collisions between drones and various aircraft structures. The aim of this section is to identify data which can be used to validate other models (Task 5) and/or provide data points for the database (Task 6).

Where applicable the 'primary target material' is identified. This is classified as the first region the drone impacts (i.e. for leading edge impacts this is likely to be the skin). Note that collision results using highly-simplified, generic drones were not included in this Appendix.

A.6.1 ASSURE studies (USA)

As discussed in Sections 2.2.1 and 2.3.2, ASSURE undertook a broad modelling exercise, assessing a CS-23 business jet and CS-25 airliner models against both a popular consumer quadcopter and a fixed wing drone. These were assessed against a four-level damage classification system determined by ASSURE; this system is detailed in Appendix A.1. The following tables summarise the collision modelling results against each airframe. It includes the additional parameter studies that investigate the effects of impact location, impact velocity and drone mass through scaling of the drone's volume. Note that impact locations stated in the tables are defined in the source documents [9, 10], however they generally transition from the root of the target (location 1) to the tip of the target (final location).

Table A-18 ASSURE: NIAR Airliner Model vs DJI Phantom 3, predicted collision results

Study Reference	Impact Data		Threat Data		Target Data				Outcome (ASSURE Classification)
	Closing Velocity [knots]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
ASSURE [9]	250	Direct	DJI Phantom 3	1.2	Boeing 737-800 Vertical Stabiliser	Root	Al 2024-T3	1.0 - 1.5mm	Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 2			Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 3			Level 3
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Loc 3			Level 3
	110	Direct	DJI Phantom 3	1.2		Loc 3			Level 2
	365	Direct	DJI Phantom 3	1.2		Loc 3			Level 4
	250	Direct	DJI Phantom 3	1.2		Tip			Level 3
	250	Direct	DJI Phantom 3	1.2	Boeing 737-800 Horizontal Stabiliser	Root	Al 2024-T3	1.5 - 2.0mm	Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 2		1.0 - 1.5mm	Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 3			Level 4
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Loc 3			Level 4
	110	Direct	DJI Phantom 3	1.2		Loc 3			Level 2
	365	Direct	DJI Phantom 3	1.2		Loc 3			Level 4
	250	Direct	DJI Phantom 3	1.2		Loc 4		1.5 - 2.0mm	Level 4
	250	Direct	DJI Phantom 3	1.2		Tip			Level 4
	250	Direct	DJI Phantom 3	1.2	Boeing 737-800 Wing Leading Edge	Loc 1	Al 2024-T3	1.5 - 2.0mm	Level 3
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Loc 1			Level 3
	110	Direct	DJI Phantom 3	1.2		Loc 1			Level 2
	365	Direct	DJI Phantom 3	1.2		Loc 1			Level 4
	250	Direct	DJI Phantom 3	1.2		Loc 2			Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 3			Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 4			Level 2
	250	Direct	DJI Phantom 3	1.2	Boeing 737-800 Windshield	Centre	Laminated Glass	Unknown	Level 2
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Centre			Level 3
	110	Direct	DJI Phantom 3	1.2		Centre			Level 1
	365	Direct	DJI Phantom 3	1.2		Centre			Level 4
	250	Direct	DJI Phantom 3	1.2		Corner			Level 2
	250	Direct	DJI Phantom 3	1.2		Centre frame	Al 7075-T6	Unknown	Level 2

Table A-19 ASSURE: NIAR Business Jet Model vs DJI Phantom 3, predicted collision results

Study Reference	Impact Data		Threat Data		Target Data				Outcome (ASSURE Classification)
	Closing Velocity [knots]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
ASSURE [9]	250	Direct	DJI Phantom 3	1.2	Learjet 31A Vertical Stabiliser	Root	Al 2024-T3	1.0 - 1.5mm	Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 2			Level 3
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Loc 2			Level 4
	87	Direct	DJI Phantom 3	1.2		Loc 2			Level 2
	325	Direct	DJI Phantom 3	1.2		Loc 2			Level 4
	250	Direct	DJI Phantom 3	1.2		Tip			Level 2
	250	Direct	DJI Phantom 3	1.2	Learjet 31A Horizontal Stabiliser	Root	Al 2024-T3	1.0 - 1.5mm	Level 3
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Root			Level 4
	87	Direct	DJI Phantom 3	1.2		Root			Level 2
	325	Direct	DJI Phantom 3	1.2		Root			Level 4
	250	Direct	DJI Phantom 3	1.2		Loc 2			Level 4
	250	Direct	DJI Phantom 3	1.2		Tip			Level 4
	250	Direct	DJI Phantom 3	1.2	Learjet 31A Wing Leading Edge	Root	Al 2024-T3	1.5 - 2.0mm	Level 3
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Root			Level 3
	87	Direct	DJI Phantom 3	1.2		Root			Level 2
	325	Direct	DJI Phantom 3	1.2		Root			Level 3
	250	Direct	DJI Phantom 3	1.2		Loc 2			Level 2
	250	Direct	DJI Phantom 3	1.2		Tip			Level 2
	250	Direct	DJI Phantom 3	1.2	Learjet 31A Windshield	Centre	Laminated Glass	Unknown	Level 2
	250	Direct	DJI Phantom 3 (volume scaled)	1.8		Centre			Level 2
	87	Direct	DJI Phantom 3	1.2		Centre			Level 1
	325	Direct	DJI Phantom 3	1.2		Centre			Level 3
	250	Direct	DJI Phantom 3	1.2		Centre frame	Al 2024-T3	Unknown	Level 2

Table A-20 ASSURE: NIAR Airliner Model vs Precision Hawk, predicted collision results

Study Reference	Impact Data		Threat Data		Target Data				Outcome (ASSURE Classification)
	Closing Velocity [knots]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
ASSURE [10]	250	Direct	Precision Hawk	1.81	Boeing 737-800 Vertical Stabiliser	Root	Al 2024-T3	1.0 - 1.5mm	Level 4
	250	Direct	Precision Hawk (volume scaled)	3.60		Root			Level 4
	110	Direct	Precision Hawk	1.81		Root			Level 2
	365	Direct	Precision Hawk	1.81		Root			Level 4
	250	Direct	Precision Hawk	1.81		Loc 2			Level 3
	250	Direct	Precision Hawk	1.81		Loc 3			Level 4
	250	Direct	Precision Hawk	1.81		Tip			Level 4
	250	Direct	Precision Hawk	1.81	Boeing 737-800 Horizontal Stabiliser	Root	Al 2024-T3	1.5 - 2.0mm	Level 4
	250	Direct	Precision Hawk	1.81		Loc 2		1.0 - 1.5mm	Level 4
	250	Direct	Precision Hawk (volume scaled)	3.60		Loc 2			Level 4
	110	Direct	Precision Hawk	1.81		Loc 2			Level 2
	365	Direct	Precision Hawk	1.81		Loc 2			Level 4
	250	Direct	Precision Hawk	1.81		Loc 3			Level 4
	250	Direct	Precision Hawk	1.81		Loc 4		1.5 - 2.0mm	Level 4
	250	Direct	Precision Hawk	1.81		Tip			Level 4
	250	Direct	Precision Hawk	1.81	Boeing 737-800 Wing Leading Edge	Loc 1	Al 2024-T3	1.5 - 2.0mm	Level 3
	250	Direct	Precision Hawk	1.81		Loc 2			Level 3
	250	Direct	Precision Hawk	1.81		Loc 3			Level 3
	250	Direct	Precision Hawk (volume scaled)	3.60		Loc 3			Level 4
	110	Direct	Precision Hawk	1.81		Loc 3			Level 2
	365	Direct	Precision Hawk	1.81		Loc 3			Level 4
	250	Direct	Precision Hawk	1.81		Loc 4			Level 3
	250	Direct	Precision Hawk	1.81	Boeing 737-800 Windshield	Centre	Laminated Glass	Unknown	Level 2
	250	Direct	Precision Hawk (volume scaled)	3.60		Centre			Level 3
	110	Direct	Precision Hawk	1.81		Centre			Level 1
	365	Direct	Precision Hawk	1.81		Centre			Level 3
	250	Direct	Precision Hawk	1.81		Corner			Level 2
	250	Direct	Precision Hawk	1.81		Centre frame	Al 7075-T6	Unknown	Level 2

Table A-21 ASSURE: NIAR Business Jet Model vs Precision Hawk, predicted collision results

Study Reference	Impact Data		Threat Data		Target Data				Outcome (ASSURE Classification)
	Closing Velocity [knots]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
ASSURE [10]	250	Direct	Precision Hawk	1.81	Learjet 31A Vertical Stabiliser	Root	Al 2024-T3	1.0 - 1.5mm	Level 4
	250	Direct	Precision Hawk	1.81		Loc 2			Level 4
	250	Direct	Precision Hawk	1.81		Tip			Level 4
	250	Direct	Precision Hawk (volume scaled)	3.60		Tip			Level 4
	87	Direct	Precision Hawk	1.81		Tip			Level 2
	325	Direct	Precision Hawk	1.81		Tip			Level 4
	250	Direct	Precision Hawk	1.81	Learjet 31A Horizontal Stabiliser	Root	Al 2024-T3	1.0 - 1.5mm	Level 4
	250	Direct	Precision Hawk (volume scaled)	3.60		Root			Level 4
	87	Direct	Precision Hawk	1.81		Root			Level 2
	325	Direct	Precision Hawk	1.81		Root			Level 4
	250	Direct	Precision Hawk	1.81		Loc 2			Level 4
	250	Direct	Precision Hawk	1.81		Tip			Level 4
	250	Direct	Precision Hawk	1.81	Learjet 31A Wing Leading Edge	Root	Al 2024-T3	1.5 - 2.0mm	Level 2
	250	Direct	Precision Hawk	1.81		Loc 2			Level 3
	250	Direct	Precision Hawk (volume scaled)	3.60		Loc 2			Level 3
	87	Direct	Precision Hawk	1.81		Loc 2			Level 2
	325	Direct	Precision Hawk	1.81		Loc 2			Level 3
	250	Direct	Precision Hawk	1.81		Tip			Level 3
	250	Direct	Precision Hawk	1.81	Learjet 31A Windshield	Centre	Laminated Glass	Unknown	Level 4
	250	Direct	Precision Hawk (volume scaled)	3.60		Centre			Level 4
	87	Direct	Precision Hawk	1.81		Centre			Level 1
	325	Direct	Precision Hawk	1.81		Centre			Level 4
	250	Direct	Precision Hawk	1.81		Corner			Level 1
	250	Direct	Precision Hawk	1.81		Centre frame	Al 2024-T3	Unknown	Level 4

In addition to airframe collision testing, the ASSURE study also investigated the severity of drone engine ingestion (discussed in Section 2.4.1). A simple, publicly available jet engine model – typical of mid-sized business jet – was used for this exercise. Results for these tests are outlined in Table A-22. Note this model was a simplified, generic configuration which may not fully-represent a modern aero engine, so this should be considered when interpreting the results. ASSURE are currently undertaking an additional study, within input from engine manufacturers to address on these limitations.

Table A-22 ASSURE: Drone generic business jet engine, predicted collision results

Study Reference	Impact Data			Threat Data		Target Data		Outcome (ASSURE Classification)
	Closing Velocity [knots]	Blade Speed [RPM]	Aspect (Yaw / Pitch)	Threat	Mass [kg]	Target	Primary Material	
ASSURE [11]	180	8500	Direct	DJI Phantom 3	1.20	Business Jet Engine Outer Blade	Ti-6Al-4V	Level 3
	180	8500	Direct	DJI Phantom 3 Motor			Ti-6Al-4V	Level 1
	180	8500	Direct	DJI Phantom 3 Camera			Ti-6Al-4V	Level 1
	180	8500	Direct	DJI Phantom 3 Battery			Ti-6Al-4V	Level 1
	180	8500	Direct	DJI Phantom 3	1.20	Business Jet Engine Inner Blade	Ti-6Al-4V	Level 1
	180	8500	Direct	DJI Phantom 3 Motor		Generic Engine Nose cone	Al-2024	Level 1
	180	8500	Direct	DJI Phantom 3 Camera			Al-2024	Level 1
	180	8500	Direct	DJI Phantom 3 Battery			Al-2024	Level 1
	180	8500	Direct	DJI Phantom 3	1.20	Business Jet Engine Outer Blade (Thick)	Ti-6Al-4V	Level 1
	180	8500	Y = 0° P = 90°	DJI Phantom 3	1.20	Business Jet Engine Outer Blade	Ti-6Al-4V	Level 2
	180	2000	Direct	DJI Phantom 3	1.20		Ti-6Al-4V	Level 1
	250	6000	Direct	DJI Phantom 3	1.20		Ti-6Al-4V	Level 1
	180	8500	Direct	Precision Hawk	1.81	Business Jet Engine Outer Blade	Ti-6Al-4V	Level 3
	180	8500	Direct	Precision Hawk Motor			Ti-6Al-4V	Level 2
	180	8500	Direct	Precision Hawk Camera			Ti-6Al-4V	Level 2
	180	8500	Direct	Precision Hawk Battery			Ti-6Al-4V	Level 1
	180	8500	Direct	Precision Hawk	1.81	Business Jet Engine Inner Blade	Ti-6Al-4V	Level 2
	180	8500	Direct	Precision Hawk Motor		Business Jet Engine Nose cone	Al-2024	Level 1
	180	8500	Direct	Precision Hawk Camera			Al-2024	Level 1
	180	8500	Direct	Precision Hawk Battery			Al-2024	Level 1
	180	8500	Direct	Precision Hawk	1.81	Business Jet Engine Outer Blade (Thick)	Ti-6Al-4V	Level 2
	180	8500	Y = 180° P = 0°	Precision Hawk	1.81	Business Jet Engine Outer Blade	Ti-6Al-4V	Level 2
	180	2000	Direct	Precision Hawk	1.81		Ti-6Al-4V	Level 1
	250	6000	Direct	Precision Hawk	1.81		Ti-6Al-4V	Level 2

A.6.2 CAAC collaboration (China)

In addition to the physical testing activities detailed in Appendix A.5.1, the CAAC also undertook modelling activities to validate their methods and to explore alternative collision conditions. Table A-23 summarises the leading edge modelling activities outlined in Section 2.2.2. This includes a parametric study assessing different internal slat stiffener configurations.

➨ **Table A-23** CAAC: Airliner Leading Edge vs DJI Inspire, predicted collision results

Study Reference	Impact Data		Threat Data		Target Data				Outcome
	Closing Velocity [m·s^{-1}]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
CAAC [16]	152.8	Direct	DJI Inspire	3.428	Airliner LE (novel anti-birdstrike design)	Between ribs	Al 2024-T6	1.2 - 2.0	Penetration (entire drone)
	151	Direct	DJI Inspire	3.428	Airliner leading edge Swept 33.5° (Slat variant)	Mid Slat 1: (160mm 85°)	Al 7075-T6	1mm + 1mm	Penetration
	151	Direct	DJI Inspire	3.428		Mid Slat 2: (130mm 85°)	Al 7075-T6		Penetration
	120		DJI Inspire	3.428			Al 7075-T6		Skin Failure
	180		DJI Inspire	3.428			Al 7075-T6		Penetration
	151	Direct	DJI Inspire	3.428		Mid Slat 3: (100mm 80°)	Al 7075-T6	1.27mm + 1.27mm	Penetration
	151	Direct	DJI Inspire	3.428		Mid Slat 4: (60mm 70°)	Al 7075-T6	2.54mm	Skin Failure

Table A-24 summarises the modelling validation exercise as outlined in Section 2.3.3. These replicate test conditions and the outcome is determined using the same methodology as in Appendix A.5.1.

Table A-25 summarises a parametric study assessing the effect of drone aspect on the resulting damage outcome of the representative airliner windshield. The study notes that all yaw and pitch angles assessed represented "normal angles" of the drone, with the exception of the -135° pitch condition.

Table A-24 CAAC: Airliner Windshield vs Drones, predicted collision results

Study Reference	Impact Data		Threat Data		Target Data				Outcome
	Closing Velocity [m·s^{-1}]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
CAAC [22]	150.7	Y = 0° P = 3.6°	DJI Phantom 4 Pro	1.36	Airliner windshield	Centre	Laminated Windshield	22.5	Outer ply damage
	150.7	Y = 0° P = 8.5°	DJI Phantom 4 Pro	1.36		Corner			Outer ply damage
	158.6	Y = 24.4° P = 45°	DJI Mavic	0.7		Centre			Outer ply damage
	154.8	Y = -24.4° P = 45°	DJI Phantom 4 Pro	1.36					All glass plies and PVB damaged
	153.4	Direct	DJI Phantom 4 Pro (Two batteries)	1.819					Outer and mid glass ply damage
	118.5	Direct	DJI Inspire	3.33					Outer ply damage

Table A-25 CAAC: Airliner Windshield vs DJI Phantom 4 Pro, parametric study

Study Reference	Impact Data		Threat Data		Target Data				Outcome (CAAC Classification)
	Closing Velocity [m·s^{-1}]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
CAAC [22]	154.4	Direct	DJI Phantom 4 Pro	1.36	Airliner windshield	Centre	Laminated Windshield	22.5	Safe
	154.4	Y = 0° P = -135°	DJI Phantom 4 Pro	1.36					Dangerous
	154.4	Y = 0° P = -45°	DJI Phantom 4 Pro	1.36					Dangerous
	154.4	Y = 0° P = -30°	DJI Phantom 4 Pro	1.36					Dangerous
	154.4	Y = 0° P = 45°	DJI Phantom 4 Pro	1.36					Dangerous
	154.4	Y = -45° P = 0°	DJI Phantom 4 Pro	1.36					Safe
	154.4	Y = 45° P = 0°	DJI Phantom 4 Pro	1.36					Safe
	154.4	Y = 24.4° P = 45°	DJI Phantom 4 Pro	1.36					Already unairworthy

A.6.4 Federal University of Minas Gerais (Brazil)

As discussed in Section 2.2.3, the Federal University of Minas Gerais undertook a ‘modelling only’ exercise to assess the effect of drone impacts against a representative airliner leading edge. This included studies to explore the effect on damage levels of impact angles (aspects) and material thicknesses.

Table A-26 outlines the results of component level calibration results for a DJI Phantom 3. These results were compared to those detailed in the ASSURE study [9].

Table A-27 and Table A-28 summarise the parametric studies undertaken between the DJI Phantom 3 drone and representative airliner leading edge. It should be noted that the drone model was constructed by modelling the motors, camera and battery components only. These were connected by one-dimensional elements with an assigned polycarbonate material to represent the fuselage and gimbal. To facilitate comparisons with a 1.8kg bird, the drone model was then scaled by increasing the prescribed densities by 1.5. However, omission of the polycarbonate fuselage is expected to increase the severity of impact as it removes the 'crumple zone' around the stiffer components (i.e. motors). Also, positive density scaling will result in overly-dense components, rather volume scaling, which was employed by the ASSURE study. It is therefore recommended that these results be interpreted with caution.

➨ **Table A-26** UFMG: Flat Plate vs DJI Phantom 3 component modelling calibration results

Study Reference	Impact Data		Threat Data		Target Data			Outcome
	Closing Velocity [knots]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Primary Material	Primary Thickness [mm]	
UFMG [15]	250	Direct	(DJI P3) Battery		Flat Plate	Al 2024-T3	1.60	No Penetration
	250	Direct				Al 2024-T3	6.35	No Penetration
	100	Direct				Al 2024-T3	3.18	No Penetration
	250	Direct	(DJI P3) Motor			Al 2024-T3	1.60	Penetration
	250	Direct				Al 2024-T3	6.35	No Penetration
	250	Direct	(DJI P3) Camera			Al 2024-T3	1.60	No Penetration

➡ **Table A-27** UFMG: Airliner Leading Edge vs DJI Phantom 3, drone position parametric study

Study Reference	Impact Data		Threat Data		Target Data				Outcome
	Closing Velocity [knots]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
UFMG [15]	250	Direct	DJI Phantom 3 (density scaled by a factor of 1.5)	1.8	Airliner Leading Edge	Between Ribs	Al 2024-T3	2.0	Penetration (Most critical)
	250	Y = 22.5° P = 0°					Al 2024-T3	2.0	Penetration
	250	Y = 45° P = 0°					Al 2024-T3	2.0	Penetration
	250	Y = 67.5° P = 0°					Al 2024-T3	2.0	Penetration
	250	Y = 90° P = 0°					Al 2024-T3	2.0	Penetration

Table A-28 UFMG: Airliner Leading Edge vs DJI Phantom 3, spar parametric study

Study Reference	Impact Data		Threat Data		Target Data				Outcome
	Closing Velocity [knots]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
UFMG [15]	250	Direct	DJI Phantom 3 (density scaled by a factor of 1.5)	1.8	Airliner Leading Edge	Between Ribs	Al 2024-T3 (Skin)	3.0 (Skin)	Penetration (spar exposed)
	250	Direct						5.0 (Skin)	Penetration (localised)
	250	Direct			Airliner Leading Edge (No skin)		Al 7050-T7451 (Spar)	7.0 (Spar web)	Rupture
	250	Direct						9.0 (Spar web)	Rupture
	250	Direct						12.0 (Spar web)	No Rupture
	250	Direct			Airliner Leading Edge Inc. spar spines (No skin)		Al 7050-T7451 (Spar)	7.0 (Spar web)	Localised Rupture

A.6.5 Delft University of Technology (Netherlands)

As discussed in Section 2.3.5, a recent MSc thesis assessed the collision severity of a DJI Phantom 3 against the geometry of an AW-109 windshield. Results of the parametric studies, which include: variations of impact aspect and windshield thickness, are summarised in Table A-29. Note the variation of boundary condition relates to the lack of included airframe to provide representative stiffness and as such, a full clamped boundary condition would provide overly-conservative results.

Table A-29 TU Delft: CS-27 Small Rotorcraft Windshield (AW109) vs DJI Phantom 3, parametric study

Study Reference	Impact Data		Threat Data		Target Data				Outcome
	Closing Velocity [m·s^{-1}]	Aspect (Yaw/ Pitch)	Threat	Mass [kg]	Target	Location	Primary Material	Primary Thickness [mm]	
TU Delft [21]	80	Direct	DJI Phantom 3	1.216	CS-27 Small Rotorcraft (AW-109) Windshield	Centre	Acrylic	9.3	Penetration
	80	Direct	DJI Phantom 3 (volume scaled)	0.608		Centre	Acrylic	9.3	No penetration, Fragmentation
	80	Direct		0.304		Centre	Acrylic	9.3	No penetration nor fragmentation
	80	Direct	DJI Phantom 3	1.216		Centre	Acrylic	16	No penetration nor fragmentation
	80	Direct				Centre	Acrylic	14	Large hole formed
	80	Y = 45° P = 0°				Centre	Acrylic	14	Large hole formed

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