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UAS Airborne Collision Severity Evaluation

Executive Summary – Structural Evaluation

July 2017

Executive Summary
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LIST OF ACRONYMS

BBA	Building Block Approach
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CG	Center of Gravity
DIC	Digital Image Correlation
ELOS	Equivalent Level of Safety
FAA	Federal Aviation Administration
FE	Finite Element
FEA	Finite Element Analysis
GA	General Aviation
LiPo	Lithium Polymer
MSU	Mississippi State University
NAS	National Airspace System
NIAR	National Institute for Aviation Research
PCB	Printed Circuit Board
SPH	Smoothed-Particle Hydrodynamics
sUAS	Small Unmanned Aerial System
UAS	Unmanned Aerial System
VTOL	Vertical Take-off and Landing

ABSTRACT

According to the latest industry forecast studies, the Unmanned Aerial System (UAS) market volume is expected to reach 4.7 million units by 2020 [1]. Nonetheless, safety, regulatory, social, and technical challenges need to be addressed before the sight of an unmanned aircraft in the sky becomes as common and accepted by the public as its manned counterpart. The effect of an airborne collision between a UAS and a manned aircraft is a concern to the public and government officials at all levels. The primary goal of regulating UAS operations into the National Airspace System (NAS) is to assure an appropriate level of safety. Research is needed to define airborne hazard severity thresholds for collisions between unmanned and manned aircraft, or collisions with people on the ground.

The results presented in this report and the technical volumes [2] [3] [4] focus the initial effort on analyzing a small quadcopter and a small fixed-wing UAS configuration impacting on a typical commercial transport jet and a typical business jet aircraft. This research will help determine airworthiness requirements for unmanned aircraft based on their potential hazard severity to other, already certified, airspace users in the NAS. The resulting severity thresholds will be based on UAS characteristics (kinetic energy, structure, shape, materials, etc.) under credible encounter scenarios and will provide for test criteria used to evaluate applicable operational and airworthiness standards. UAS that meet test criteria based on thresholds for these characteristics may be approved for operations over or near people on the ground and may be certified as airworthy under different criteria than other UAS [7]. Due to the complexity of the problem, full-scale test article availability, time and budget constraints, it was decided to conduct the R&D effort by using National Institute for Aviation Research (NIAR) physics based Finite Element (FE) modeling techniques based on the Building Block Approach. Conducting these type of impact studies by analysis provides better insight into the crashworthiness response of the target and the projectile. Damage evaluation criteria are proposed to quantify aircraft damage to the different impact scenarios summarized in this report.

Studies were conducted to analyze the damage introduced into different areas in the aircraft structure for both the commercial and business jet aircraft configurations. According to the simulations presented in chapter 4 of technical volumes II [3] and III [4], an airborne collision between a commercial transport jet and either a 1.2 kg (2.7 lb) quadcopter UAS or a 1.8 kg (4.0 lb) fixed-wing UAS at 128.6 m/s (250 knots) may result in a damage severity level of medium-high (3-4) in the horizontal and vertical stabilizer, medium (2-3) in the leading edge of the wing and medium-low (2) in the windshield. Equally, an airborne collision between a business jet and either a 1.2 kg (2.7 lb) quadcopter UAS or a 1.8 kg (4.0 lb) fixed-wing UAS may result in a damage severity level of medium-high (3-4) in the horizontal and vertical stabilizer, medium (2-3) in the leading edge of the wing and medium-low (2) for quadcopter to high (4) for fixed-wing UAS in the windshield. Correspondingly to what was observed in component level physical testing, the simulations predicted that most of the damage is produced by relatively dense and stiffer UAS parts (motors, camera, etc.). Additional parametric studies were conducted to analyze the effect of the projectile mass, impact velocity, and UAS architecture.

This research concluded that UAS impacts are likely to cause more damage than bird strikes for an equivalent initial kinetic energy. UAS impacts were generally associated with greater damage levels due to the hard-bodied mechanical construction of the UAS, with its components made of dense and rigid materials. Therefore, a 4 lb bird and a 4 lb UAS will introduce different levels of damage to the aircraft.

1. INTRODUCTION

According to the latest industry forecast studies, the Unmanned Aircraft System (UAS) market volume is expected to reach 4.7 million units by 2020 [1]. Nonetheless, safety, regulatory, social, and technical challenges need to be addressed before the sight of an unmanned aircraft in the sky becomes as common and accepted by the public as its manned counterparts. The effect of an airborne collision between a UAS and a manned aircraft is a concern to the public and government officials at all levels. The primary goal of regulating UAS operations into the National Airspace System (NAS) is to ensure an appropriate level of safety. Research is needed to define airborne hazard severity thresholds for collisions between unmanned and manned aircraft.

The results presented in this report and the technical volumes [2] [3] [4] focus the initial effort on analyzing two configurations of small UAS (sUAS), multi-rotor vertical take-off and landing (VTOL) and fixed-wing, impacting on a typical commercial transport jet and a typical business jet aircraft, certified under *14 CFR Part 25* or *Part 23* requirements [5] [6].

1.1 PROJECT SCOPE

This research will help determine airworthiness requirements for unmanned aircraft based on their potential hazard severity to other, already certified, airspace users in the NAS. The resulting severity thresholds will be based on UAS characteristics (kinetic energy, structure, shape, materials, etc.) under credible encounter scenarios and will provide for test criteria used to evaluate applicable operational and airworthiness standards. UASs that meet test criteria based on thresholds for these characteristics may be approved for operations over or near people on the ground and may be certified as airworthy under different criteria than other UAS [7].

The main research questions being answered through this research are [7]:

- What are the hazard severity criteria for an UAS collision (mass, kinetic energy, etc.)?
- What is the severity of an UAS collision with an aircraft in the air?
- Can an UAS impact be classified similar to a bird strike?
- Will an UAS impacting an engine be similar to a bird engine ingestion?
- What are the characteristics of an UAS where it will not pose a risk to an aircraft if a collision in the air was to happen?
- Can the severity of an UAS mid-air collision with an aircraft be characterized into categories based on the UAS? What would those categories look like?

It is important to emphasize that the intent of this research was not to do an assessment of already certified products (*e.g. 14 CFR Part 23/25/27/29/33*) but to analyze the characteristics of small UAS that contribute to damage of the airframe of manned aircraft result of an airborne collision.

1.2 TECHNICAL APPROACH

Due to the complexity of the problem, full-scale test article availability, time and budget constraints, it was decided to conduct the R&D effort by using National Institute for Aviation Research (NIAR) physics based Finite Element (FE) modeling techniques based on the Building Block Approach methodology. Conducting these types of impact studies by analysis provides better insight into the crashworthiness response of the target and the projectile. With physical testing, it is not possible to quantify internal energy distributions during the transient impact dynamic event; it is extremely complicated to control the exact impact locations and attitude of the UAS projectile, due to availability of expensive test articles, long setup times, and to control the exact impact location and attitude of the UAS projectile.

1.2.1 Building Block Approach FE Model Development and Validation

In order to build the UAS and target aircraft FE models, the NIAR and Mississippi State University (MSU) followed a physics based modeling approach. This methodology developed by the NIAR takes advantage of advances in computational power, the latest computational tools, years of research in understanding the fundamental physics of the crashworthiness event, generated test-to-test variability data, and verification & validation (V&V) modeling methods. The method follows the building block approach illustrated with a diagram in Figure 1.

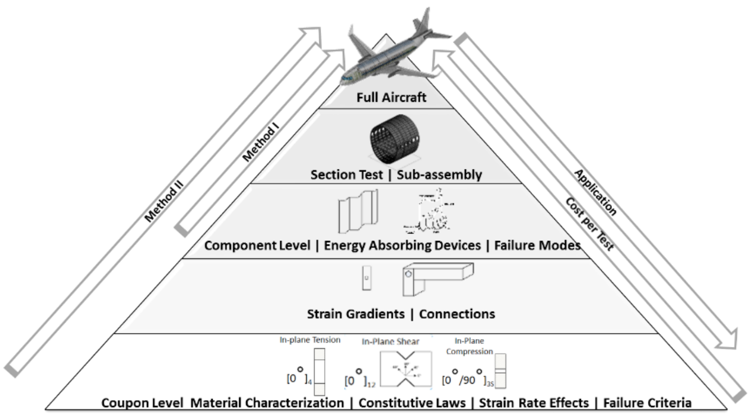


Figure 1. Building block approach for NIAR commercial transport jet model

The building block approach is the incremental development of analysis and supporting tests where typically there is an increase in size and complexity of the test article and a decrease in number of supporting tests. In order to develop this method, it is necessary to have a good understanding of the physics and testing variability from the coupon to the system level. Full-scale level test results do not drive the definition of the numerical model; it is driven by a predefined, verification and validation building block modeling methodology.

Using this approach, simulations should be able to predict the system level test results within the scatter of the physical system test results. An objective verification criterion is used to evaluate the numerical models, where the correlation level between simulation and testing is defined by an understanding of the test-to-test variability of the physical system under evaluation.

1.2.2 Verification of the Finite Element Model: Coupon to Sub-Assembly Level Testing

FE models of a typical quadcopter and fixed-wing UAS were developed for the airborne collision studies. Different component level tests were conducted to verify the UAS FE models. The following paragraphs will summarize the testing conducted as well as identify further areas of work.

Coupon Level Testing:

- Basic coupon level testing verification was performed for the various material systems of the UAS.
- Coupon level verification studies from technical literature were conducted.

Component Level Testing:

- The polycarbonate UAS body of the quadcopter was subject to an impact of 110 J in a drop tower test. The event was filmed with high-speed cameras, and the reaction load and respective impulse were measured and recorded.
- The UAS batteries, cameras and motors from both UAS configurations were tested in a compressed air gun facility under impact velocities similar to those of the mid-air collision being studied in this project, between 110 and 250 knots (56.6 and 128.6 m/s). The kinematics were captured with high-speed cameras, the reaction loads and the strains in the impacted panel were measured with four load cells and thirteen strain gages respectively, and a Digital Image Correlation (DIC) system captured the displacements and deformations of the panel at the impacted area.

Sub-Assembly Level Testing:

- The full quadcopter UAS assembly (excluding the battery) was released from a height of 17 feet (5.18 m) and impacted into a rigid flat plate, where the reaction loads were measured and recorded. The kinematics were captured with high-speed cameras.

All tests were virtually replicated with the FE simulations. The simulation models correlated within the scatter of the data of the aforementioned test conditions. Therefore, it can be concluded that the FE models were verified for the conditions set by the physical tests.

The models are intended to be used for assessing impact dynamics with aircraft structures and to simulate mid-air collisions. These FE models should be limited to relative impact velocities between 110 and 250 knots (56.6 and 128.6 m/s), for which component level tests verified the behavior of the main components of the UAS. Further coupon to component level tests should be conducted in the future in order to use these UAS FE models for ground collisions impact scenarios or lower velocity airborne collisions with General Aviation (GA) aircraft and rotorcraft.

1.2.3 Description of UAS Models

Two different UAS architectures were selected to conduct the airborne collision studies: a quadcopter and a fixed-wing configuration. The selection of the specific model was based on a market study performed by Montana State University for this project [2]. These models were considered as projectiles in the collision studies.

1.2.3.1 Quadcopter Configuration

The investigations of Montana State University [2] concluded that the DJI Phantom family are the most common UAS under 2.3 kg (5 lb), with a presence of more than 61% of the market. Consequently, the DJI Phantom 3 Standard edition was selected as baseline to define the quadcopter UAS FE model for the collision study.

The Phantom 3 is a 1.2 kg (2.7 lb) quadcopter configuration intended for recreational and commercial aerial photography and accessible to the public. Table 1 shows the basic dimensions (in mm) and relevant specifications of the selected quadcopter UAS. More details can be found in chapter 2 of technical volume II [3]. The quadcopter UAS is constructed with a polycarbonate plastic body/casing that acts as primary structure and it mounts four electric motors, a Lithium-Polymer (LiPo) battery, and a camera with metallic casing. Most of the electronics are concentrated in a Printed Circuit Board (PCB) inside the plastic body.

NIAR purchased a unit of the DJI Phantom 3 and reverse engineered the geometry, material properties, and mass distribution of the UAS following the process illustrated in Figure 2. Figure 3 presents the level of detail achieved with the quadcopter FE model, in which features as small as 0.8 mm (0.031 in) have been captured with the mesh.

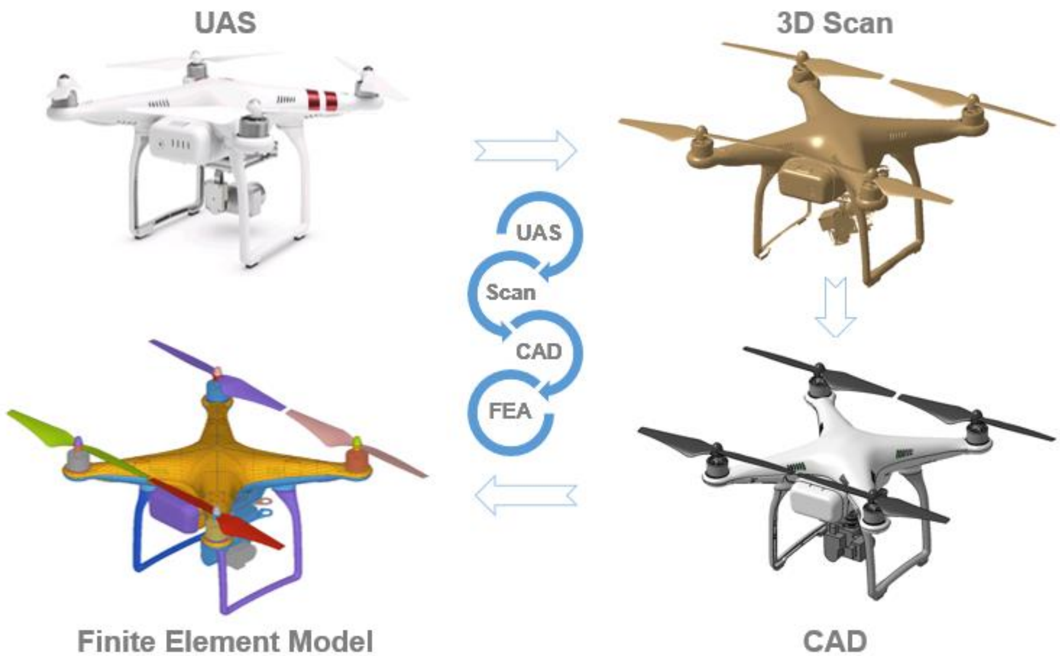


Figure 2. Reverse engineering process

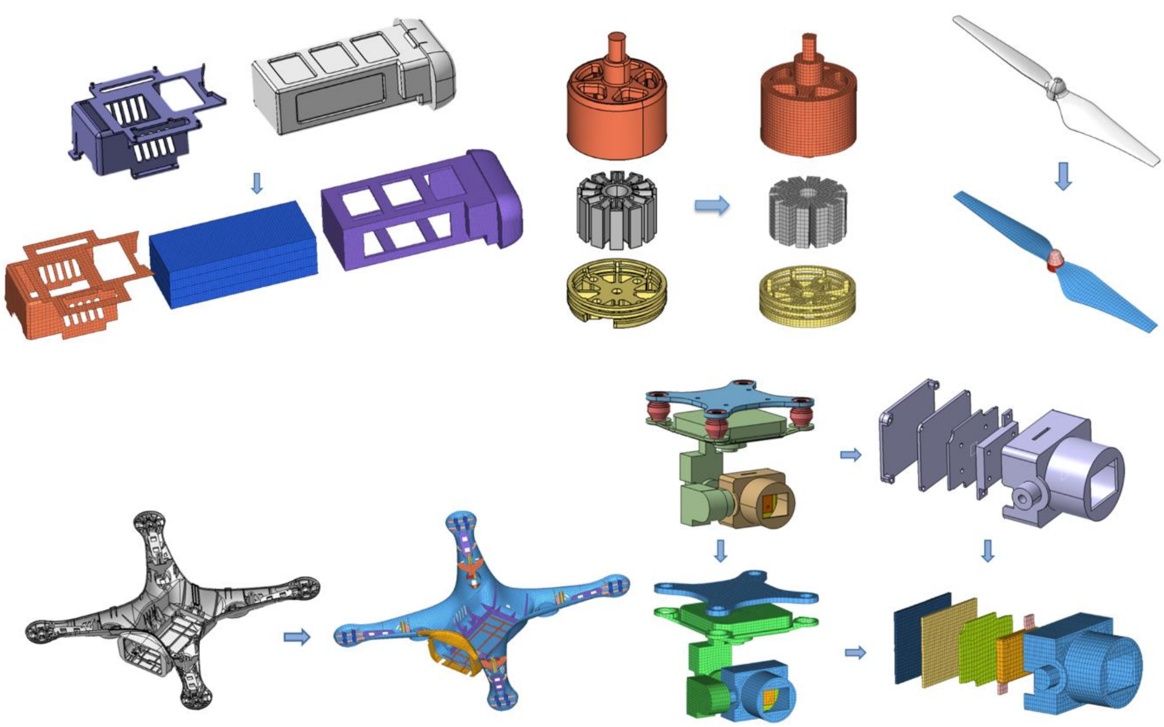


Figure 3. Quadcopter UAS FE model overview

1.2.3.2 Fixed Wing Configuration

Similarly, Montana State University identified the Precision Hawk Lancaster as a representative UAS model within the 4-8 lb mass range for fixed-wing configurations [2]. The Precision Hawk Lancaster HawkEye Mark III is a lightweight fixed-wing UAS, designed for precision agriculture applications shown in Figure 4. The specifications relevant for this project are presented in Table 1. Following the selection process, the UAS FE model was developed by MSU, as discussed in chapter 2 of technical volume III [4].

The construction of this fixed-wing UAS consists of a forward fuselage structure comprised of PCBs; expanded polystyrene wings, vertical tail, and horizontal stabilizer; and carbon/epoxy composite wing spars and tail booms. The PCBs are used as multifunctional structural elements.

Following an analogous procedure as with the quadcopter UAS, the fixed-wing UAS was reverse engineered based on the process illustrated in Figure 2. Figure 5 shows some details of the final fixed-wing UAS FE model.

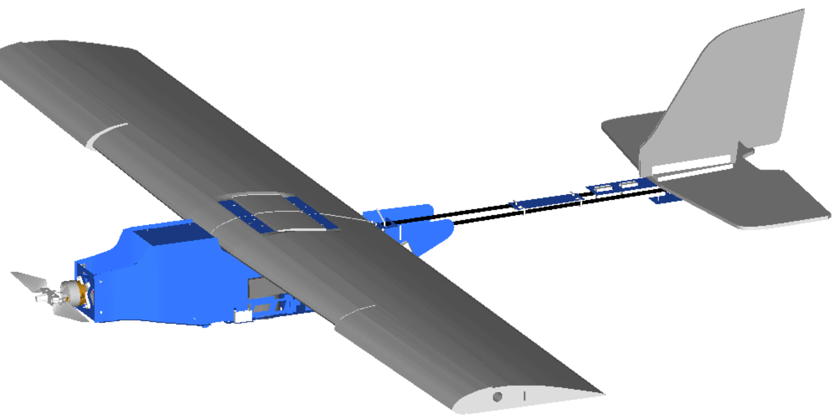


Figure 4. Precision Hawk Lancaster Hawkeye Mark III – Fixed-wing UAS

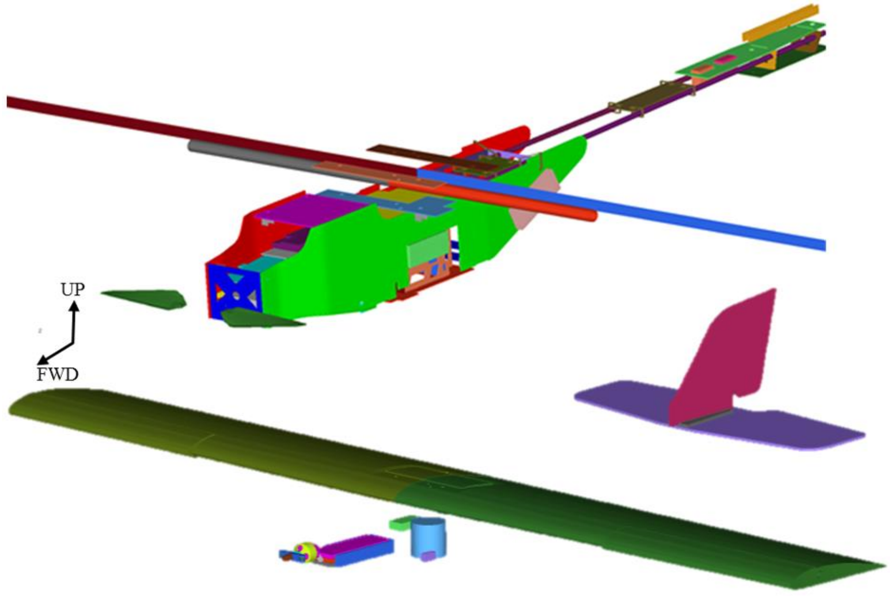
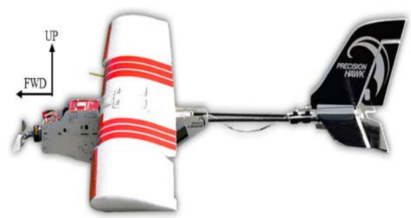


Figure 5. Fixed-wing UAS FE model overview – shell (top) and solid elements (bottom)

1.2.3.3 Quadcopter and fixed-wing UAS specifications

Table 1 shows a comparison of the most relevant specifications and dimensions of both selected UAS, the DJI Phantom 3 and the Precision Hawk Lancaster Hawkeye Mk-III. More details can be found in the respective technical report [3] [4].

Table 1. Relevant specifications of the selected UAS

Selected UAS	DJI Phantom 3	Precision Hawk Lancaster Hawkeye III
Image		
Mass	1,216 g	1,800 g
Dimensions	290x289x186 mm	Length: 800 mm Wingspan: 1,500 mm
Max. Horizontal Speed	16.0 m/s	19.5 m/s
Max. Service Ceiling	6,000 m	4,000 m
Battery - LiPo	364 g (4 cell)	335 g (3 cell)
Motor(s) – Brushless DC	56 g x 4	76 g x 1
Max. Motor Speed	1,240 rad/s	1280 rad/s
Camera	52 g	372 g

1.2.4 Description of Manned Aircraft Models

A review of the airspace was conducted to select a representative commercial transport jet and business jet. A summary of the justification for selection of representative aircraft models is provided in this section. Further information can also be found in the research conducted by Montana State University [2] as part of work for Work Package II. The models of these aircraft were considered as targets in the collision studies.

1.2.4.1 Commercial Aircraft

It was concluded that narrow-body single-aisle aircraft such as the Boeing 737 or the Airbus 320 families are the most popular commercial transport jets in use throughout the world. Thus, a generic model of the narrow-body single-aisle aircraft (referred to as commercial transport jet in this report) configuration, of similar size and construction, was reverse engineered. Figure 6 presents the CAD model developed at NIAR for the commercial transport jet.

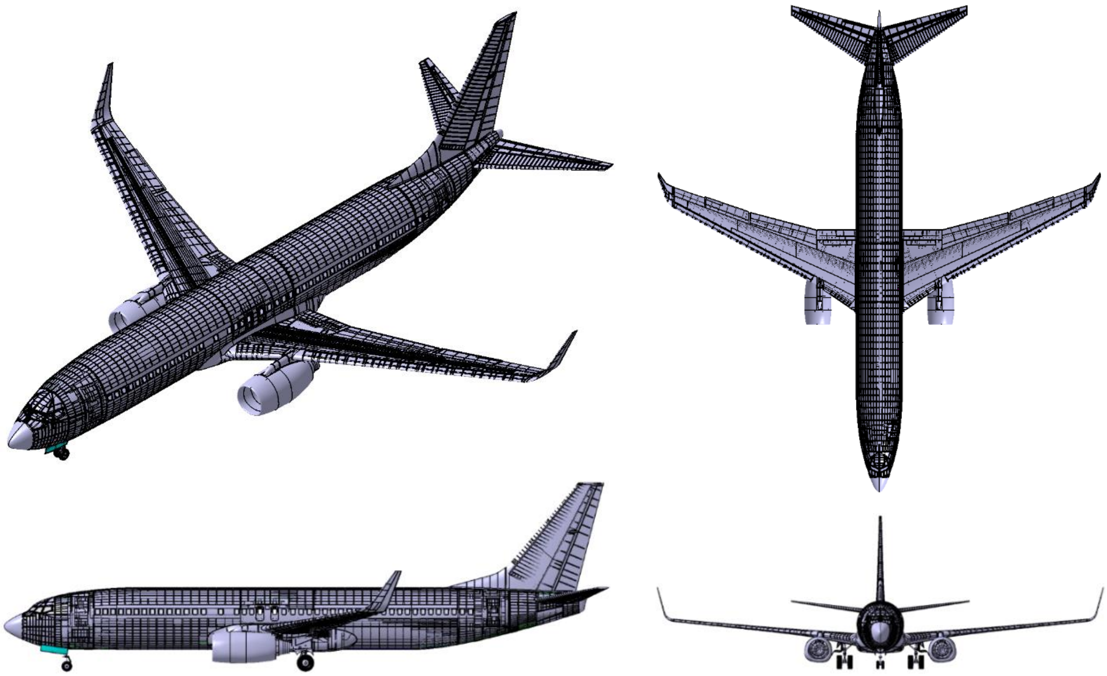


Figure 6. NIAR commercial transport jet aircraft model developed for crashworthiness research

1.2.4.2 Business Jet Aircraft

Similarly, the Learjet 31A was selected as a representative aircraft for the business jet category. Although this aircraft is not the most registered by the FAA, it has similar dimensions and specifications in comparison to many other business jets [2]. Thus, a generic model of similar size and construction, as the Learjet 31A, was reverse engineered and will be referred to as business jet in this report. Figure 7 shows the CAD model developed at NIAR for the business jet.

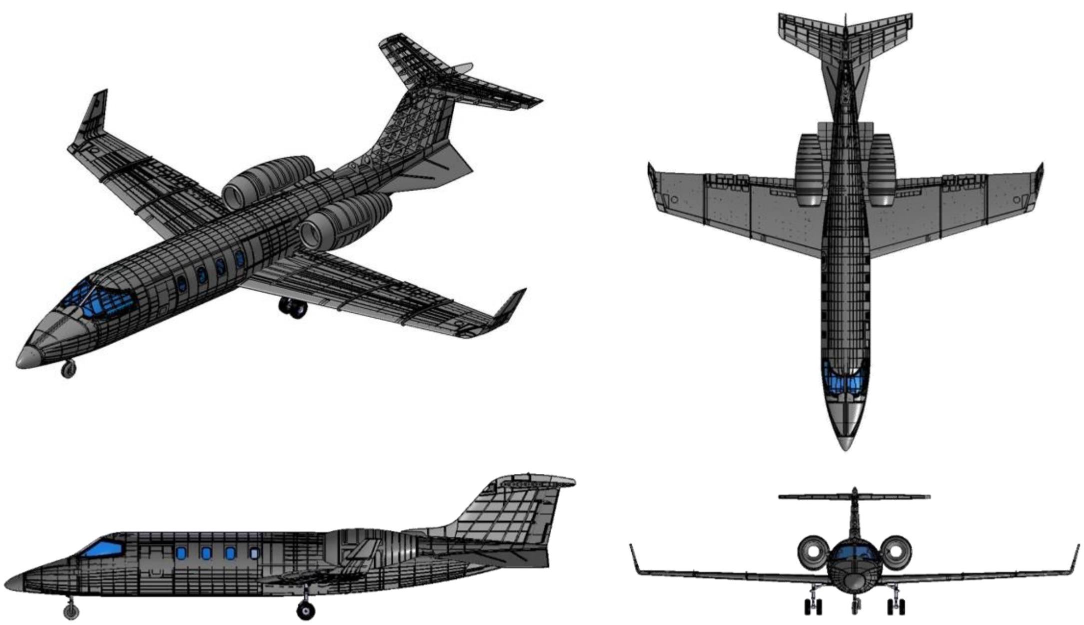


Figure 7. NIAR business jet aircraft model developed for crashworthiness research

1.2.5 Selected Impact Conditions

As presented in Chapter 4, following the airworthiness requirements listed in the FAA General Operating and Flight Rules (*14 CFR Part 91*) [8], it was assumed that the most probable high velocity impact scenario was either at landing/take-off or at holding flight phases. For these cases and considering the categories of aircraft being studied in this report, the maximum flight speed is limited to 200 KIAS (*14 CFR Part 91.117 (b)*), which at 2,500 ft is approximately 208 knots (107 m/s). Considering a frontal impact between the UAS and the aircraft to be a worst-case scenario, an impact velocity can be established by adding the relative speeds of both bodies. Therefore, and considering the specifications of the two UAS discussed above as well as in [3] and [4], an impact velocity of 250 knots (128.6 m/s) was defined for all the baseline airborne collision studies.

Moreover, a parametric study was completed with the objective of identifying the most critical local impact conditions and narrowing down the number of simulations to be run in each of the impacted aircraft subassemblies. To achieve this, the quadcopter UAS FE model was impacted into a wing leading edge FE model, developed and validated through simulation and testing by NIAR in a previous project for bird strike [9]. The influence of the yaw angle of the quadcopter UAS and the local position of its Center of Gravity (CG) with respect to the impacted aircraft was studied.

Based on the results obtained in these parametric studies, a quadcopter UAS orientated at 45 degrees impacting with the CG aligned with the leading edge of the target between the two closest ribs was identified as the most severe impact condition in terms of overall damage and failure of components. This impact condition was consequently selected as a baseline for the initial conditions of the collision study involving the commercial transport and business jet targets.

For the fixed wing configuration, the aircraft was oriented in the flight path axis, as most of the masses would be aligned, and therefore will concentrate most of the energy transfer in a localized area.

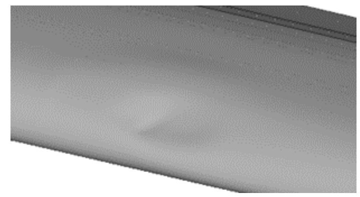
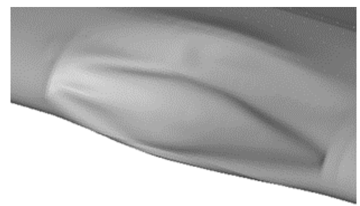
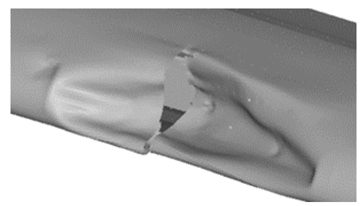
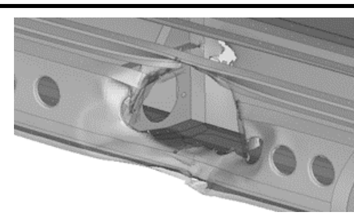
This study also highlighted the importance of having ideal initial conditions to produce the worst-case levels of damage. Small deviations in the impact location might underestimate the severity of the event.

1.2.6 Proposed Evaluation Criteria for Airborne Collisions

The results from over 140 impact scenarios were analyzed and categorized relative to one another, and a set of impact severity criteria were defined as shown in Table 2.

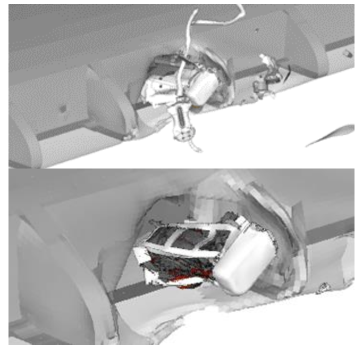
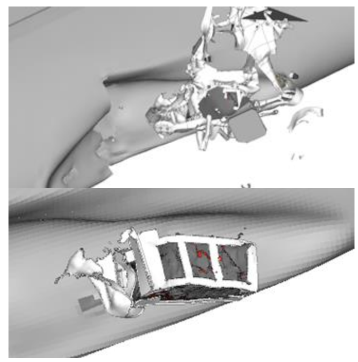
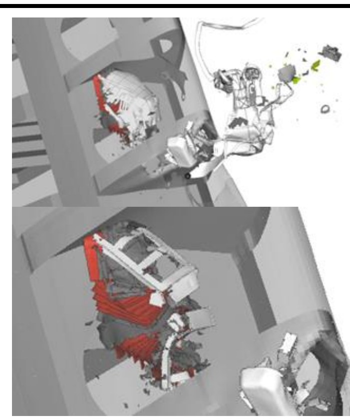
The lowest damage category, Level 1, generally corresponds to a minimal amount of localized damage. The next category, Level 2, represents significant visible damage to the external surface of the aircraft with some internal component damage but with no appreciable skin rupture. The third category, Level 3, describes impact events where the outer surface of the aircraft is compromised in a way that could allow ingress of foreign objects into the airframe, with some damage to substructure. Finally, Level 4 indicates damage that includes all of the preceding aspects as well as extensive damage to internal components and possibly compromising part of the primary structure.

Table 2. Damage level categories

Severity	Description	Example
Level 1	• Airframe undamaged. • Small deformations.	
Level 2	• Extensive permanent deformation on external surfaces. • Some deformation in internal structure. • No failure of skin.	
Level 3	• Skin fracture. • Penetration of at least one component into the airframe.	
Level 4	• Penetration of UAS into airframe. • Failure of parts of the primary structure.	

The risk of fire associated with damaged LiPo type batteries was addressed for each simulation based on the trends observed during component level ballistic testing [3] and the particular kinematics of a given impact scenario. Table 3 presents the criteria used in this study. Note that the label of “Fire Risk” indicates a potential outcome rather than an impending event due to the qualitative nature of the assessment. Further studies and physical testing into this phenomenon would be required in order to determine any additional severity. During component level testing that the fire risk corresponded inversely to the velocity of the impact; higher velocities caused the battery to disintegrate reducing the heat generated after impact, while lower velocities allowed the battery pack to remain consolidated, increasing the post-impact heat generation.

Table 3. Risk of battery fire

Fire Risk	Description	Example
Yes	• UAS (including the battery) penetrates the airframe. • Battery deforms but stays undamaged. • Validation tests showed that partly damaged batteries created heat and sparks.	
No	• The UAS does not penetrate the airframe.	
No	• UAS (including the battery) penetrates the airframe. • The battery sustains great damage, destroying its cells. • Validation tests showed that completely damaged batteries did not create heat or sparks.	

2. AIRBORNE COLLISION SEVERITY EVALUATION

2.1 UNMANNED AIRCRAFT SYSTEMS IMPACT SEVERITY CLASSIFICATION

Conventional 14 CFR system safety analyses include hazards to flight crew and occupants that may not be applicable to unmanned aircraft. However, UAS operations may pose unique hazards to other aircraft and people on the ground. It is necessary to determine hazard severity thresholds for UAS using safety characteristic factors that affect the potential severity of UAS in collisions with other aircraft in possible airborne encounters. The factors that determine the outcome of an airborne collision are numerous and complex and are highly dependent on the structural design and materials used for the construction of the UAS. The criteria summarized in Table 2 and Table 3 were used to evaluate the UAS Impact Severity Classification.

2.2 COMMERCIAL TRANSPORT JET AIRBORNE COLLISION

As introduced in chapter 3 of technical volumes II [3] and III [4], the target areas selected for impact on the NIAR commercial transport jet were the vertical stabilizer, horizontal stabilizer, wing leading edge, and windshield. Sixteen explicit dynamic simulations of impacts of the 1.2 kg (2.7 lb) quadcopter UAS and of the 1.8 kg (4.0 lb) fixed-wing UAS into the commercial transport jet were conducted. As defined in section 1.2.5, an impact velocity of 250 knots (128.6 m/s) was selected for these airborne collision studies. Figure 8 and Figure 9 illustrate the locations selected for impact with the commercial transport jet for the two UAS configurations. Table 4 and Table 5 summarize the results of the collision studies, in terms of severity level and risk of fire, for the quadcopter and fixed-wing configurations respectively.

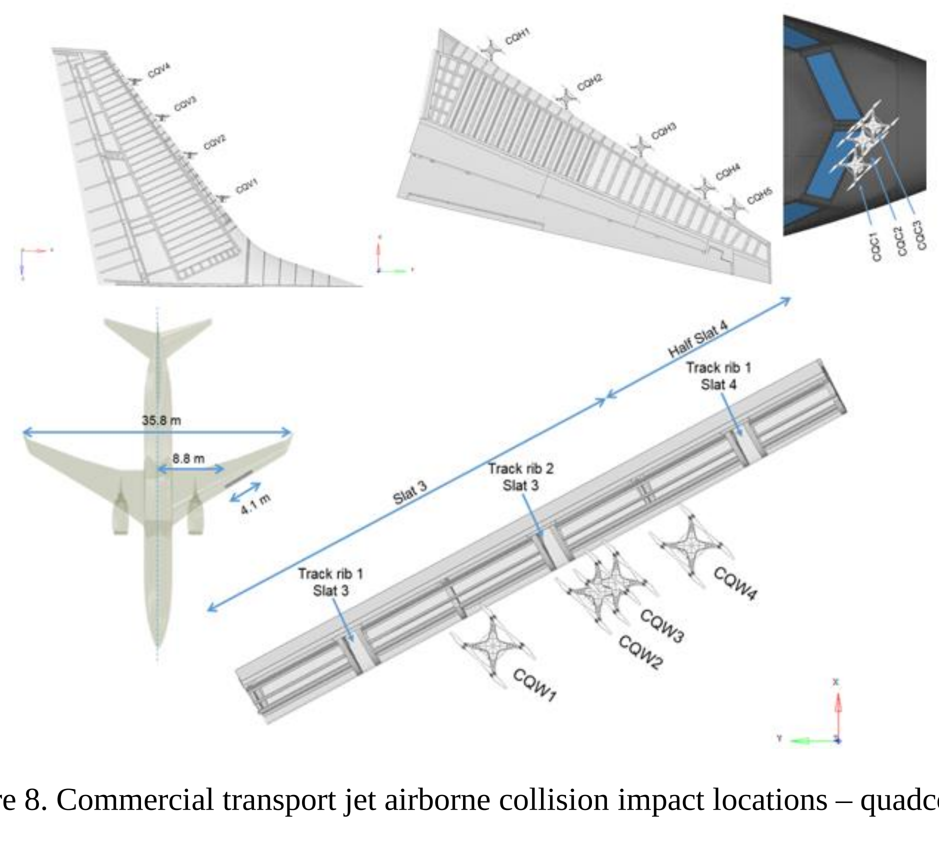


Figure 8. Commercial transport jet airborne collision impact locations – quadcopter UAS

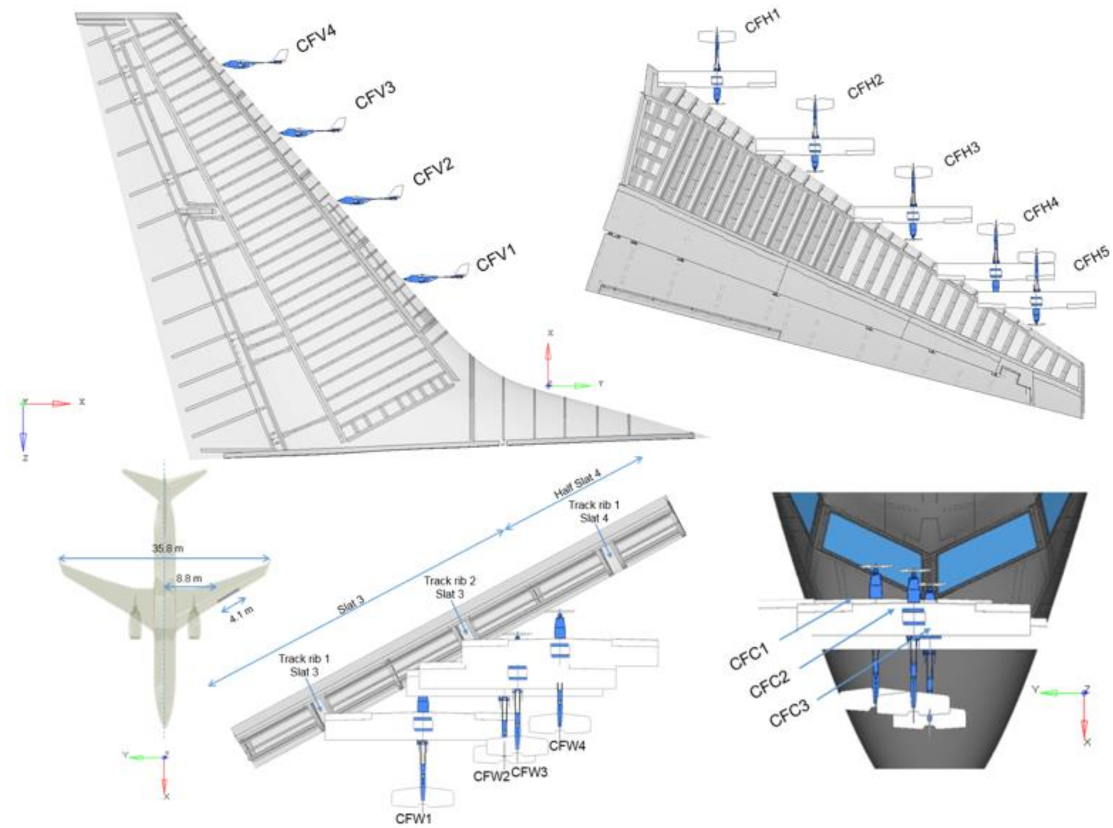


Figure 9. Commercial transport jet airborne collision impact locations – fixed-wing UAS

Table 5 and Table 5 show consistent levels of damage at all locations for each impact target component, indicating that the impact behavior of the UAS for a given target structure is generally not affected by local features in the structure; the energy level of the impact is such that localized structural variations do not significantly increase or decrease the overall damage level. The impact to the vertical stabilizer (CFV2) showed a reduced damage severity level due to a subjective assessment that the damage was the least critical of the vertical stabilizer impacts. The nomenclature convention for the simulation cases is shown in technical volumes II [3] and III [4].

A damage severity level 4 was achieved in outer parts of the horizontal stabilizer, as shown in Tables 5 and 6, when the collision involves the quadcopter and in nearly all the areas of the horizontal and vertical stabilizers for the fixed-wing cases. In these scenarios, the front spar, considered to be a primary structure, was damaged and even perforated. These were the most severe cases found in the UAS collision with the commercial transport jet.

Additionally, it was observed that the nature of the impact caused the battery to penetrate the airframe and remain partially damaged in three cases involving the horizontal stabilizer when colliding only with the quadcopter UAS, creating the potential for post-impact fire risk.

Table 4. Commercial transport jet airborne collision simulation results for 1.2 kg (2.7 lb) quadcopter UAS – Severity levels and risk of battery fire

	Commercial Transport Jet															
	Vertical Stabilizer				Horizontal Stabilizer					Wing				Windshield		
Case	CQV1	CQV2	CQV3	CQV4	CQH1	CQH2	CQH3	CQH4	CQH5	CQW1	CQW2	CQW3	CQW4	CQC1	CQC2	CQC3
Severity	Level 3	Level 3	Level 3	Level 3	Level 3	Level 3	Level 4	Level 4	Level 4	Level 3	Level 3	Level 3	Level 2	Level 2	Level 2	Level 2
Fire Risk	No	No	No	No	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No

Table 5. Commercial transport jet airborne collision simulation results for 1.8 kg (4.0 lb) fixed-wing UAS – Severity levels and risk of battery fire

	Commercial Transport Jet															
	Vertical Stabilizer				Horizontal Stabilizer					Wing				Windshield		
Case	CFV1	CFV2	CFV3	CFV4	CFH1	CFH2	CFH3	CFH4	CFH5	CFW1	CFW2	CFW3	CFW4	CFC1	CFC2	CFC3
Severity	Level 4	Level 3	Level 4	Level 4	Level 4	Level 4	Level 4	Level 4	Level 4	Level 3	Level 3	Level 3	Level 3	Level 2	Level 2	Level 2
Fire Risk	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

A summary of the results, in terms of energy balance, of all quadcopter UAS cases is shown in Figure 10 and a corresponding summary for the fixed-wing UAS is shown in Figure 11. For each case, the bar represents a summation of all the different energies involved in the impact event, measured at 10 ms and normalized with the total energy at time zero. Each block indicates the ratio (in percentage) of energy versus total initial energy.

As shown in Figure 10 and Figure 11 for each one of the impact conditions we can quantify how the initial kinetic energy of the UAS prior to impact is transformed into aircraft and UAS internal energies through the structural deformations induced during impact; a residual UAS kinetic energy that is a function of the UAS post impact debris mass moving at a post-impact residual velocity; friction energy which is a function of the sliding contact energy between the UAS and the aircraft structure, and eroded energy from the mass of the UAS and aircraft eroded elements to increase the stability of the calculation. Conclusions on how the energy is distributed can be established by analyzing these plots in detail.

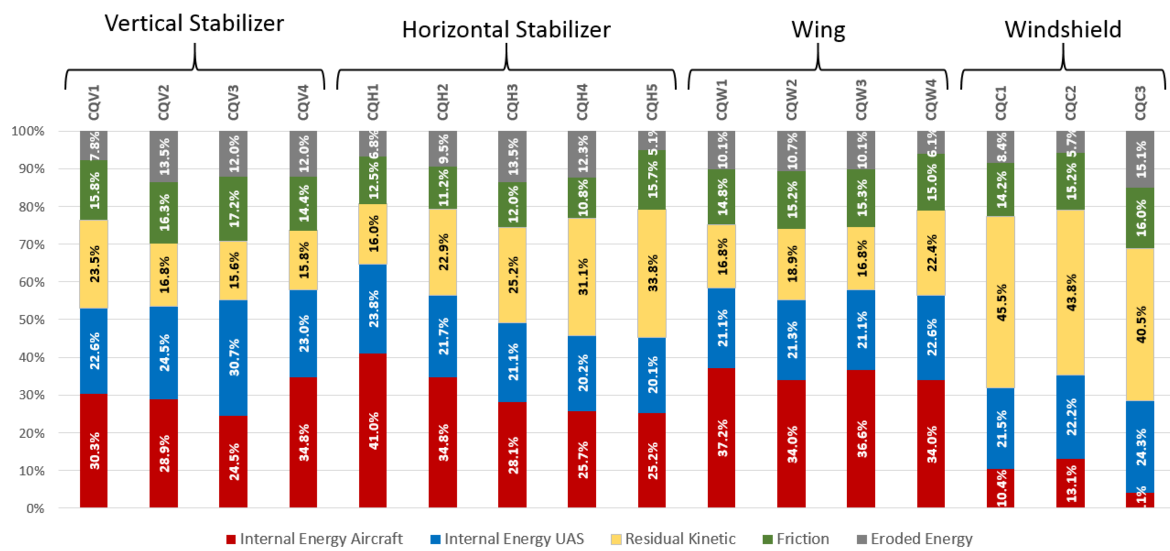


Figure 10. Commercial transport jet airborne collision – Energy summary for 1.2 kg (2.7 lb) quadcopter UAS

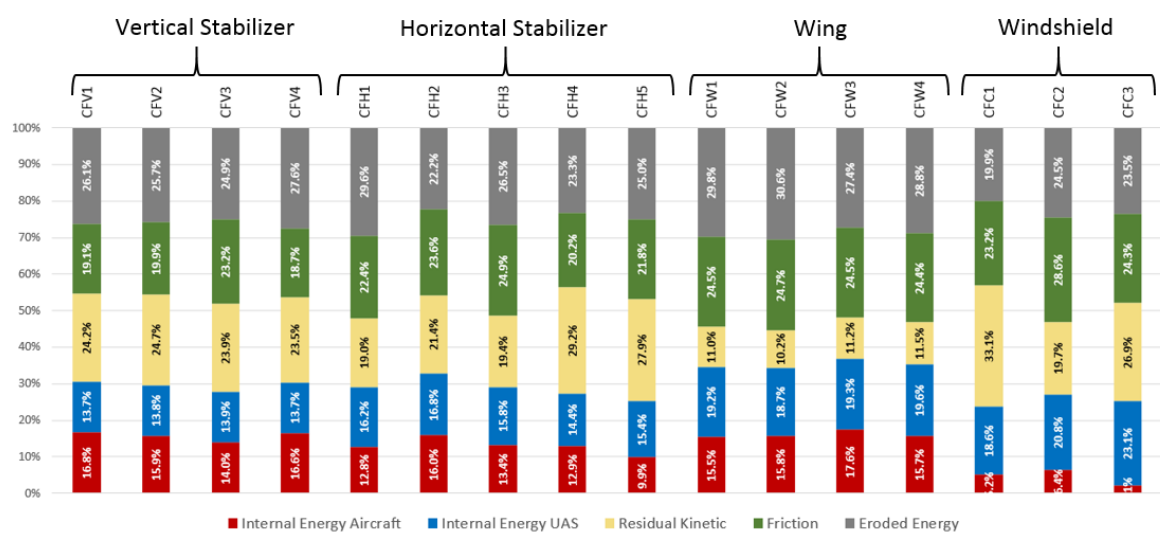


Figure 11. Commercial transport jet airborne collision – Energy summary for 1.8 kg (4.0 lb) fixed-wing UAS

If compared with other areas of the commercial transport jet, the UAS impacts on the windshield present a much higher residual kinetic energy. Due to the low angle impact in the transparency (~45°), the UAS impacts were deflected without inducing considerable damage to the windshield. The windshield is constructed with a thick multilayered transparency with very high stiffness. Consequently, a significant fraction of the deformation due to the impact was absorbed by the UAS, since the internal energy of the UAS is much greater than that of the aircraft.

2.3 BUSINESS JET AIRBORNE COLLISION

As introduced in chapter 3 of technical volumes II [3] and III [4], the target areas selected for impact on the NIAR business jet were vertical stabilizer, horizontal stabilizer, wing leading edge, and windshield. Sixteen explicit dynamic simulations of impacts of the 1.2 kg (2.7 lb) quadcopter UAS and of the 1.8 kg (4.0 lb) fixed-wing UAS into the business jet were conducted. As defined in section 1.2.5, an impact velocity of 250 knots (128.6 m/s) was defined for these airborne collision studies. Figure 12 and Figure 13 illustrate the locations selected for impact with the business jet. Table 7 and 8 summarize the results of the collision studies, in terms of severity level and risk of fire, on the business jet for the quadcopter and fixed-wing configurations respectively.

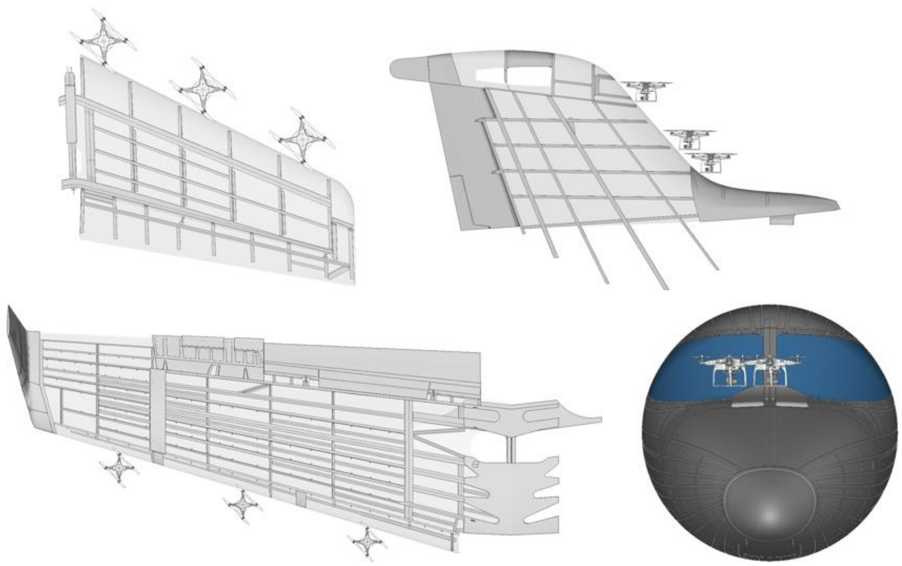


Figure 12. Business jet airborne collision impact locations – quadcopter UAS

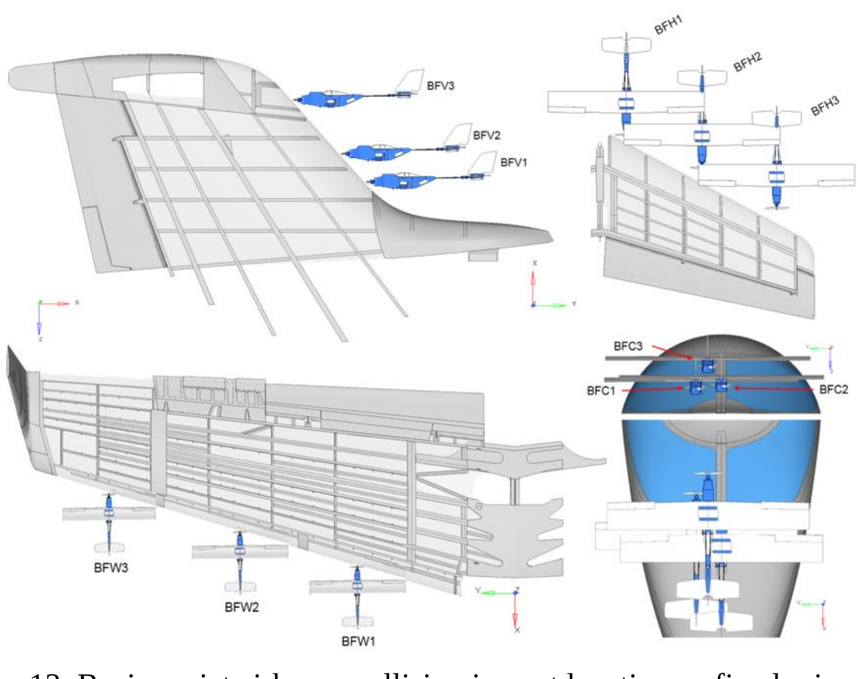


Figure 13. Business jet airborne collision impact locations – fixed-wing UAS

Table 6. Business jet airborne collision simulation results for 1.2 kg (2.7 lb) quadcopter UAS–Severity levels

	Business Jet										
	Vertical Stabilizer			Horizontal Stabilizer			Wing			Windshield	
Case	BQV1	BQV2	BQV3	BQH1	BQH2	BQH3	BQW1	BQW2	BQW3	BQC1	BQC2
Severity	Level 3	Level 3	Level 2	Level 3	Level 4	Level 4	Level 3	Level 2	Level 2	Level 2	Level 2
Fire Risk	Yes	No	No	Yes	No	Yes	Yes	No	No	No	No

Table 7. Business jet airborne collision simulation results for 1.8 kg (4.0 lb) fixed-wing UAS–Severity levels

	Business Jet											
	Vertical Stabilizer			Horizontal Stabilizer			Wing			Windshield		
Case	BFV1	BFV2	BFV3	BFH1	BFH2	BFH3	BFW1	BFW2	BFW3	BFC1	BFC2	BFC3
Severity	Level 4	Level 4	Level 4	Level 4	Level 4	Level 4	Level 2	Level 3	Level 3	Level 4	Level 1	Level 4
Fire Risk	No	No	No	No	No	No	No	No	No	No	No	No

It was observed that for the cases involving the quadcopter, only at outer parts of the horizontal stabilizer severity reached Level 4 damage. On the other hand, for the fixed-wing UAS, all the cases involving the stabilizer plus two out of three cases on the windshield presented Level 4. Impacts to the wing displayed lower levels of damage. A skin that was slightly thicker than the stabilizer and the pipe of the anti-icing system absorbed most of the damage, protecting the front spar from a direct impact of the UAS.

Furthermore, it was observed that in every quadcopter impact case involving the inboard area of a lifting surface, the battery penetrated into the airframe and remained partially damaged, creating potential for post impact fire risk. On the contrary, none of the cases involving the fixed wing induced risk of battery fire.

A summary of the results of all quadcopter and fixed-wing UAS impact cases is shown in Figure 14 and Figure 15 respectively. Similar to the commercial transport jet, the UAS impacts on the windshield resulted in a much higher residual kinetic energy due to the deflection of the projectile.

Moreover, the PCB fuselage construction of the fixed-wing UAS behaved in a quasi-brittle fashion than the polycarbonate-bodied quadcopter UAS, breaking into many smaller pieces upon impact, which appears in the energy balance as a greater amount of eroded energy for each case.

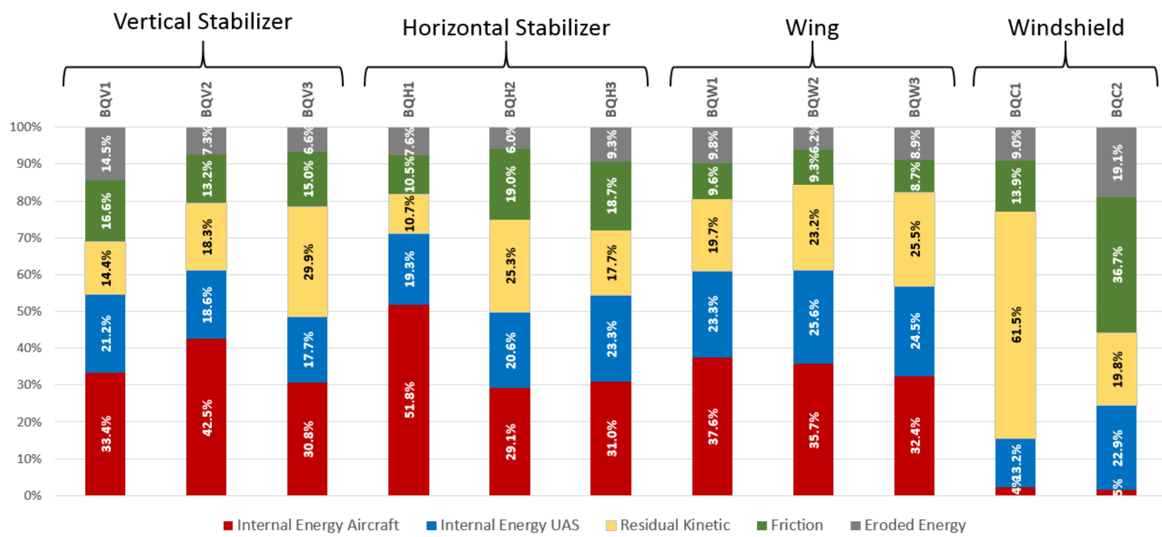


Figure 14. Business jet airborne collision – Energy summary for 1.2 kg (2.7 lb) quadcopter UAS

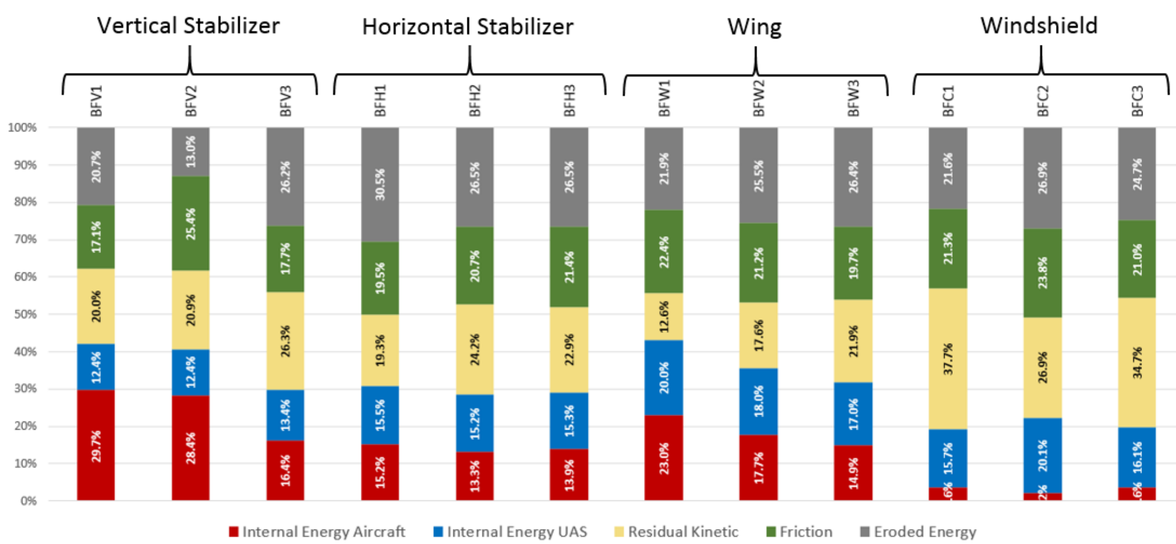


Figure 15. Business jet airborne collision – Energy summary for 1.8 kg (4.0 lb) fixed-wing UAS

2.4 AIRBORNE COLLISION SEVERITY STUDY CONCLUSIONS – COMMERCIAL TRANSPORT JET

According to the simulations presented in chapter 4 of technical volumes II [3] and III [4], an airborne collision between a commercial transport jet and either a 1.2 kg (2.7 lb) quadcopter UAS or a 1.8 kg (4.0 lb) fixed-wing UAS at 250 knots may result in a damage severity level of medium-high (3-4) in the horizontal and vertical stabilizer, medium (2-3) in the leading edge of the wing and medium-low (2) in the windshield. Figure 16 illustrates the impact severity levels at different locations on the commercial transport jet airframe analyzed.

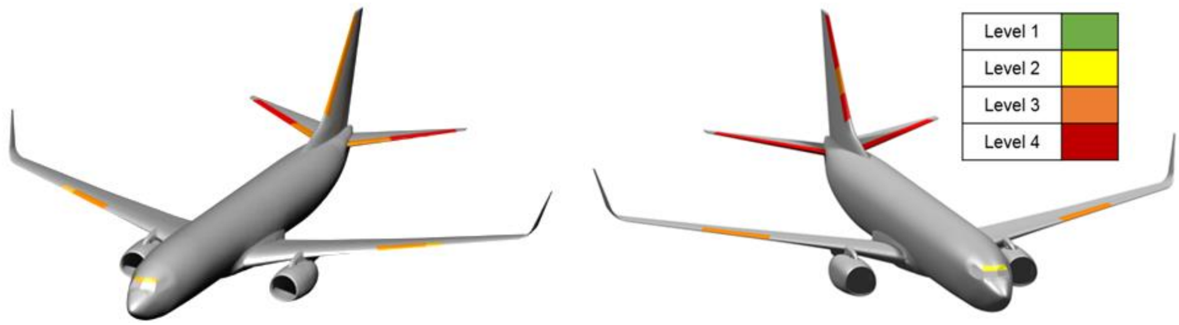


Figure 16. Summary of 1.2 kg (2.7 lb) quadcopter (left) and 1.8 kg (4.0 lb) fixed-wing (right) UAS collision severity levels on commercial transport jet type aircraft

2.5 AIRBORNE COLLISION SEVERITY STUDY CONCLUSIONS – BUSINESS JET

According to the simulations presented in chapter 4 of technical volume II [3], an airborne collision be-tween a business jet and a 1.2 kg (2.7 lb) quadcopter UAS at 250 knots may result in a damage severity level of medium-high (3-4) in the horizontal and vertical stabilizer, medium (2-3) in the leading edge of the wing and medium-low (2) in the windshield.

Similarly, as presented in technical volume III [4] an airborne collision between a business jet and a 1.8 kg (4.0 lb) fixed-wing UAS at 250 knots may result in a damage severity level of high (4) in the horizontal and vertical stabilizer, medium (2-3) in the leading edge of the wing and high (4) in the windshield. Figure 17 illustrates the severity levels at different locations of the business jet airframe analyzed. Most of the damage to both aircraft was produced by the stiffer structural components (motors, battery, camera, etc.) of the UAS. This is consistent with the observations from component level physical testing and simulations (chapter 2 of technical volumes II and III).

Figure 17. Summary of 1.2 kg (2.7 lb) quadcopter (left) and 1.8 kg (4.0 lb) fixed-wing (right) UAS collision severity levels on business jet type aircraft

3. IMPACT KINETIC ENERGY AND UAS ARCHITECTURE PARAMETRIC STUDIES

The kinetic energy of a mid-air collision between an UAS and the two manned aircraft being studied in this project was characterized in terms of the UAS mass and relative impact velocity. The parametric study and calculated damage severity levels were compared to those of the corresponding baseline simulations. The results of this study are summarized in the following two subsections. The worst-case impact conditions for each location identified in the airborne collision studies were used as a baseline for the parametric analyses. The effect of the UAS configuration on the damage experienced by the target aircraft during airborne collisions was assessed.

3.1 MASS

The quadcopter UAS was scaled-up from an initial mass of 1.2 kg (2.7 lb) to a final value of 1.8 kg (4.0 lb) to assess the potential increase in damage severity imparted by a heavier UAS as described in chapter 4 of technical volume II [3]. Similarly, the fixed-wing UAS was scaled-up from 1.8 kg (4.0 lb) to 3.6 kg (8.0 lb), as discussed in technical volume III [4]. An impact velocity of 250 knots (128.6 m/s) was defined for these airborne collision studies. Table 8 and Table 9 present the levels of severity of the impacts with the scaled-up UASs compared to their respective baseline simulations.

Table 8. Mass scaled impact simulation results – quadcopter UAS

	Commercial Transport Jet				Business Jet			
	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield
Quadcopter UAS Baseline 1.2 kg (2.7 lb)	Level 3	Level 4	Level 3	Level 2	Level 3	Level 4	Level 3	Level 2
Quadcopter UAS Scaled-up 1.8 kg (4.0 lb)	Level 3	Level 4	Level 3	Level 3	Level 4	Level 4	Level 3	Level 2

Table 9. Mass scaled impact simulation results – fixed-wing UAS

	Commercial Transport Jet				Business Jet			
	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield
Fixed-wing UAS Baseline 1.8 kg (4.0 lb)	Level 4	Level 4	Level 3	Level 2	Level 4	Level 4	Level 3	Level 4
Fixed-wing UAS Scaled-up 3.6 kg (8.0 lb)	Level 4	Level 4	Level 4	Level 3	Level 4	Level 4	Level 3	Level 4

The mass of the UAS in this parametric study contributed to a linear increase in the kinetic energy of the collision. The increased kinetic energy resulted in increased damage severity levels in five of the sixteen simulations and more extensive damage for those cases where the damage level classification remained the same.

3.2 IMPACT VELOCITY

The impact velocity was varied to determine impact reactions at typical aircraft minimum landing, holding and cruise speeds for the commercial transport and business jets in order to assess the minimum and maximum damage that can be expected for similar mid-air collisions. The landing velocity considered for the commercial transport and business jets was (respectively) 110/87 knots (56.7/44.8 m/s), and the cruise velocities 365/325 knots (187.8/167.2 m/s). The holding velocity was 250 knots (128.6 m/s) for both aircraft. The UAS mass was fixed to the baseline value.

Table 10. Velocity impact simulation results – 1.2 kg (2.7 lb) quadcopter UAS

	Commercial Transport Jet				Business Jet			
	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield
Landing Velocity (110/87 knots)	Level 2	Level 2	Level 2	Level 1	Level 2	Level 2	Level 2	Level 1
Holding Velocity (250/250 knots)	Level 3	Level 4	Level 3	Level 2	Level 3	Level 4	Level 3	Level 2
Cruise Velocity (365/325 knots)	Level 4	Level 4	Level 4	Level 4	Level 4	Level 4	Level 3	Level 3

Table 11. Velocity impact simulation results – 1.8 kg (4 lb) fixed-wing UAS

	Commercial Transport Jet				Business Jet			
	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield
Landing Velocity (110/87 knots)	Level 2	Level 2	Level 2	Level 1	Level 2	Level 2	Level 2	Level 1
Holding Velocity (250/250 knots)	Level 4	Level 4	Level 3	Level 2	Level 4	Level 4	Level 3	Level 4
Cruise Velocity (365/325 knots)	Level 4	Level 4	Level 4	Level 3	Level 4	Level 4	Level 3	Level 4

As shown in Table 10 and Table 11, the UAS impacts resulted in increased damage severity levels for seven of the sixteen cruise velocity cases. The landing velocity cases showed decreased severity levels in all sixteen cases studied over the baseline, all of them equal or below level 2. The damage was more extensive at higher velocities even for cases where the severity level remained the same. An increase (or decrease) in the impact velocity resulted in a quadratic increase (or decrease) in total impact energy.

3.3 CONCLUSIONS VELOCITY AND MASS INFLUENCE ON IMPACT DAMAGE

Mass (m) and velocity (V) have a linear and quadratic (respectively) relationship with the severity of the collision, as expected from the equation of kinetic energy (E).

$$E = \frac{1}{2} m V^2$$

The impact velocity contributed to a greater amount of damage than the mass of the UAS (for more details see chapter 5 of technical volumes II [3] and III [4]). However, incremental increases in either parameter correlate to increased severity and extent of airframe damage.

Consequently, both velocity and mass have been identified as key factors on the severity of an airborne collision between a UAS and an aircraft. Aircraft velocities above minimum landing speeds are considered critical for masses equal to or above 1.2 kg (2.7 lb).

Note that the minimum landing velocity was selected to stablish an absolute lower limit for impact velocity in the collision studies. However, a higher velocity is typical at normal operation of aircraft at take-off and landing, and therefore greater damage levels are expected. A more detailed velocity analysis would be required to obtain conclusions of the actual risk posed at those flight phases.

Finally, in this study the UAS masses investigated were between 1.2 and 3.6 kg (2.7 and 8.0 lb). Lower mass UASs will need to be studied in the future in order to determine a threshold in mass that will introduce level 1 or no damage into the airframe.

4. COMPARISON TO BIRD IMPACT

This study was conducted with the goal of determining whether a UAS impact can be considered equivalent to a bird strike with identical mass and initial velocity (kinetic energy). Idealized birds of two different masses, 1.2 kg (2.7 lb) and 1.8 kg (4.0 lb) were selected for the comparison with the quadcopter UASs (see Chapter 6 of [3]). Similarly, 1.8 kg (4.0 lb) and 3.6 kg (8.0 lb) birds were selected for the comparison with the fixed-wing UASs (see Chapter 6 of [4]). No 8.0 lb bird strike analyses for the wing and windshield were conducted since *14 CFR Part 25.631* only requires 8.0 lb bird strike testing for the empennage.

The NIAR has conducted numerous studies of bird strike events and compared the results with physical testing [9]. Smooth Particle Hydrodynamics modeling techniques (SPH) [10] were used to define the gelatin substitute bird models. These SPH bird models have been validated with experimental data [9].

Table 12 and Table 13 presents structural damage severity levels for each impact simulation. For all the cases, the UAS created equal or more damage than the analogous bird. Hence, the bird strike cannot be considered equivalent to a UAS collision with the same mass and initial impact energy.

Table 12. UAS and bird impact simulation results – quadcopter UAS

	Commercial Transport Jet				Business Jet			
	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield
Quadcopter UAS Baseline 1.2 kg (2.7 lb)	Level 3	Level 4	Level 3	Level 2	Level 3	Level 4	Level 3	Level 2
Bird 1.2 kg (2.7 lb)	Level 3	Level 2	Level 2	Level 2	Level 2	Level 2	Level 2	Level 1
Quadcopter UAS Up-scaled 4 lb (1.8 kg)	Level 3	Level 4	Level 3	Level 3	Level 4	Level 4	Level 3	Level 2
Bird 4 lb (1.8 kg)	Level 3	Level 2	Level 2	Level 2	Level 2	Level 2	Level 2	Level 1

Table 13. UAS and bird impact simulation results – fixed-wing UAS

	Commercial Transport Jet				Business Jet			
	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield
Fixed-wing UAS Baseline 1.8 kg (4.0 lb)	Level 4	Level 4	Level 3	Level 2	Level 4	Level 4	Level 3	Level 4
Bird 1.8 kg (4.0 lb)	Level 3	Level 2	Level 2	Level 2	Level 2	Level 2	Level 2	Level 1
Fixed-wing UAS Scaled 3.6 kg (8 lb)	Level 4	Level 4	Level 4	Level 3	Level 4	Level 4	Level 3	Level 4
Bird 3.6 kg (8 lb)	Level 3	Level 2	N/A	N/A	Level 2	Level 2	N/A	N/A

The simulations presented in chapter 6 of technical volumes II [3] and III [4] identified that airborne collisions involving hard-bodied projectiles have characteristic features that distinguish them from bird strikes. Primarily, the damage zones showed notable dents and penetrations due to the discrete masses and rigid, dense materials. The initial dents and penetrations induced by the impact of the metallic motor allowed the UAS to break through the skin of the aircraft and damage internal components (including the forward spar) in the majority of the simulations.

Figure 18 presents an example of the comparison quadcopter UAS/Bird Strike, in this case against the horizontal stabilizer of the business jet. The quadcopter UAS created a smaller region of impact damage but the penetration through the skin caused further perforation of the forward spar and damage to internal components of the aircraft. In contrast, the bird deformed considerably the external surface of the stabilizer, but with no penetration into the airframe. Consequently, the UAS impact is considered Level 4 damage while the bird impact was classified as Level 2.

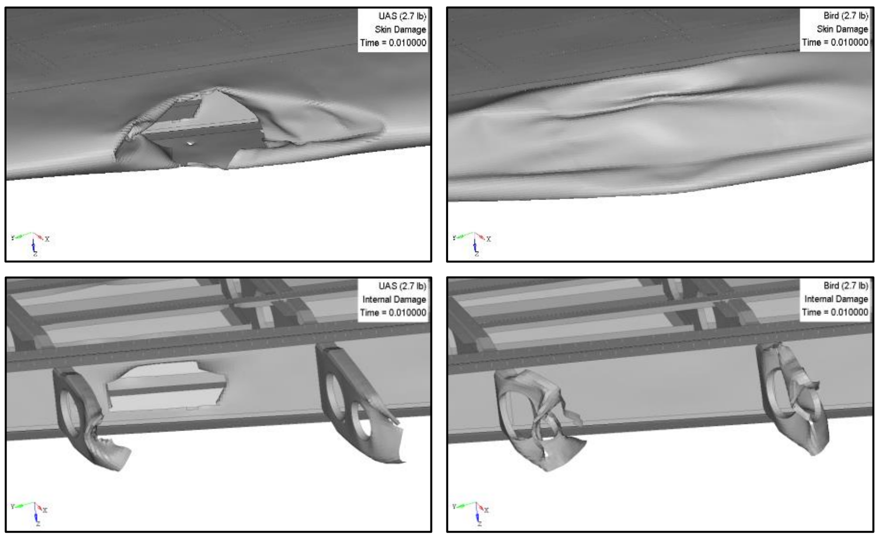


Figure 18. Comparison of damage after impact of a 1.2 kg (2.7 lb) UAS/Bird into a business jet horizontal stabilizer

4.1 BIRD STRIKE – UAS STRIKE COMPARISON CONCLUSIONS

UAS impacts are likely to cause more damage than bird strikes with an equivalent initial kinetic energy (mass and velocity). Since birds behave like a fluid during high velocity impacts, density is the main parameter that drives the magnitude of the damage in the target structure. In contrast, UASs do not exhibit this behavior. Structural rigidity (a combination of the structural geometry and material properties) drives the magnitude of the damage in the target structure.

The UAS impacts shown in this study were associated with greater damage levels than equivalent bird strikes due to the dense, rigid construction of the UAS. Initial motor impact and consequent penetrations exacerbated subsequent impact damage as other high-density UAS components (*i.e.* battery, camera, etc.) impacted the underlying aircraft structure causing progressively more structural damage, as well as in some cases the UAS ingress into the airframe. Therefore, a 4lb/8lb bird and a 4lb/8lb UAS will introduce profoundly different levels of damage to the aircraft structure. Even though *14 CFR Part 25* aircrafts were designed to withstand bird impact under the conditions described in *14 CFR 25.631: Bird Strike* and *14 CFR 25.775: Windshields and windows*, aircrafts may not experience the same level of safety as with bird strikes when impacted by an UAS equivalent in weight [5] [6].

5. UAS SYSTEM ARCHITECTURE

This study was conducted with the goal of determining whether airborne collisions involving 1.8 kg (4.0 lb) quadcopter or fixed-wing UAS architectures can be considered equivalent to one-another. The simulations utilized identical boundary conditions and impact energies.

As shown in the impact comparison presented in chapters 6 and 7 of technical volumes II [3] and III [4], airborne collisions involving hard-bodied projectiles have characteristic features that distinguish them from bird strikes. The primary similarity between the UAS simulations shown in chapter 7 is that the dense, rigid components (motors and batteries) of both UAS models created penetrations in the aircraft skin which allowed the remaining mass of the UAS to enter the airframe and damage the internal components. The results of the comparison are shown in Table 15.

Table 14. Quadcopter and fixed-wing UAS impact simulation results comparison

	Commercial Transport Jet				Business Jet			
	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield	Vertical Stabilizer	Horizontal Stabilizer	Wing	Windshield
Up-scaled Quadcopter 1.8 kg (4.0 lb)	Level 3	Level 4	Level 3	Level 3	Level 4	Level 4	Level 3	Level 2
Baseline Fixed-wing 1.8 kg (4.0 lb)	Level 3	Level 4	Level 3	Level 2	Level 4	Level 4	Level 3	Level 3

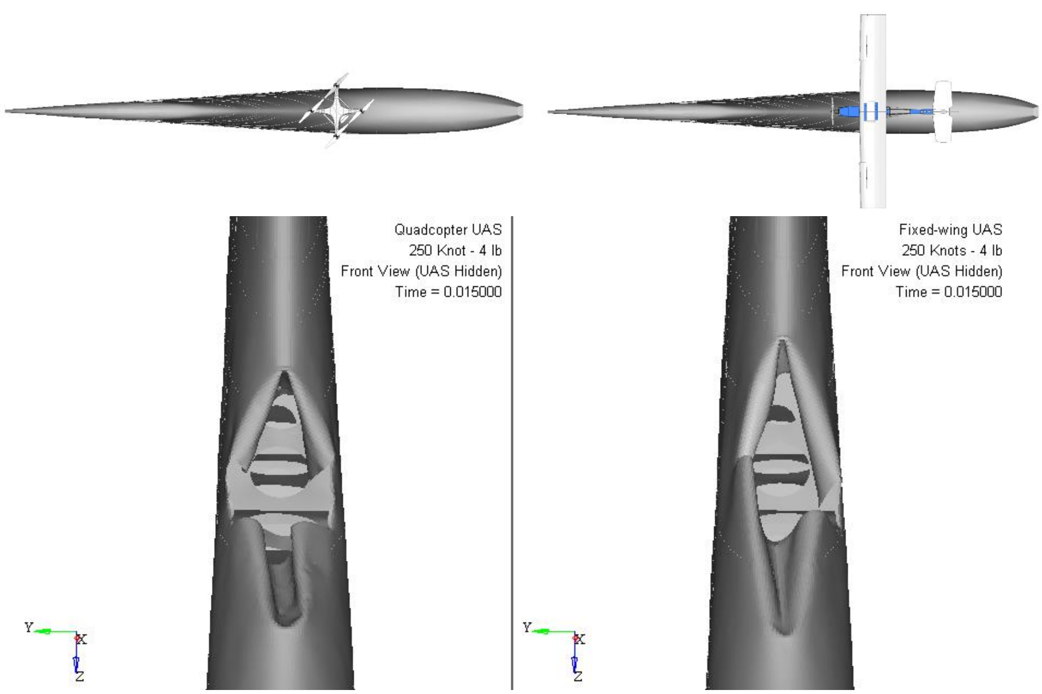


Figure 19. Comparison of damage after impact of a fixed-wing and a quadcopter 1.8 kg (4.0 lb) UAS into a business jet vertical stabilizer

The differences perceived in the damage severity levels between quadcopter and fixed-wing UASs of the same mass indicate that the layout of the main UAS components is critical to the energy transfer during an airborne collision. The predicted critical damage occurs when the majority of the masses were aligned with the impact direction. The quadcopter UAS was oriented at the most critical yaw angle configuration, 45° [3]. At this orientation, the quadcopter UAS motor and battery align with the impact axis similar to the fixed wing configuration as shown in Figure 19; therefore, the damage levels to the aircraft airframe are similar for both UAS architectures.

6. RECOMMENDATIONS

The research presented in this report has shown that there is a risk of primary aircraft structure failures for several of the impact scenarios analyzed (commercial transport and business jet aircrafts) with the 1.2 kg (2.7 lb) quadcopter and the 1.8 kg (4.0 lb) fixed-wing sUAS configurations.

Further research is needed to support the airborne collision work:

The primary goal of regulating UAS operations in the NAS is to assure an appropriate level of safety. This goal is quantified by national aviation agencies as an "Equivalent Level of Safety" (ELOS) with that of manned aviation. There are major key differences between manned and unmanned aviation that span the requisite level of automation, as well as the distinct variety of architectures and materials used for the construction of UASs. These differences could introduce new failure modes and required probabilistic risk assessment [11].

In order to have an equivalent level of safety, the Range Commanders Council UAS guidelines stated that any UAS operation or test must show a level of risk to human life no greater than that for an operation or test of a piloted aircraft [12]. The aforementioned metrics can be used to provide statistical probabilities of UAS mid-air collisions according to specific parameters defined for the evaluation. Not all collisions lead to catastrophic accidents. The large variability in UAS configurations and potential aircraft impact locations suggests that a given aircraft may survive certain UAS collisions.

The risk assessment to develop an airborne collision UAS impact severity classification can be divided into three elements:

- **Estimation of the probability of mid-air collision** between UAS and manned aircraft. This will be a function of the operating airspace, aircraft operated within the airspace, and the UAS configurations operating within the shared airspace. Methods to estimate the probability of impact are presented in references [13][14].
- **Evaluation of severity of damage after collision for typical UAS**. Assess damage severity for mid-air collisions scenarios between unmanned aircraft (Classes base on weight, architecture, operational characteristics (altitude, velocity)) and manned aircrafts (commercial, GA, rotorcraft, etc.). Several groups advocate use of simplified ballistic penetration models [15] and similar principles for establishing existing bird strike requirements or kinetic energy thresholds [16][17]. The objective of this project will be to evaluate the severity of a typical quadcopter and fixed-wing UAS airborne collision. These results will be compared with current proposed penetration mechanics and energy based criteria.

- Once the probability of an airborne collision is determined, **the damage models can be combined with the probabilistic collision models to define appropriate Equivalent Level of Safety criteria.**

Using the data presented in this report and the data that will be developed in Phase II for GA aircraft and rotorcraft a project should be carried out in the near future to define the acceptable Equivalent Level of Safety criteria to regulate UAS operations in the NAS.

7. REFERENCES

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