RESEARCH PROJECT EASA.2020.C04

Vulnerability of manned aircraft to drone strikes

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Guidance on the design of drones, based upon outcomes of drone collision severity studies (D8.1, D8.2)

QinetiQ is the prime lead in this 'Horizon 2020' research framework which is sponsored by the European Commission and contracted through EASA.

Cody Technology Park | Farnborough | England I GU14 0LX | + 44 (0) 1252 392 000 | www.QinetiQ.com

Executive Summary

This report presents data and information to satisfy deliverables D8.1 and D8.2, under Task 8 of QinetiQ's 'Vulnerability of manned aircraft to drone collisions' programme for EASA.

Within this programme it has been shown that, in some circumstances, mid-air collisions between crewed aircraft and mass-market consumer/prosumer drones may cause hazardous damage [22] [16], i.e. sufficient to threaten the safety of flight. The purpose of 'Task 8' was to develop design guidelines that could mitigate the severity of potential mid-air collision events, and to explore how guidelines could be codified into a draft design standard and/or draft test standard for future drone products.

The analysis work that underpins this report exploits data, methods and knowledge that has been generated through QinetiQ's broader experience of drone collision assessments and the following previously-reported activities within this programme:

- Down-selection of example drones and crewed aircraft (Task 2) [1];
- Identification and prioritisation of local target regions for each category of crewed aircraft (Task 2) [1];
- Statistical analysis of aircraft flight data to evaluate probabilistic collision speeds (Task 2) [1];
- Description of QinetiQ's drone collision simulations methods used in this programme (Task 3) [2];
- Development and validation of drone threat models using QinetiQ's methodologies (Task 4) [13];
- Development and validation of Local Target Models for a wide range of aircraft (Task 5) [14];
- Development of a Collision Modelling Framework, based upon QinetiQ's methods (Task 5) [15];
- Synthesis of drone collision with aircraft (Task 5) [22]; and
- Development of a PC-based Drone Collision Results Tool, based upon QinetiQ's post-processing methods (Task 6) [16].
- Assessment of drone design features/attributes, and the effect that they have on collision severity (Task 7) [12].

The report begins with a summary of the work completed within the wider research programme in Section 2, with accompanying images in Appendix A. This is relevant because the recommendations made within this document are based upon knowledge gained through these earlier activities.

<u>Design guidelines</u>

Section 3 describes a high-level requirement linked to the objectives of this project, for drone OEMs to consider collision severity when designing their products. This is followed by a series of thirteen drone design guidelines to aid the development of future drone products. The first six guidelines are identified as being 'Primary' and have been developed further into an early draft design standard in Section 5. The remaining Guidelines are marked as 'Secondary' and include criteria that affect impact severity, but may not be practical to implement for *all types* of drone.

<u>Design standards</u>

Section 4 discusses the types of evidence that a standard could call for. A rules-based design standard was agreed to be most appropriate because it minimises the need for specialist capabilities or facilities, and minimises the risk of unexpected non-conformance during certification. The basis of a draft design standard has been created, and is described in Section 5.

The draft design standard includes four criteria, which are presented for review by the Regulator alongside the large volume of vulnerability data and evidence that has been generated within this programme. These outputs are draft proposals and would require further work to develop them into an official Open category standard.

For the consumer-grade drones that are the focus of this programme, the dominant factor in determining the collision hazard severity is the impact energy. This is a function of the mass of the drone and the relative speeds of the drone, crewed aircraft and any applicable rotating components on the crewed aircraft e.g. rotors. Many of these factors can be controlled, influenced or bounded at the design stage by the drone OEM. It is therefore important that manufacturers actively seek to minimise the mass of their products through careful design and optimisation against the legitimate needs of their product. The maximum speed capabilities of the drone is also relevant, as it influences the potential collision speeds and can greatly increase the impact energy in the event of a head-on collision.

It is difficult to establish a strict requirement for mass reduction, and the maximum speed of specific products may vary depending upon their operational use case. However, the use of 'drone classes' in existing regulations [10] have a positive influence. To supplement this, the draft design standards include a proposal to avoid combinations of high drone speeds and high product masses, in order to discourage the development of products that would increase collision hazards for crewed aviation.

For fixed wing drones, the configuration of the propulsion system can have a significant effect on the severity of a collision. In particular puller propeller configurations, with the motor at the front of the UAS, have greater damage potential than equivalent pusher propeller designs. This is because head-on collisions with a puller propeller design will cause the hard motor and propeller to impact the crewed aircraft at the sum of the UAS and aircraft speeds. An equivalent motor impact for a pusher prop would be from a rearwards direction, so the collision speed would be reduced. Based upon this, a draft design standard proposes that puller propeller configurations should be avoided for lower classes of drone, which are most relevant to the consumer market.

A further draft design standard recommends design parameters for horizontally-oriented spinners, which are typically mounted to propeller hubs on fixed wing UAS. Constraints on the external geometry of spinners prevent the use of spinner profiles that are more likely to puncture/fail aircraft structures in the event of a collision. The possibility of including additional criteria to improve the energy absorption characteristics of the spinner has also been identified, though further work would be required to develop appropriate design rules.

The final draft design standard option addresses observations that, in some collision scenarios, the motors of multi-rotor drones can be responsible for initiating hazard damage to the aircraft. It was identified that damage can be mitigated by the inclusion of tough 'bumper' structures around the motors and/or the use of folding (or frangible) motor arms. The draft design standard therefore proposes that bumper structures should be used on C1 (or higher) class drones, though this is increased to C2 class where frangible or folding arms are used. Further work is required to provide guidance on the design of bumper structures and motor arm frangibility criteria.

<u>Observations on crewed aircraft</u>

Observations have been made about key vulnerabilities of the example aircraft representations assessed within this programme. These observations are limited to design features that were predicted to be vulnerable to drone collisions, but where credible design mitigations could exist. They focus on empennage leading edges structures, and light fixed wing/rotorcraft windshields. In particular, it is recommended that the design of all aircraft windshields (regardless of their respective bird strike requirements) should utilise appropriate material technologies (which could include high-toughness materials and/or laminated constructions) and screen thicknesses to minimise the risk of injury to aircrew in the event of mid-air impacts

Summary

Outputs from this programme provide EASA with a world-class understanding of the vulnerability of crewed aircraft to mid-air collision with different types of commonly-available drone within the Open category.

This report includes information in the form of design guidelines, draft standards and observations that will aid:

- Drone manufactures in developing products that partially mitigate the potential collision hazards with crewed aircraft;
- Regulators in deciding whether to initiate the development of formal high-level requirements and associated standards to address drone collision threats;
- Aircraft manufacturers, with information on specific vulnerabilities of the aircraft representations assessed within this programme.

Further work

Finally, a series of seven recommendations have been made to extend and capitalise on the methods and outputs from this programme. These include further work to:

- Mature the draft standards;
- Maintain and extend knowledge of collision threats for emerging classes of aircraft and drones;
- Assess collision probabilities, which can be combined with the data from this programme;
- Expand the scope of the work to consider ground collision events, such as impacts against personnel.

Contents

Abbreviations

Acronym	Description
ADS-B	Automatic Dependent Surveillance–Broadcast
ANSP	Air Navigation Service Provider
ASSURE	Alliance for System Safety of UAS through Research Excellence
CAD	Computer Aided Design
CE	Conformité Européenne (European Conformity)
C-UAS	Counter-Uncrewed Air System
DAA	Detect And Avoid
EASA	European Union Aviation Safety Agency
EU	European Union
EN	European Norm (European standard)
eVTOL	Electric Vertical Take-Off and Land
FAA	Federal Aviation Authority
FE	Finite Element
FEM	Finite Element Model
FPV	First Person View
FTIR	Fourier-Transform Infrared Spectroscopy
GA	General Aviation
HEC	Hazard Effect Classification
HS	Horizontal Stabiliser
IEA	Impact Effect Assessment
LE	Leading Edge
MTOM	Maximum Take-Off Mass
MW	Main Wing
OEM	Original Equipment Manufacturer
prEN	Proposed European Norm (Draft European standard)
PVB	Polyvinyl Butyral
RGB	Red Green Blue
SQEP	Suitably Qualified and Experienced Personnel
TBD	To Be Determined
TE	Trailing Edge
UAS	Uncrewed Air System
UK	United Kingdom
VF	Vertical Fin

1. Introduction

1.1 Background and scope of the programme

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 crewed aviation.

Whilst aircraft collision risks such as bird strike have benefitted from decades of research, the rapid emergence and evolution of consumer drone technologies has required a more-agile response from regulators and the research community.

EASA has been active in monitoring and addressing the risks and threats associated with mid-air collisions between drones and crewed aircraft . Indeed regulatory efforts have been directed to address and minimize the likelihood of a collision occurring, and creating the conditions to safely achieve gradual integration of drone operations in airspace traditionally allocated to crewed aircraft.

In 2016, EASA assembled a 'Drone Collision' Task Force [3] to consider potential mid-air collision threats between crewed aircraft and small, consumer-grade drones. The consumer-market drone category was selected on the basis of several considerations, including: the size and anticipated growth of this market segment; the possibility to operate such drones within the Open category with no need of specific authorization from the Authority ("buy and fly") and the absence of a requirement for coordination with the Air Navigation Service Provider (ANSP) or specific Detect And Avoid (DAA) systems. Focus on the consumer market, means that the drones of interest typically occupy the lower mass classes within the Open category.

The Drone Collision Task Force in 2016 identified further research requirements with input from a broad group of industry stakeholders. Recommendations from the Task Force report [3] 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 crewed aircraft types [4,5].

The current programme, 'Vulnerability of Manned Aircraft to Drone Strikes' (EASA.2020.C04) [6] 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, as defined within EASA's Tender Specification [6] and project description:

- *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 [7] is split into nine tasks, as depicted in Figure 1-1. The work within the programme has been documented over the last 3½ year in reports to EASA, some of which have been published on their website [8].

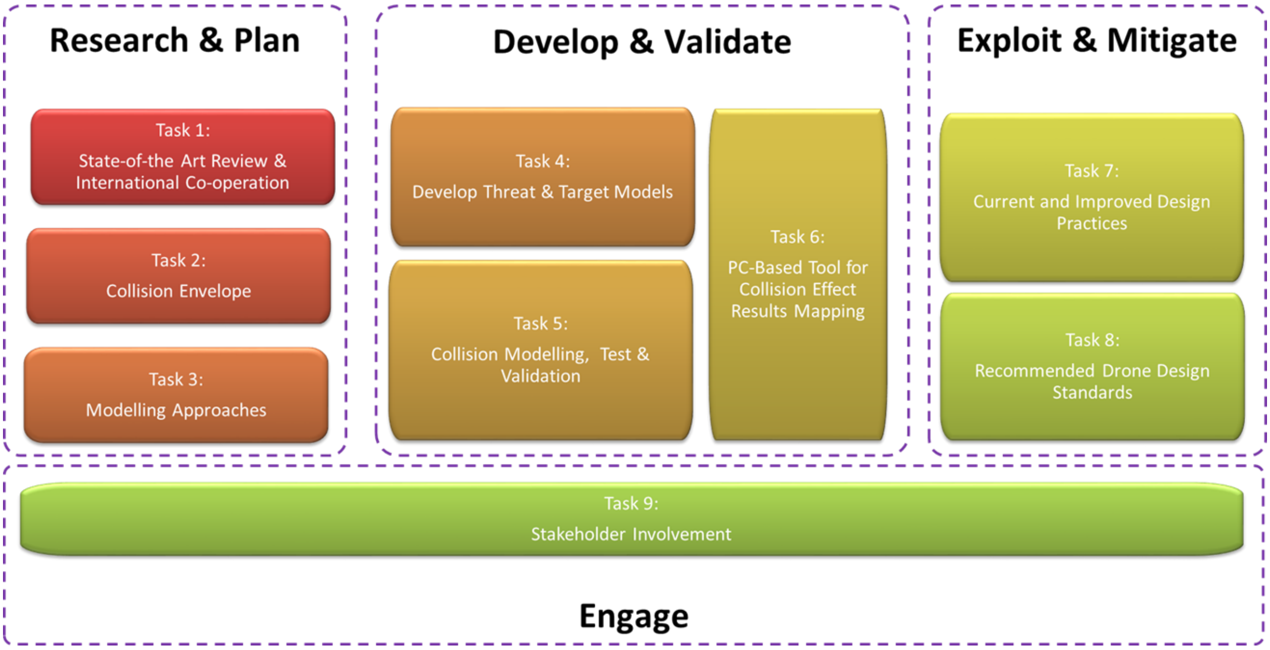

Figure 1-1: Programme structure

1.2 Scope of report

This report presents data and information to satisfy deliverable D8.1 and D8.2, within Task 8 of QinetiQ's 'Vulnerability of Manned Aircraft to Drone Strikes' programme.

The aim of the report is to provide drone design guidelines and a draft design standard that will manage and mitigate the hazard associated with potential drone strikes against crewed aircraft.

The report begins, in Section 2, with a summary of the work completed within the wider research programme. This is relevant because the recommendations made within this document are based upon knowledge gained through these earlier activities.

Observations and recommendations are provided in the following sections:

- Section 3: Guidelines on design practices to reduce the severity of drone collisions.
- Section 4: Factors affecting the development and specification of standards.
- Section 5: Development of a design standard.
- Section 6: Observations on design practices for crewed aircraft and opportunities to address identified vulnerabilities.
- Section 7: Recommendations for further work, to exploit the knowledge developed within this programme.

Additional information that supports the data presented in the main body of the report is included in Appendices. This includes examples illustrating the history of the programme in Appendix A, a summary of certification requirements for crewed aircraft in Appendix B, and draft text for a drone design standard in Appendix C.

2. Summary of completed research activities

Through a series of managed research activities, the majority of the programme has been dedicated to developing a comprehensive understanding of drone collisions, and their effect on crewed aircraft. Outputs from these activities have provided EASA with tools and quantitative data on the vulnerability of different categories of crewed aircraft to popular modern drones within EASA's Open category, during different phases of flight.

This section of the report provides a summary of the background work completed to date, including the extensive development and validation of simulation methods that have been employed throughout the programme.

2.1 State-of-the-art review

At the start of the programme, a review was undertaken of worldwide literature relating to the assessment of drone strikes by analysis or test. The methods, findings and results from existing research, along with details of confirmed drone-related mid-air collision events, was compiled into a report that has since been published on EASA's website [9].

At the time of writing, the focus in the literature was mainly on fixed wing crewed aircraft, including Leading Edge (LE) impacts and, secondary to that, windshields and engine ingestions. The majority of studies identified were based upon, or included, a version of the DJI Phantom drone, which was a highly popular product from 2013. Other examples of multi-rotor drones ranged from the 0.3kg DJI Spark up to the 3.4kg DJI Inspire, plus a 1.8kg (4.0lb) fixed wing Precision Hawk. Whilst the data available from the literature was highly relevant to the objectives of this programme, it was not sufficient to meet EASA's broad objectives.

As part of the literature review, strong links were made with leading international research organisations and related programmes. These linkages provided opportunities for greater collaboration, which has maximised the benefit of world-wide investment in this important area of research.

In addition to data identified through the literature review, QinetiQ has been active in the assessment of drone collisions since 2016 [11]. Early activities included a major programme in which the windshields of multiple aircraft (including fixed wing and rotorcraft platforms) were evaluated by simulation and full-scale drone impact testing. This built upon existing bird strike analysis and test methodologies, but included pioneering new workflows to characterise the drones and develop new test facilities with an on-site partner organisation, Natural Impacts. The finite element (FE) based methods, tools, facilities and models developed by QinetiQ within this, and subsequent programmes provided the capability to underpin the research being undertaken for EASA.

2.2 Drone threat models

Following a market survey and consultation with market-leading drone OEMs, five drones (listed below) were selected for study within this programme. These represent popular, modern mass-market consumer/prosumer products within the EASA's Open category. They include a variety of current and emerging styles of multi-rotor and fixed wing configurations, including a low-cost first person view, 'FPV' drone. The products were selected based upon their ubiquity and also how representative they are of a wider sub-class of drones within the marketplace, and <u>not</u> because they were perceived to present a greater threat than comparable products from other manufacturers. The below list includes a description of the drone type, the example product, and the asweighed mass of a procured specimen[1]. Photographs of each of the selected drones are shown in Appendix A.1.

• Pocket-sized compact camera drone:	DJI Mavic Mini	(249g)
• Racing-style FPV drone:	Eachine Wizard X220s	(540g)
• Prosumer compact folding camera drone:	DJI Mavic 2	(905g)
• Fixed wing drone:	Delair UX11	(1365g)
• Professional camera drone:	DJI Inspire 2	(3426g)

Although the EASA Open category may include drones up to 25kg, it was determined, with agreement from the project Stakeholders, that most mass-market consumer/prosumer products are at the lower-end of this mass range i.e. with a maximum take-off mass of approximately 4kg.

Each of the selected drone products have been developed into a detailed finite element model for use in collision simulations[2]. This followed a multi-stage approach involving reverse-engineering of the geometry, identification and mechanical characterisation of materials, development and calibration of components and sub-assemblies, and final assembly of the models [2]. Each model was incrementally calibrated and validated through a pyramid of tests, as shown in Figure A-2 of Appendix A.2. Images of an example drone model, illustrating the level of detail, are show Appendix A.3.

Reverse engineering of the geometry was achieved through detailed survey of assembled and dis-assembled drone products using photogrammetric and surface scanning methods. The scan data was then used to develop accurate but simplified CAD representation of the airframe and key components. Where data was not available from the literature or the manufacturers, the materials used in each drone were identified using a combination of Fourier-transform infrared spectroscopy (FTIR) methods for non-metallic parts and a Scanning Electron Microscope using a dispersive X-ray detector for metallic parts. Where necessary, bespoke testing was undertaken to characterise the mechanical properties of materials, including non-linear behaviours and failure.

Motors, batteries and cameras were identified as being critical items within each drone, and these were represented in greater detail as separate sub-assemblies within the threat models. The FE representations of these components were calibrated and validated via a series of static crush and dynamic impacts tests against Hopkinson Bars. An example of one of the component impact tests, alongside a simulation of the event, is shown in Appendix A.4.

For most of the drone models a further stage of validation was undertaken, in which a whole drone was impacted against a Hopkinson bar and the results were compared against simulations. An example of this is shown in Appendix A.5.

2.3 Aircraft structures

The scope of the research programme included a requirement to assess the vulnerability of aircraft within the following EASA Certification Specifications (CS): CS-23 'Normal, Utility, Aerobatic and Commuter Aeroplanes', CS-25 'Large Aeroplanes', CS-27 'Small Rotorcraft', and CS-29 'Large Rotorcraft'.

Following a review of typical aircraft types within these classifications, it was observed that the CS-23 and CS-27 classifications included a broad range of aircraft styles, so it was decided to split them into three and two sub-classes, respectively. The final list of aircraft categories are:

- CS-23 single propeller general aviation;
- CS-23 twin propeller general aviation;

[1] Note that the mass of some products depends upon the system configuration options. The masses shown in this table are correct for the configurations that were assessed within this programme.

[2] The Inspire 2 model was developed and validated by QinetiQ prior to the start of this programme.

- CS-23 small business jet;
- CS-25 commercial jet airliner;
- CS-27 small rotorcraft (lower);
- CS-27 small rotorcraft (upper);
- CS-29 large rotorcraft.

Example aircraft were selected to represent each of the above categories and models of each were developed, as shown in Appendix A.6. The selection of representative aircraft was based upon a review of popular types with traditional aluminium alloy airframes.

A peer-reviewed prioritisation exercise was completed to down-select critical impact locations for each of the aircraft. This assessment was based on the relative probability of a feature being impacted; the perceived vulnerability of the feature to impact damage; and the criticality of the feature to the safety of the aircraft and its occupants. The following features were selected[3] and are highlighted in Appendix A.6:

- Wing and empennage leading edge structures (fixed wing aircraft)
- Windshield structures (all aircraft classifications)
- Wing struts (low-end CS-23 aircraft)
- Propellers (low-end CS-23 aircraft)
- Main rotor and tail rotors (rotorcraft)
- Main rotor pitch linkages (rotorcraft)

Based upon this list, a series of 'local target models' were developed for drone strike simulations [13]. These were Finite Element Models (FEM) developed using a combination of data from measurements of physical aircraft hardware, repair manuals, literature and collaborative input from the ASSURE programme[4]. Examples of local targets are shown in Appendix A.7.

Appropriate material models, required for the FEM, for each type of crewed aircraft local target were calibrated and validated via a pyramid of bespoke testing, published tests and QinetiQ background data. This included quasi-static and impact tests using a range of projectiles including ball bearings, simulated engine fragments, drone components and whole drones against representative panels and aircraft structures.

The aircraft represented within this programme are of traditional metallic construction, with leading edge components manufactured from 2024-T3 aerospace aluminium alloy. Material models for this alloy were calibrated against multiple sources of data, including impact testing against different thickness panels.

Work has also been undertaken to validate modelling approaches for common windshield materials, including acrylic, glass, PVB and polycarbonate.

These model development and validation activities ensured that the collision modelling activities to proceed with confidence in the fundamental analysis methods.

2.4 Validation of collision simulations

The final stages of validation for the collision modelling capability involved drone impact testing against full-scale aircraft structures. Results from these tests, alongside QinetiQ background data from other test programmes, published test results and published high-quality simulation results, provided data by which the performance of QinetiQ's drone collision simulations were validated [14].

[3] Aero engine ingestion events were also identified as being of interest, but assessment of these was based upon a review of third-party data from the literature.
[4] ASSURE is the FAA's Centre of Excellence for Uncrewed Air Systems research in the US. The programme provides research to aid the safe integration and exploitation of UAS within the US national and international infrastructure, including relevant activities investigating airborne collisions.

The drone impact testing utilised bespoke gas gun rigs to accurately and repeatable launch whole/cut-down drones at speeds up to 280ms^{-1}. Full-scale tests included launching of modern multi-rotor drones into General Aviation wings, rotating tail rotors, pitch control linkages and main rotor blades. Example imagery from these tests is shown in Appendix A.8.

2.5 A scalable simulation framework

Whilst practical, economic and logistical constraints meant that the number of full-scale impact tests included in the programme was relatively small (in-line with a traditional pyramid model), the same limitations do not apply to the simulation technologies. Instead a 'modelling mushroom' philosophy (as illustrated in Figure A-3 of Appendix A.2) was developed, where early modelling work mirrors the lower-level test programme but the resulting validated capability is exploited to assess a large number of aircraft-level collision scenarios.

To aid the efficiency and quality of the collision simulation work, a 'collision modelling framework' was established based upon existing QinetiQ tools and approaches [15]. This framework standardised and semi-automated the set-up and post-processing of simulations once each of the drone and target FE models had been generated. Using the framework tools and processes, different combinations of drone threats and aircraft 'targets' could be combined, aligned, oriented and assigned collision speeds before simulation files are created for submission to the finite element solver, 'Abaqus Explicit'.

2.6 Collision scenarios

For each of the 24 local target models (across the 7 example aircraft), multiple impact locations and speeds have been evaluated for each of the drones [22]. In most cases, three collision speeds have been assessed through simulation. A lower-bound speed typically represents a low-level scenario such as take-off/landing of each of the crewed aircraft, and the upper-bound speed represents a higher-altitude phases of approach/climb. The third speed is based upon a probabilistic analysis of historical ADS-B derived aircraft flight data and a database of drone sightings, to estimate the speed at which a collision is most likely to occur for each category of aircraft.

In all cases, assumptions were made about the operating speed of the drones, which were combined with the aircraft speeds (different for each aircraft type) to give a collision speed to represent a direct, head-on impact. For low level scenarios (take-off/landing), it was assumed that the drone is operating at its maximum speed, including 'Sport Mode' if applicable. For scenarios between 500ft and 1,000ft height above ground, the cruise speed of the drone was assumed. For scenarios above 1,000ft, it was assumed that the drone pilot is using their available battery power to achieve high altitudes rather than normal flight, so multi-rotor drones were assumed to have negligible forward velocity whilst fixed wing drones were assumed to be at cruise conditions.

A description of the drone operating assumption and the work undertaken to establish this statistically-derived collision speed can be found in the 'Task 2 Collision Envelope' report, which has been published on EASA's website [1].

2.7 Aircraft damage classification

In order to process and compare the large number of collision results (from simulations and tests) in this study, it was necessary to develop metrics to classify the severity and effect of damage to the aircraft structures. These were based upon EASA's Impact Effect Assessment (IEA) and Hazards Effect Classification (HEC) methodologies [3].

For each collision result, an IEA level was assigned to classify the severity and extent of damage to the local impact region, based upon a four-level scale. A higher IEA represents a greater level of damage to the impacted local target region. Based upon the IEA and also the type of aircraft, a HEC was then assigned to indicate how this damage is expected to affect the continued safe flight of the aircraft and crew. The HEC output uses a two-level scale, where hazards are defined as either 'High' or 'Low'. The criteria used to establish the IEA and HEC classifications were developed by QinetiQ, with input from the EASA's Drone Collision Task Force findings, and industry experts within the project's Stakeholder Group [22].

An example of the criteria used to define the IEA level for different types/severities of damage is illustrated in Appendix A.9. This also shows how the IEAs map across to different HEC levels for each category of fixed wing aircraft. Appendix A.10 then shows an example of sentencing on a local target which condenses the results of 72 separate simulations.

It should be noted that a High HEC represents a hazardous condition that may directly or indirectly lead to injuries and/or fatalities, but it does not mean that such an outcome is inevitable.

2.8 PC-based drone collision results tool

Approximately 1,500 detailed collision simulations have been conducted to generate data on the vulnerability of each category of crewed aircraft. This has been a major computational exercise, greatly aided by automated workflows to minimise manual interventions and maximise utilisation of software licenses and hardware.

Once each simulation was completed via the collision modelling framework, QinetiQ's post-processing scripts were used to generate imagery, collision animations and data about the event. These were then reviewed to assign IEA and HEC classifications and the information was entered into a database.

The 'QinetiQ Drone Collision Results Tool' [16] was written to act as a repository for, and a means by which to readily access, the simulation and test data from the programme. This tool enables a non-expert user to view summary tables of results and also to interrogate the database of collision simulations to extract details of specific scenarios, which can be filtered by aircraft category and impact location. This database includes IEA and HEC data, as well as relevant imagery and animations of collision simulation results.

Functionality has also been included to estimate the outcome of collisions involving drones of different masses and collision velocities, based upon interpolation of known results within the dataset.

Further processing of the data is also possible within the tool, to assess the vulnerability of different aircraft to drone collisions. This is achieved by estimating probability that a randomly-located drone collision will result in a High (rather than a Low) HEC for a selected aircraft, drone and collision speed/phase of flight.

To accompany this tool, a report has been provided to EASA discussing the results of the collision simulations and vulnerability assessments. This highlights particularly vulnerable areas of each of the example aircraft and also identifies scenarios in which a High HEC event would not be expected. At the time of writing, this report is not publically available.

2.9 Summary findings of collision vulnerabilities

Results have shown that all of the example aircraft considered within this programme are vulnerable to drone strikes within the established envelope of credible collision velocities and drone masses. As expected, the severity of damage increases with collision velocity, so aircraft are less vulnerable at lower speeds and – in some cases – are able to withstand collisions with the lighter-weight drones.

Findings from the research work completed suggests the following particular vulnerabilities for each of the aircraft categories.

CS-23 aircraft:

- The lightweight CS-23 single propeller GA example was shown to be particularly vulnerable to impacts to its horizontal stabiliser, windshield and wing strut. At some impact locations, hazardous levels of damage (High HEC) are predicted for collisions with the 0.25kg pocket-sized compact drone at take-off speeds.

- The faster CS-23 twin-propeller GA example was slightly more robust and is less vulnerable to the lightest drone. However, its horizontal stabiliser, main wing and windshield may not sustain hazardous levels of damage if impacted by the 0.54kg FPV (and heavier drones) at take-off speeds.
- The high performance CS-23 business jet example is a more substantial airframe and, despite its increased operating speeds, performs much better than the GA aircraft. The horizontal stabiliser and vertical fin were shown to be most vulnerable to damage, though only the 3.4kg professional camera drone produced a predicted High HEC at the lowest considered speed (defined as crewed aircraft take-off speed in Section 2.6). At higher speeds, the FPV and heavier drones have the potential to cause hazardous damage. Whilst aero engines were not within the scope of this work, data from the literature [17, 18, 19] suggests that ingestion of any of the drones would cause blade damage but containment failure is not expected i.e. a Low HEC.

CS-25 Large Aircraft:

- The CS-25 jet airliner example was also predicted to be vulnerable to horizontal stabiliser impacts, with the 0.54kg FPV (and heavier drones) having the potential to cause hazardous damage at the lowest considered speeds (take-off speeds). The conclusions about engines are the same as for the CS-23 business jet.

CS-27 Small Rotorcraft:

- Work completed suggests that the lightweight CS-27 rotorcraft example is particularly vulnerable to tail rotor, main rotor pitch linkages and windshield impacts, where all drone can cause hazardous levels of damage.
    - High HEC damage was predicted to occur in the windshield for all drones during approach, and for the 0.54kg FPV and 3.4kg professional camera drone at hover. All drones can cause High HEC due to tail rotors, even at hover and drones greater than 250g were also shown to be capable of causing High HEC damage to the main rotor blades and pitch control linkages at hover.
- The upper-tier CS-27 rotorcraft example was shown to be vulnerable to windshield impacts by even the smallest drone when the acrylic screen variant is fitted. However, the alternative polycarbonate screen performs very well and was able to deflect event the heaviest 3.4kg professional camera drone.
- Furthermore, for the upper-tier CS-27 rotorcraft, an appropriate tail rotor test specimen was not available but, based upon the results of the lightweight CS-27 configuration, it is assumed that all of the drones would be capable of causing a High HEC in the event of a collision. Through impact testing, it was shown that the composite main rotor blade could withstand an impact with a 0.9kg drone whilst hovering, but collision with the same drone at cruise could cause a High HEC. The main rotor pitch linkages were shown to withstand collisions with the 0.54kg drone, but the 0.9kg drone could cause a High HEC at cruise speeds.

CS-29 Large Rotorcraft:

- The CS-29 rotorcraft example was assessed against windshield and rotor blade impacts. The 0.54kg FPV and heavier drones were shown to have the potential to achieve a High HEC against the example acrylic windshield. Although a suitable test specimen was not available for use within this
- programme, third-party evidence [21] suggests that CS-29 rotorcraft main rotors could withstand impacts with drones up to 1.81kg; however, results for heavier drones were not available. The same source in the literature [21] also suggests that 0.9kg drones could cause a High HEC against tail rotors, though no tests were conducted with lighter drones than this to determine a threshold value.

2.10 Collision mitigation investigations

In the later stages of the project, the collision simulation framework was used to evaluate the effectiveness of different drone design strategies to mitigate the severity of mid-air collision events. Comparisons were made against the following example aircraft structures:

- Leading Edge (LE) of Horizontal Stabiliser (HS) of the CS-23 Business Jet, and;
- Windshield of the CS-29 Large Rotorcraft.

By way of comparison with established impact threats, and to explore the limits of frangibility and homogeneity in drone design, early work included simulation of bird and drone strikes. Results from parameter studies provided evidence that drone collisions are more damaging than equivalent-mass bird strikes. In some cases, the velocity at which the drone caused a High HEC was approximately 55% that of an equivalent bird strike (the critical velocity for the bird was 80% greater than that of the drone).

In a follow-on activity, each of the five drones were scaled (by volume) to 0.9kg, and collisions simulations were run to assess the severity of damage caused by each drone *design*. Results showed differences in severity across the multi-rotor drone designs, but these variations were small compared to the bird-drone comparison.

Following this, a series of parameter studies were undertaken to explore potential design variables/features that could be used to manage potential collision hazards through updated drone design practices.

Of the considered design modifications that were explored, only a few achieved significant benefit against one or both of the two example aircraft target structures. Observations from these studies, the earlier aircraft vulnerability assessments, and other QinetiQ drone collision activities, have been exploited within later section of this report to inform the design of future drone products.

2.11 Additional exploitation of research for ground collision assessment

An additional task, outside the original scope of the programme, was undertaken to support EASA in evaluating the methods to estimate ground “critical areas” for small drones. The “critical area” is the region where high energy, injurious debris may be dispersed during a crash. EASA identified that the current methodology may be over-conservative for this size of drone and was reviewing an alternative, more realistic method.

QinetiQ undertook an independent study, whereby impacts were simulated between a ~3.4kg professional camera drone and rigid (e.g. tarmac) and soft (e.g. wet clay soil) ground targets. Two scenarios were tested, representing loss of power during forward flight at a height of 50m, and another representing a vertical drop-case at terminal velocity.

Outputs from this study supported the proposed methodology, which may result in a reduction in critical ground collision areas for some classes of UAS. If required further work, exploiting the methods and capabilities used within this programme, could be undertaken to assess a wider range of impact conditions and drones.

3. Drone design guidelines

3.1 Introduction and scope

The aims of this project include identification and recommendation of drone design strategies/guidelines that will minimise mid-air collision hazards, and drafting of an associated design and/or test standard.

When considering how to formulate appropriate guidelines and standards, the following 'high-level objective' has been inferred from the scope of the programme:

> *"That drone products be designed and constructed in such a way as to minimise the hazard to crewed aircraft, in the event of a mid-air collision"*

The scope of the measures to meet the above 'high level objective' are as follows:

- They aim to minimizing hazards to crewed aviation, from mid-air collisions with consumer drones that typically align with the lower classes of the Open category. However, they could be applied more widely to non-consumer products within the Open category and lower-end of the Specific category;
- They addresses safety hazards at the aircraft level as a consequence of potential impact damage, rather than being purely based upon the level of damage to impacted components;
- They could be applied to one or more drone classes, or could be common to all within the Open category;
- They seek to minimise hazards in the event of a collision, and do not address the likelihood of a collision event occurring.

3.2 Guidelines

The following guidelines (the 'Guidelines') are based upon conclusions from the work presented under Task 7 [12], observations from the drone collision simulation work undertaken throughout this programme, and QinetiQ's experiences on other drone collision programmes.

The first six Guidelines have been identified as 'Primary' because they have been developed into a design standard later in this report, while the remaining are described as 'Secondary'. The Secondary Guidelines include criteria that may not be appropriate to enforce for *all types* of drone so, instead, they are expressed as advice to designers.

3.2.1 Primary Guidelines

Guideline 1: OEMs should strive to minimise the mass of drone products. Overly-heavy constructions that are not required to meet the legitimate operational and safety use-case requirements of the product, should be avoided.

> *Why: Results from this study have shown a strong correlation between the effective impact kinetic energy*[5] *and the severity of its outcome. Minimising the mass of a drone product will reduce the threat that it poses in the event of a collision.*

[5] Impact kinetic energy is defined by ½.m.v^2, where 'm' is the mass of the drone and 'v' is the relative impact velocity (accounting for the velocity of the drone and the aircraft). This assumes that the mass of the drone is small compared with that of the crewed aircraft, which is an appropriate assumption for the mass-market Open Category drones considered in this project.

Guideline 2: OEMs should limit the maximum speed of their products, either through the physical capabilities of the propulsion system or software controls. Excessive maximum speeds, that are not required to meet the legitimate operational and safety use-case of the product, should be avoided.

Why: Results from this study have shown a strong correlation between the effective impact kinetic energy of a collision and the severity of its outcome. Kinetic energy is a function of velocity-squared, so the outcome is particularly sensitive to this parameter. It is noted that the collision velocity must also account for the speed of the crewed aircraft, but limiting the speed of the drone will mitigate the threat associated with a worst-case collision.

Note: EASA's drone classification system [10] limits the maximum speed of 'C0' and 'C1' class drones. No restrictions are placed on the maximum speed of other drones classes within the Open category (C2, C3 and C4).

Guideline 3: For fixed wing drones, 'pusher propeller' designs are preferred, rather than 'puller propeller' configurations.

Why: In a puller propeller configuration the motor is installed at the front of the drone, with its axis aligned with the direction of travel. In a frontal collision this dense, high stiffness component will directly impact the aircraft with a speed equal to the sum of the drone and aircraft speeds. In a similar frontal impact with a puller propeller configuration, the aft-mounted motor is less likely to impact the aircraft directly. A direct impact with the motor would occur in the event of a rearwards collision, but in this case the collision velocity would be equal to the crewed aircraft speed minus the drone speed. The difference in impact speeds for these two cases is therefore double the flight speed of the drone.

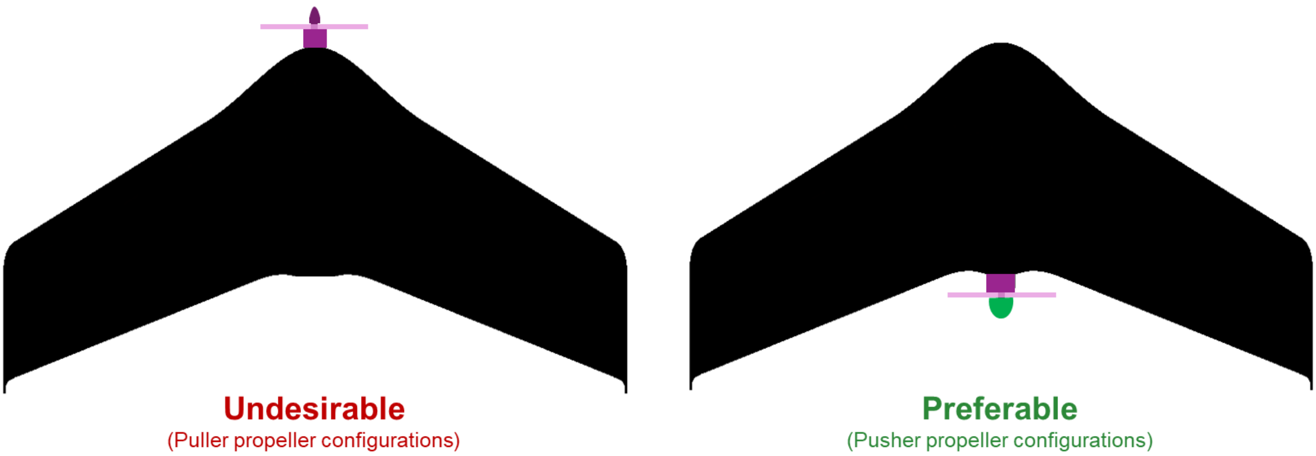

Figure 3-1: Schematic illustrating preference for pusher propeller configurations

Guideline 4: Where spinners are used on horizontally-mounted motors, slender and /or pointed designs should be avoided, and the potential of energy-absorbing mechanisms considered.

Why: Slender, small-diameter spinners and, by analogy, exposed spindles and other pointed features, could concentrate impact forces in the event of a collision; this can lead to premature initiation of damage and a more-severe hazard. Large-diameter spinners (or a flat-face with no features to intensify impact loads) were shown to be preferable.

OEMs should also explore the potential to incorporate energy absorbing materials and/or features into spinner designs.

Figure 3-2: Schematic illustrating preference for larger-diameter spinners

Guideline 5: Frangible and/or folding motor arms are preferred to excessively stiff/strong constructions. However, designs must also comply with the structural integrity requirements of all relevant standards.

Why: During an impact in which the motors strike the aircraft, frangible or articulating arms will fail/fold back, rather than allowing inertia loads from the fuselage to be reacted through the motors. This reduces the likelihood of damage prematurely initiating at the motor impact site.

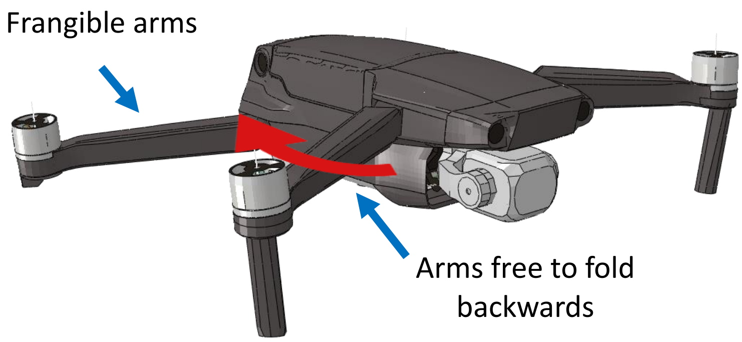

Figure 3-3: Example of folding arms, with limited capacity to transmit impact loads

Guideline 6: The use of tough but flexible 'bumpers' around motors, to distribute and attenuate impact forces, is desirable. Beneficial effects can be achieved by increasing the effective area of the motor to reduce stress concentrations around the stiff motor body and improve the distribution of impact loads. There is also potential to tailor the stiffness and crush performance of the bumper to further attenuate forces, and minimise the hazard posed by the motors.

Why: Motors are typically the first point of contact during drone collisions. The severity of the outcome can be influenced by the level of damage that they cause. This can be mitigated by including 'bumper' features that attenuate peak impact forces, reduce stress concentrations around stiff motor bodies, and increase the effective size of motor installation.

3.3 Secondary Guidelines

Guideline 7: For multi-rotor drones , it is desirable to vertically offset major sub-assemblies such as motors and externally-mounted camera systems from the centre of mass of the fuselage/body of the drone.

Why: As well as spreading the impact over a wider area, applying a vertical offset between the body and major sub-systems can reduce the mass of components that directly collide with certain classes of target structure. For example, horizontally-aligned main rotor blades are relatively slender so the blade may only strike the body, the motors or the camera. In the case of horizontally-aligned leading edges, even if the offset is insufficient to prevent the whole drone being impacted, only part of it would be able to strike the tip of the aerofoil whilst the remaining components will impact an angled part of the structure. In these scenarios, this effectively reduces the mass of the projectile, which addresses the dominant collision severity variable i.e. kinetic energy.

The below figure shows an example of vertically offset motors, and how they may affect impacts against slender horizontally-aligned aircraft structures such as leading edges.

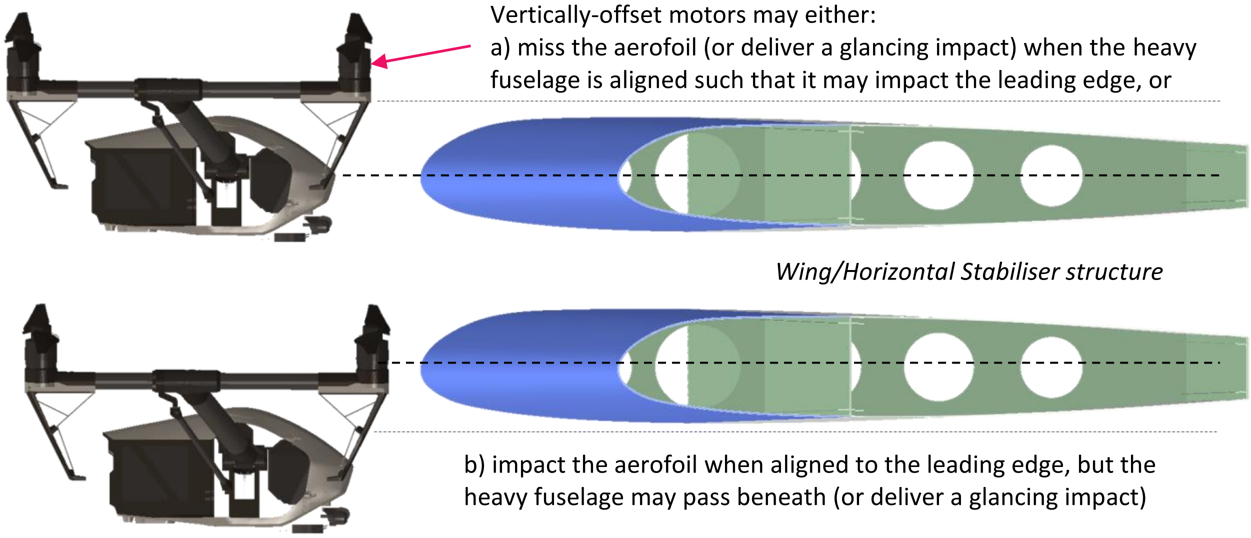

Figure 3-4: Views of example drone impacting a slender leading edge structure

Guideline 8: Major components such as cameras, batteries, discretely packaged mission systems and motors should not be installed directly adjacent to each other without gaps between them. These gaps should not be filled with stiff/incompressible material. Furthermore, the structure that each of the systems are mounted to should be designed to deform and/or fail in the event of a collision.

Why: Offsetting components reduces peak impact loads by disassociating each of the major masses. It also allows them to break apart and separate upon impact, rather than acting as a single train of projectiles. As an example, for frontal impacts, in-line camera structures can become sandwiched between the target and the heavier body of the drone. This has been observed to concentrate loads on the target structure and increase the severity of damage.

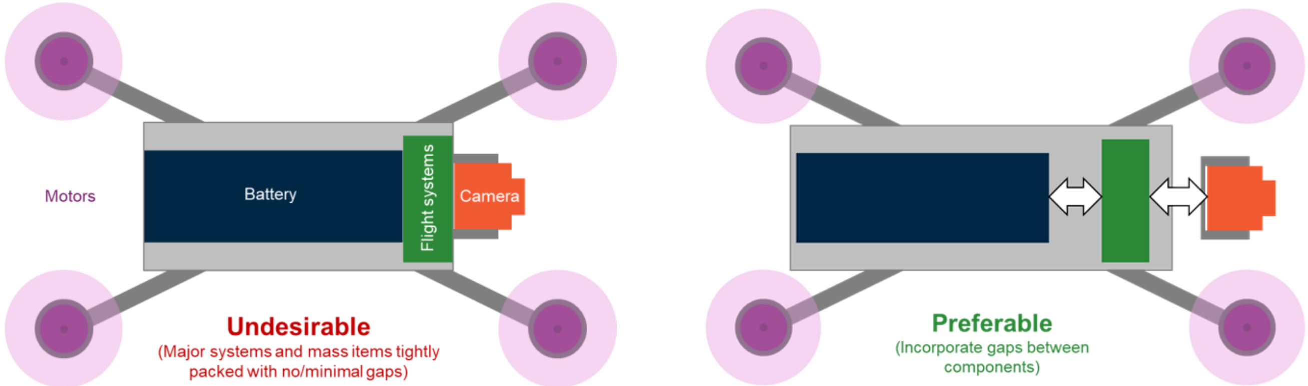

Figure 3-5: Schematic showing preference for spacing between system components

Guideline 9: Major components such as cameras, batteries, discretely packaged mission systems and motors should not be installed on a common axis or, where possible, a common plane. Instead, it is desirable to offset them vertically and/or laterally and distribute them within the available volume.

Why: Distribution of components and installing them on different axes/planes encourages them to deflect and separate during a collision rather than act as a single train of components.

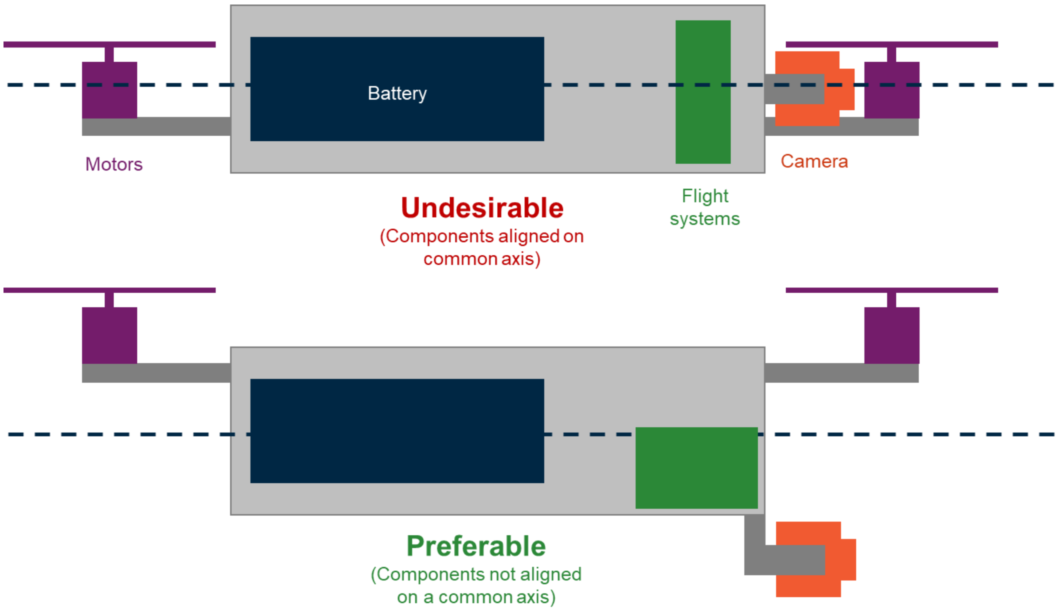

Figure 3-6: Schematic showing preference for offset and/or distributed components

Guideline 10: Pouch-style batteries (in rolled or layered configurations), with cases that are not excessively strong under high-speed impact conditions are preferred, rather than batteries containing cylindrical steel-case cells.

Why: The cylindrical steel-cased cells, which are found in some drones and many non-drone consumer products, are less frangible than the pouch-style cells that are more-commonly used in drones. Under high-speed impact conditions, batteries with pouch-style cells will tend to break apart whereas the cylindrical cells will retain greater structural integrity and become more formidable projectiles. Furthermore, during hi-speed impact testing with fully-charged cells, it was observed that the cylindrical cells were prone to self-ignition, which may pose a secondary hazard.[6]

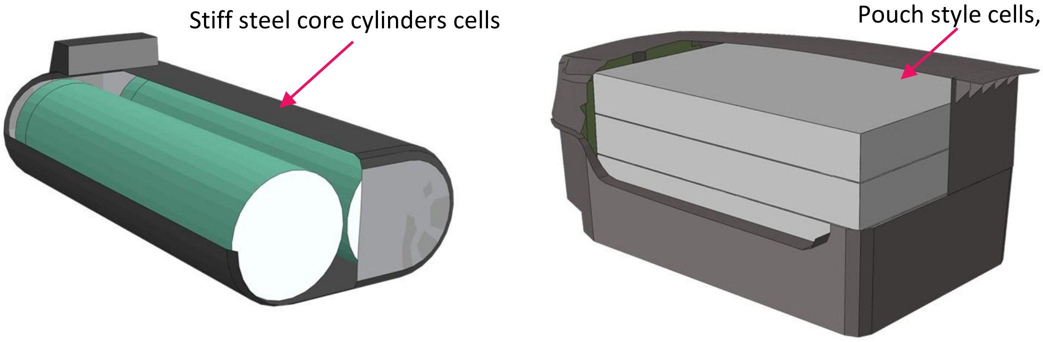

Figure 3-7: Images showing two battery types. Pouch-style batteries are preferred in the event of collisions.

Guideline 11: Where front-mounted cameras are used, avoid excessively stiff and strong cases which can act to concentrate impact forces in the event of a collision. Frangible plastic cases and thin lens barrels are preferred.

Why: Using more-frangible camera structures rather than stiff, strong cases will reduce the concentration of loads on the aircraft structure as the camera is pressed into it by the mass of the drone.

Guideline 12: The use of bulk crushable foam materials in fuselage structures is desirable. When used, for example in fixed wing configurations, the major system components should be 'buried' and secured within the fuselage rather than being exposed to direct impacts, as illustrated in the below figure.

Why: The crushable foam materials used in the example fixed wing drone were effective at mitigating the severity of collisions. Securely encapsulating the major components of the drone within a crushable foam fuselage reduces the likelihood of them directly impacting the aircraft structure and allows them to be decelerated (relative to the aircraft) over a greater time period.

[6] Although this was a conclusion from the current study, a member of the Stakeholder group has suggested that there may be other advantages of using cylindrical cells, including their increased resistance to low-velocity impacts. Design decisions on the type of batteries should consider the dominant safety requirements that are relevant to the product and its anticipated operation.

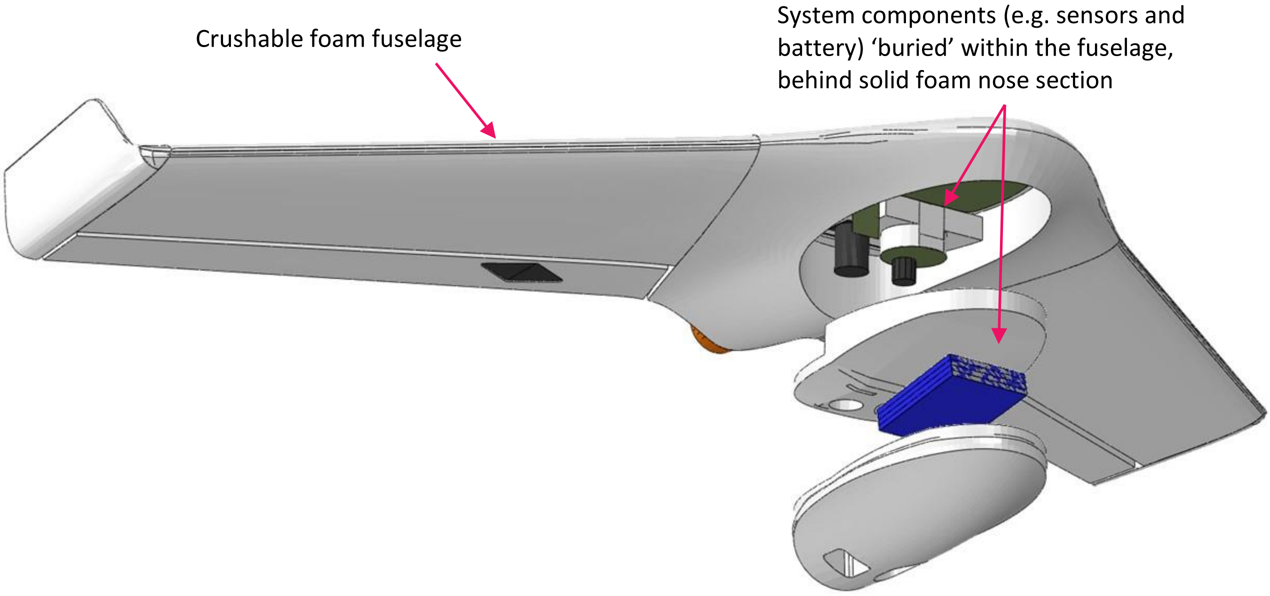

Figure 3-8: Example of drone systems 'buried' within a crushable foam fuselage

Guideline 13: Features that promote the deflection of the drone in the event of an impact and attenuate peak impact forces are desirable. Examples may include tough, 'springy' legs/undercarriage that engage with the aircraft structure in the early stages of a collision event.

Why: Measures that reduce the rate at which the drone is decelerated (relative to the aircraft) and/or encourage it to be deflected over/under/around the structure rather than penetrating it can be effective at reducing the severity of damage.

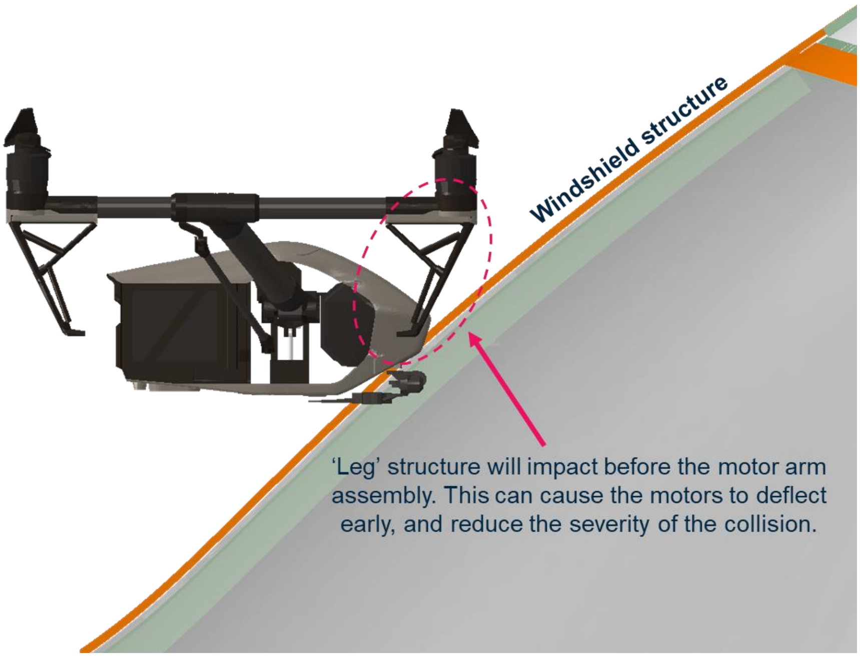

Figure 3-9: Example feature that can aid deflection of the drone and attenuate impact forces

4. Factors affecting the development and specification of standards

4.1 Formalising the Guidelines

Publication of the drone design Guidelines in Section 3 is an expedient means by which to share best available information with designers and manufacturers. However, whilst the Guidelines provide information that can be used to manage and reduce the damage potential of future drones, their adoption by manufacturers would only be on a voluntary basis.

Through working with drone manufacturers in the project's Stakeholder group, it is clear that there is an ongoing commitment to continued improvements in aviation safety. However, regulators may review the body of knowledge made available by this project to assess whether additional, specific actions should be recommended.

As discussed in Section 3.1, the scope of the project also includes the development of a draft design and/or test standard, based upon the Guidelines.

4.2 Types of evidence

This sub-section considers what forms of evidence might be appropriate when assessing whether new drone designs meet the 'high-level objective'. Identification of preferred evidentiary methods provides a basis on how design and/or test standards could be formulated.

Possible sources of evidence could include combinations of the following:

- **Physical testing:** Comparison of observed/measured results against defined criteria;
- **Validated simulation:** Comparison of engineering simulation results against defined criteria;
- **Deterministic pass/fail criteria:** Against specific design requirements (design standard);
- **Technical argument:** Demonstrating that design measures meet the intent of the standard.

The individual merits of these are discussed below.

4.2.1 Physical collision testing (test standard)

Physical impact testing of representative aircraft structures, to demonstrate their compliance with conventional impact threat requirements such as bird strike, is commonplace within the industry. Furthermore, if a test-based certification approach were to be adopted, then it may negate the need for additional design standards, which would allow greater flexibility over designs. However, impact testing of drones as part of routine drone product certification processes is not currently considered to be appropriate for the following reasons:

- Full-scale testing of high-speed drone collisions is a complex activity that requires highly-specialist equipment and experience in order to ensure reliable impact conditions. Any undesired variation in the impact conditions e.g. drone orientation, could introduce significant uncertainty into the results, which would undermine the benefits of a practical approach.
- Testing of this nature may be appropriate when assessing the ability of an aircraft structure to withstand a well-defined, standardised threat. However, it wouldn't be appropriate to assess different drones against a single standardised deformable target, because this would need to be representative of different local target regions, such as leading edges and windshields. Even if a range of targets were

to be defined (representing different aircraft features and designed for different drone masses), a method of accounting for different drone masses and performance characteristics would need to be conceived. This could involve scalable targets with a single pass/fail criteria, or multiple impact tests against each target to determine the velocity at which the target is overcome by the drone. Either way, considerable further work would be required to determine metrics to assess whether the tested product is compliant with severity expectations associated with its mass and Class.

- Tests against a rigid, instrumented target could be used to compare impact forces between different drones. However, this would not capture the complex interplay between the drone and a wide variety of deformable targets, so further work would be required to interpret the results.
- A requirement to include physical testing in a drone certification programme would introduce significant expense and risk to the later stages of a product development programme. A representative physical prototype would be required and failure of a test could result in lengthy delays and costly re-work.

4.2.2 Validated simulation (simulated tests)

Validated simulation, such as the work that has been undertaken within this research programme, is considered to be an appropriate method for demonstrating the collision performance of new drone designs.

Unlike testing-based methods, simulation allows full control over the impact conditions and target specimens, the ability to assess multiple collision scenarios with minimal additional cost. Simulation also allows assessments to be made earlier within the design cycle rather than requiring manufactured test specimens. Furthermore, a simulation-based approach would not place specific design restrictions on the design of drones, as the pass/fail criteria would be based upon simulated collision outcomes rather than strict compliance with a design standard. However, a simulation-based approach would require access to specialist skills, tools and data, which are unlikely to be native to current drone design organisations; these capabilities are currently located in a small number of centres of excellence, worldwide. It should also be noted that a simulation-based approach would also introduce additional risk into the development and certification process, because compliance could not be guaranteed by design. However, this risk may be mitigated through preliminary assessments early in the design phase, comparisons with known products, and experience.

Where simulation is used, an appropriately-detailed finite element representation of the drone design should be simulated colliding with at least two types of target, including leading edge and windshield structures such as the example configurations used within Task 7 of this programme. The velocities and energies at which the drone causes High HEC level damage to the target structures would then be compared against baseline results for current drone designs.

This work would need to be undertaken to a similar standard to that performed within this study, using suitably qualified and experienced personnel (SQEP) in the field of drone collision simulation.

4.2.3 Standards based on design criteria (design standard)

The Guidelines have been written to define positive steps that can be taken to minimise collision threats. They could be reformulated as a design standard, to provide evidence of compliance with a high level objective requirement aimed at minimizing the probability that a collision would result in a hazardous event.

4.3 Status of drone collision evidence to support the development of a draft standard

The majority of this programme has been dedicated to developing a broad and detailed understanding of collisions between modern consumer/prosumer drones and the major classes of crewed aviation. This has provided a world-class understanding of aircraft vulnerabilities to drone strikes, and the relative threat posed by different types of commonly-available drone within the Open category. In the later stages of the programme, the assessment methods were used to evaluate the effect of drone design features (and other attributes) on the resultant collision severities. Results and observations from both phases of the programme have been used to inform the content of this report.

Outputs from the programme have successfully highlighted links between key design parameters and aircraft-level damage severity. These, and other potentially beneficial features, have been captured in the Guidelines.

Consequently it was determined that a draft standard should be formulated on the basis of these design Guidelines. These focus on measures that can be taken at the design stage, rather than the specification of testing a standard to demonstrate compliance of a manufactured product. The technical reasons for not proposing testing-based compliance evidence were elaborated upon in Section 4.2.1. Furthermore, a design standard was considered to be commensurate with industry's need to minimise certification risks.

A draft design standard, containing proposals for four sets of criteria, has been developed and is described further in Section 5. These proposals would require further work to convert them into an official Open category standard (EN or prEN). If the Regulator decides to progress any of the recommendations, then the task of analysing, repackaging and adapting the formulated drafts in a way that is compatible with European Norms and with the overall legal, societal and industrial landscape, is left to future official standardization working groups.

5. Development of a design standard

This section describes the contents of a draft design standard, that is based upon findings of this study.

Not all of the Guidelines have been translated into design criteria within this draft standard. This is because some Guidelines may not be relevant, or may be overly-restrictive, for certain types of current or future drones. Instead, work has concentrated upon the design variables and recommendations that are practically achievable and are expected to have the greatest effect on minimising the severity of potential mid-air collisions. The six Primary Guidelines (Section 3) have been condensed into four separate criteria, which are discussed below.

5.1 Proposed criteria

5.1.1 Impact energy: Drone mass and maximum speed criteria

As an outcome of this programme, impact energy was identified as being the dominant variable in determining the severity of a collision[7]. This is defined by the mass of the drone and the collision speed, both of which can be influenced at the design stage.

The effect of drone mass and drone speed, on the probability that a mid-air collision will result in a hazardous condition for different categories of crewed aircraft, is evaluated in a separate QinetiQ deliverable to EASA [22]. Example data from this report is shown in Figure 5-1 (Business Jet) and Figure 5-2 (Large Rotorcraft). Here, the probability (expressed as a percentage) that a of a given mid-air collision results in a hazardous condition, increases with the mass and velocity of the drone. A similar trend exists for all categories of aircraft.

Drone Collision Vulnerability: CS-23 Light Business Jet										
		Flight Case		Take Off		Aircraft Speed		66.9m/s		
		Drone Velocity								
		10m/s	15m/s	20m/s	25m/s	30m/s	35m/s	40m/s	45m/s	50m/s
Drone Mass	0.25kg	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.50kg	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.75kg	0%	0%	0%	0%	2%	2%	2%	16%	16%
	1.00kg	0%	0%	2%	2%	16%	16%	16%	16%	16%
	1.25kg	2%	2%	16%	16%	16%	16%	16%	16%	16%
	1.50kg	2%	16%	16%	16%	16%	16%	16%	16%	16%
	1.75kg	16%	16%	16%	16%	16%	16%	16%	16%	16%
	2.00kg	16%	16%	16%	16%	16%	16%	16%	16%	16%
	2.25kg	16%	16%	16%	16%	16%	16%	16%	16%	25%
	2.50kg	16%	16%	16%	16%	16%	16%	16%	25%	25%
	2.75kg	16%	16%	16%	16%	16%	16%	25%	25%	36%
	3.00kg	16%	16%	16%	16%	16%	25%	25%	36%	36%
	3.25kg	16%	16%	16%	16%	25%	25%	36%	36%	36%
	3.50kg	16%	16%	16%	16%	25%	36%	36%	36%	36%
	3.75kg	16%	16%	16%	25%	36%	36%	36%	36%	36%
	4.00kg	16%	16%	25%	25%	36%	36%	36%	36%	36%

➨ Figure 5-1: Estimated probabilities that a multi-rotor drone colliding with a CS-23 Business Jet will result in a hazardous condition. Data is presented for drones of different masses and speeds.

[7] The relationship with energy was shown to apply to consumer-class drones, which are typically less than 4kg mass. The direct correlation may vary for larger drones that distribute impact loads over wider areas, but increasing the impact energy of a given drone will consistently lead to increased damage severity.

Drone Collision Vulnerability: CS-29 Large Rotorcraft										
				Flight Case	Hover		Aircraft Speed		0.0m/s	
		Drone Velocity								
		10m/s	15m/s	20m/s	25m/s	30m/s	35m/s	40m/s	45m/s	50m/s
Drone Mass	0.25kg	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.50kg	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0.75kg	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1.00kg	0%	0%	0%	0%	0%	0%	0%	0%	15%
	1.25kg	0%	0%	0%	0%	0%	0%	0%	15%	15%
	1.50kg	0%	0%	0%	0%	0%	0%	15%	15%	15%
	1.75kg	0%	0%	0%	0%	0%	0%	15%	15%	30%
	2.00kg	0%	0%	0%	0%	0%	15%	15%	30%	30%
	2.25kg	0%	0%	0%	0%	0%	15%	15%	30%	30%
	2.50kg	0%	0%	0%	0%	0%	15%	30%	30%	30%
	2.75kg	0%	0%	0%	0%	15%	15%	30%	30%	30%
	3.00kg	0%	0%	0%	0%	15%	15%	30%	30%	30%
	3.25kg	0%	0%	0%	0%	15%	30%	30%	30%	30%
	3.50kg	0%	0%	0%	0%	15%	30%	30%	30%	30%
	3.75kg	0%	0%	0%	15%	15%	30%	30%	30%	30%
	4.00kg	0%	0%	0%	15%	15%	30%	30%	30%	30%

Figure 5-2: Estimated probabilities that a multi-rotor drone colliding with the frontal fuselage a hovering (zero ground speed) CS-29 Large Rotorcraft, will result in a hazardous condition. Data is presented for drones of different masses and speeds. Note that the probabilities exclude rotor blade impacts, though results for rotors are provided in other project reports [22].

Drones of up to 25kg maximum take-off mass (MTOM) are permitted within the Open category. For products with class markings C2 to C4 (inclusive), no limits are currently placed on the maximum flight speed of the drone.

A draft standard (shown in Appendix C.1) has been proposed to define an acceptable maximum performance envelope that could be applied to all or some classes of drone within the Open category. The envelope bounds the maximum permissible speed capabilities of a drone (in straight and level flight) as a function of its MTOM. In the draft proposal, the maximum allowable speed of $40ms^{-1}$ is based upon the perceived legitimate requirements of a small aerobatic drone weighing less than 0.75kg, though this would need to be refined through further consultation.

The proposed performance envelope is limited to drones of up to 4kg MTOM since this captures consumer products, which are the focus of this study. However, it could be extended to account for drones up to 25kg within the Open category.

The restrictions imposed by this proposed requirement are in addition to limitations prescribed by other relevant standards and/or regulations. Note also that the proposed limitations on performance envelope would not fully mitigate collision threats, but it would mitigate against drone configurations that are likely to pose elevated hazards.

5.1.2 Fixed wing propulsion: Pusher and puller propeller configurations

Results from this study showed that, for fixed wing drones, 'puller propeller' configurations represent a greater potential collision hazard to crewed aircraft than equivalent 'pusher propeller' designs. The reasons for this are briefly explained in the Guidelines (Section 3).

Potential responses to this finding could include the measures below, or combinations thereof:

- Avoid puller propeller designs within the Open category
- Avoid puller propeller designs within certain classes of UAS within the Open category
- Require additional design mitigations/constraints for puller propeller UAS configurations, e.g. spinner designs identified in Section 5.1.3.

The focus on this study is on consumer drones, which are typically less than 4kg MTOM. Provided that they meet the other technical requirements of their class, these products may be eligible to be certified as C2 or below. Lightweight (<0.25kg) C0-certified designs are considered to represent a reduced threat, because their small, lightweight motors will have lower damage potential. Therefore, the draft standard (shown in Appendix C.2) proposes that puller propeller designs should be avoided in C1 and C2 classes.

Where this results in puller propeller fixed wing drones being certified as C3 (or higher), their operation will be restricted to the 'A3' sub-category within EASA's rules for UAS operation [10]. The A3 sub-category of operation requires users to operate the drone away from uninvolved people or properties, which effectively excludes urban areas where crewed aircraft may be operating. Whilst this doesn't directly address collisions over more-rural areas it does encourage the adoption of lower-threat designs.

It is noted that there is precedent for the exclusion of puller propeller designs from drone classes, because a similar restriction applies in prEN 4709-001:2021 [20].

5.1.3 Fixed wing spinner design

It is common for 'spinners' to be installed over the hub of a propeller of fixed wing drones. These spinners come in various forms, including conical, hemi-spherical and elliptical shapes of various aspect ratios and constructions. In some cases, spinners are omitted from the design and the hub of the propeller, attachment features and/or central spindle are exposed.

Results from this study showed that slender, small-diameter spinners and, by analogy, exposed spindles and other pointed features, could concentrate impact forces and prematurely initiate damage in the event of a collision. Large-diameter spinners (or a flat-face with no features to intensify impact loads) were shown to be preferable.

A set of criteria have been defined in Appendix C, to bound the external shape of the spinner, whilst maintaining design freedom within these constraints. In addition to the geometric constraints, a placeholder requirement has been included for the development of spinner designs that attenuate peak impact forces during a collision. This would require further work as there wasn't scope to undertake a detailed design exploration and optimisation study within this programme.

5.1.4 Multi-rotor motor bumpers

Results from the study indicate that the motors of multi-rotor drones can be responsible for initiating damage in aircraft structures during collision events. In the case of aircraft leading edge structures, motors that penetrate the skins may also perforate or penetrate Primary Structure, such as spar webs.

The motors of drone configurations with frangible or folding arms were observed to cause less-severe damage than stiff installations, because the impact forces are limited by their own inertia. However, where stiff, strong, non-articulating arms are used, then the inertia of the whole drone may also contribute to the forces being reacted when the motors impact the aircraft.

As an example, stiff, strong, non-articulating arms are common in aerobatic, FPV-oriented products, which are typically be designed to withstand moderate-to-severe impacts with terrain.

Motor guards, or 'bumpers' of various designs are found on some drone products, to protect rotating components and reduce ground-collision hazards. Results from the research indicated that the use of bumper structures, which increase the effective diameter of the motors and cover exposed edges, can suppress the initiation of damage in aircraft structures reduce the severity of a collision. There may also be potential to improve the effectiveness of bumpers through the use of tailored-stiffness, crushable materials/structures.

A draft standard for motor arms and bumpers is provided in Appendix C.4.

Further work is required to develop practical and effective bumper design guidance. If this concept is to be expanded upon, then it is recommended that the following factors should be considered:

- Appropriate frangibility criteria, that doesn’t compromise structural integrity and airworthiness of the UAS;
- Geometry of the bumper, with respect to the motor installation;
- Stiffness, strength and impact performance requirements of the bumper, for drones of different MTOW;
- Effectiveness of designs against windshield and leading edge targets.

5.2 Pro-active maintenance of knowledge and guidance

Mainstream high-volume drone manufacturers operate with short product cycles, which allows for rapid evolution of designs and exploitation of new technologies. A review of current products (at the time of writing) provided confidence that the outputs from this programme of research remain valid for modern drone configurations, this cannot be guaranteed in the long-term.

Where emerging trends in drone design fall outside the envelope of drone configurations assessed within this programme, then it is recommended that further research is undertaken to fill knowledge gaps through validated simulation. This will ensure that the Guidelines and standard remain relevant to the latest development in technologies and use-cases, and exploit best available knowledge for design and certification. Pro-active knowledge management and continuous improvement of design practices and standards will be essential to the maintenance of aviation safety and successful integration of UAS technologies.

6. Crewed aircraft design

6.1 Introduction

It was not an objective of this project to recommend changes to crewed aircraft certification requirements or designs. However, the work has highlighted vulnerabilities in the representative example aircraft and it is unlikely that these would be fully-mitigated through changes to drone design alone.

Regulations already include provision for a variety of impact threats against aircraft structures, though the certification requirements vary between aircraft classifications (see Appendix B). Where they apply, bird strike requirements include threats of comparable masses and collision speeds to drone threats. However, it has been shown within this research programme that drones represent a greater threat than an equivalent mass bird. Therefore, even where a bird strike requirement applies, it cannot be assumed that a drone strike of the same mass and/or energy would not result in a hazard.

Comments relating to crewed aircraft are limited to observations that may be of relevance to aircraft designers, and recommendations that would have a significant positive effect on the vulnerability of crewed aircraft.

6.2 Observation on empennage structures

It was observed that empennage structures and, in particular, horizontal stabilisers are vulnerable to damage in the event of drone collisions. This result was not surprising for lightweight General Aviation aircraft, but the example CS-23 Business Jet and CS-25 airliner were also shown to be vulnerable to drones of 0.5kg and above during the Approach/Climb phases of flight.

It is not known whether the empennage structures of the aircraft that were assessed in this study are typical, or whether they are lower-bound configurations. Furthermore, it is not known whether a more-detailed, type-specific fault tree analysis of the predicted damage levels would allow a less conservative interpretation of the potential hazard (the Hazard Effect Classification) than has been applied within this study[8]. Therefore, the above observation has been recorded in lieu of a direct recommendation. This is intended to draw attention to potential vulnerabilities of empennage structures and the likelihood that thin leading edges and spar webs may be damaged/perforated/penetrated in the event of drone collisions.

For reference, the thicknesses of the 2024-T3 aluminium alloy leading edge skins and spar webs of the CS-23 Business Jet and CS-25 airliner evaluated in this programme are shown below.

CS-23 Business Jet Horizontal Stabiliser

- LE Skins: 1.016mm
- Spar Web: 1.016mm

CS-25 Large Aircraft Horizontal Stabiliser (at locations registering High HECs)

- LE Skins: 1.0mm
- Spar Web: 2.0mm inboard location / 0.8mm outboard location

[8] In this study, it was necessary to define consistent metrics for IEA and HEC levels. Any level of perforation/tearing of a spar web (primary structure) is regarded as a High HEC condition, regardless of the size of damaged region or its span-wise location.

6.3 Recommendation on windshield structures

Forward-facing windshields are exposed to drone impacts and their failure would be highly hazardous to the safety of the aircrew.

Windshield constructions vary significantly between aircraft categories and types, but most of the lightweight fixed wing and rotorcraft aircraft considered within this programme utilised relatively thin, single-ply acrylic screens. These are shown to have poor impact performance and may be damaged/penetrated by popular classes of consumer drones within the Open category.

Within this programme, a comparison of windshield technologies demonstrated that polycarbonate materials provide great improvements in impact performance over more-traditional acrylic screens[9] [22]. Whilst polycarbonate does have disadvantages over acrylic (it is more easily scratched), its superior impact performance is recognised by manufacturers and it is offered on some aircraft e.g. Robinson R22/R44/R66 and AW109, as an optional alternative to acrylic.

It is therefore recommended that the design of all aircraft windshields (regardless of their respective bird strike requirements) should utilise appropriate material technologies (which could include high-toughness materials and/or laminated constructions) and screen thicknesses to minimise the risk of injury to aircrew in the event of mid-air impacts.

[9] In addition to the evidence presented within this programme, the Robinson Helicopter Company has published videos demonstrating the toughness of their recently developed polycarbonate screen options during impact scenarios [23].

7. Future Work

The recommendations contained within this report are based upon a large body of evidence that has been generated by the project activities summarised in Section 2. The following areas of further work are recommended to build-upon, exploit and maximise the value of the outputs from this programme:

- Focussed studies to support the maturation of the draft design standards into an Open category standard (EN or prEN);
- Updating aircraft vulnerability dataset to include unique features of emerging class of eVTOL crewed aircraft, which may operate in areas where the risk of drone collision is greater;
- Updating aircraft vulnerability dataset with simulations of impacts against composite airframe structures;
- Exploitation of collision simulation and aircraft vulnerability methodologies, to understand hazards associated with larger drones in the Open and Specific categories;
- Maintenance of drone collision simulation data, with periodic updates to reflect future drone design trends and technologies.
- Estimation of collision probabilities and impact conditions. This information could be used alongside the vulnerability data (developed within this programme) to estimate the likelihood of a hazardous collision occurring during normal operations, or in the event that a drone is sighted in the vicinity of an airport. Outputs would support policy-making, C-UAS scenario planning and aid decision making by Air Traffic Controllers and airport authorities. This could be extended further by using air accident statistics to estimate the likelihood that a hazardous (High HEC) condition will lead to injuries/fatalities.
- Exploitation of the drone collision capability to assess the severity of ground collision events, including impacts with personnel.

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Appendix A. Programme summary supporting data

A.1 Drones used in programme

Figure A-1 shows photographs of the five drones used in this programme.

Figure A-1: Drones used in programme 'Vulnerability of Manned Aircraft to Drone Strikes' (EASA.2020.C04) (not to scale)

A.2 Illustrative test and modelling pyramid

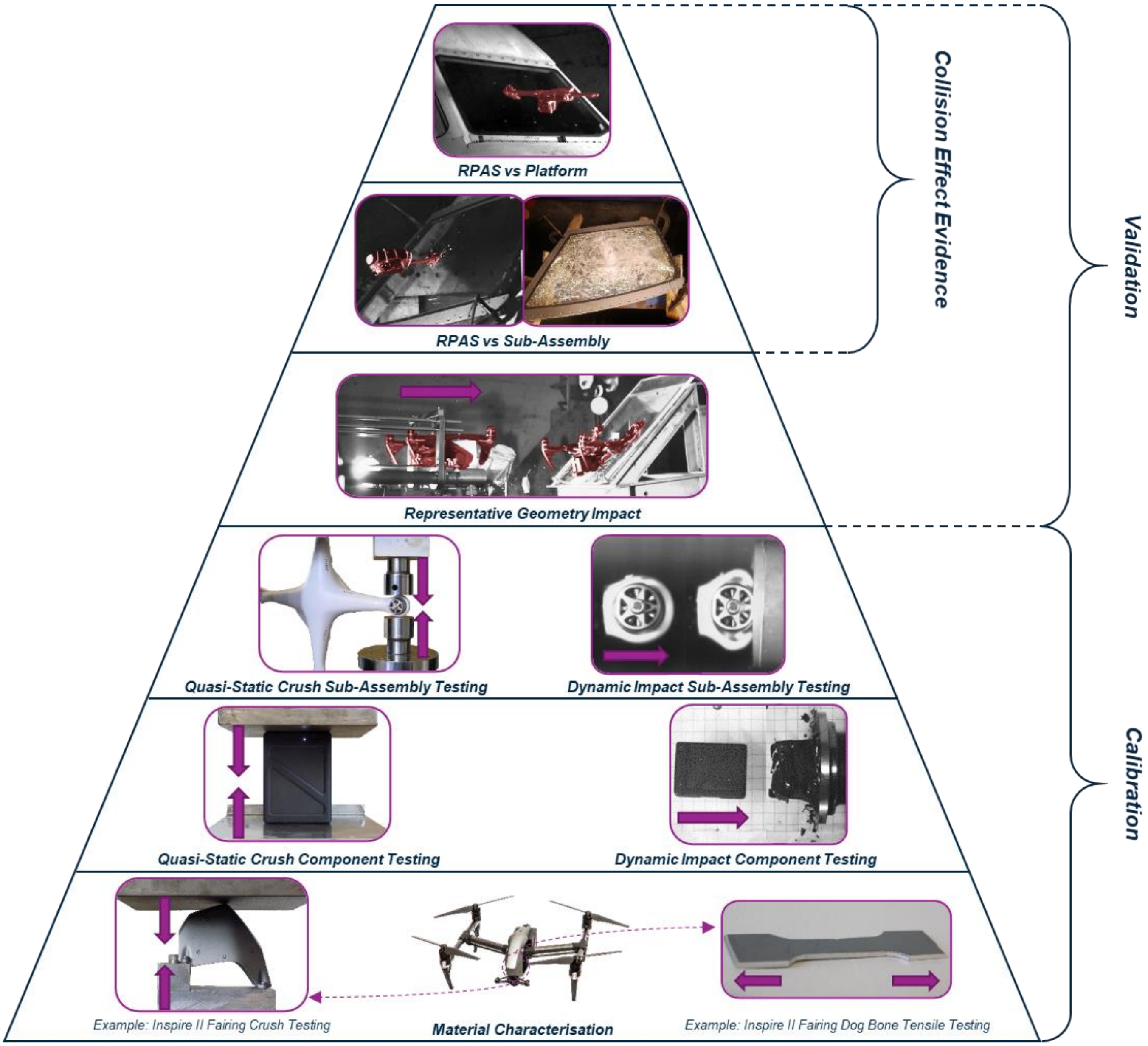


Figure A-2: Illustrative test pyramid

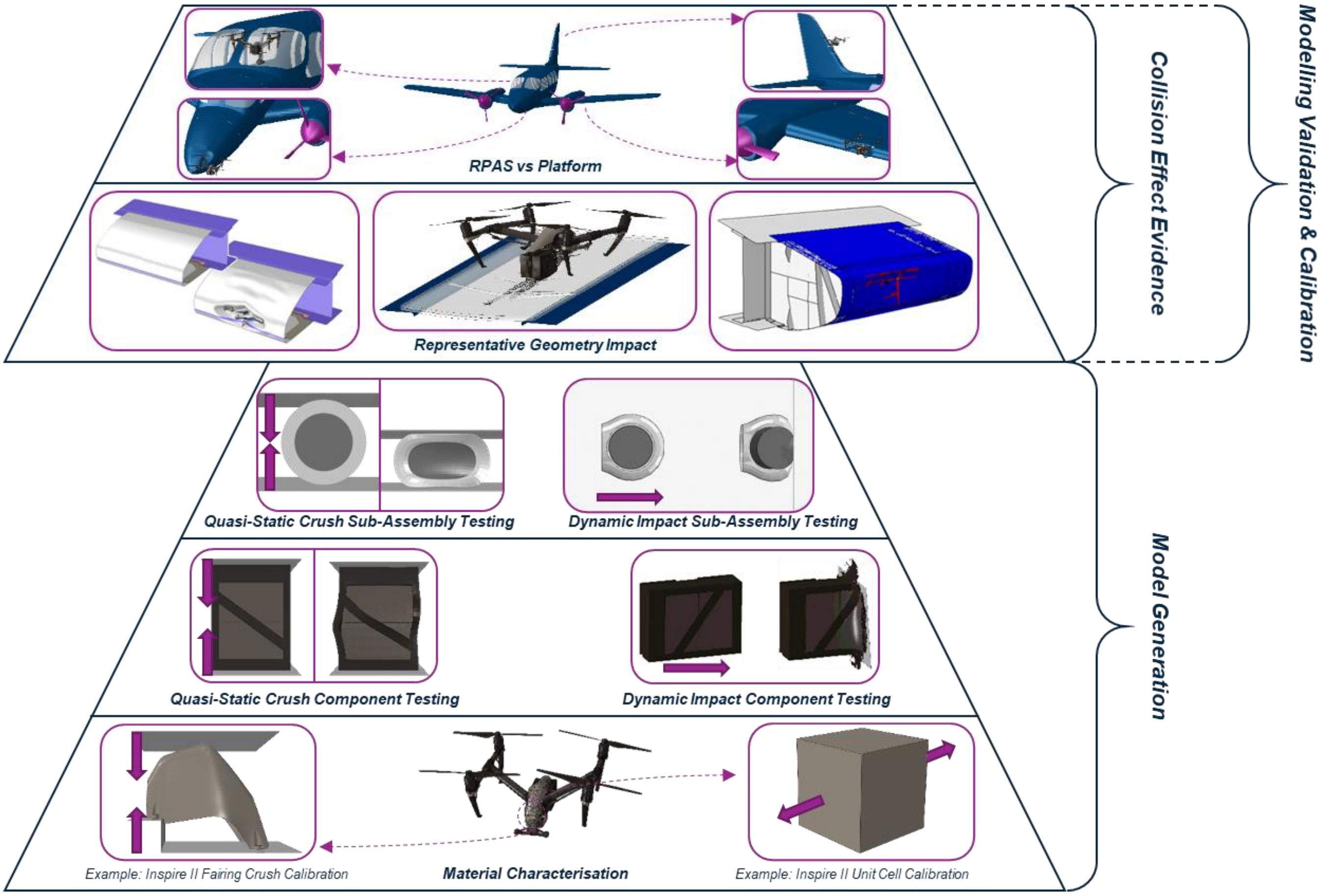


Figure A-3: Illustrative 'modelling mushroom'

A.3 Example of drone model

The FE model of a meshed Mavic 2 frame and internal components are shown in Figure A-4.

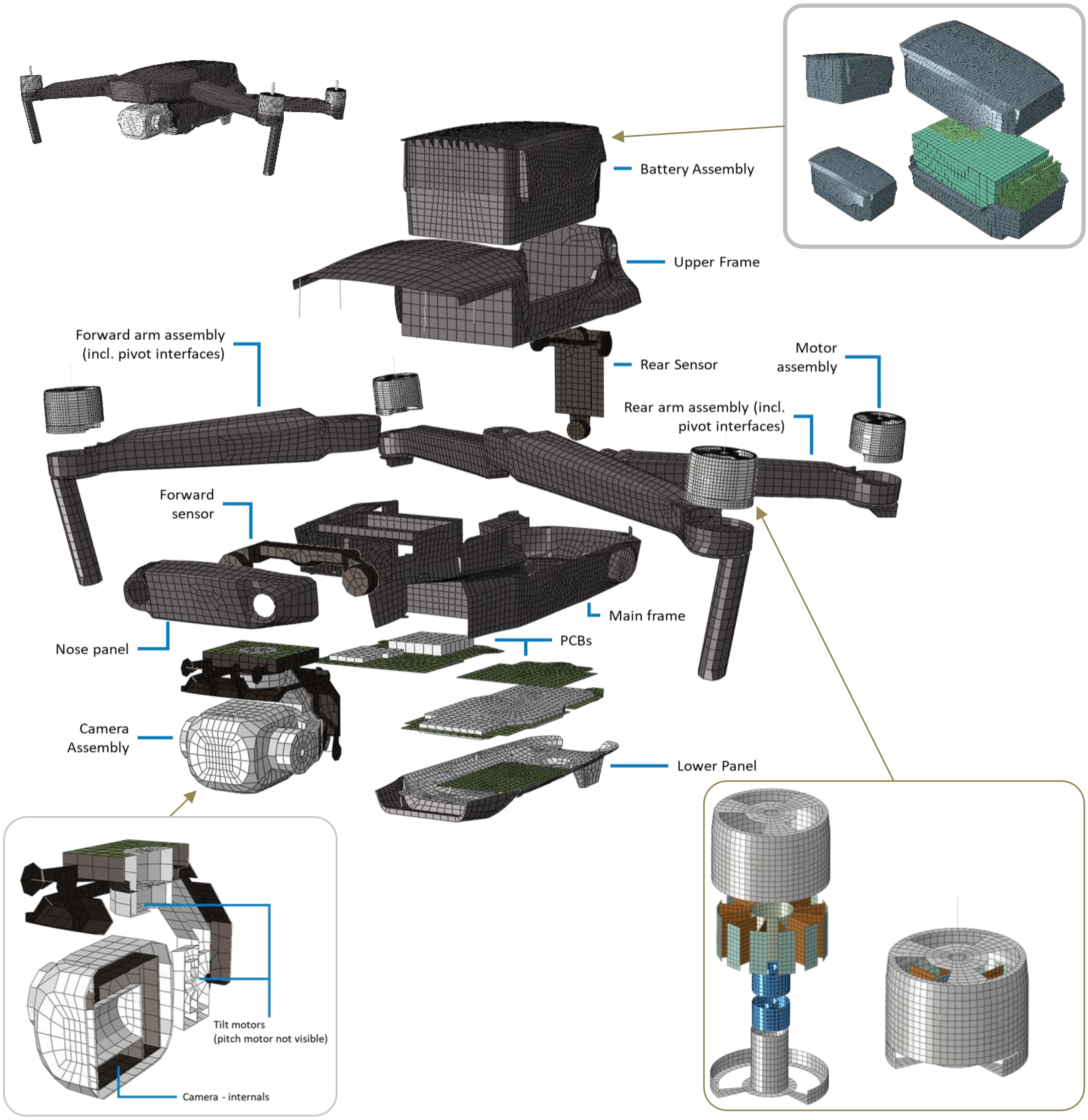
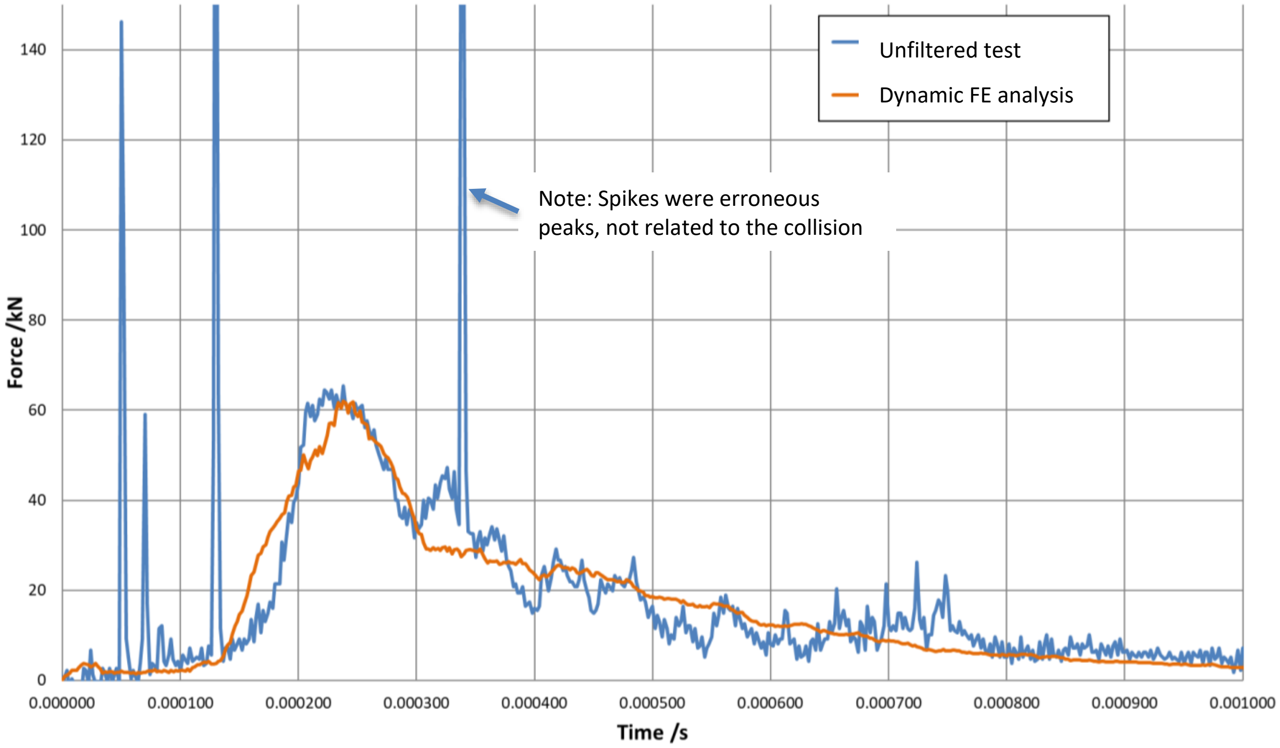


Figure A-4: DJI Mavic 2 assembly FE mesh, including internal components

A.4 Example of component dynamic test and validation

For example, Figure A-5 shows the unfiltered force-time response of a test and FE prediction for the Mavic 2 battery against a Hopkinson bar at 59.5ms^{-1}. Also shown are images from the high speed video alongside the corresponding FE predictions chosen at the same time, showing a good correlation.



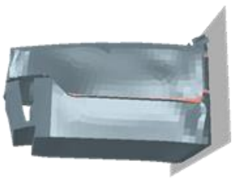
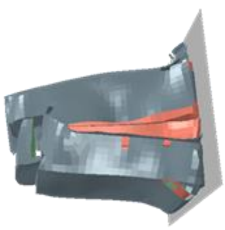
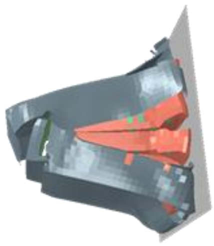
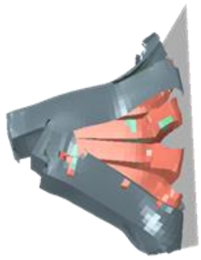
Time (s)	0	0.0002	0.0004	0.0006	0.0008
Physical Test					
FEA Prediction					

Figure A-5: DJI Mavic 2 battery – test and predicted results of Hopkinson bar impact at 59.5 ms^{-1}

A.5 Example of full drone assembly dynamic test and validation

Figure A-6 shows an example of whole-drone validation testing. In this case, the Mavic 2 drone is shown impacting a rigid target, alongside a simulation of the same event at a velocity of 53.2 ms^{-1}.

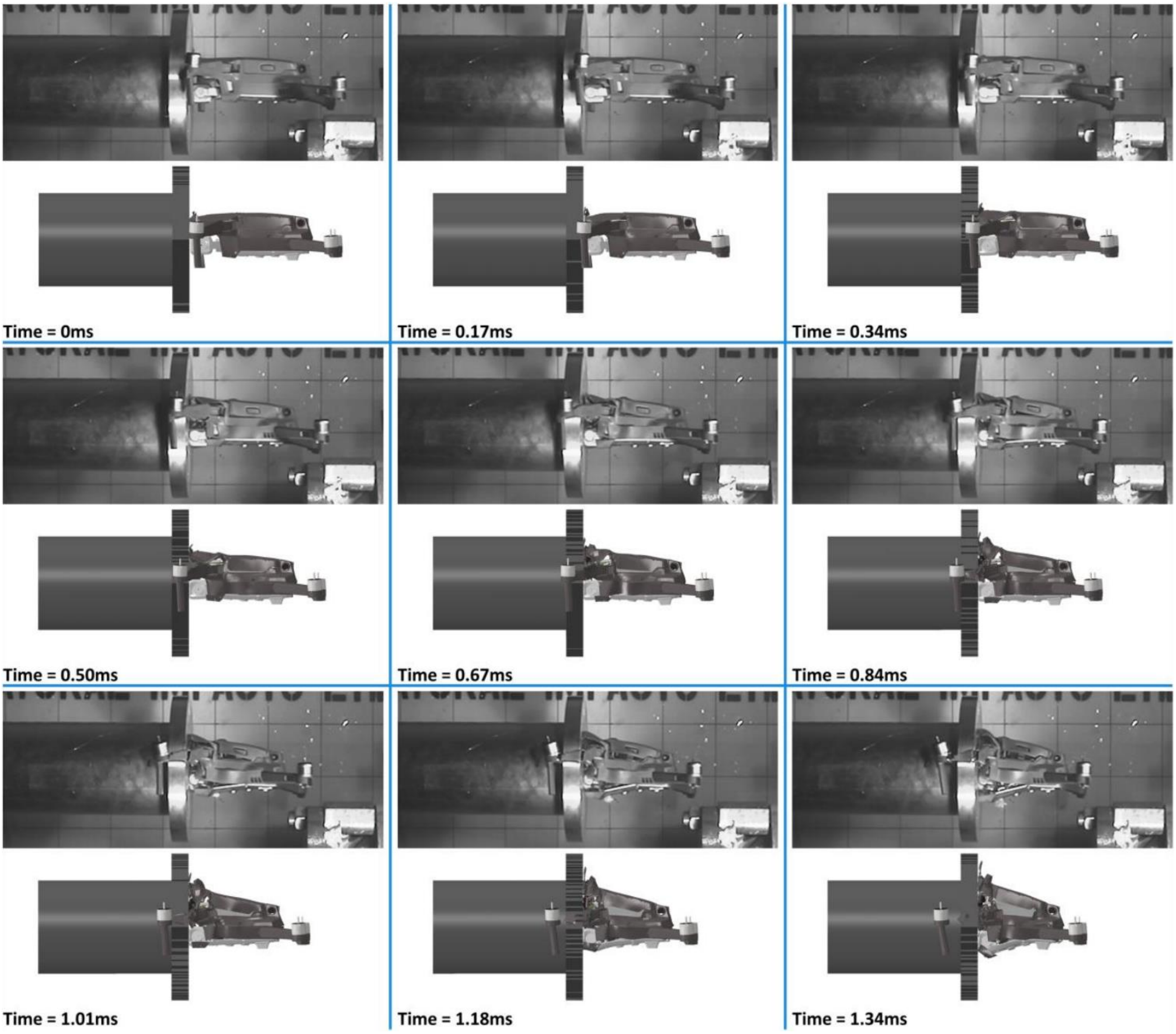


Figure A-6: DJI Mavic 2 assembly – test and predicted results of rigid target impact at 53.2 ms^{-1}

A.6 Target aircraft models

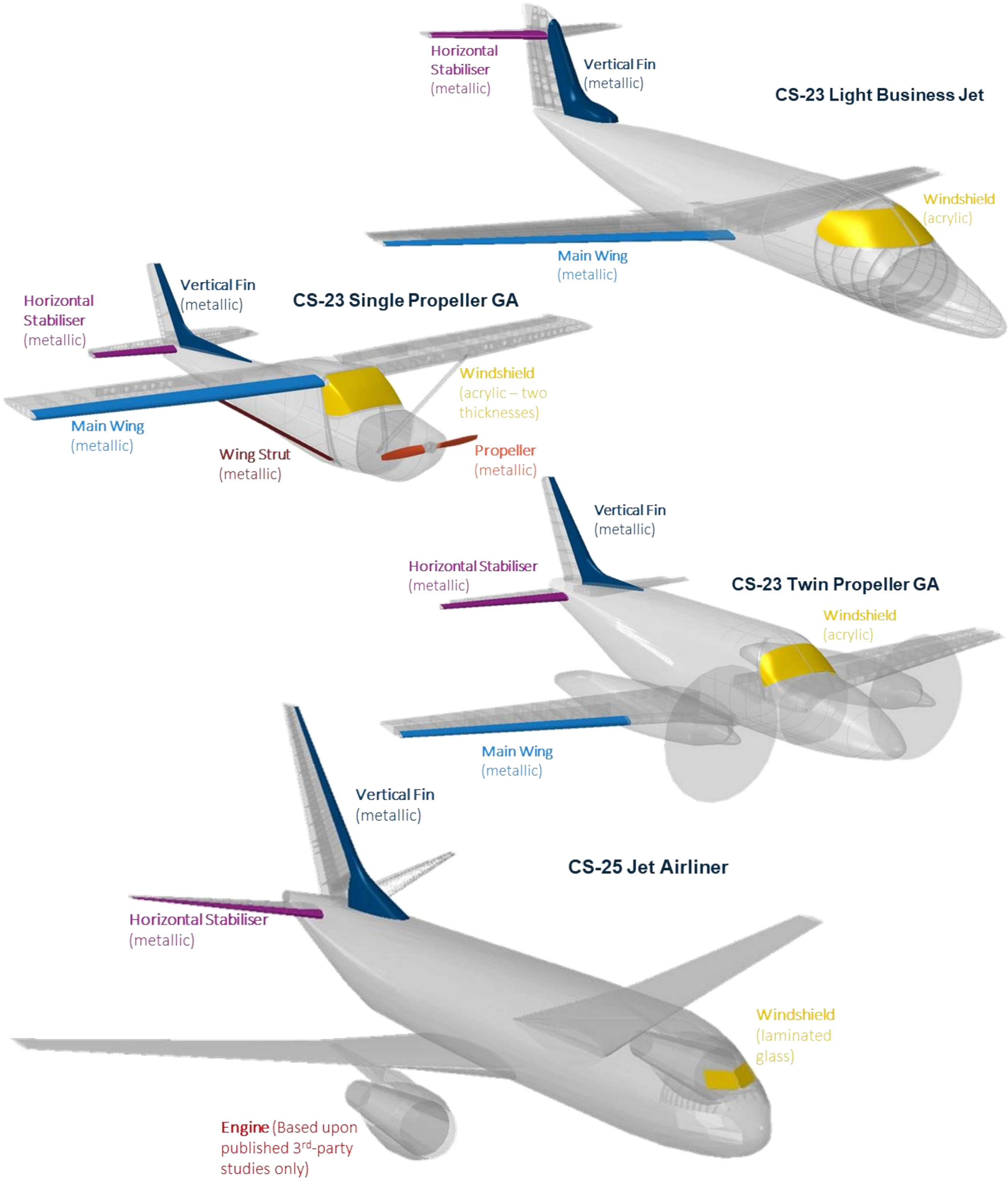


Figure A-7: Aircraft structures: target models – fixed-wing (not to scale)

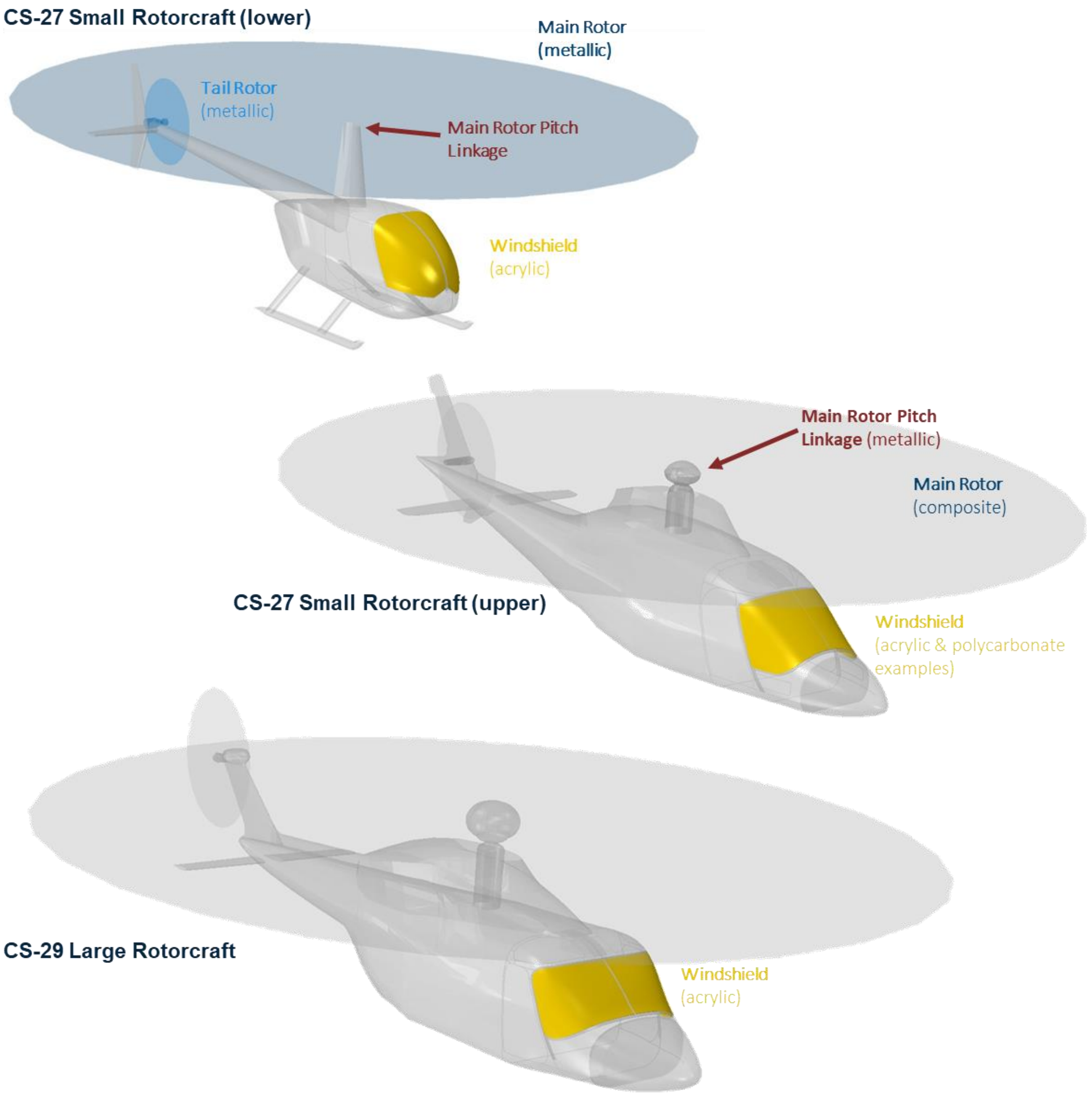


Figure A-8: Aircraft structures: target models – rotorcraft (not to scale)

A.7 Example of local target models

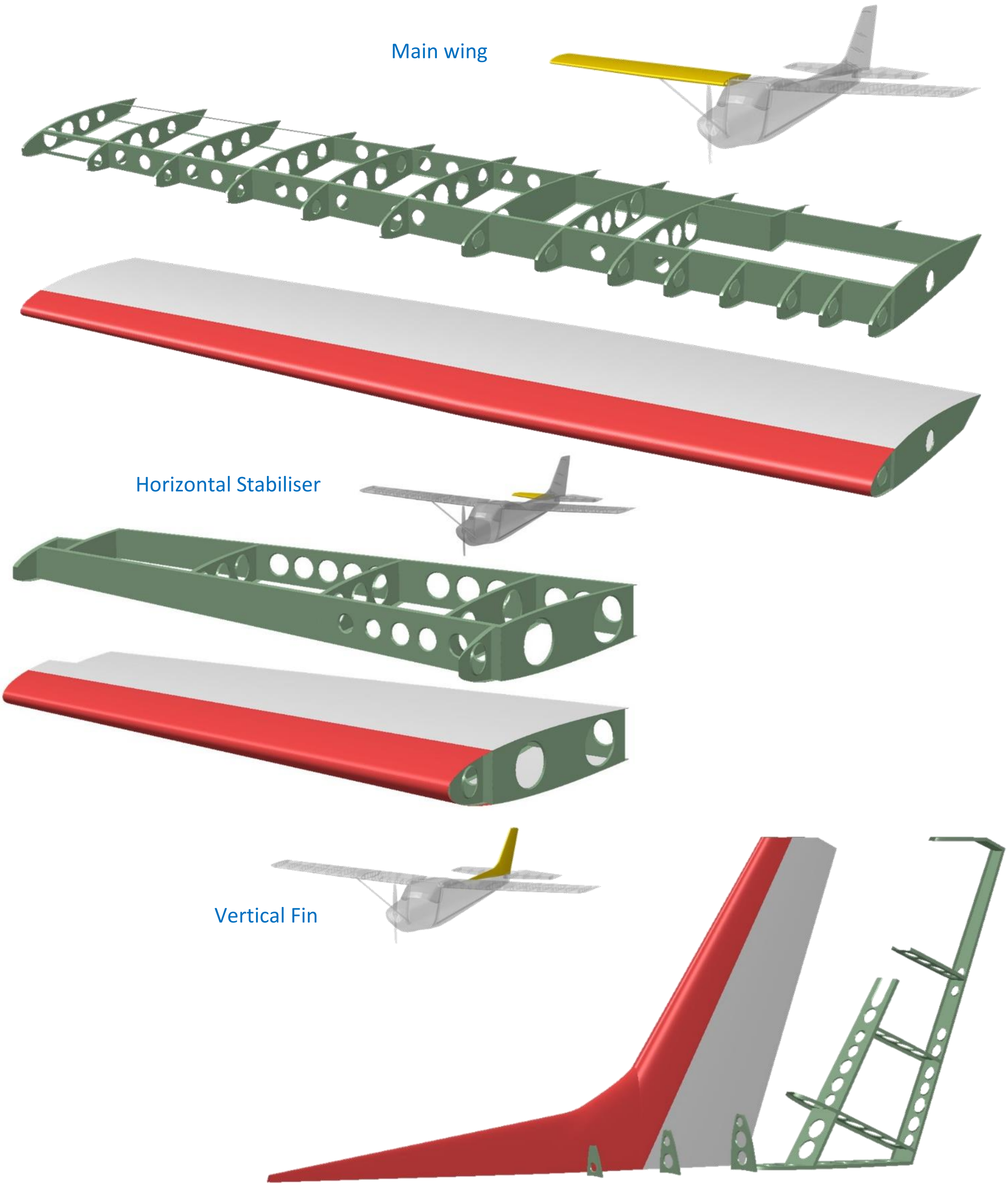
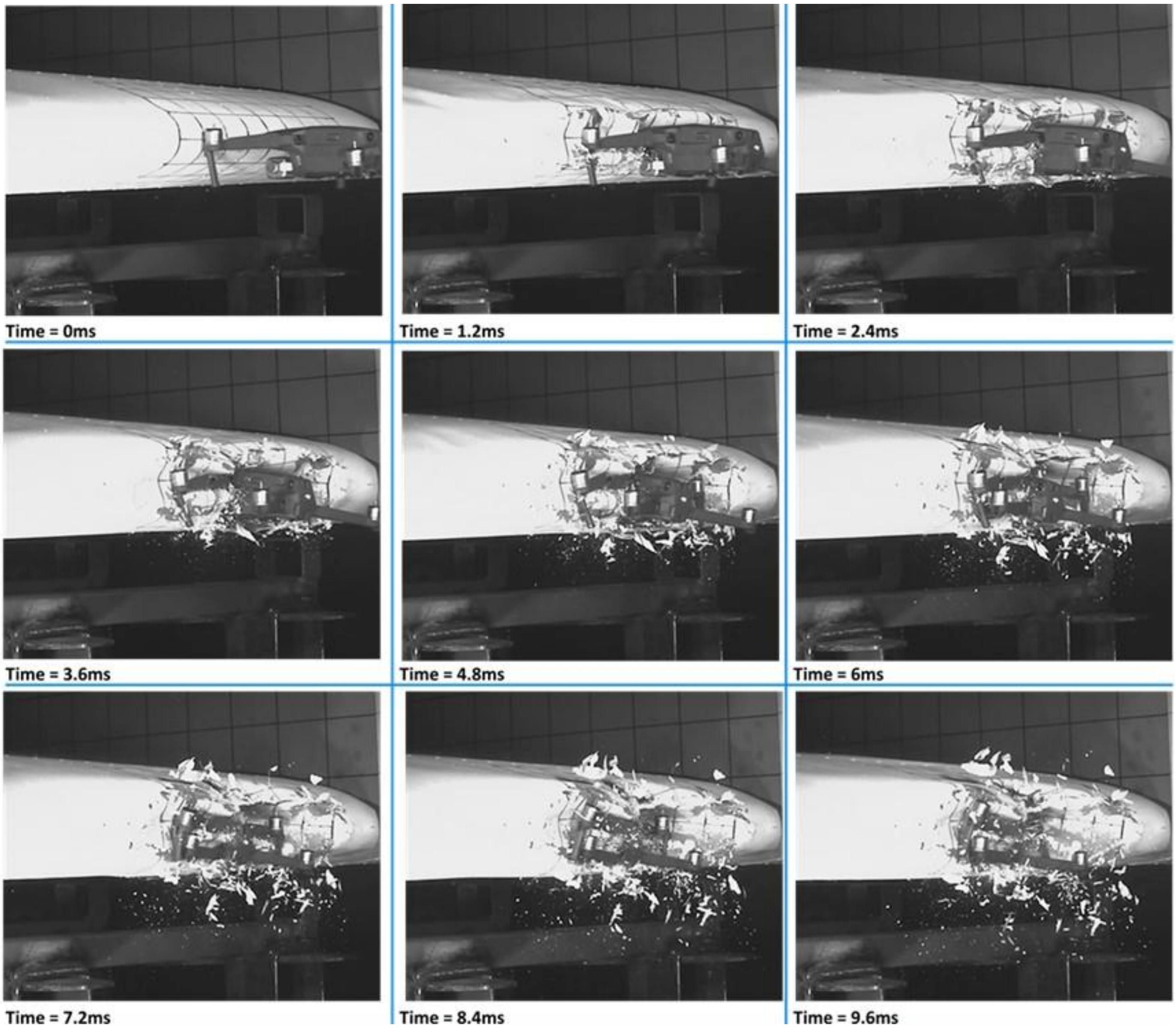


Figure A-9: Local target model detail for CS-23 single-propeller General Aviation aircraft

A.8 Examples of full scale model validation

A.8.1 Leading edge of CS-23 single propeller General Aviation aircraft

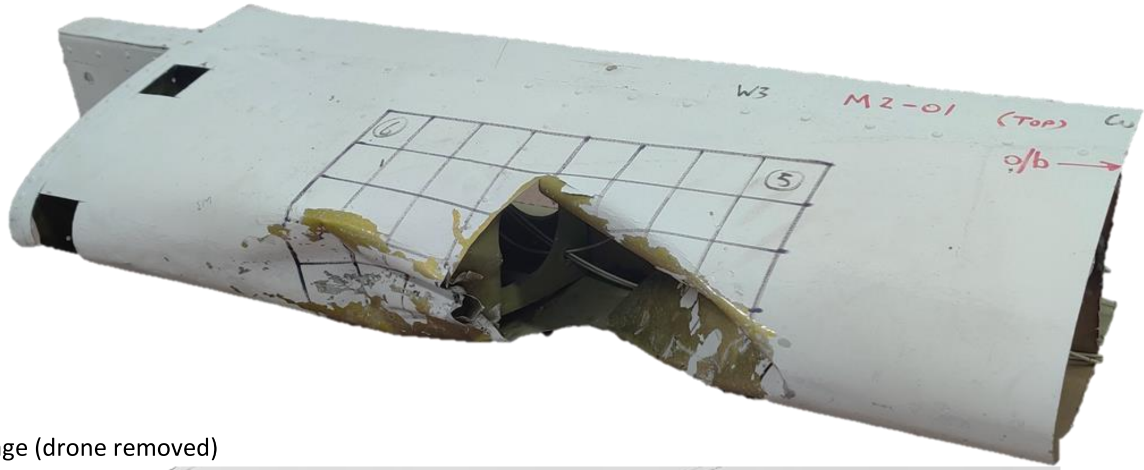
An example of high-speed video imagery is shown in Figure A-10 shows frames from high-speed camera footage of a Mavic 2 drone impacting the leading edge of CS-23 single propeller aircraft wing, with a collision speed of 50 ms^{-1}. The drone impacted adjacent to a riblet, and a tear initiated at the tip of the riblet. As the impact continued, this failure propagated and allowed the drone to enter the wing structure, where it came to rest inside the wingbox.



➨ **Figure A-10:** Validation test: Mavic 2 impact on riblet of the leading edge of the wing of a CS-23 single propeller aircraft at 50.0ms^{-1}, example high speed video frames

The simulation of this test showed good correlation with the physical test results. The extent of damage and failure mode were similar between the test and simulation, as shown in Figure A-11. The simulation also correctly predicted that the drone would become lodged within the wing structure.

a) Post-test image



b) Predicted damage (drone removed)

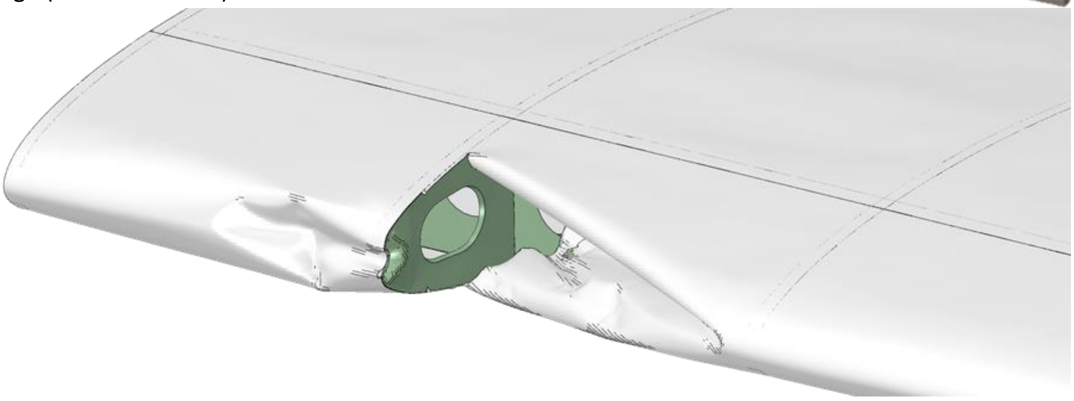
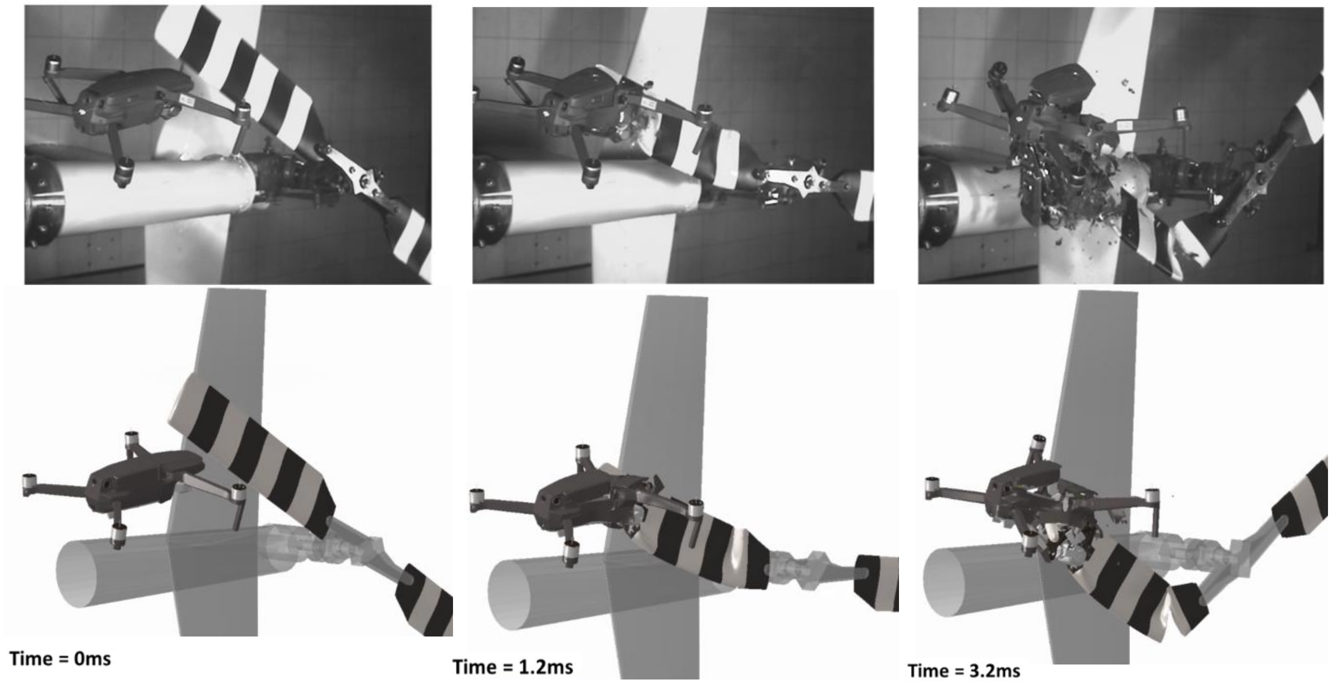


Figure A-11: Validation test: Mavic 2 impact on riblet of the leading edge of the wing of a CS-23 single propeller aircraft at 50.0ms^{-1}, compared to simulation

A.8.2 Tail rotor of CS-27 small rotorcraft

Another example of the validation testing and aligned analysis is shown in Figure A-12. Here a drone was launched into a rotating CS-27 tail rotor, and the results compared against a simulation of the same event. It can be seen that the failure response of the tail rotor is correctly captured by the model, including crushing damage at the impact site and tearing near the root of the blade.



➨ **Figure A-12:** Validation test - Mavic 2 drone colliding with a CS-27 tail rotor rotating at 3393 rpm. Images from test are shown on the top and simulation results for the same impact time are underneath.

A.8.3 Main rotor pitch linkage of CS-27 Small Rotorcraft

Validation testing was carried out on a CS-27 Small Rotorcraft main rotor pitch linkage. An example test is shown in Figure A-13. Here a drone was launched at a pitch linkage installed in a stationary main rotor hub (including stubs of rotor blades). As seen in the images of the post-test linkage and the simulated part, similar levels of deformation were captured, and the overall effective reduction in length correlated well between simulation and physical test.

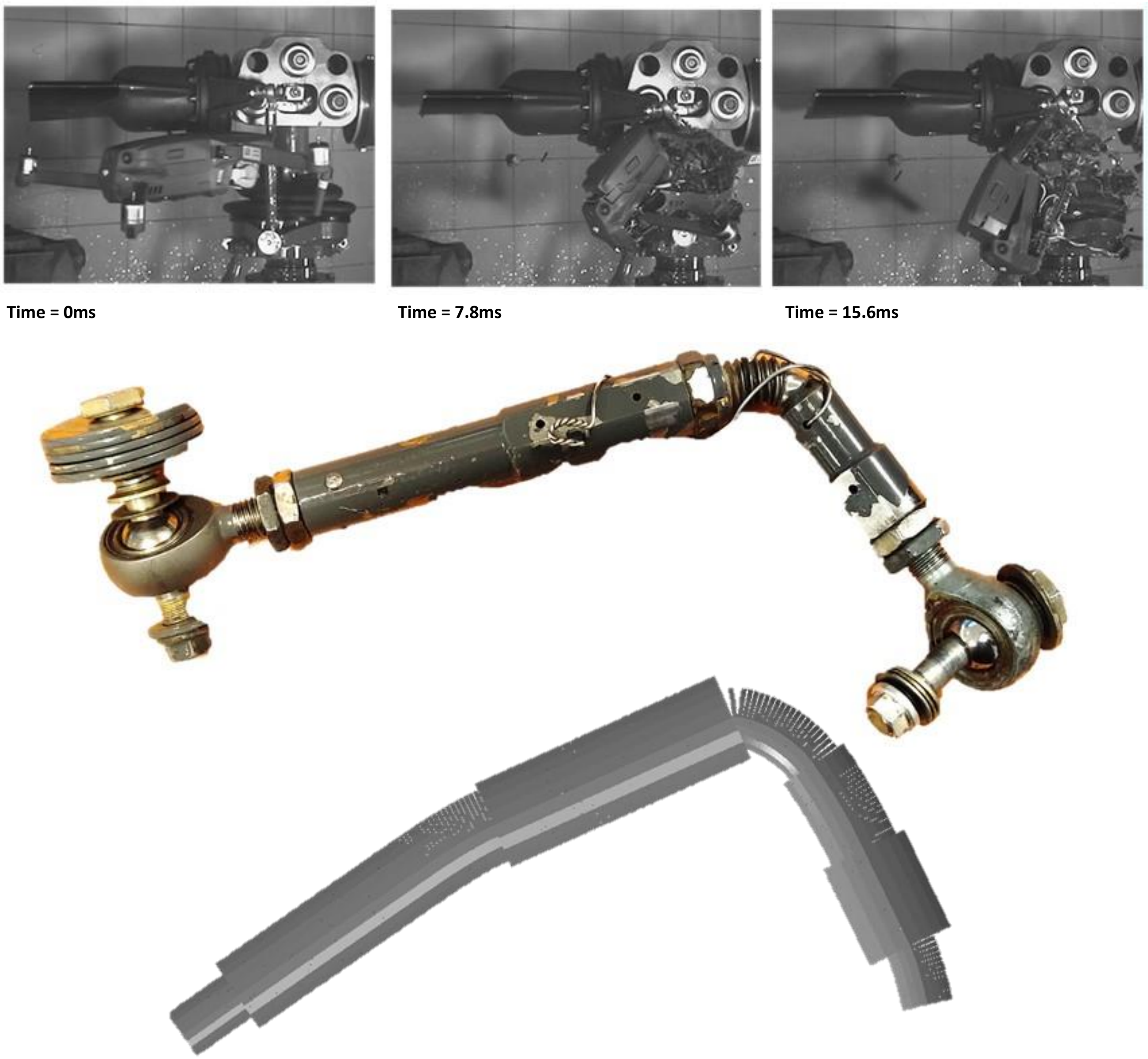


Figure A-13: Validation test - Mavic 2 drone colliding with a CS-27 main rotor pitch linkage at 45.0ms^{-1}. Images from test are shown on the top and a comparison of linkage deformation between the simulation and test are underneath.

A.9 Example of damage classification

The EASA 'Drone Collision' Task Force report [3] defines a two-part methodology by which to assess the safety implications of a drone collision. First, the method considers the level of damage sustained by the local target region and assigns an IEA classification. This IEA is then used along with knowledge of the aircraft type and impact location to determine a HEC that indicates the severity of threat to the continued safety of the aircraft, crew and passengers.

A process to determine (or 'sentence') the IEA level was developed so that it could be applied consistently and with minimal ambiguity when assessing different damage outcomes.

A different set of damage criteria were devised for each type of aircraft structure e.g. leading edges, windshields, rotor blades etc. In most cases, the criteria used to define each IEA level is relatively simple, but some structures have a greater variety of relevant damage and failure modes, and so require a more comprehensive system. Table A-1 shows an example of a more-complex IEA classification scheme for leading edge structures, where the following damage and failure modes are considered:

- Deformation of the LE;
- Perforation of the LE, and;
- Damage to main spar primary structure i.e. the main spar.

A separate IEA level is determined for each mode of damage using the descriptions shown in Table A-1, and the final IEA level is the maximum of the three.

An advantage of this method is that the final IEA accounts for the severity of each mode of damage. Therefore a minor crack in the LE skin with minimal deformation to the LE profile is not assigned the same level as full penetration of a drone or major deformation of the structure over multiple rib bays.

It is worthy of note that only failure in the primary structure attracts a Level 4 IEA as there is no equivalent severity for deforming or perforating/penetrating the LE. Furthermore, the primary structure damage severity does not include a Level 2 definition, but jumps from no damage (Level 1) to plastic deformation at Level 3 and material failure at Level 4. This is because any level of damage to the primary structure is considered to be significant i.e. Level 3 or above.

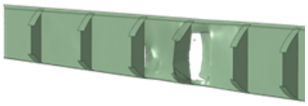
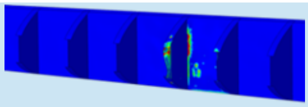
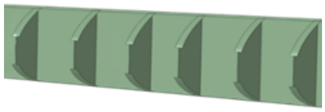
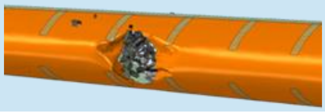
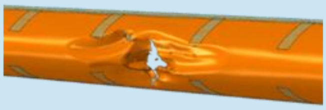
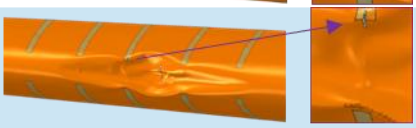
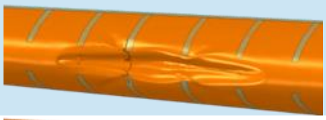
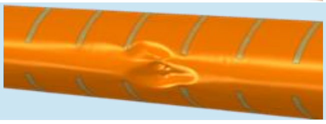
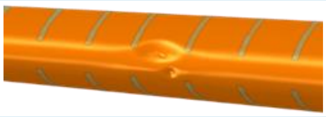
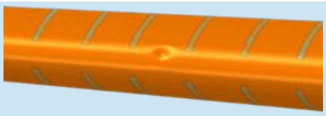
Damage type	IEA	Description	Example	
Primary structure	Level 4	Localised material failure of spar and/or loss of global wing stiffness	S4	
	Level 3	Plastic deformation of spar, or drone enters wingbox via cut-outs	S3	
	Level 1	No damage to spars	S1	
Leading Edge Penetration	Level 3	Whole drone penetrates skin	P3c	
		At least one major part of drone penetrates skin	P3b	
		Major rip to skin but no major drone parts penetrate skin	P3a	
	Level 2	Minor rip to skin but no major drone parts penetrate skin	P2b	
		Drone perforates but does not penetrate skin	P2a	
	Level 1	No failure of LE skins	P1	
Leading Edge deformation	Level 3	Major deformation of LE over > 2 rib bays' width	D3b	
		Major deformation of LE over 1-2 rib bays' width	D3a	
	Level 2	Major deformation of LE over 1 rib bay's width	D2b	
		Moderate/Minor deformation over < 1 rib bay's width	D2a	
	Level 1	Minor dents	D1	

Table A-1: IEA definitions for LE structures

A.10 Example of damage effect

The HEC definitions at aircraft level have been specified by EASA in their Task Force report [3] and shown here in Table A-2. The definitions are split into 5 levels of severity, which are further sub-sets of two higher categories: High and Low[10]. The High and Low classifications are used within this study to denote the criticality of collision damage at the aircraft-level. It should be noted that a High HEC does not mean that an accident, injuries or fatalities are assured, but it does indicate a hazardous situation in which such outcomes are possible.

Severity Level	**High**		**Low**		
Hazard Classification	**1 (most severe)**	**2**	**3**	**4**	**5 (least severe)**
Effect on A/C	Normally with hull loss	Large reduction in Functional capabilities or safety margins	Significant reduction in Functional capabilities or safety margins	Slight reduction in Functional capabilities or safety margins	No effect on operational capabilities or safety
Effect on Occupants (excluding. Flight Crew)	Multiple fatalities	Serious or fatal injury to a small number of passengers or cabin crew	Physical distress, possibly including injuries	Physical discomfort	Inconvenience
Effect on Flight Crew	Fatalities or incapacitation	Physical distress or excessive workload impairs ability to perform tasks	Physical discomfort or a significant increase in workload	Slight increase in workload	No effect on flight crew
Effect on Operations	Total loss of separation. Total loss of control, mid-air collision, flight into terrain or high speed surface movement collision.	Large reduction in separation or a total loss of air traffic control for a significant period of time	Significant reduction in separation or significant reduction in air traffic control capability.	Slight reduction in separation or slight reduction in air traffic control capability. Significant increase in air traffic controller workload.	Slight increase in air traffic controller workload.

➨ **Table A-2:** EASA's Hazard Effect Classification at Aircraft Level, taken from the EASA Drone Collision Task Force report [3]

The HEC associated with each level of damage (IEAs) on each type of structure, have been developed with input from a range of sources, including:

- EASA Drone Collision Task Force survey results and conclusions;
- EASA subject matter experts;
- QinetiQ subject matter experts;
- Members of the project Stakeholder Group;

Table A-3 shows an example of how IEAs are mapped to HECs for leading edge structures. Note that these mappings are different for each of the four sub-categories of fixed wing aircraft, and also whether the leading edge is a main wing (MW), horizontal stabiliser (HS) or vertical fin (VF). Non-primary structure damage to the horizontal stabiliser of smaller aircraft is considered to be more serious because of the effect it may have on the control authority of the elevators in pitch.

[10] For reference, the HEC level RGB colour scheme shown in later tables is:
High: (255, 199, 206); Low: (198, 239, 206)

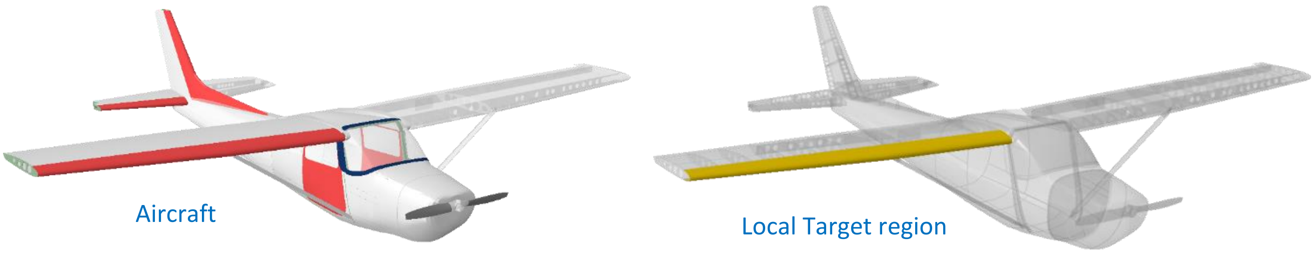
Damage type	IEA	Description	HEC												Note
			CS23-GA1 (Single prop GA)			CS23-GA2 (Twin prop GA)			CS23-BJ1 (Business Jet)			CS25-JA2 (Jet Airliner)			
			MW	HS	VF	MW	HS	VF	MW	HS	VF	MW	HS	VF	
Primary structure	L4	Localised material failure of spar and/or loss of global wing stiffness	H	H	H	H	H	H	H	H	H	H	H	H	Cracking/perforation/penatration of the LE spar
	L3	Yielding of the spar or drone enters wingbox via cut-outs	L	L	L	L	L	L	L	L	L	L	L	L	Permanent deformation of the spar but no failure
	L1	No damage to spars	L	L	L	L	L	L	L	L	L	L	L	L	
Leading Edge Penetration	L3	Whole drone penetrates skin	L	H	L	L	L	L	L	L	L	L	L	L	Secondary hazards e.g. battery fire, not included.
		At least one major part of drone penetrates skin	L	L	L	L	L	L	L	L	L	L	L	L	Secondary hazards e.g. battery fire, not included.
		Major rip to skin but no major drone parts penetrate skin	L	L	L	L	L	L	L	L	L	L	L	L	
	L2	Minor rip to skin but no major drone parts penetrate skin	L	L	L	L	L	L	L	L	L	L	L	L	
		Drone perforates but does not penetrate skin	L	L	L	L	L	L	L	L	L	L	L	L	
	L1	No failure of LE skins	L	L	L	L	L	L	L	L	L	L	L	L	
Leading Edge deformation	L3	Major deformation of LE over > 2 rib bays' width	L	H	L	L	H	L	L	H	L	L	L	L	Horizontal stabiliser damage may degrate elevator control authority for small- to medium-sized aircraft
		Major deformation of LE over 1-2 rib bays' width	L	H	L	L	L	L	L	L	L	L	L	L	Horizontal stabiliser damage may degrate elevator control authority for small aircraft
	L2	Major deformation of LE over 1 rib bay's width	L	L	L	L	L	L	L	L	L	L	L	L	Localised damage may affect handling qualities and stall performance but managable
		Moderate/Minor deformation over < 1 rib bay's width	L	L	L	L	L	L	L	L	L	L	L	L	Localised damage may affect handling qualities and stall performance but managable
	L1	Minor dents	L	L	L	L	L	L	L	L	L	L	L	L	

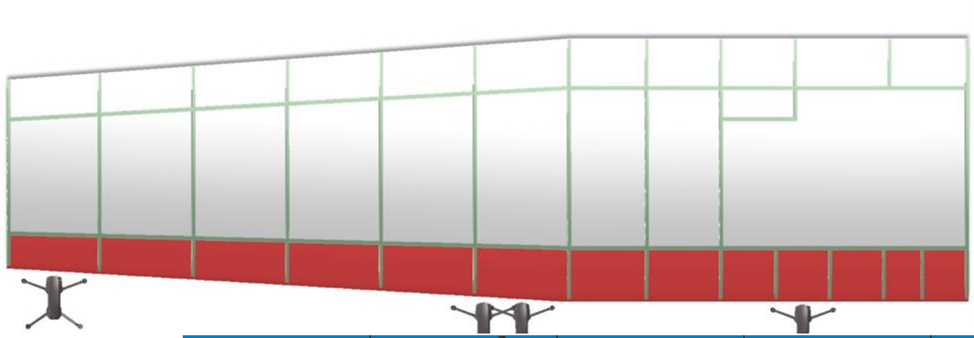
Table A-3: HEC sentencing for LE structures (MW=Main Wing; HS=Horizontal Stabiliser; VF=Vertical Fin)

A.11 Example of IEA and HEC sentencing

Figure A-14 shows the sentenced results for **extent** (IEA1-4) and **effect** of damage (HEC High-Low) for drone collisions against the wing of a representative small, CS-23 single propeller GA aircraft evaluated at a range of velocities and at four locations.

The table in the figure represents the outcome 72 separate simulations consisting of 4 locations on a local target, using the 5 drones (plus one backwards scenario) with the 3 levels of velocity.





Sentenced results from simulation

Location Reference	Flight Case	AC Speed [ms⁻¹]	Mavic Mini Combined Velocity [ms-1]	IEA	HEC	FPV Combined Velocity [ms-1]	IEA	HEC	Mavic 2 Combined Velocity [ms-1]	IEA	HEC	UX11 (Forwards) Combined Velocity [ms-1]	IEA	HEC	UX11 (Backwards) Combined Velocity [ms-1]	IEA	HEC	Inspire 2 Combined Velocity [ms-1]	IEA	HEC
L01	Take-Off	30.9	43.9	2	L	57.9	3	L	50.9	3	L	54	3	L	7.7	1	L	57	3	L
	50th %	57.6	57.6	2	L	57.6	3	L	57.6	3	L	78.2	3	L	37	2	L	57.6	3	L
	Max SL	64.3	72.3	2	L	79.2	3	L	78.2	3	L	84.9	4	H	43.7	2	L	72.3	3	L
L02	Take-Off	30.9	43.9	2	L	57.9	3	L	50.9	3	L	54	3	L	7.7	1	L	57	3	L
	50th %	57.6	57.6	2	L	57.6	3	L	57.6	3	L	78.2	3	L	37	2	L	57.6	4	H
	Max SL	64.3	72.3	2	L	79.2	3	L	78.2	3	L	84.9	3	L	43.7	2	L	72.3	4	H
L03	Take-Off	30.9	43.9	2	L	57.9	3	L	50.9	3	L	54	3	L	7.7	1	L	57	4	H
	50th %	57.6	57.6	3	L	57.6	3	L	57.6	3	L	78.2	3	L	37	2	L	57.6	4	H
	Max SL	64.3	72.3	3	L	79.2	3	L	78.2	4	H	84.9	3	L	43.7	2	L	72.3	4	H
L04	Take-Off	30.9	43.9	2	L	57.9	2	L	50.9	2	L	54	3	L	7.7	1	L	57	3	L
	50th %	57.6	57.6	2	L	57.6	2	L	57.6	2	L	78.2	3	L	37	2	L	57.6	4	H
	Max SL	64.3	72.3	2	L	79.2	3	L	78.2	3	L	84.9	4	H	43.7	2	L	72.3	4	H
Envelope	Take-Off	30.9	43.9	2	L	57.9	3	L	50.9	3	L	54	3	L	7.7	1	L	57	4	H
	50th %	57.6	57.6	3	L	57.6	3	L	57.6	3	L	78.2	3	L	37	2	L	57.6	4	H
	Max SL	64.3	72.3	3	L	79.2	3	L	78.2	4	H	84.9	4	H	43.7	2	L	72.3	4	H

➨ **Figure A-14:** CS-23 Single Propeller GA (CS23-GA1-MW) Main Wing – collision sentencing

Appendix B. External threats Certification Requirement

Components	Requirement	Title	Threat Category	Threat Specification	A/C Conditions	Pass/Fail Criteria
CS23 Commuter						
Windshield	CS 23.775(h)	Windshields and Windows	Bird	Bird 0.91 kg (2 lbs)	VFE	continued safe flight and landing,
CS23 High Performance and Jets						
Windshield	By Special Condition CRI typically	Windshields and Windows	Bird	Bird 0.91 kg (2 lbs) Tested on W Screen.	VFE	continued safe flight and landing,
Airframe	By Special Condition CRI typically	Bird Strike	Bird	0.91 kg by analysis on A/F critical areas only	Worst Case	continued safe flight and landing,
CS25 Large Aeroplane						
Complete Aeroplane	CS 25.631	Bird strike damage	Bird	4 lbs	VC at sea-level or 0·85 VC at 2438 m (8000 ft.),Vc	continued safe flight and landing
Empennage	FAR 25.631	Bird strike damage	Bird	8 lbs	Vc	continued safe flight and landing
Windshield	CS25.773b4	absence of openable windows	Sever Hail	multiple 2 inch ice balls impact (ANSI/ASTM F 320-10)	approach & landing	it is shown that an area of the transparent surface will remain clear sufficient for at least one pilot to land the aeroplane safely in the event
windshield	CS 25.775	Windshields and windows	Bird	4 lbs	VC at sea-level or 0·85 VC at 2438 m (8000 ft.),	must withstand, without penetration
CS29 Large Rotorcraft						
Windshield, Main Rotor, Tail Rotor, Exposed flight control system components	29.631	Bird strike	Bird	Bird 1 kg (2.2 lbs)	Vne or Vh (whichever is lesser) and altitude up to 8000 ft.	No penetration in the windshield - Category A rotorcraft capable of continued safe flight and landing after impact - Category B rotorcraft capable of safe landing after impact
CS E: Engines						
Engine	E540, E800	Strike and Ingestion of Foreign Matter; Bird Strike and Ingestion	Large Bird Impact; Hard Body Impact	Bird Mass between 1,85 and 3,65 kg,	Engine speed 100 % T/O, Aircraft seed >200 kt	No hazardous engine effect

Components	Requirement	Title	Threat Category	Threat Specification	A/C Conditions	Pass/Fail Criteria
Engine	E790	Ingestion of Rain and Hail	large hailstones	One 25-millimetre diameter hailstone for Engines with inlet throat areas of not more than 0.0645 m2. One 25-millimetre diameter and one 50-millimetre diameter hailstone for each 0.0968 m2 of inlet throat area, or fraction thereof, for Engines with inlet throat areas of more than 0.0645 m2.	Maximum true air speed, for altitudes up to 4500 metres, associated with a representative aircraft operating in rough air, with the Engine at Maximum Continuous power/ thrust,	Must not cause unacceptable mechanical damage or unacceptable power or thrust loss after the ingestion, or require the Engine to be shut down.
Engine	E780	Icing Conditions	Ice shedding/ Ice Slab	The applicant should determine the ice slab dimensions by linear interpolation between the values of AMC E780 Table 3, based on the actual Engine's inlet highlight area. (from 88.5 cm3 to 1435 cm3)	The ingestion velocity and the Engine operating conditions must be determined. Those conditions shall be appropriate to the Engine installation on the aircraft.	Engine will function satisfactorily following the ingestion. No unacceptable: (1) Immediate or ultimate reduction of Engine performance, (2) Increase of Engine operating temperatures, (3) Deterioration of Engine handling characteristics, and (4) Mechanical damage.
CS P: Propellers						
Propeller	P360	Bird Impact	Bird	Birds which are specified in the aircraft specifications applicable to the intended installation of the Propeller. The mass of the bird must not exceed 1.8 kg,	most critical location and the flight conditions which will cause the highest blade loads in a typical installation	No Major or Hazardous Propeller Effect.

Table B-1: Certification requirements for relevant crewed aircraft classifications, taken from the EASA Drone Collision Task Force report [3]

Appendix C. Draft design standard

This appendix contains a series of four separate criteria for a draft design standard, to achieve the 'high level objective' outlined in Section 3.1. They are written as outline criteria and some require additional work to develop appropriate metrics and verification methods.

C.1 Draft Standard for Combined MTOM – Maximum Speed

The following draft standard has been developed from Guideline 1 and Guideline 2 in Section 3 of the main text.

Criteria and Compliance for Open category UAS

Combined MTOM – Maximum Speed Requirement

Performance requirements

1. The combined MTOM – Maximum Speed requirement shall be such that, when plotted on the area in Figure C-1, the point shall lie in the green zone.

Verification method

Requirement (1) – Combined MTOM – Maximum Speed determination:

- Determine the MTOM of the drone and its maximum speed in levelled flight. Plot the results on Figure C-1.

Pass criteria

1. The determined point lies in the green zone in Figure C-1.

Drone mass (kg)	**Maximum speed** (m/s)									
	0 - 5	>5 - 10	>10 - 15	>15 - 20	>20 - 25	>25 - 30	>30 - 35	>35 - 40	>40 - 45	>45 - 50
0 - 0.25										
0.25 - 0.5										
0.5 - 0.75										
0.75 - 1										
1 - 1.25										
1.25 - 1.5										
1.5 - 1.75										
1.75 - 2										
2 - 2.25										
2.25 - 2.5										
2.5 - 2.75										
2.75 - 3										
3 - 3.25										
3.25 - 3.5										
3.5 - 3.75										
3.75 - 4										

Figure C-1: Proposed combined MTOM – Maximum Speed criteria

C.2 Draft Standard for Fixed Wing Propulsion System

The following draft standard has been developed from Guideline 3 in Section 3 of the main text.

Design Criteria and Compliance for Class 1-2 Open category Fixed Wing UAS

Fixed Wing Propulsion System Requirement

Introduction

For fixed wing uncrewed air systems, puller propeller configurations can cause significantly greater damage to crewed aircraft in the event of a collision, compared with equivalent pusher propeller designs.

Design Requirements

1. For fixed wing UAS only: Puller propeller configurations, in which the propeller or airscrew is located ahead of the motor, should be avoided.

Verification method

Requirement (1) – Propulsion system configuration determination:

- OEM to identify product certification class, in accordance with EASA Regulations (EU) 2019/947 and (EU) 2019/945.
- OEM to declare the propulsion system configuration of the UAS

Pass criteria

1. Where the certification class of a fixed wing drone is C1 or C2, the OEM must certify that the propulsion system meets the Design Requirement.

C.3 Draft Standard for Fixed Wing Spinner

The following draft standard has been developed from Guideline 4, in Section 3 of the main text.

Design Criteria and Compliance for Open category Fixed Wing UAS

Fixed Wing Spinner System Requirement

Introduction

It is common for 'spinners' to be installed over the hub of a propeller of fixed wing drones. These spinners come in various forms, including conical, hemi-spherical and elliptical shapes of various aspect ratios and constructions. In some cases, spinners are omitted from the design and the hub of the propeller, attachment features and/or central spindle are exposed.

The design of the spinner can influence whether the drone is deflected away from the airframe in a collision scenario, or whether it initiates failure and increases the hazard to the aircraft. This is particularly important for puller propeller configurations, where the speed at which the propeller and motor assembly directly impact the aircraft may be greatest.

Design Requirements

1. At its root, the diameter of the spinner shall be equal to, or greater than, that of the driving motor.
2. The outer mould line of the spinner shall be bounded by a conic and a flat-ended cylinder with the same root diameter and total length as the proposed design (Figure C-2).
3. The tip of the spinner should have a minimum radius of [TBD]mm or, if the tip is truncated, the diameter of the truncated front face should be at least [TBD]mm.
4. The spinner shall have a stiffness/crush response to minimise forces imparted on impact.

Verification method

Requirement (1) – Spinner dimension determination:

- Determine the root diameter of the spinner (Ds) and the major diameter of the driving motor (Dm)
- Determine the length of the spinner (Ls), measured from the tip to the frontal face of the propeller

Requirement (2) – Spinner shape determination:

- Demonstrate, via drawings, Computer Aided Design (CAD) or measurements, that the outer mould line of the spinner fits within the bounding shapes identified above.

Requirement (3): Tip shape determination:

- Determine, via drawings, CAD or measurements, the geometry of the spinner tip.

Requirement (4) – Spinner stiffness/crush response determination:

- *Further work required to develop a standardised test to determine:*
    - *How a tailored stiffness and crush-strength design would benefit different types/masses of drone*
    - *An appropriate, simple test scenario, such as a plate punch case that could be evaluated by calculation, test or non-linear finite element analysis.*

Pass criteria

1. OEM declaration that the spinner root diameter (Ds) is greater than, or equal to, that of the motor (Dm)

2. OEM declaration that the outer mould line of the spinner meets Design Requirement 2
3. OEM declaration that the tip geometry of the spinner meets Design Requirement 3
4. OEM declaration and evidence that the spinner design meets the stiffness and crush requirements (to be developed)

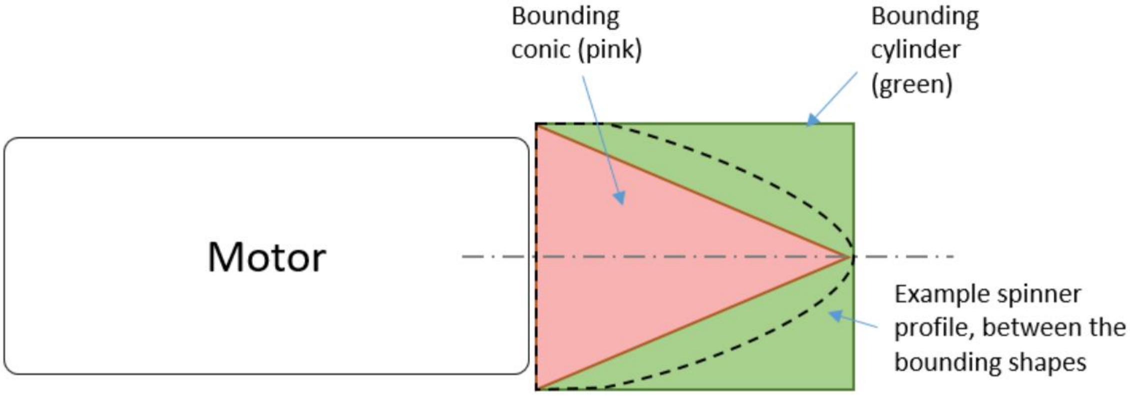


Figure C-2: Spinner bounding outer mould line

C.4 Draft Standard for Multi-Rotor Arms and Motor "Bumpers"

The following draft standard has been developed from Guideline 5 and Guideline 6 in Section 3 of the main text.

Design Criteria and Compliance for Open category multi-rotor UAS

Multi-rotor arms and bumpers

Introduction

The motors of multi-rotor UAS can be responsible for initiating hazardous damage in crewed aircraft structures during collision events. In the case of aircraft leading edge structures, motors that penetrate the skins may also proceed to perforate or penetrate Primary Structure, such as spar webs.

The motors of UAS configurations with frangible or folding arms have been observed to cause less damage to aircraft than stiff installations, because the impact forces are limited by their own inertia and that of the arm. However, where stiff, strong, non-articulating arms are used, then the inertia of the whole UAS may also contribute to the forces being reacted when the motors impact the crewed aircraft.

Motor guards or 'bumpers' can be effective in reducing impact damage from motors, and therefore reduce the severity of mid-air collisions. Further work is required to provide practical guidance on bumper design that could be applied to UAS of different types.

This standard requires the use of 'bumpers' around motors of C2 class UAS, or C1 UAS without frangible or folding motor arms.

Design Requirements

For multi-rotor UAS in C1 (or higher) classes:

1. A bumper structure should be installed around all flight motors, unless the UAS is certified as C1 class and has folding or frangible motor arms
2. *Further work is required to specify acceptable bumper size, shape, stiffness and crush performance*

Verification method

Requirement (1) – Arm articulation

- Determine whether the motor arms articulate, such that they are unlikely to react impact loads applied to the motors.

Requirement (1) – Arm frangibility

- Determine whether the motor arms would fail when a force equal to [TBD]-times the MTOW of the drone is applied in a forwards, aftwards, or sidewards directions.

Requirement (2) – Bumper configuration

- *Further work is required to specify acceptable bumper size, shape, stiffness and crush performance*

Pass criteria

1. OEM declaration of compliance and evidence against Design Requirements.

European Union Aviation Safety Agency

European Union Aviation Safety Agency

Konrad-Adenauer-Ufer 3
50668 Cologne
Germany

Project website Vulnerability of Manned Aircraft to Drone Strikes | EASA (europa.eu)

Tel. +49 221 89990- 1000
Mail research@easa.europa.eu
Web www.easa.europa.eu

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