The FAA's Center of Excellence for UAS Research

ASSURE

Alliance for System Safety of UAS through Research Excellence

UAS Airborne Collision Severity Evaluation

The Ninth Triennial International Fire & Cabin Safety Research

Gomez, L., Olivares, G., Baldridge, R., and Zinzuwadia, C.

October 30th, 2019

A3. UAS Airborne Collision Hazard Severity Evaluation

Title: UAS Airborne Collision Severity Evaluation 11LUAS.COE.7.2 – Low Altitude Operations Safety

ASSURE Team: WSU (lead), OSU, MSU, MTSU

Purpose: Analytically evaluate severity of UAS impacts with business jets, commercial transports, and turbofan engines

Research Questions:

- *What are the hazard severity criteria for UAS collision?*
- *What is the severity of a UAS midair collision with an aircraft?*
- *Can we classify a UAS impact similar to a bird strike?*
- *What are the characteristics of a UAS where it will not be a risk to an aircraft in case of collision in midair?*

ASSURE Principal Investigator (PI): Gerardo Olivares, Director Computational Mechanics and Crash Dynamics Laboratories, National Institute for Aviation Research – Wichita State University, gerardo.olivares@wichita.edu, 316-680-1817

Other ASSURE Performers PI's:

Wichita State University
Tom Aldag
Jaime Espinosa de los Monteros
Chandresh Zinzuwadia
Russel Baldridge
Luis Gomez

Montana State University
Doug Cairns

Ohio State University
Kiran D'Souza
James Gregory

Mississippi State University
Ratan Jha
Thomas E. Lacy Jr.
J. Mark Janus

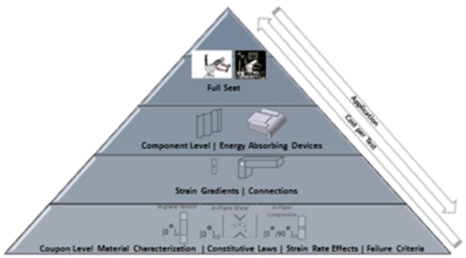
Working Packages Overview

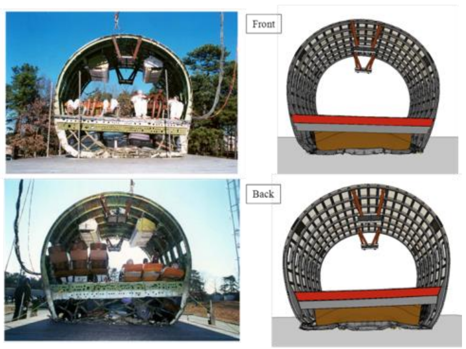
- **WP I – Projectile Definition (UAS CLASS) – Montana State University**
  - **SCOPE:** Conduct a study to classify current and future UAS that can be operated within the National Airspace System (NAS).
- **WP II – Target Definition (Aircraft Type) – Montana State University**
  - **SCOPE:** Conduct a study to classify current aircraft and rotorcraft type that can be operated within the National Airspace System (NAS).
- **WP III – UAS Type I & II Projectile – Wichita State University & Mississippi State University**
  - **SCOPE:** Define and Validate detailed Finite Element Models of the critical UAS configurations identified in WP I.
  - Additional work was conducted to validate FEA Model with experimental data following NIAR methodology for composite and metallic structures. Study the dynamic impact behavior of empty and fully charged batteries. Quantify post impact fire risk conditions.
- **WP IV (a) (b) – Aircraft Target [Narrow Body and Business Jet] – Wichita State University**
  - **SCOPE:** Use NIAR's Aircraft FEA library to define a representative PART 25 Narrow Body and Business Jet aircraft that can be subjected to a UAS impact as identified in WP I.
- **WP IV (c) – Aircraft Target [Turbines] – Ohio and Montana State Universities**
  - **SCOPE:** Develop a validated Turbine model to be used in WP V.
- **WP V (a) – Structural Safety Evaluation Mid-air Collision UAS to Aircraft – Wichita State University**
  - **SCOPE:** Identify the severity of the airframe damage due to a UAS impact using the FEA Models developed in WP III and IV.
- **WP V (b) – Ingestion Safety Evaluation Mid-air Collision UAS to Aircraft – Ohio and Montana State Universities**
  - **SCOPE:** Identify the severity of the engine damage due to a UAS ingestion using the FEA Models developed in WP III and IV.
- **WP VI (a) – Aircraft Structure Susceptibility and Crashworthiness Evaluation Standard – Wichita State University**
  - **SCOPE:** Review and summarize results from WP I through WP V. Identify differences with Bird Strike impact testing requirements. Define a series of design recommendations that can be used by UAS manufacturers to design more crashworthy UAS in the future.
- **WP VI (b) – Aircraft Ingestion Susceptibility and Crashworthiness Evaluation Standard – Montana State University**
  - **SCOPE:** Review and summarize results from WP I through WP V. Identify differences with Bird Strike ingestion testing requirements. Define a series of design recommendations that can be used by UAS manufacturers to design more crashworthy UAS in the future.

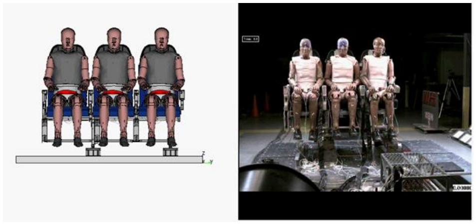
NIAR Virtual Environment Modeling Philosophy

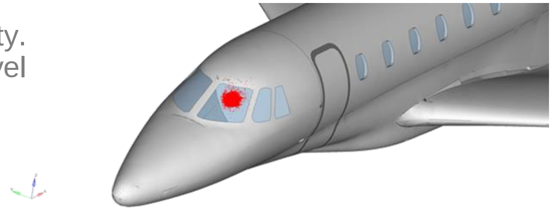
NIAR | Wichita State University | National Institute for Aviation Research

- **Non-Physics Based Modeling:**
  - This approach has been used by the aerospace industry since the introduction of simulation due to limitations in computing power and computational tools, complexity of the problems, poor understanding of the physics, lack of test-to-test variability data, and poor modeling methodologies.
  - Simulation follows system level testing. Hence models are **not predictable**.
  - Testing results are used to **calibrate** the model [non-physics based].
  - Models are evaluated by the **calibration-validation methods**.
  - The **validation criteria** is always unreasonable (5 to 10 %) and vague (peak, shape, **subjective**) due to the lack of research and understanding of the real test-to-test variability.
- **Physics Based Modeling:**
  - This approach used by NIAR takes advantage of the advances in computational power, the latest computational tools, years of research to understand the physics, generated test-to-test variability data, and verified & validated (V&V) modelling methodologies.
  - Defined modelling methodologies using the building block approach. Understanding of the physics and testing variability from the coupon to the system level. Taking a conservative modeling approach based on data derived from R&D and the Building Block Approach to define simplified models when required. The definition of the numerical model is not driven by system level test results, is driven by a predefined V&V modeling methodology.
  - Simulation **predicts** system level test results within the scope and scatter of the physical test results.
  - **Objective validation** criteria based on an understanding of the test-to-test variability. Defined objective validation metrics (i.e. Sprague and Gears). The correlation level between simulation and testing is driven by an understanding of the test-to-test variability.



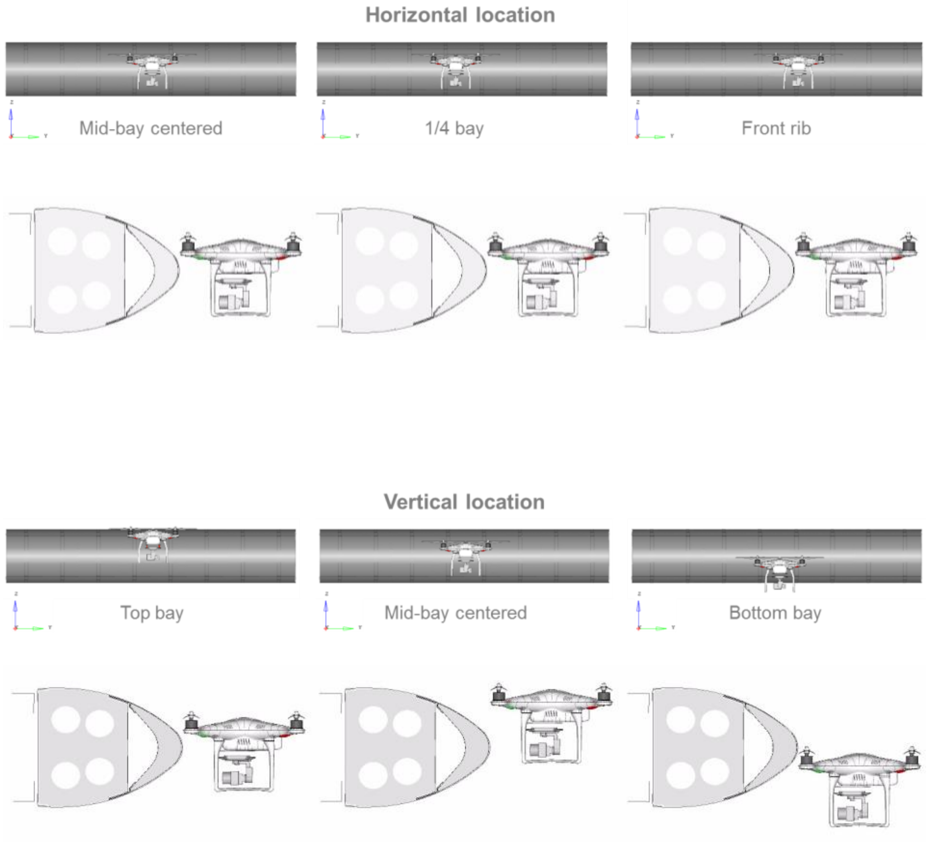






Why did we use FEA?

- Over 140 scenarios were analyzed in less than 2 months
  - Two different UAS (QuadCopter and Fixed-Wing)
  - Two different Airplane Targets (Single Aisle Commercial and Business Jet) with eight different impact locations (Wing leading edge, Horizontal Stabilizer, Vertical Stabilizer, and Windshield).
- This will have not been possible through Full Scale Physical Testing [Sourcing of test articles, control of accurate impact conditions, etc.]
- FEA allows for quick changes on impact conditions like:
  - UAS Orientation
  - UAS Velocity
  - UAS Impact location
  - UAS Mass
- FEA allows for repeatability between tests and appropriated comparisons between impact scenarios.
- FEA allows for further analysis with for small cost.
- Based on the results shown on this study we recommend that in the future we use the presented FE approach to conduct "Certification By Analysis".



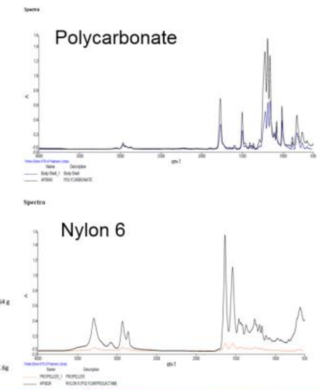
UAS Projectile [QuadCopter]

UAS – FE Model QuadCopter

Reverse Engineering Geometry

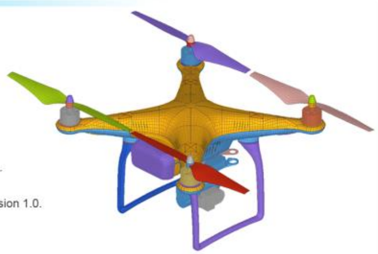
Reverse Engineering Material Identification

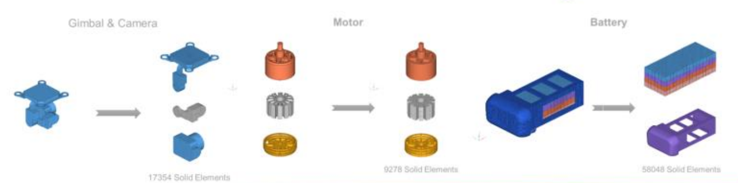
- FTIR tests were carried out by NIAR's materials lab to identify the materials of the plastic parts of the UAS
- **Body Shell:** Polycarbonate Polymer (PC)
- **Propellers:** Nylon 6 (Polycarprolactam)
- **Battery:** Composed of layers of aluminum foil, polymethylmetacrylate (PMMA), Lithium Oxyde and Carbon. Concentration calculated from thicknesses of layers.
- Battery Pouch: Aluminum Film 1145-O
- Battery Cover: Polycarbonate Polymer
- Printed Circuit Board: G-10 Fiberglass-epoxy Composite.
- Motor Shaft: Steel 4030



UAS FE Model – Discretization

- **FEA Model Parameters:**
  - 103,770 elements
  - 142,278 nodes
  - Min element = 0.8 mm (0.03 in)
  - Model time-step = 0.1 μs
  - Total mass = 1,215 g (2.68 lbs.)
  - Quality criteria per NIAR's Modeling Standards.
- **Discretization Criteria:**
  - Structure, circuit-boards and propellers modeled with shells.
  - Simplified Geometry smaller than 1.5mm (0.06 in).
  - Simplified Camera, battery and electronics internals for Version 1.0.
  - Simplified Motor Winding.
  - Gimbal Isolators modeled with discrete elements





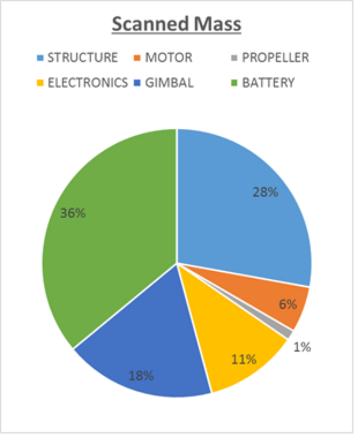
UAS – Materials

Code	Material	Source
(blue)	Polycarbonate	Ref. 1
(lime green)	Nylon	
(yellow)	Cast Aluminum 520-F	ASM
(orange)	Steel 4030	MMPDS
(green)	G-10 Fiberglass (PCB)	Ref. 2
(red)	Li-Po Battery Cell	Ref. 3
(light blue)	Aluminum Film 1145-O	ASM-4011

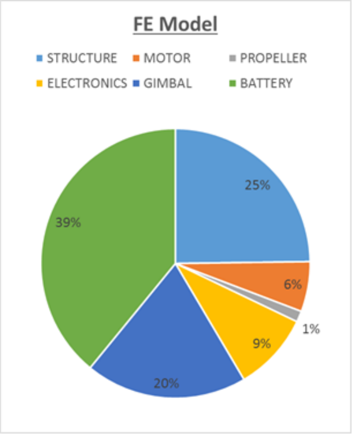
1. Dwivedi, A., Bradley, J., Casem, D., 2012, "Mechanical Response of Polycarbonate with Strength Model Fits", Army Research Laboratory, ARL-TR-5899.
2. Ravi-Chandar, K., 2007, "Mechanical properties of G-10 glass-epoxy composite", technical report, Institute for Advanced Technology, University of Texas at Austin.
3. Sahraei, E., 2014, "Characterizing and modeling mechanical properties and onset of short circuit for three types of lithium-ion pouch cells", Journal of Power Sources, Elsevier.

FE Model Weight and CG Check

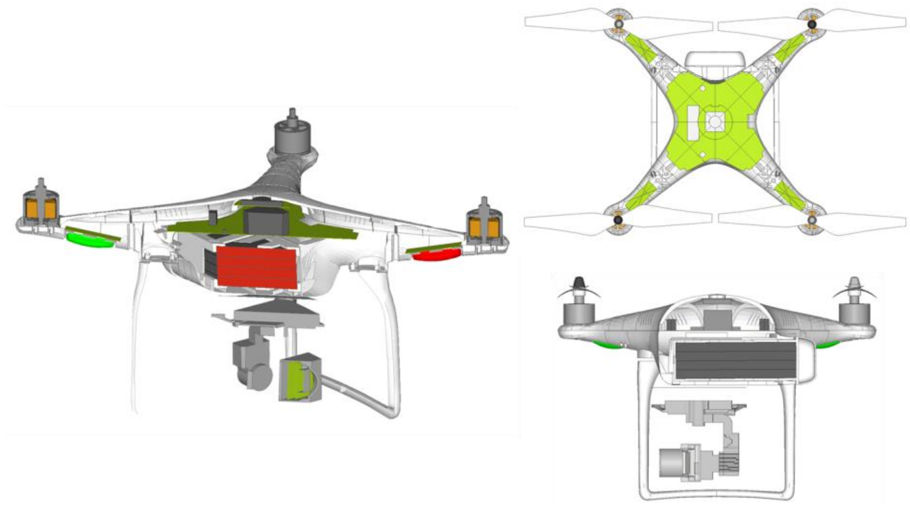
- Component Weights were documented in the Reverse Engineering Process.
- Missing electronic and miscellaneous parts were taken into consideration as non-structural masses (ELEMENT_MASS).
- Bolt masses were also considered as nodal masses.
- The total mass measured matches that specified by the OEM [1.216 kg ~ 2.68 lbs.].



Total mass = 1216.0 g
UAS Specifications

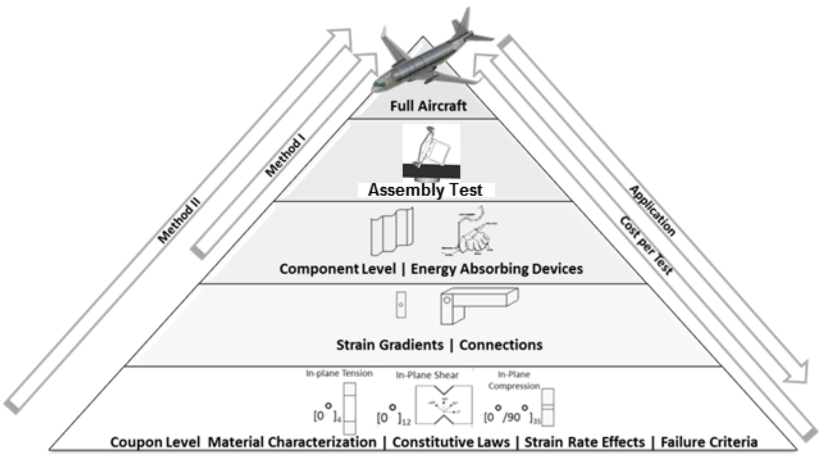


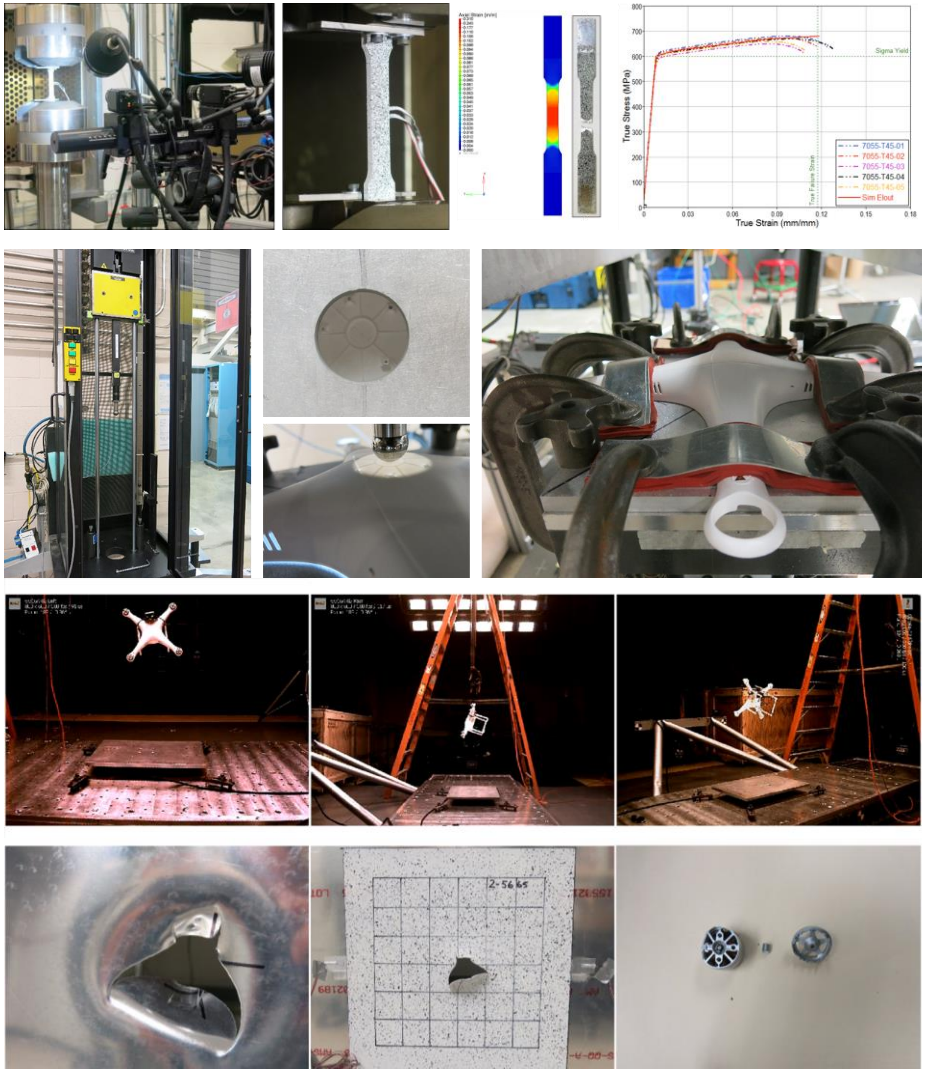
Total mass = 1215.5 g
UAS FEA Model



UAS Building Block Approach

- Coupon Level Material Validation:
  - Experimental Data
  - Literature Review Data
  - NIAR Material Database
- Component Level Validation:
  - Quasi-static and Dynamic Testing for individual components and subassemblies as required
- Full Scale Model Assembly for Predictable Simulations



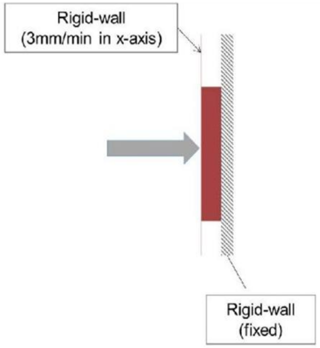


Battery Model Validation

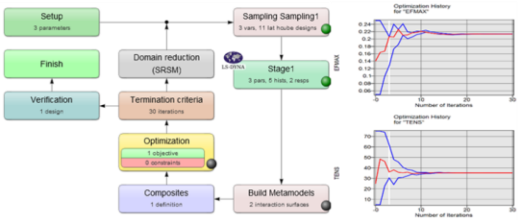
- **Objective:** To validate the battery material models. The battery was subjected to following test conditions:
  - Face compression
  - Punch indentation
- The testing results were published by E. Sahraei and T. Wierzbicki (MIT): Journal of Power Sources 201(2012) 307-321 and 247(2014)503-516. These were used as a baseline to compare results of the simulation.
- FEA Validation Model:
  - 10 layers of 0.48 mm solid elements
  - MAT_063: Crushable Foam
  - E = 500 MPa (72.5 KSI)
  - Poisson's ratio = 0.01
  - Density = 1755 kg/m3 (109.6 lb/ft3)

Face Compression

- Largest face of cell compressed between two rigid-walls at a rate of 3 mm/min.
- The load is measured as a reaction on the fixed rigid-wall.

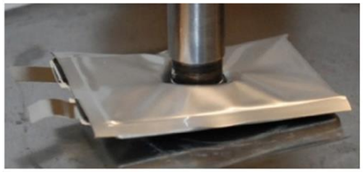


- LS-OPT was used to identify\calibrate the optimum parameter definition for the material card
- Several parameters were analyzed in the optimization process:
  - Cut-off tension
  - Elongation at failure
  - Scale factor of the stress-strain curve

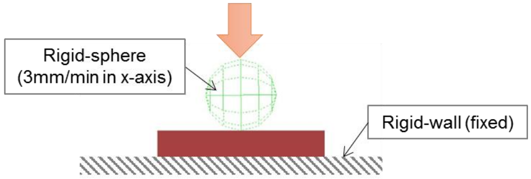


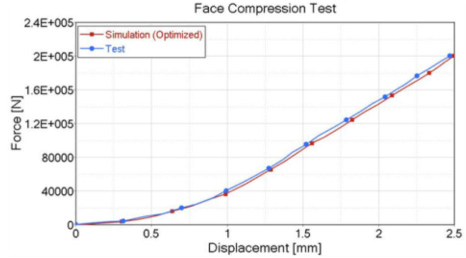
Punch Indentation

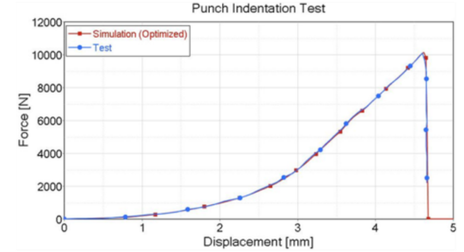
- Rigid sphere of 6.35 mm diameter with prescribed motion of 3mm/min in the X-direction compressed against cell.



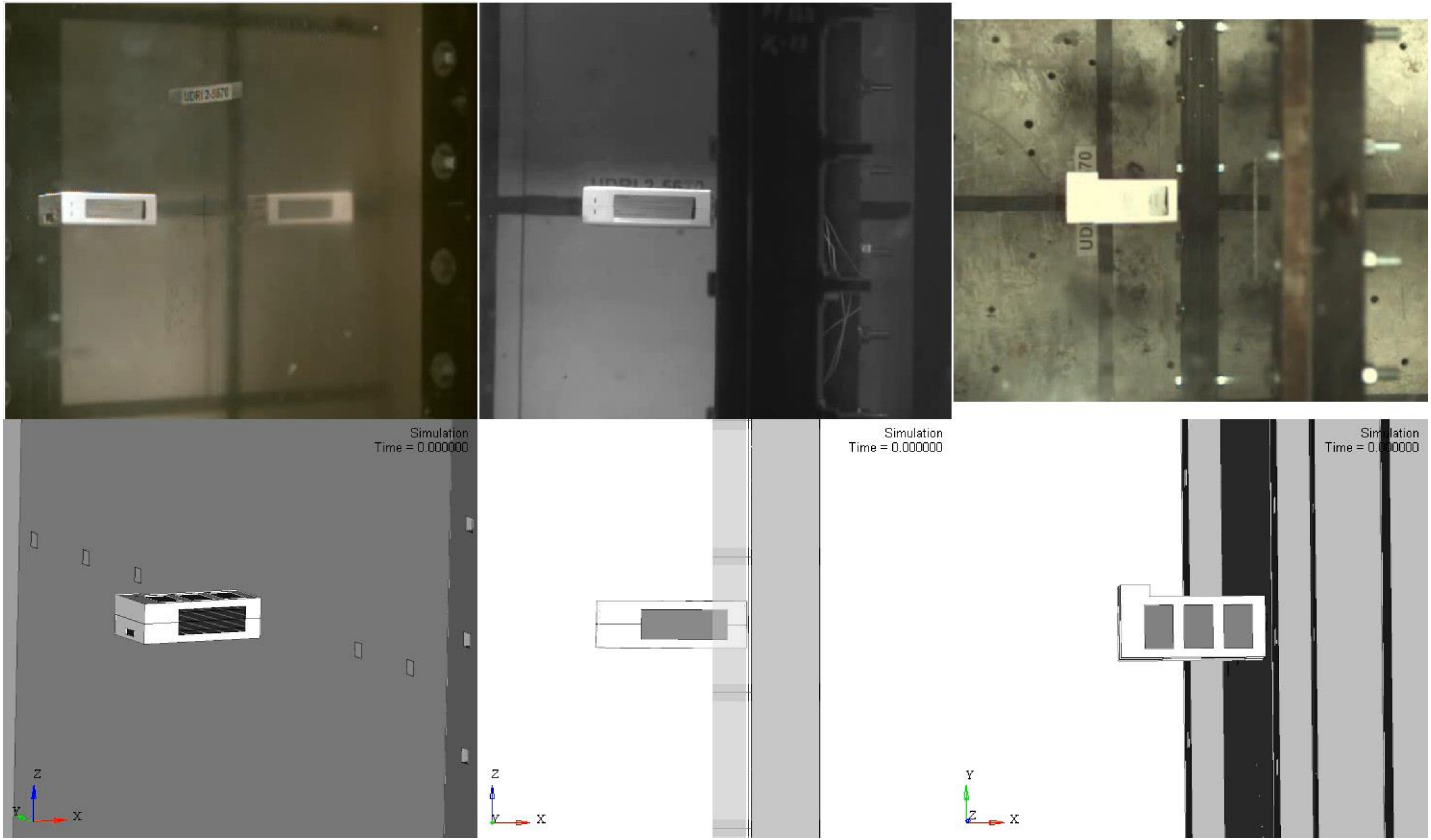
Punch indentation test. Source MIT publication.



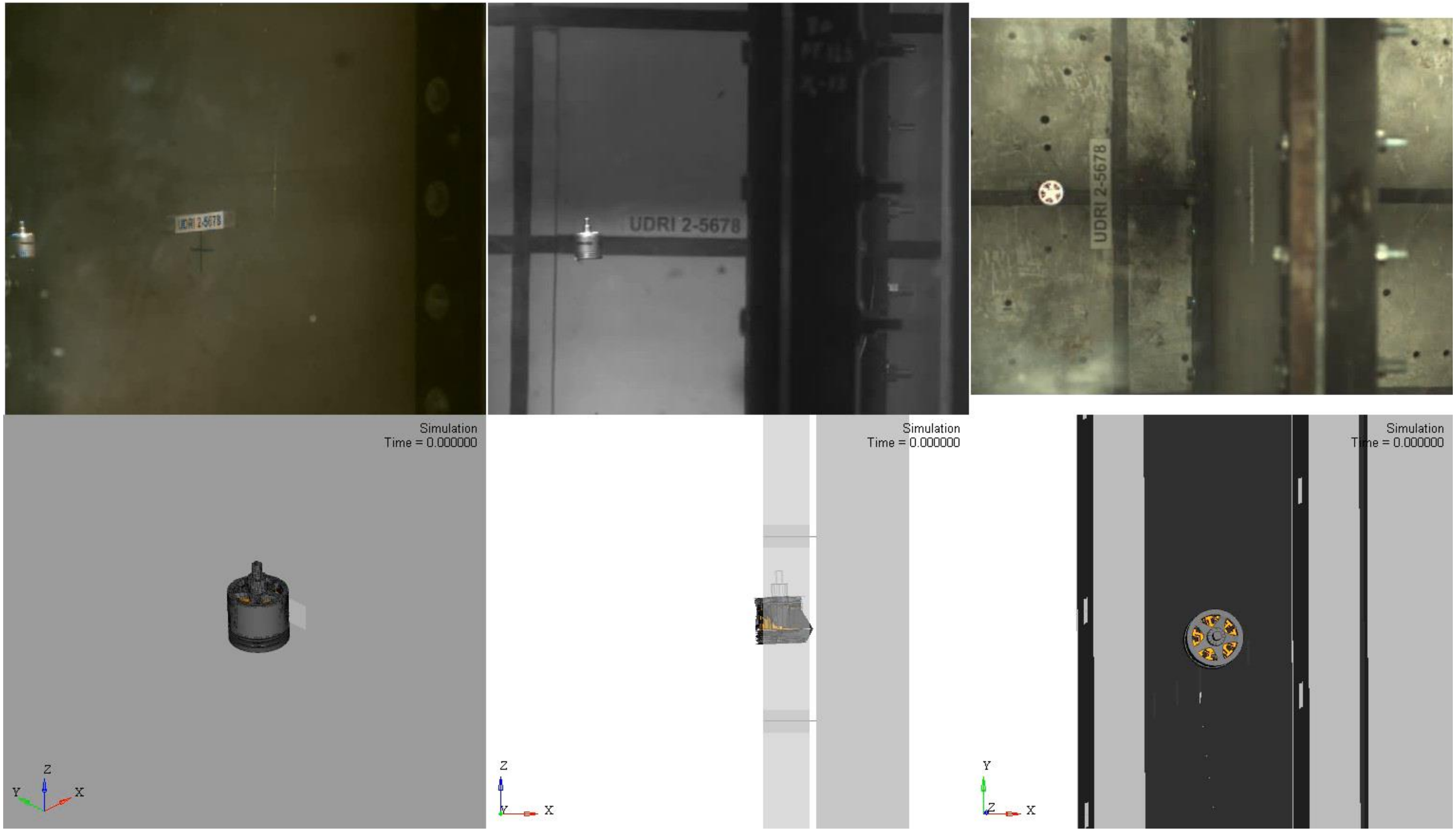




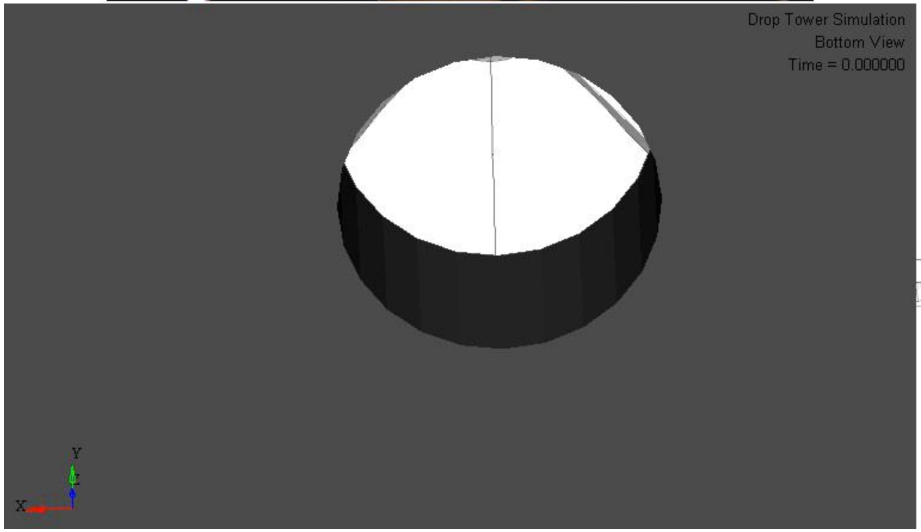
Battery – 250kts/0.063in

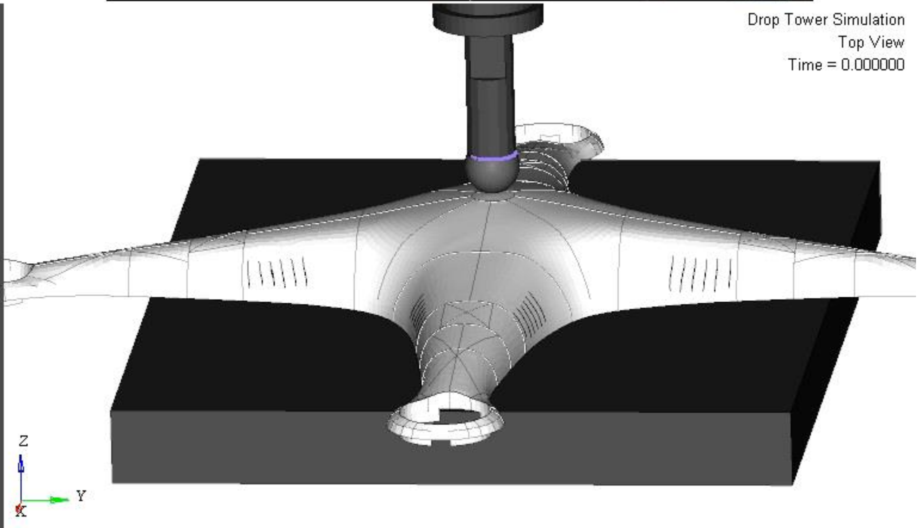


Motor – 250kts/0.25in

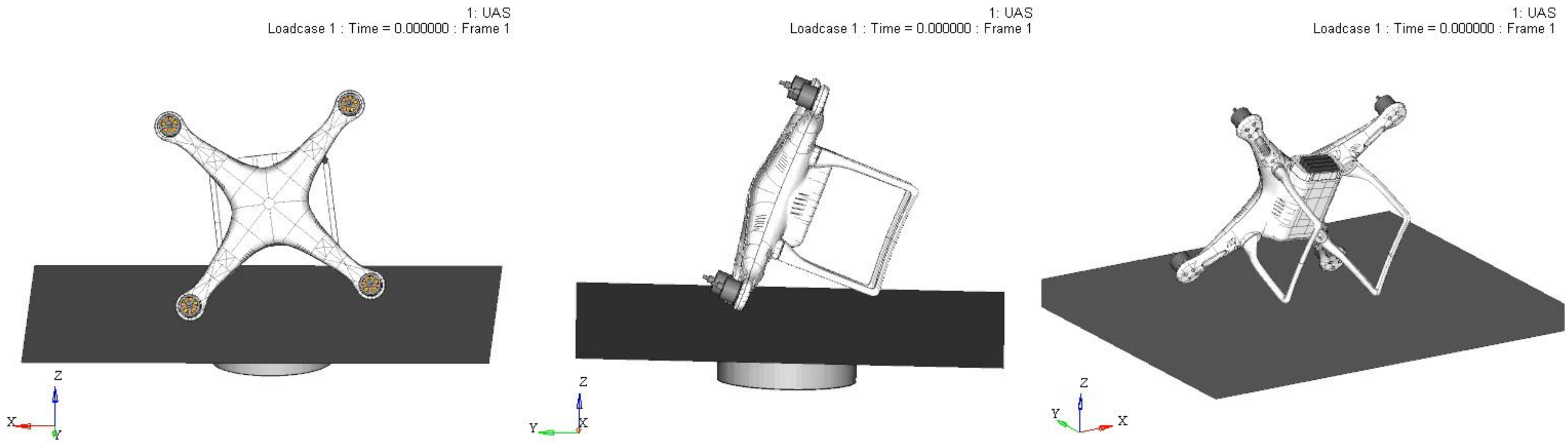


Drop Tower: Simulation vs. Test

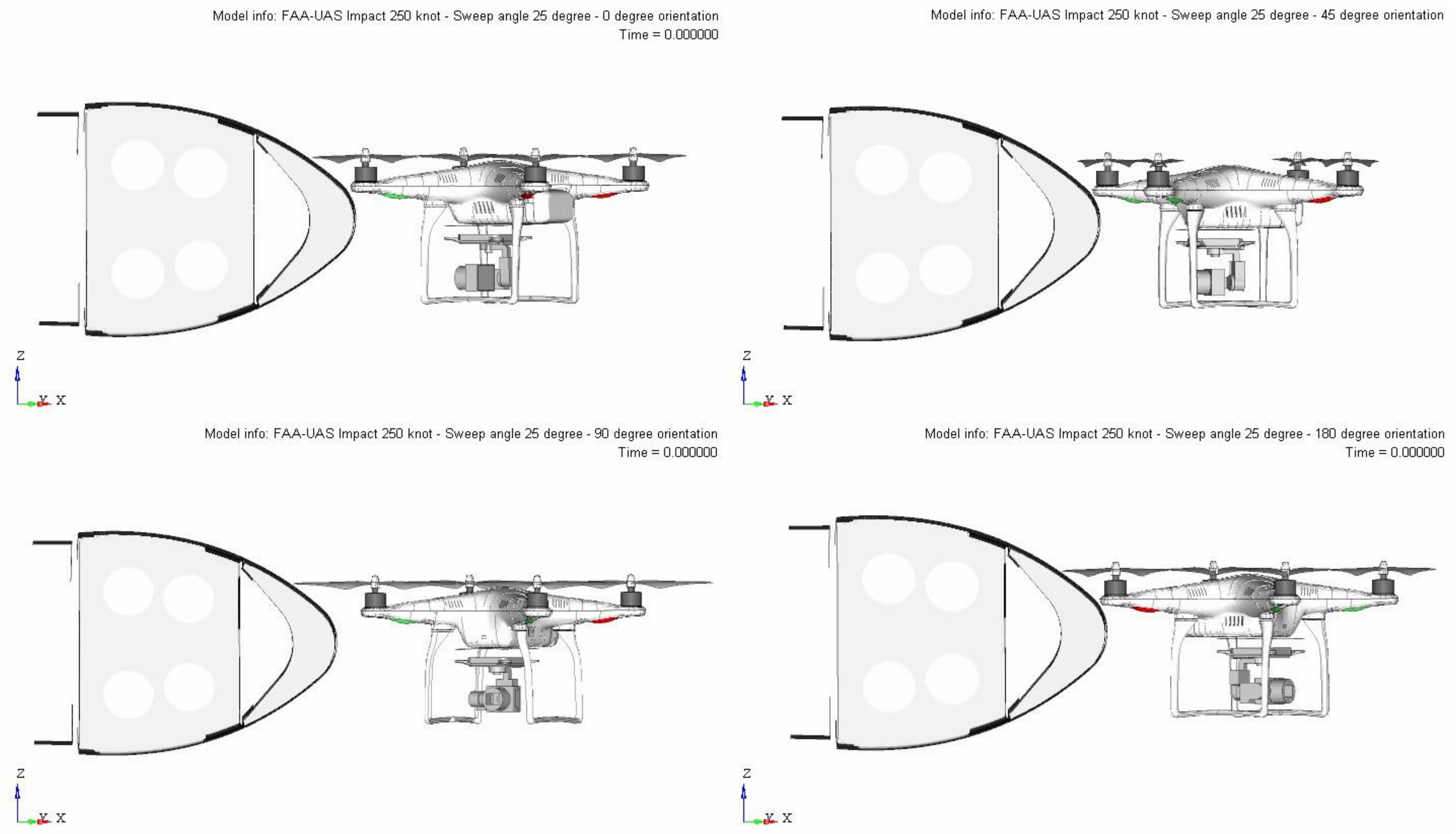




Projectile Model Development



Sweep Angle Stability Check



Aircraft Targets [NIAR Database]

NIAR Target Databases
Complete Aircrafts Models

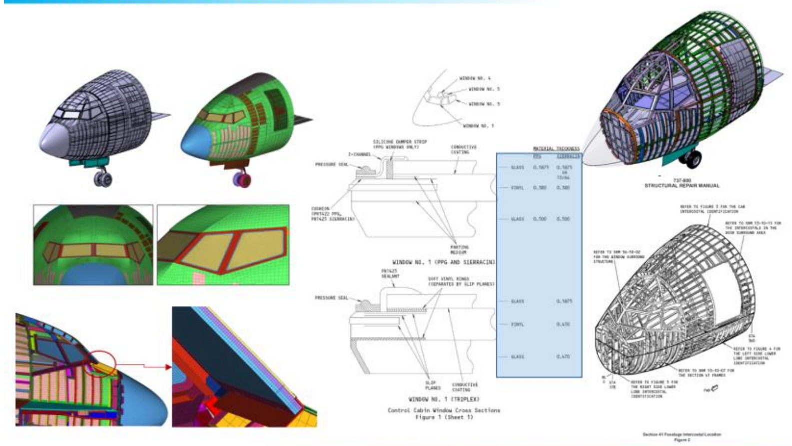
Wichita State University
National Institute for Aviation Research

<u>Commercial Transport Jet</u>

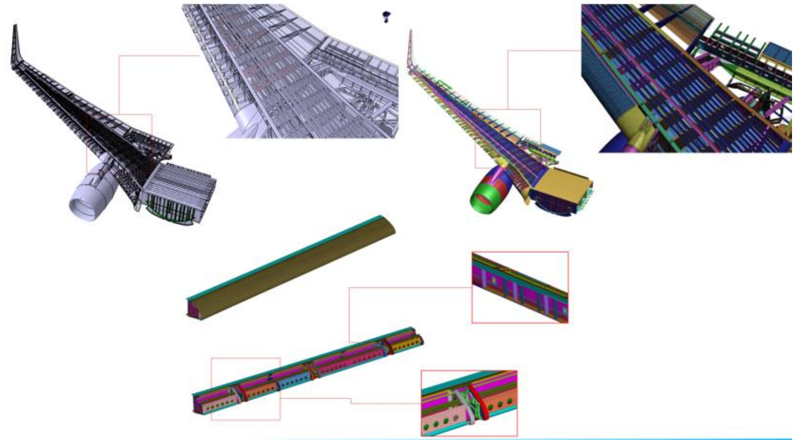
<u>Business Jet</u>

NIAR Narrow Body
Sections Details

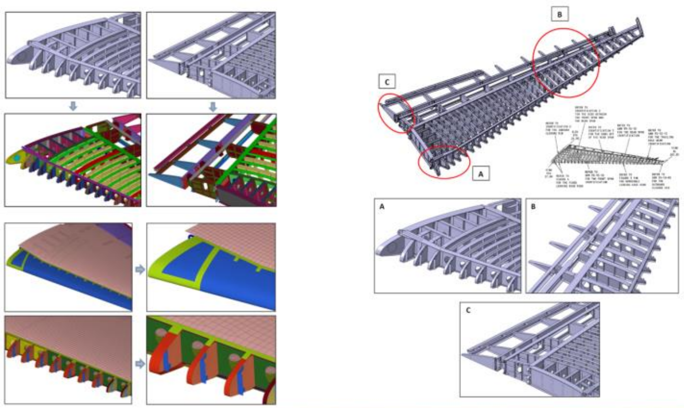
NIAR Narrow Body
Windshield Section



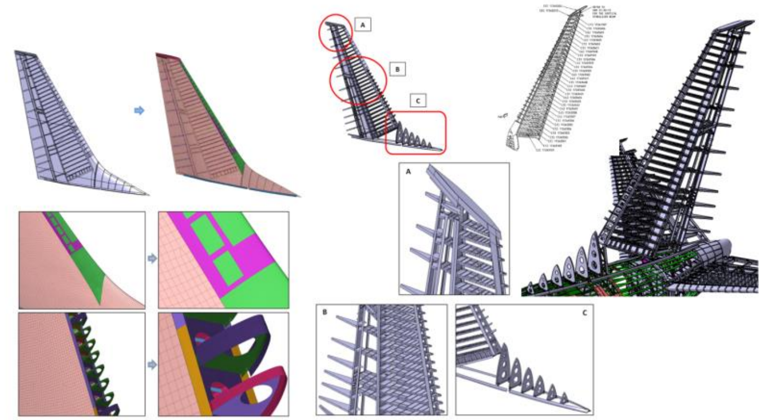
NIAR Narrow Body
Wing Section



NIAR Narrow Body
Horizontal Stabilizer Section

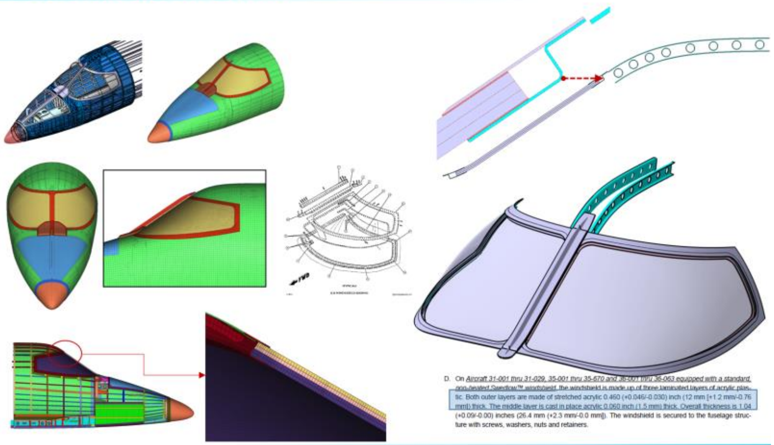


NIAR Narrow Body
Vertical Stabilizer Section



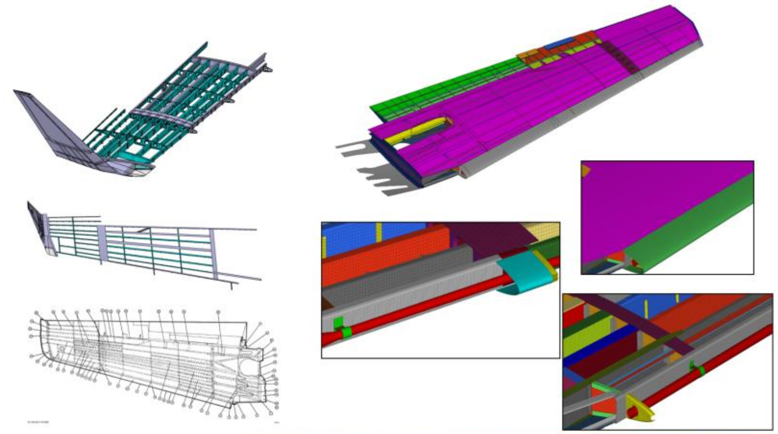
NIAR Business Jet
Sections Details

NIAR Business Jet
Windshield Section

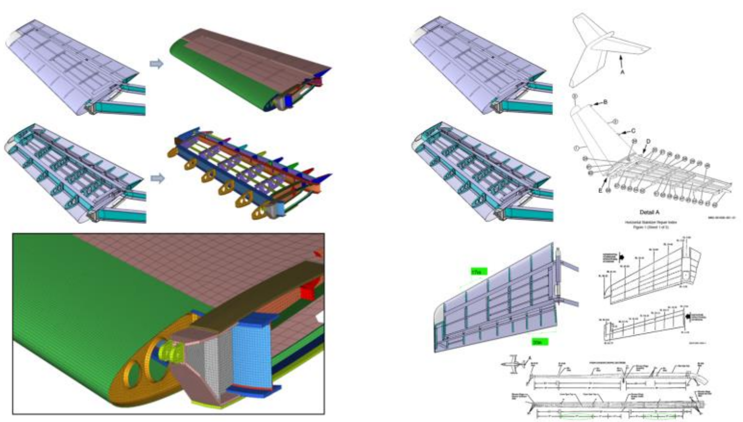


D. On Aircraft 31-001 thru 31-029, 35-001 thru 35-670 and 36-001 thru 36-063 equipped with a standard, non-heated Swedlow™ windshield, the windshield is made up of three laminated layers of acrylic plastic. Both outer layers are made of stretched acrylic 0.460 (+0.046/-0.030) inch (12 mm [+1.2 mm/-0.76 mm]) thick. The middle layer is cast in place acrylic 0.060 inch (1.5 mm) thick. Overall thickness is 1.04 (+0.09/-0.00) inches (26.4 mm (+2.3 mm/-0.0 mm]). The windshield is secured to the fuselage structure with screws, washers, nuts and retainers.

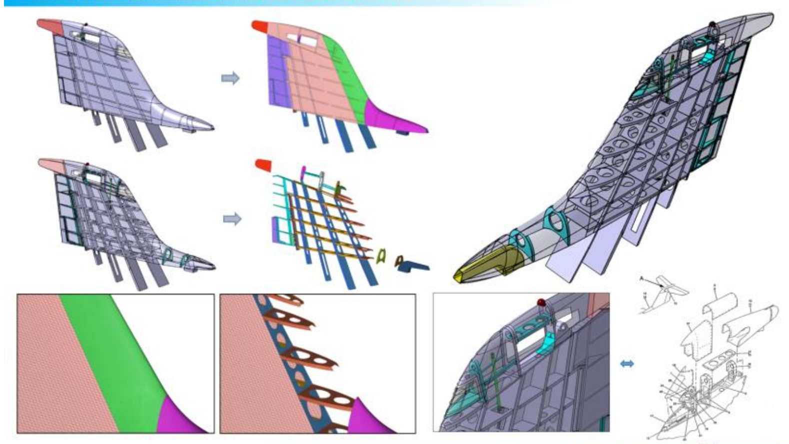
NIAR Business Jet
Wing Section



NIAR Business Jet
Horizontal Stabilizer Section



NIAR Business Jet
Vertical Stabilizer Section



Structural Safety Evaluation Mid-air Collision UAS to Aircraft

Structural Safety Evaluation Mid-air Collision UAS to Aircraft

NIAR | Wichita State University — National Institute for Aviation Research

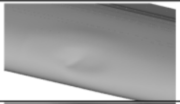
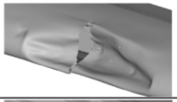
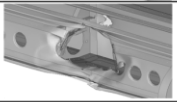
SCOPE: Define Impact scenarios that can be evaluated using the FEA Models previously developed to identify the severity of the airframe damage due to a UAS impact.

TASKS: (Performed by WSU-NIAR)

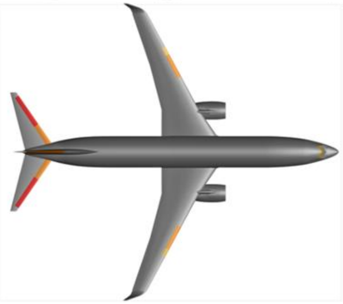
- Conduct Crashworthiness Structural FEA Simulations and damage evaluation – Narrow Body - (WSU-NIAR)
- Conduct Crashworthiness Structural FEA Simulations and damage evaluation – Business Jet - (WSU-NIAR)

DELIVERABLES: (Performed by WSU-NIAR)

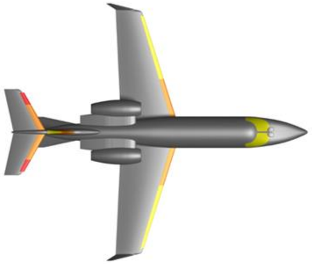
- Airframe structural damage evaluation due to mid-air collision between a UAS and a representative PART 25 Narrow Body Transport aircraft, PART 23 Business Jet Aircraft Structural components. Report – NIAR

Severity Level	Description	Example
Level 1	• Undamaged • Small deformation	
Level 2	• Extensive permanent deformation on external surfaces. • Some internal structure deformed. • No failure of skin.	
Level 3	• Skin fracture. • Penetration of at least one component.	
Level 4	• Penetration of UAS into airframe. • Damage of primary structure.	

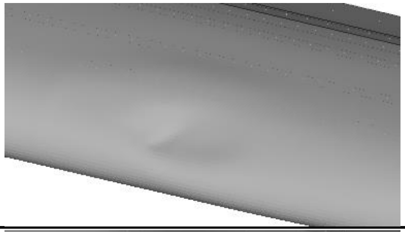
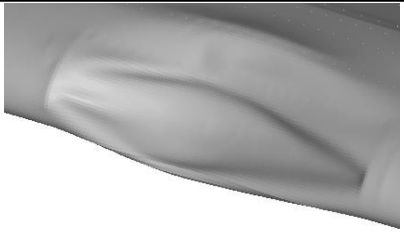
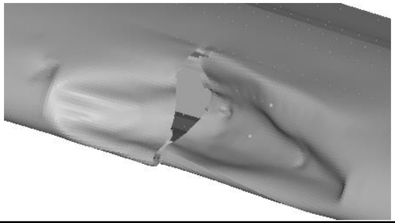
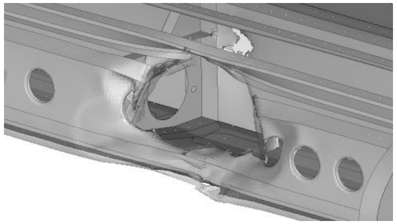
Level 1	
Level 2	
Level 3	
Level 4	



Level 1	
Level 2	
Level 3	
Level 4	

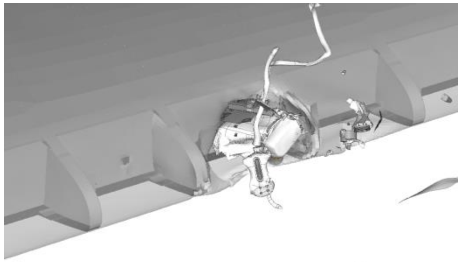
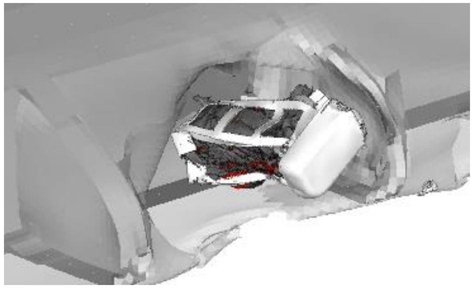
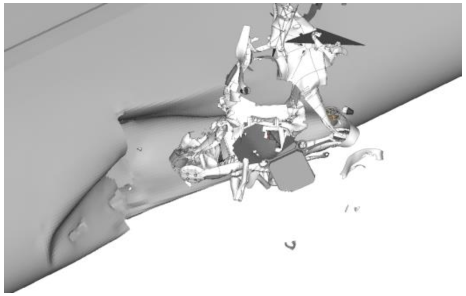
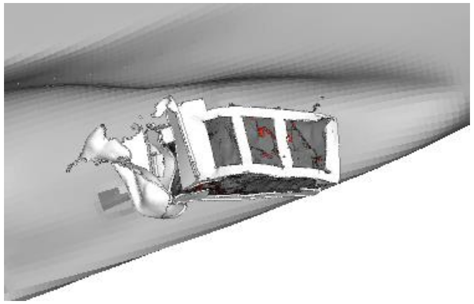
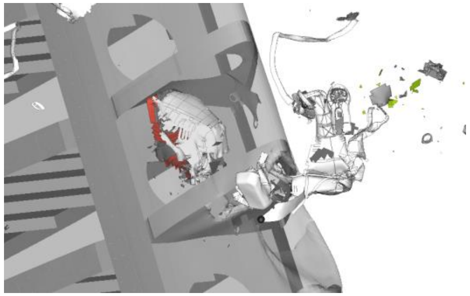
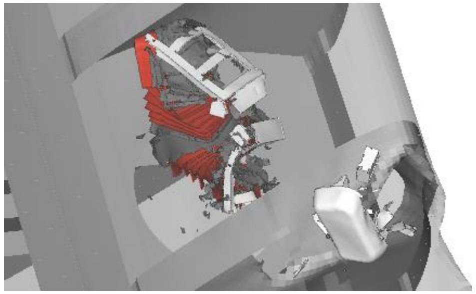


Severity Level Classification

Severity Level	Description	Example
Level 1	• Undamaged • Small deformation	
Level 2	• Extensive permanent deformation on external surfaces. • Some internal structure deformed. • No failure of skin.	
Level 3	• Skin fracture. • Penetration of at least one component.	
Level 4	• Penetration of UAS into airframe. • Damage of primary structure.	

Risk of Battery Fire

Wichita State University
National Institute for Aviation Research

Fire Risk	Description	Example (UAS Visible)	Example (UAS Hidden)
Yes	• UAS (including the battery) penetrates the airframe. • Battery deforms but stays fairly undamaged. • Validation physical 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 physical tests showed that completely damaged batteries did not create heat and sparks.		

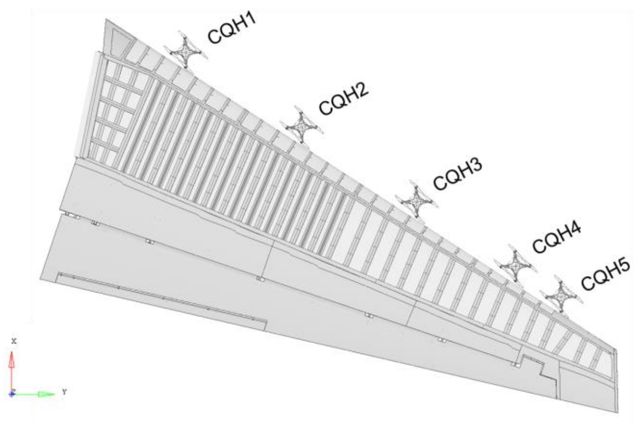
Collision Simulation Summary

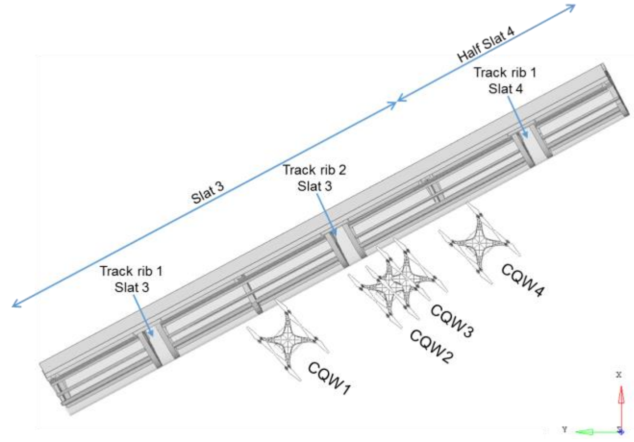
Commercial Transport Jet

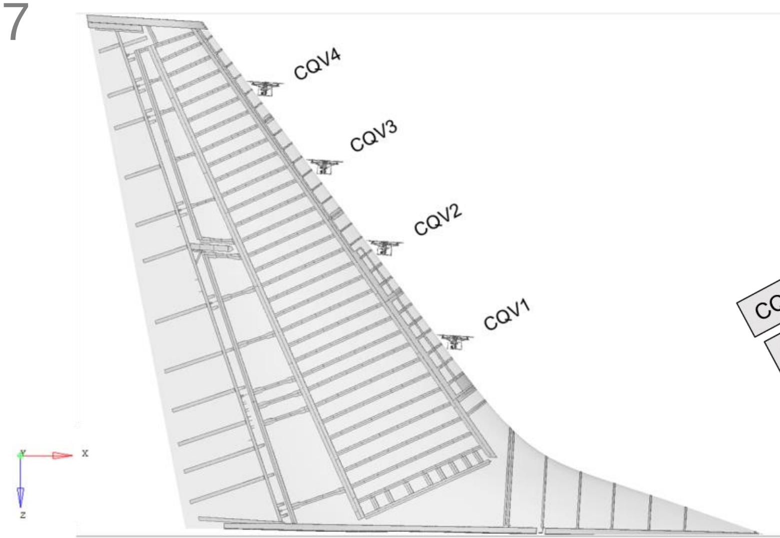
Impact Conditions and Locations

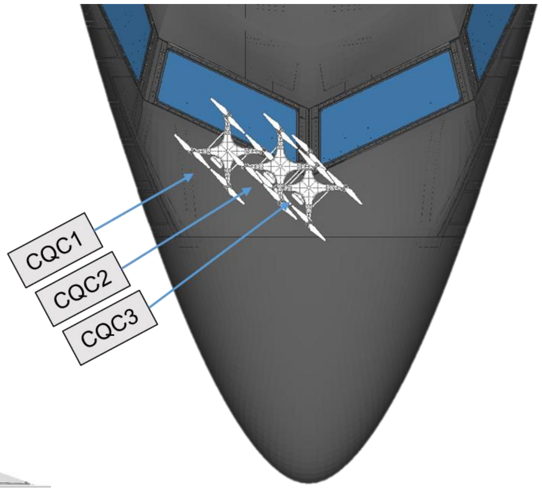
NIAR Wichita State University
National Institute for Aviation Research

- **Parameters:**
  - **16 Different impact locations**
  - **UAS Impact Velocity:** 110, 250 & 365 knots
  - **UAS Mass:** 2.67 and 4 lbs
  - **UAS vs. Bird Studies**
  - **Total of 70 impact conditions analyzed**





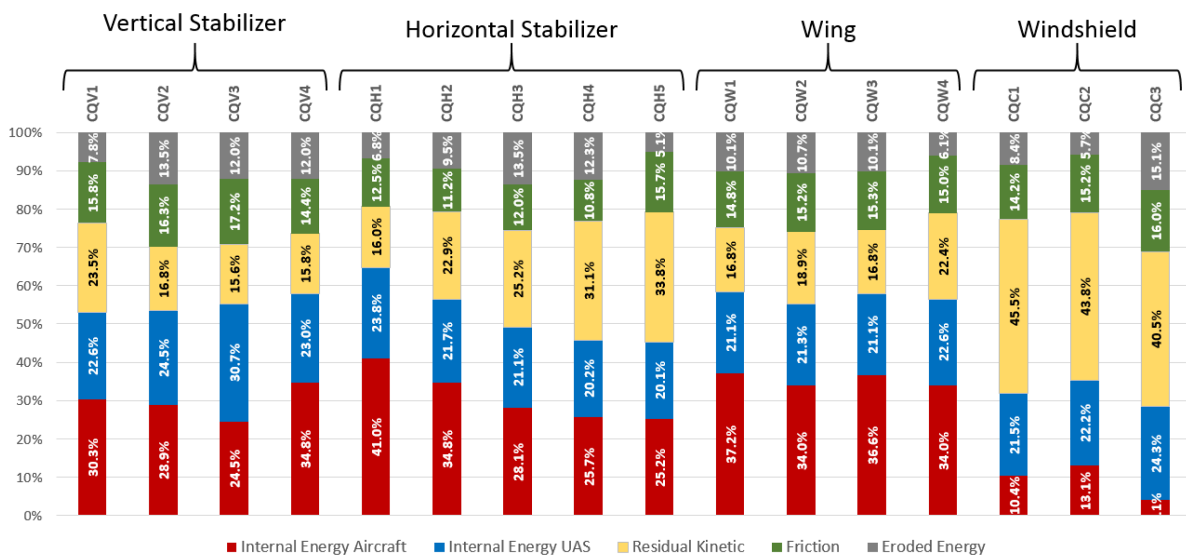




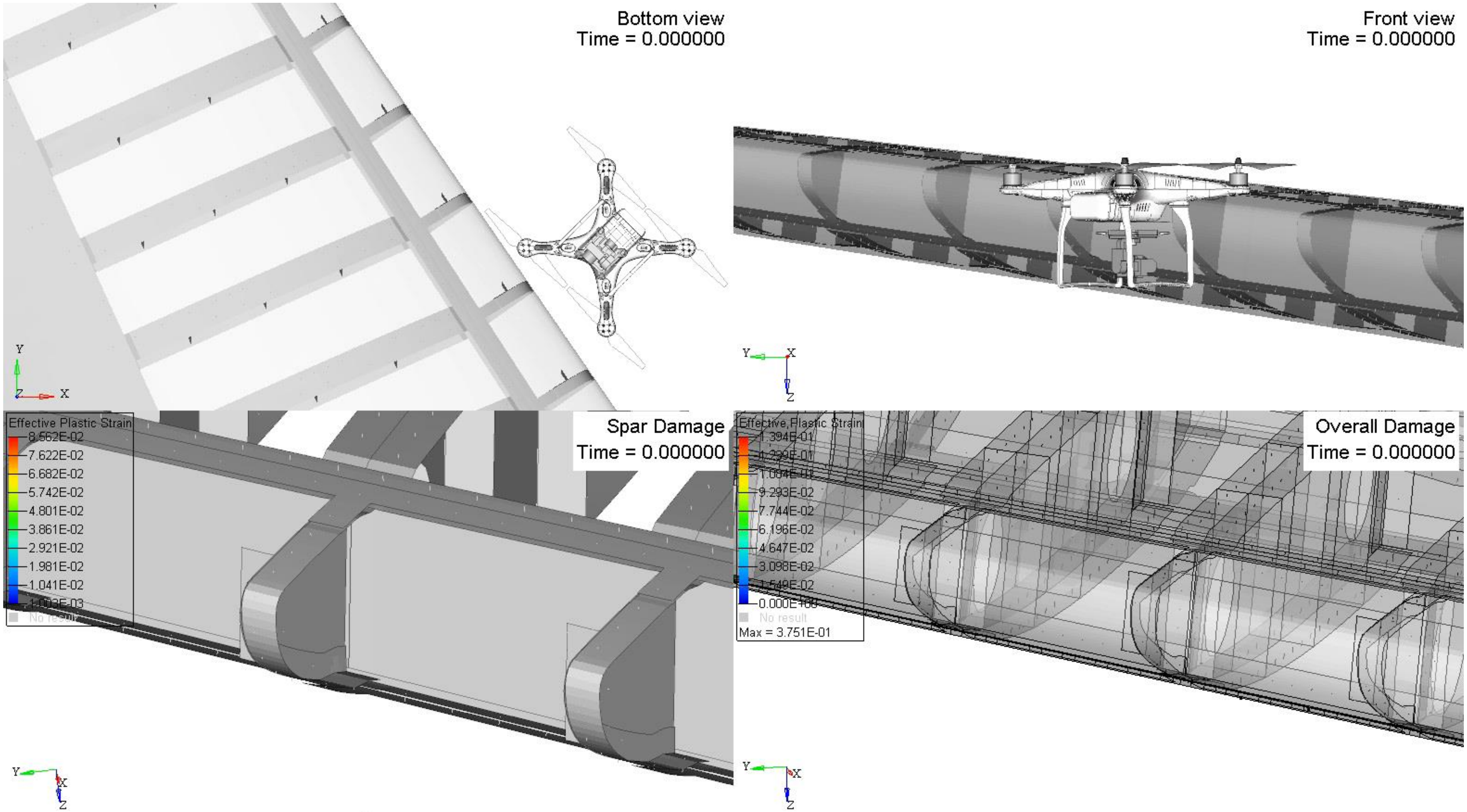
Summary – Commercial Jet

NIAR Wichita State University
National Institute for Aviation Research

	Commercial Transport Jet – Quadcopter Impact Configuration															
	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



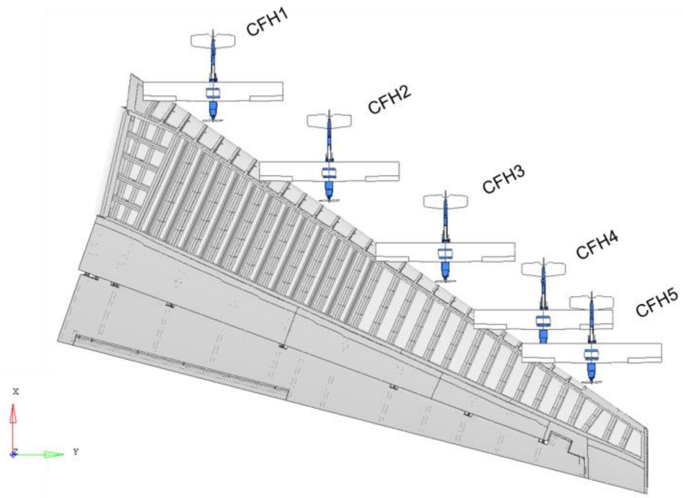
CQH3 – Damage

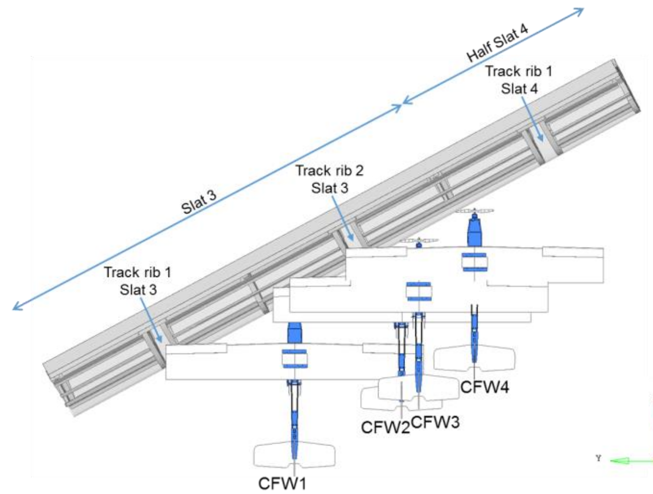


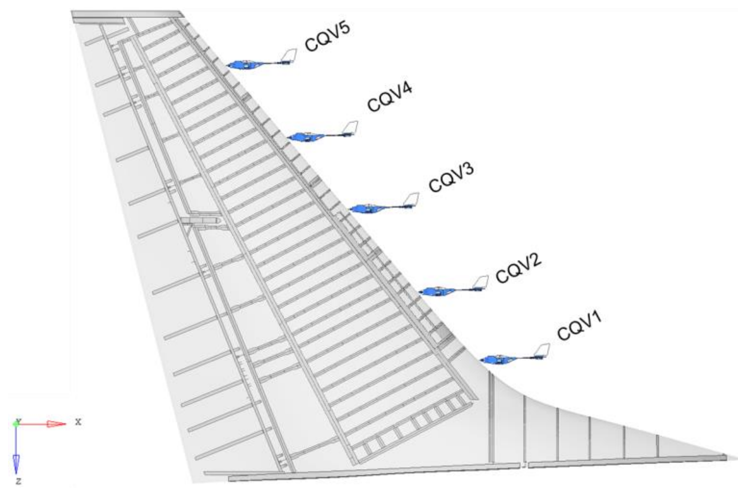
Note: Impact velocity = 250 knot

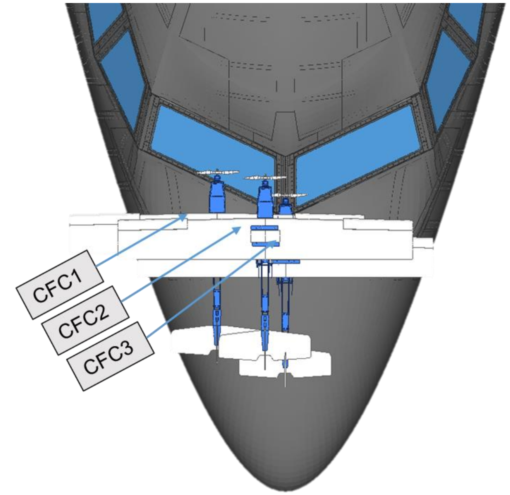
Impact Conditions and Locations

- **Parameters:**
  - **17 Different impact locations**
  - **UAS Impact Velocity:** 110, 250 & 365 knots
  - **UAS Mass:** 4 and 8 lbs
  - **UAS vs. Bird Studies**
  - **Total of 70 impact conditions analyzed**









Aircraft Structure Susceptibility Conclusions

Conclusions

What are the hazard severity criteria for UAS collision?

- Velocity and mass (kinetic energy)
  - These parameters have either a quadratic (velocity) or linear (mass) relationship with the severity of the collision.
  - Verified in parametric studies with simulations.

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

- Stiffness of components
  - Component level testing demonstrated that stiff components such as motors can produce severe damage. Testing showed penetration of motors into 0.063” aluminum panels when impacted at 250 knot.
  - Simulations predicted that most of the damage is produced by stiffer parts (motors, carbon rods, payload, etc.).
- Distribution and connection of masses.
  - Distribution of mass and stiffness in the design of the UAS is critical to the energy transfer.
  - With concentrated or aligned masses the probability of critical damage increases.
  - Simulations confirmed that the critical damage occurs when a majority of the masses are aligned with the impact direction.
- Energy absorption capability
  - Studies indicated that Polycarbonate structures showed a greater energy absorbing capability than ABS due to its greater ductility.
  - UAS designs which incorporate energy absorbing components between an impact target and items with greater stiffness reduces the damage introduced into the target.

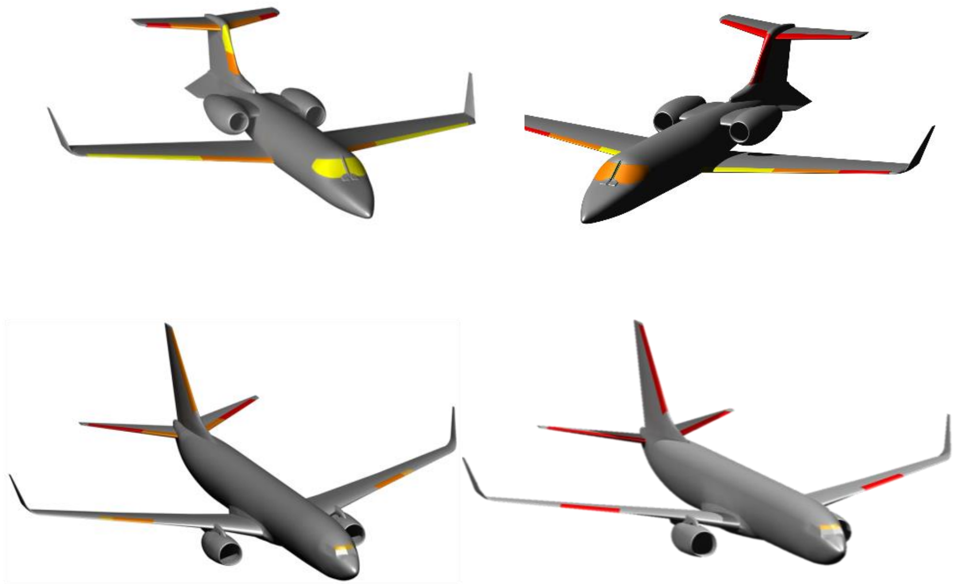
Note: conclusions do not consider engine ingestion.

Conclusions

What is the severity of a UAS midair collision with an aircraft?

- At 250 knots (holding altitude, UAS max speed added).
  - 4 lb fixed wing UAS creates damage to primary structure (Level 4) in most scenarios.
  - 2.7 lb quadcopter UAS creates damage to primary structure (Level 4) scenarios.
- At cruise speeds (325/365 knots)
  - Damage is increased in every scenario.
- At minimum landing speeds (87/110 knots)
  - Neither of the UAS considered create damage beyond 'Level 2'.
- See further work for determining threshold levels.

2.7 lb Quadcopter | 4 lb Fixed Wing



Level 1	(green)
Level 2	(yellow)
Level 3	(orange)
Level 4	(red)

Note: conclusions do not consider engine ingestion.

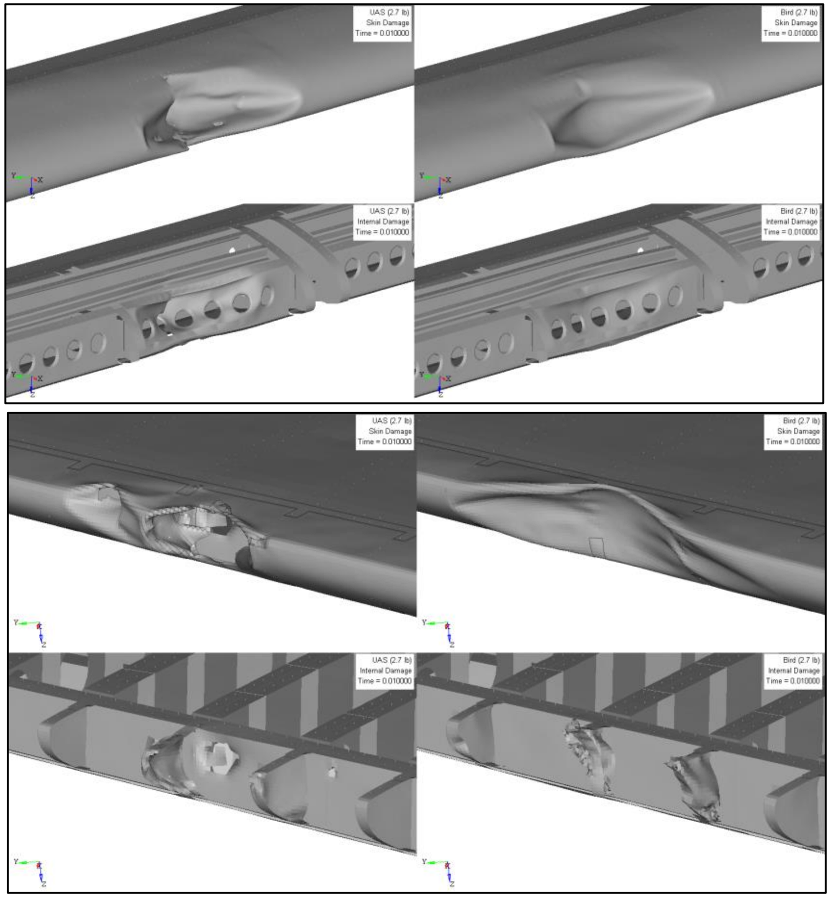
Conclusions

Can a UAS impact be classified similar to a bird strike?

- UAS collisions showed greater damage than bird strikes of equivalent energy.
  - Stiff components of the UAS play an important role
- None of the simulations predicted more damage for a bird than for a UAS impact.
  - Birds having soft bodies, distribute the impact loads.

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

UAS Bird



Note: conclusions do not consider engine ingestion.

Bird – UAS Comparison Example

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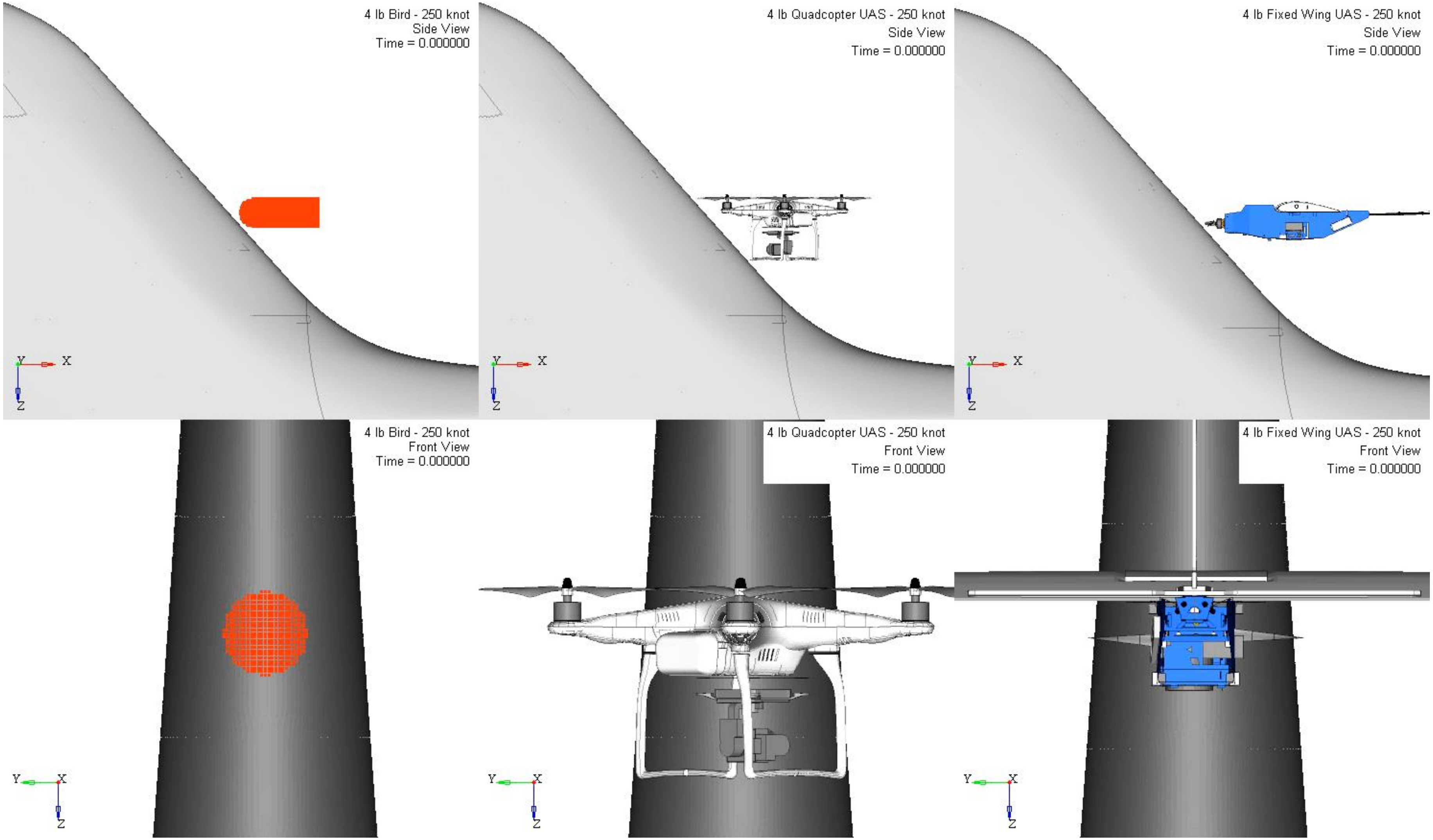
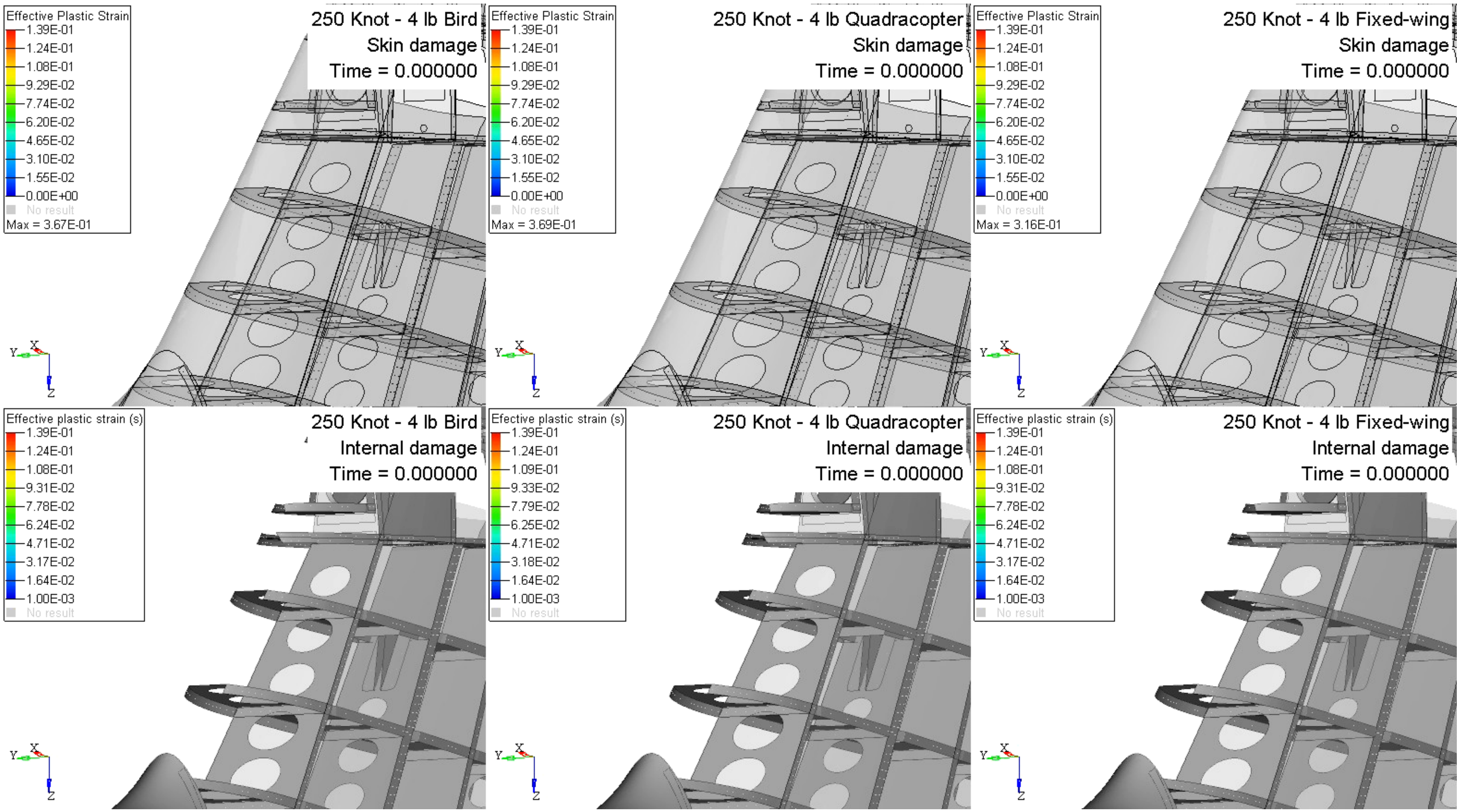


Bird – UAS Comparison Example



Conclusions

What are the characteristics of a UAS where it will not be a risk to an aircraft in case of collision in midair?

- Current studies concluded the following
  - Velocities above landing speeds are considered critical for masses equal to or above 1.2 kg (2.6lbs). Lower masses need to be investigated.
  - Energy absorbing features (e.g. PC materials) reduce the severity of the impact.
  - Alignment and concentration of masses increases damage. Designs that disperse stiff and heavy components would counteract this trend.
- Further studies and testing are required to obtain an estimation of mass, configuration, velocities that establish a threshold of no damage.
- Final report can be found at:

http://www.assureuas.org/projects/deliverables/sUASAirborneCollisionReport.php

Note: this conclusions do not consider engine ingestion.

Ongoing Work

- In 2019 NIAR, UAH, and MtSU received additional funding to continue with the research.
  - Rotorcrafts and General Aviation are being studied.
  - Results of this research are expected towards end of 2020.
- In 2019 NIAR and OSU received additional funding to continue with the research regarding Engine Ingestion.
  - Engine Manufactures heavily involved.
  - Results of this research are expected towards end of 2020.

Questions?

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