Dynamic Response of the Airliner Tail Structure During UAS Airborne Collision

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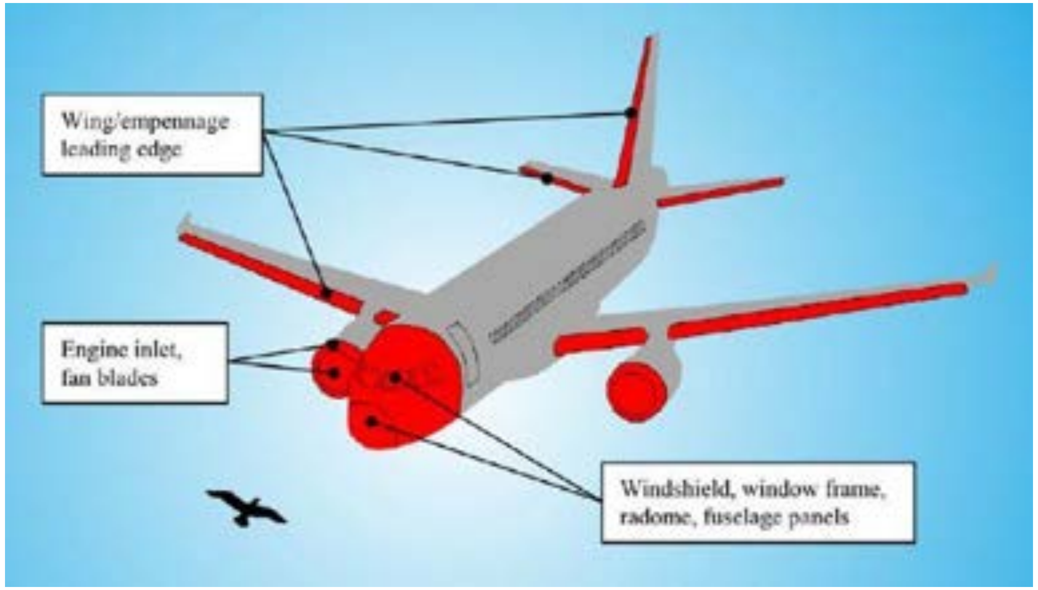
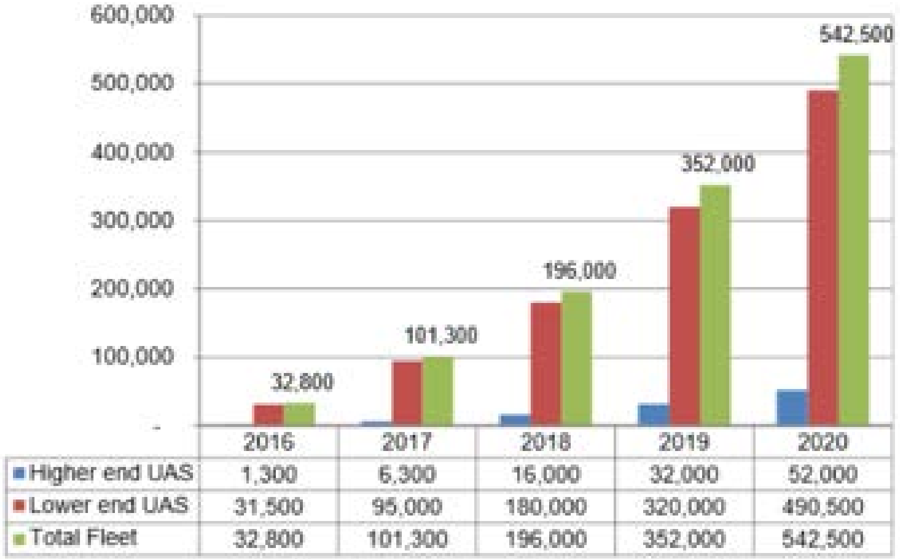
PART.1 Motivation & Background

Motivation & Background





	2016	2017	2018	2019	2020
Higher end UAS	1,300	6,300	16,000	32,000	52,000
Lower end UAS	31,500	95,000	180,000	320,000	490,500
Total Fleet	32,800	101,300	196,000	352,000	542,500

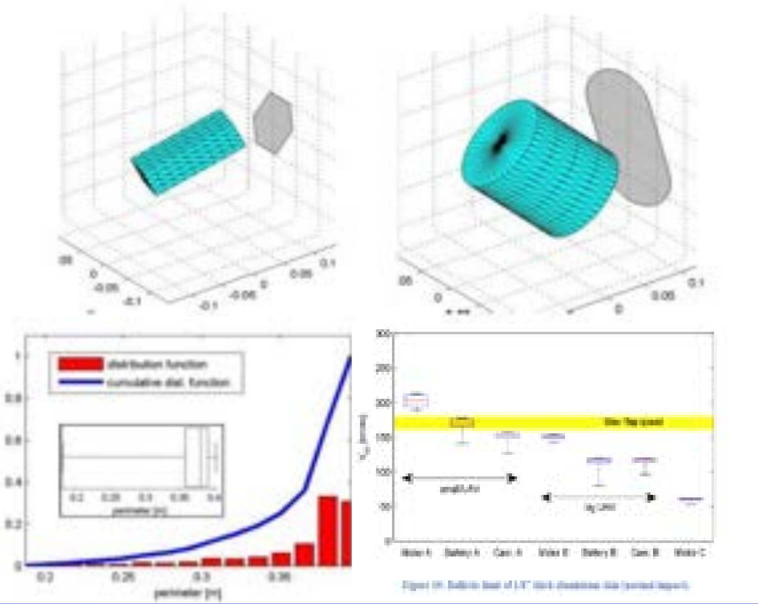
The AUVSI forecast that the UAS market volume will reach 4.7 million units by 2020

Bird strike

Hail strike

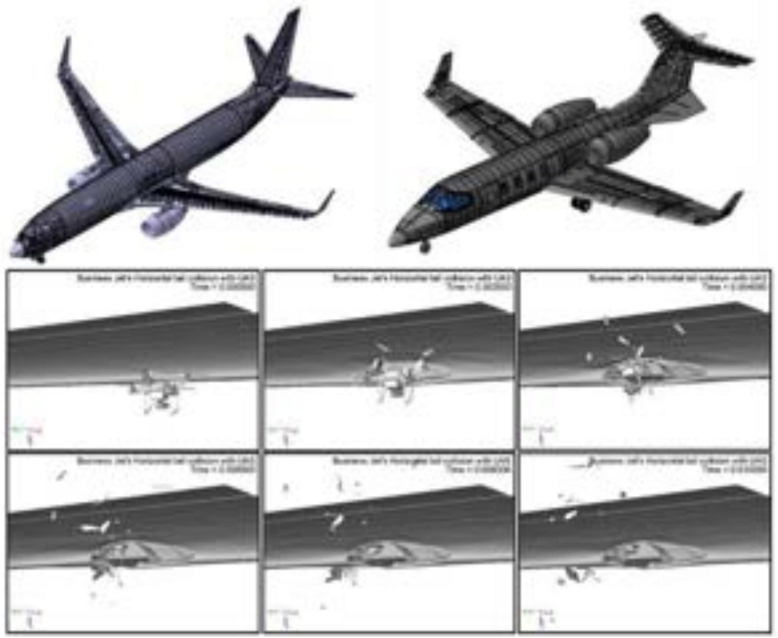
737 was hit by a drone during the landing process (17th Nov. 2017)

Motivation & Background



Potential damage assessment mid air collision small RPA (Australia, 2013)

Small remotely piloted aircraft systems drones mid air collision study (U.K. 2016)



UAS Airborne Collision Hazard Severity Evaluation (ASSURE, 2017)

This work:

Structural level drone collision ground test in accordance with **real collision scenario**.

Finite element model obtained through reverse engineering and **validated by structural level test data**.

Hazard assessment of different drone airborne collision scenarios by validated computational model.

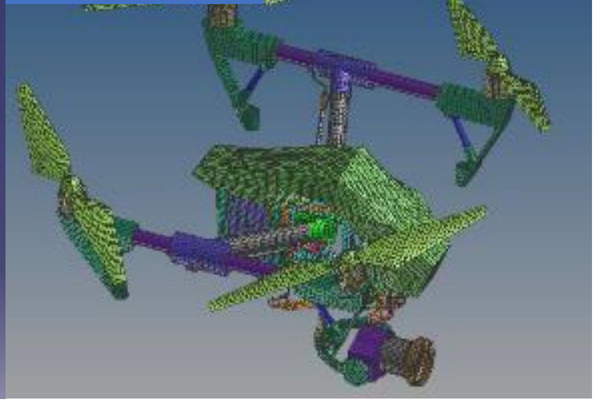
PART.2 Description of the FE Model

Description of the FE Model

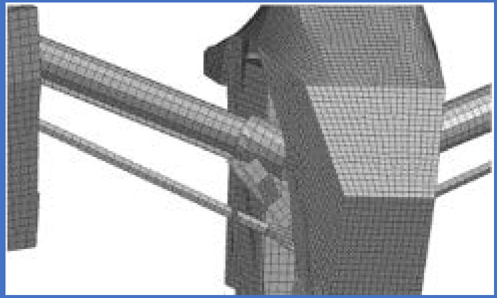
Insprie I

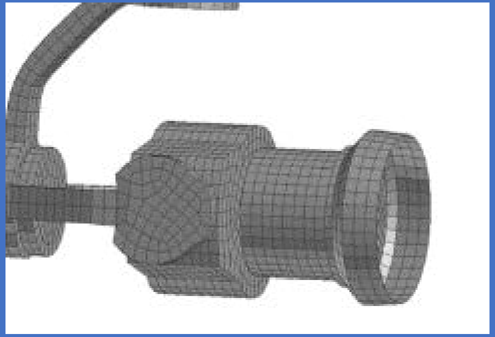
CAD model

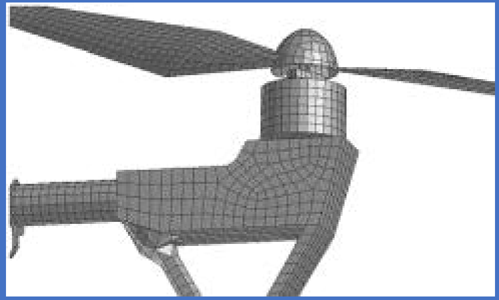
FE model

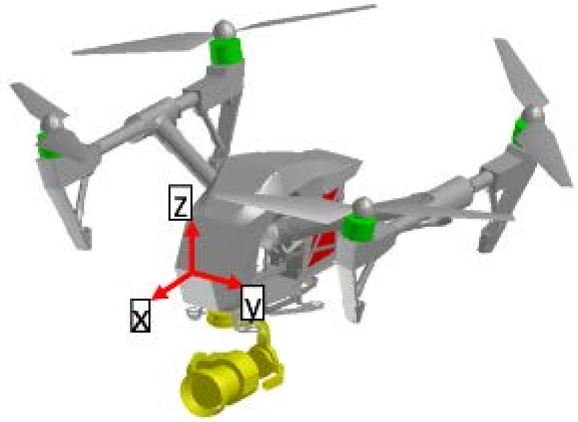


Average mesh size: 5mm









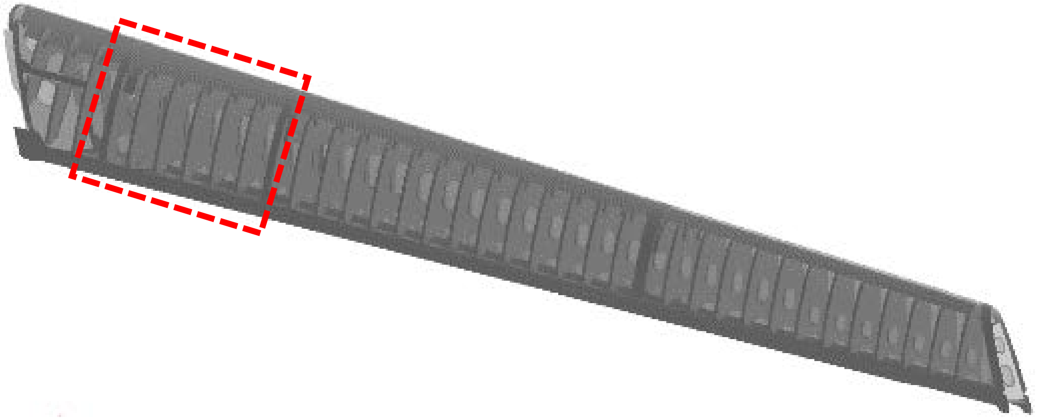
Component		Mass/kg	Center of gravity/mm
Total UAS		3.428	(-197, 0, 5)
(green)	motors	0.462	(-214, 0, 12)
(red)	battery	0.57	(-271, 0, 4)
(yellow)	camera	0.64	(-125, 0, -161)

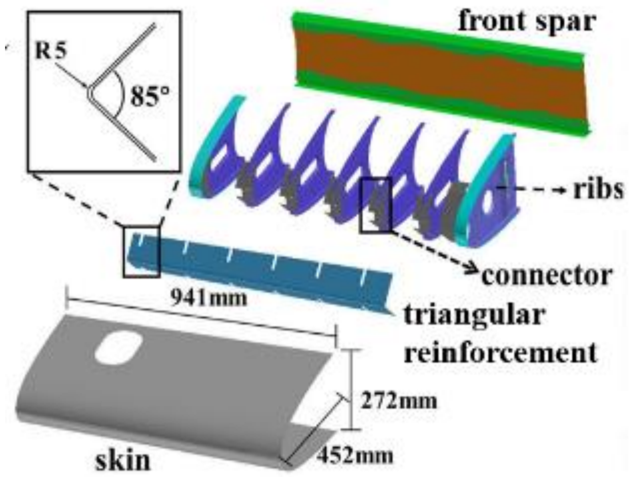
Shell elements: 22971

Solid elements: 11544

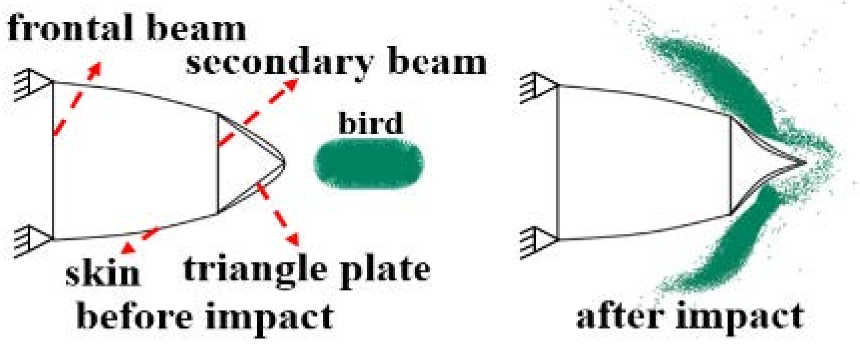
Description of the FE Model

Airliner horizontal stabilizer leading edge

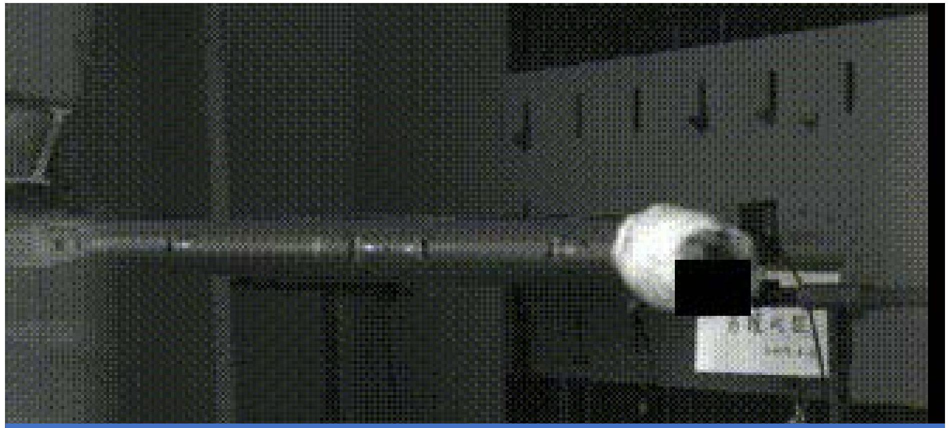




Code	Material	Thickness
	2024-T3	1.2-2mm
	7075-T6	1.27mm
	7075-T6	1.27mm
	7075-T6	1mm+1mm
	7075-T6	1.6mm
	7075-T6	2mm
	7075-T6	1.27mm



Triangular reinforcement*

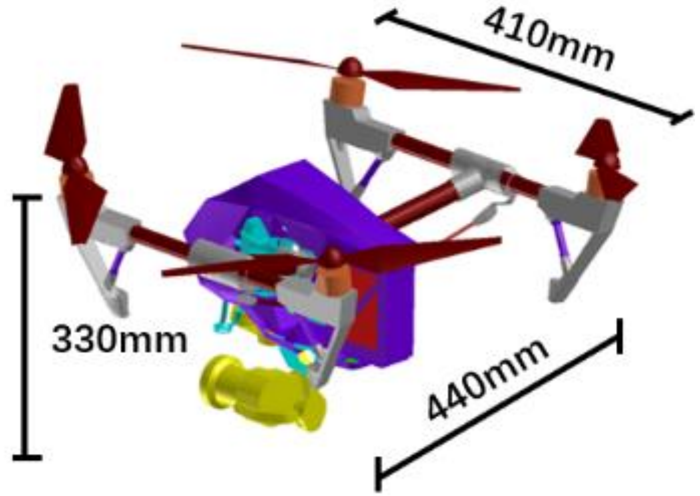


Certification for 3.6kg bird srtike

*Jun Liu et al. International Journal of Impact Engineering, 2017

Description of the FE Model

Drone material model



Code	Material
	Polycarbonate
	Polyamide 6
	Carbon Fiber Reinforced Polymer
	battery
	camera
	6061-T6 aluminum alloy
	electronic boards
	motor

PC and PA6

	Density ρ [kg/m³]	Young modulus E [GPa]	Poisson's ratio ν	Yield stress σ_Y [MPa]	Failure strain ε_{max}
PC	1180	2.35	0.3	62	0.2
PA6	1350	6.2	0.3	70	0.2

CFRP

Young's modulus E_1 [GPa]	Young's modulus E_2 [GPa]	Poisson's ratio ν_{12}	Shear modulus G_{12}[GPa]
191	9.9	0.33	6.3

Lithium-ion battery

Density ρ [kg/m³]	Young modulus E [MPa]	Poisson's ratio ν
1750	500	0.01

CFRP damage evolution

$$E_1 = \begin{cases} E_1^0 & \varepsilon_{11} < \varepsilon_i^f \\ E_1^0(1-d^f); \quad d^f = d_u^f \dfrac{\varepsilon_{11} - \varepsilon_i^f}{\varepsilon_u^f - \varepsilon_i^f} & \varepsilon_i^f \le \varepsilon_{11} < \varepsilon_u^f \\ E_1^0(1-d^f); \quad d^f = 1-(1-d_u^f)\dfrac{\varepsilon_{11}}{\varepsilon_u^f} & \varepsilon_u^f \le \varepsilon_{11} \end{cases}$$

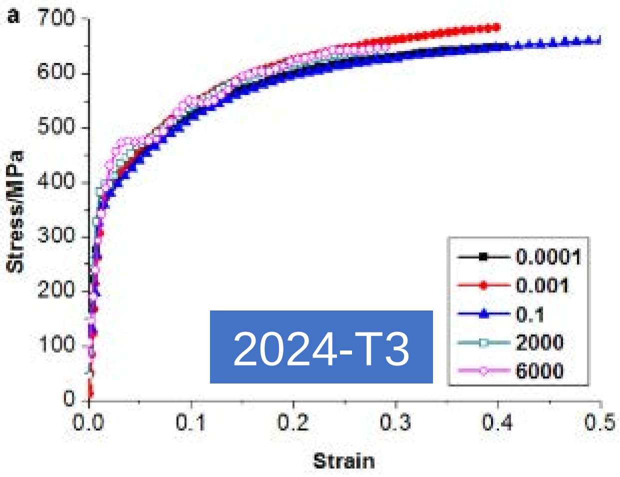
$$\begin{cases} Y = \sqrt{\dfrac{1}{2}\dfrac{\sigma_{12}^2 + \sigma_{13}^2}{G_{12}} + b\dfrac{1}{2}\dfrac{\langle \sigma_{22} \rangle^2}{E_2}} & \text{(shear damage)} \\ Y' = \sqrt{\dfrac{1}{2}\dfrac{\langle \sigma_{22} \rangle^2}{E_2}} & \text{(transverse damage)} \end{cases}$$

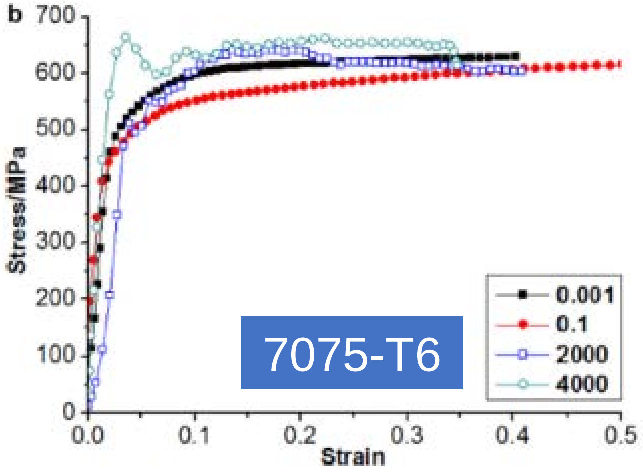
$$\begin{cases} d = \langle Y - Y_0 \rangle / Y_c & \text{(shear damage)} \\ d' = \langle Y - Y'_0 \rangle / Y'_c & \text{(transverse damage)} \end{cases}$$

$$\begin{cases} E_2 = E_2^0(1-d') \\ G_{12} = G_{12}^0(1-d) \end{cases}$$

Description of the FE Model

Aluminum alloy





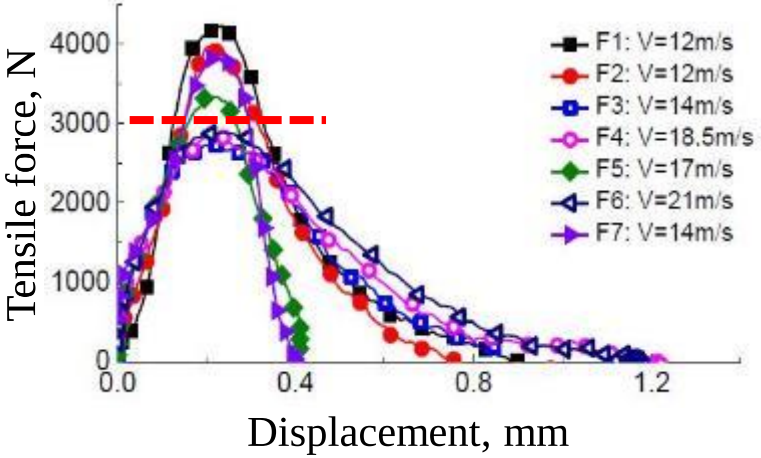
Johnson-Cook Model $\sigma = (A + B\varepsilon^{n})(1 + C\ln\dot{\varepsilon}^{*})(1 - (T^{*})^{m})$

Parameters of aluminum alloy

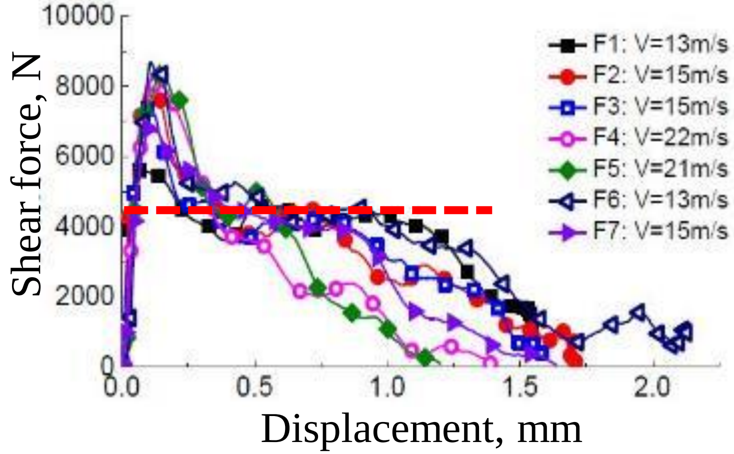
	A [MPa]	B [MPa]	n	C	ε_{max}
2024-T3	280	400	0.2	0.015	0.2
7075-T6	480	400	0.42	-0.001	0.12

Fastener (P-LINK element)

Rupture model $\left(\frac{T}{T_{MAX}}\right)^{n} + \left(\frac{S}{S_{MAX}}\right)^{m} \leq 1$



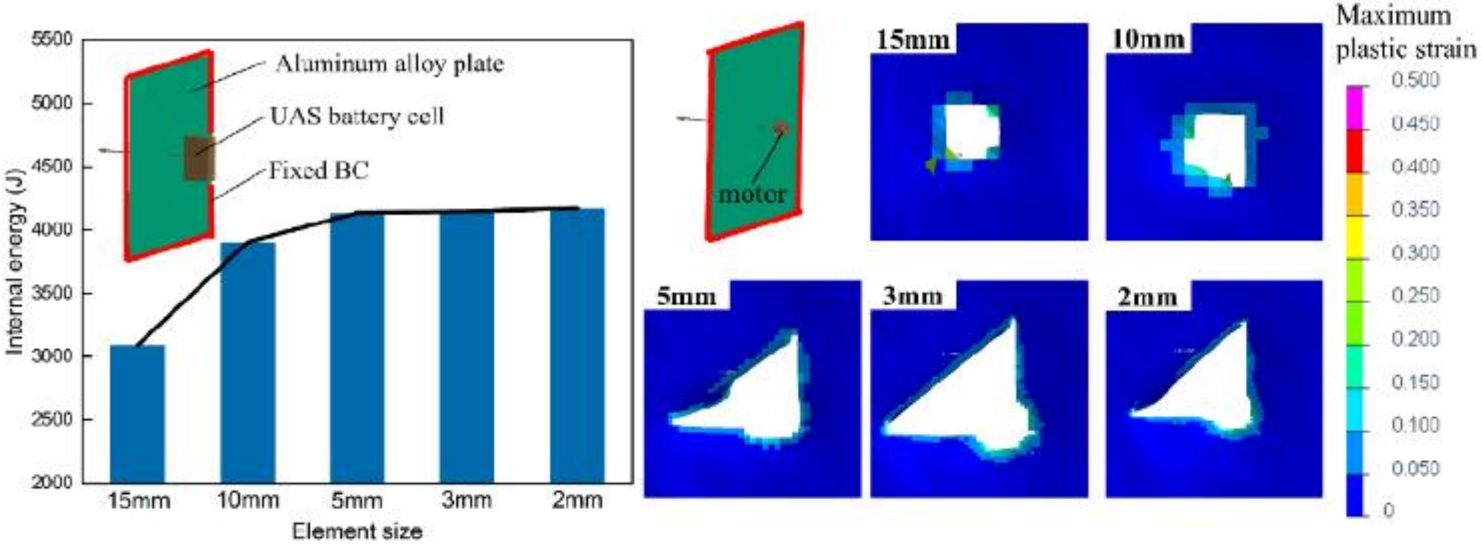
T_{MAX}=3000N



S_{MAX}=4200N

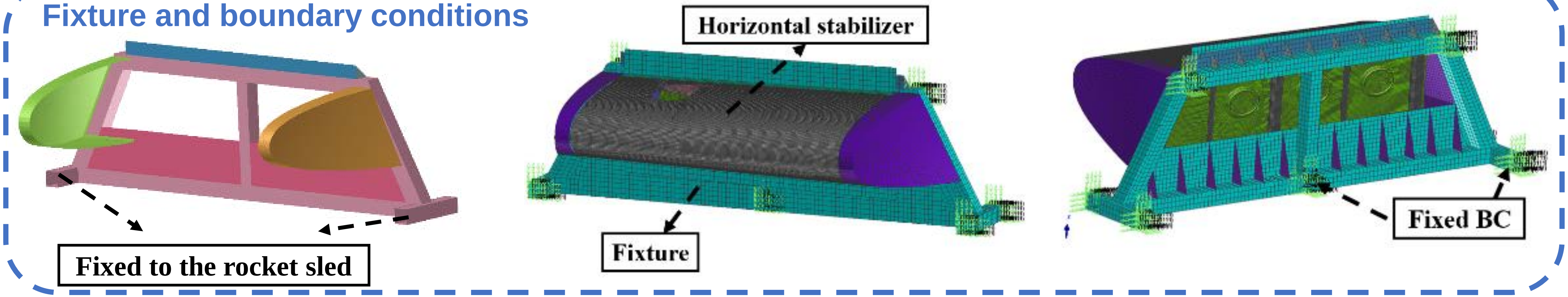
Description of the FE Model

Mesh Sensitive Test



Horizontal stabilizer section

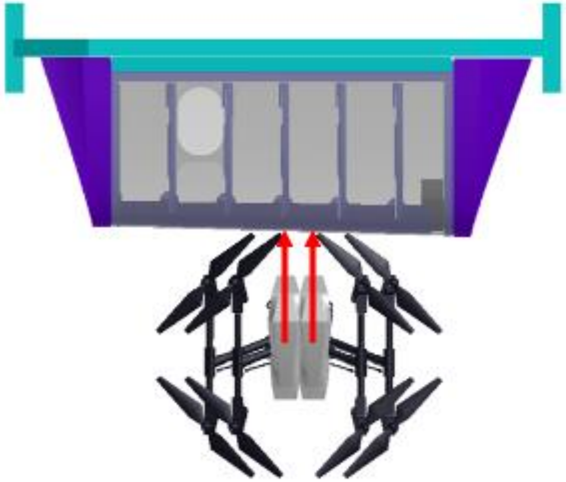
Fixture and boundary conditions



PART.3 Experimental Validation

Experimental Validation

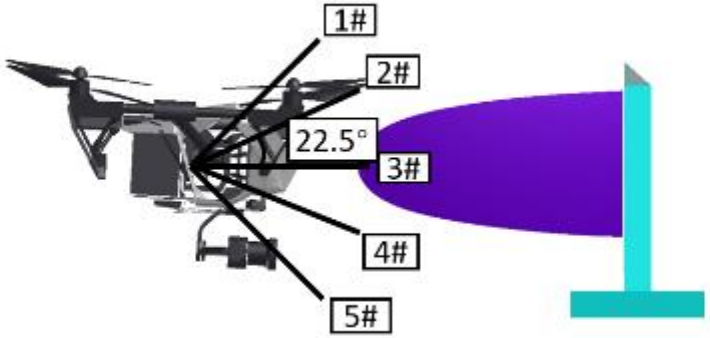
Test collision scenario determination

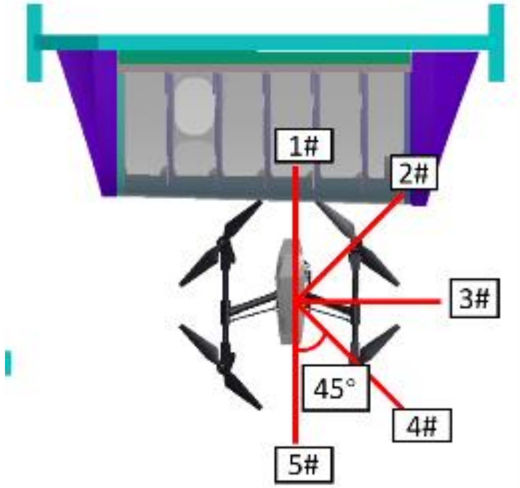


Impact locations:
on rib & between ribs

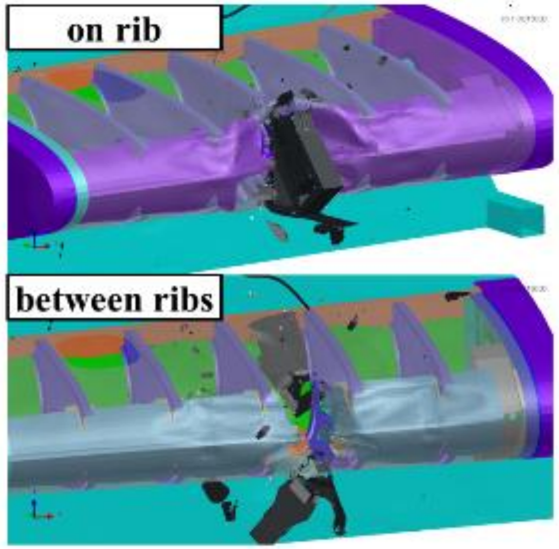
Drone attack angle:
-45°~45° at an interval of 22.5°

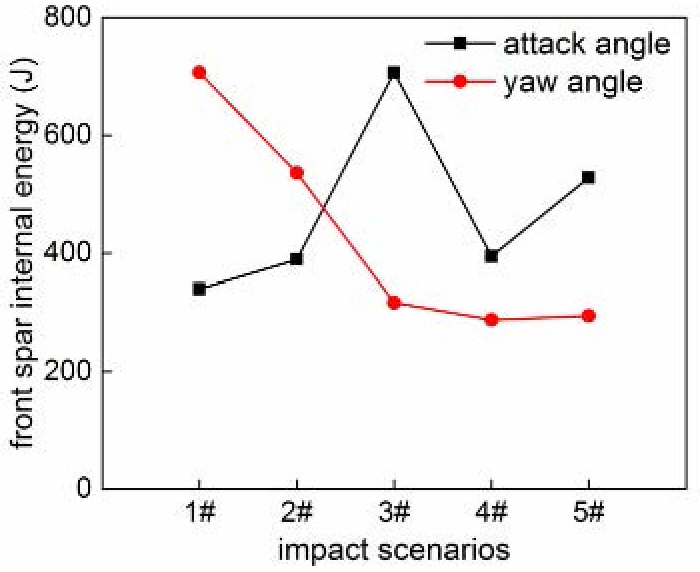
Drone yaw angle:
1°~180° at an interval of 45°





Results

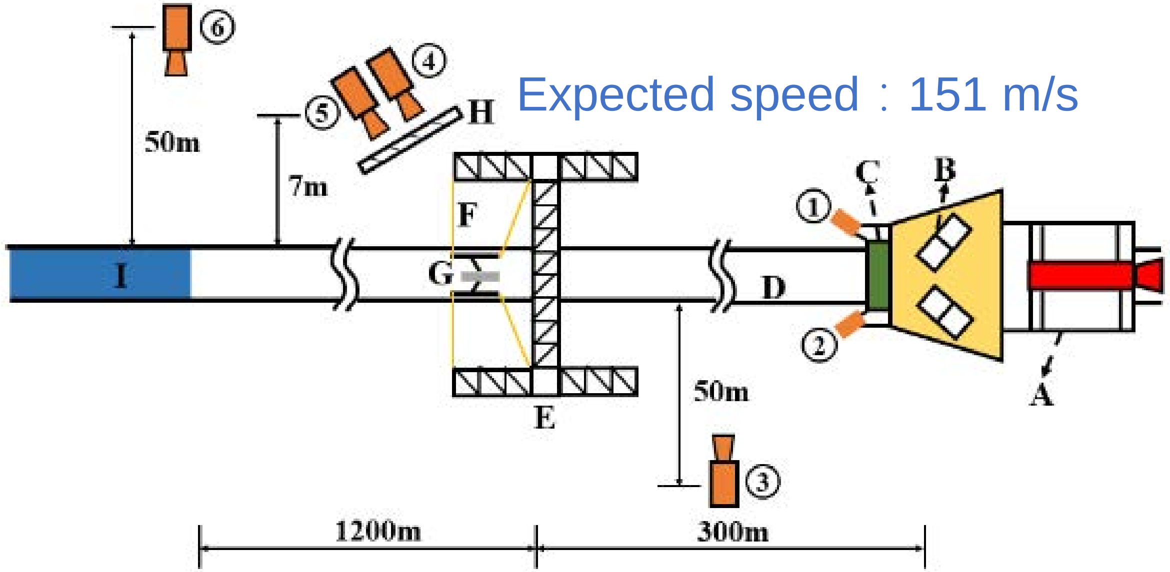




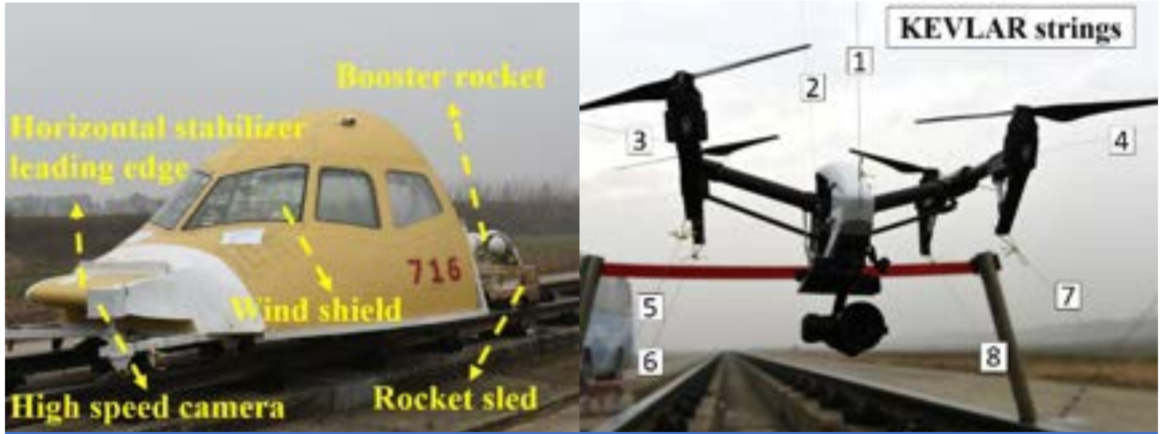
Experimental Validation

Test procedure

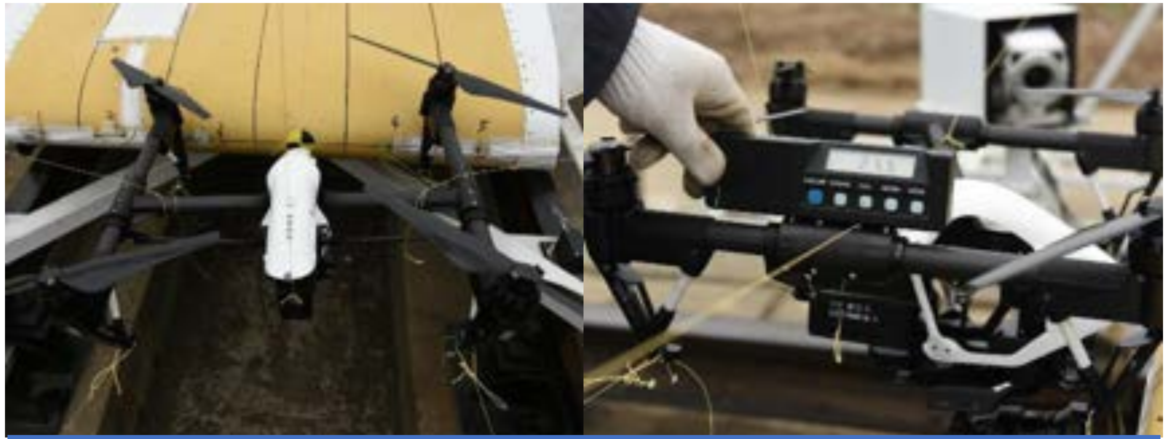
Expected speed：151 m/s



(A) rocket sled, (B) head structure and windshield, (C) horizontal stabilizer leading edge, (D) steel track, (E) fixture frame for the drone, (F) KEVLAR strings, (G) the drone, (H) shield for high-speed cameras, (I) water brake. 1-6 high-speed cameras.



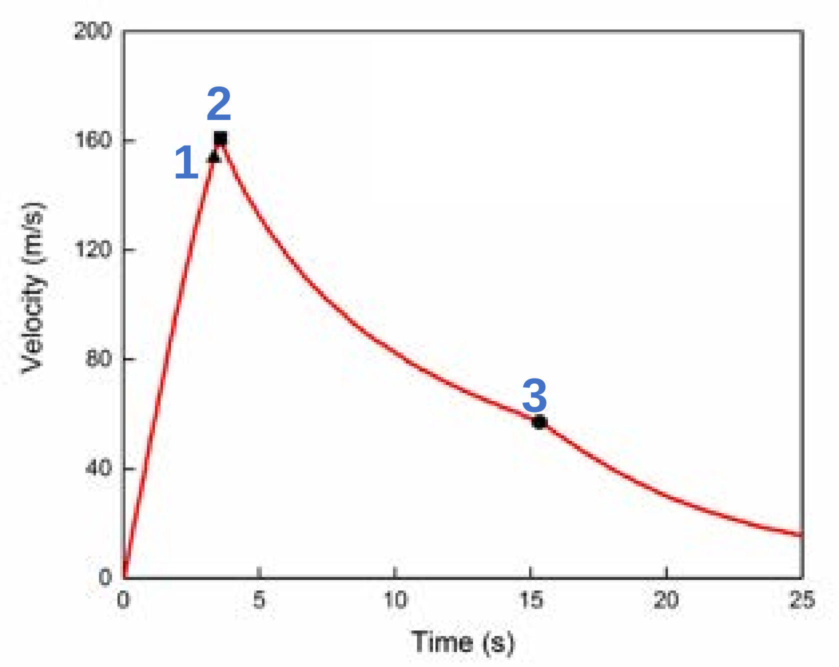
Rocket sled and Inspire I UAS



Calibration of the drone position

Experimental Validation

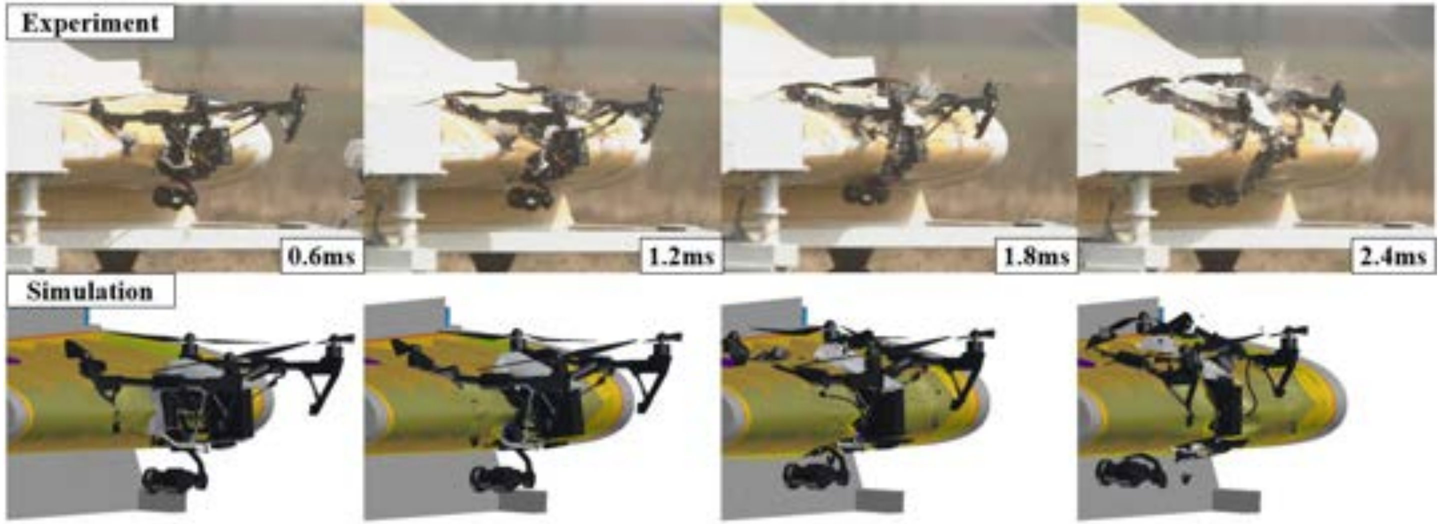
Sled velocity



1. Impact point v=152.8m/s
2. Fuel exhaustion v=159.2m/s
3. Water brake v=56.4m/s

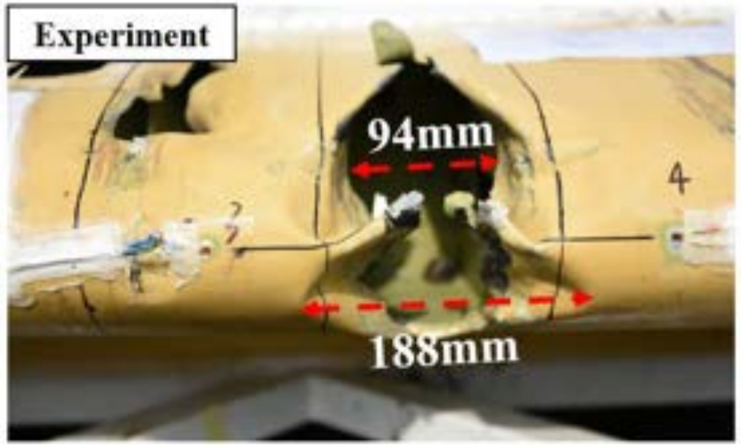
High-speed camera 4

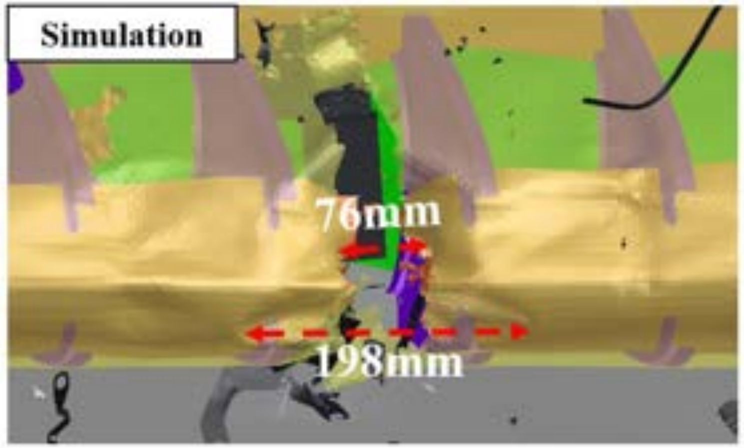
High-speed camera 1

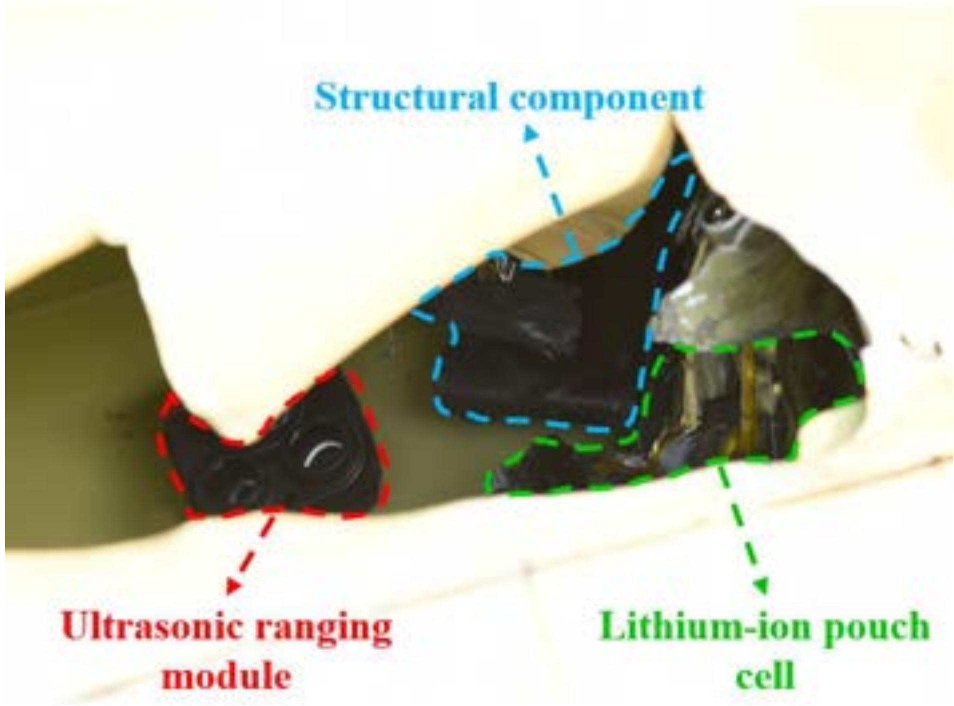


Experimental Validation

Damage features







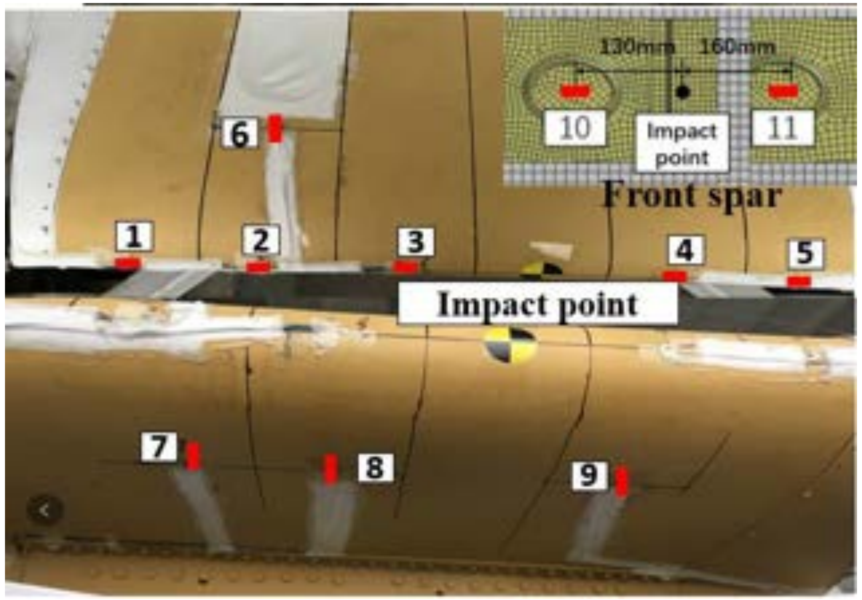
The main structure of the drone penetrated into the airframe

Some small drone components penetrated the front spar (fracture size about 15 mm)

The lithium-ion battery penetrated into the airframe had a smoke sign in the test

Experimental Validation

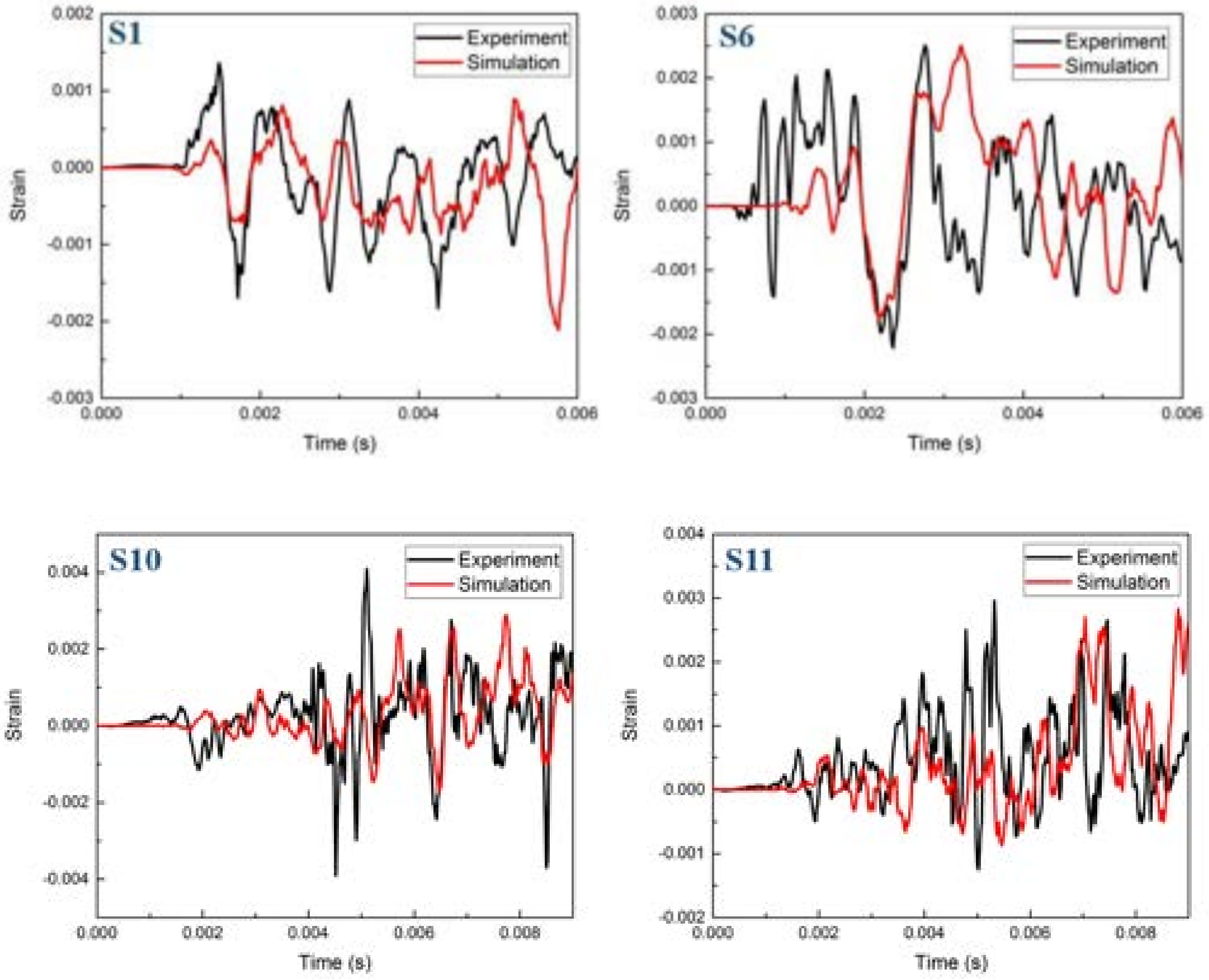
Strain signals



randomness factors during the collision process

the differences between the simplified FE model and real drone structure.

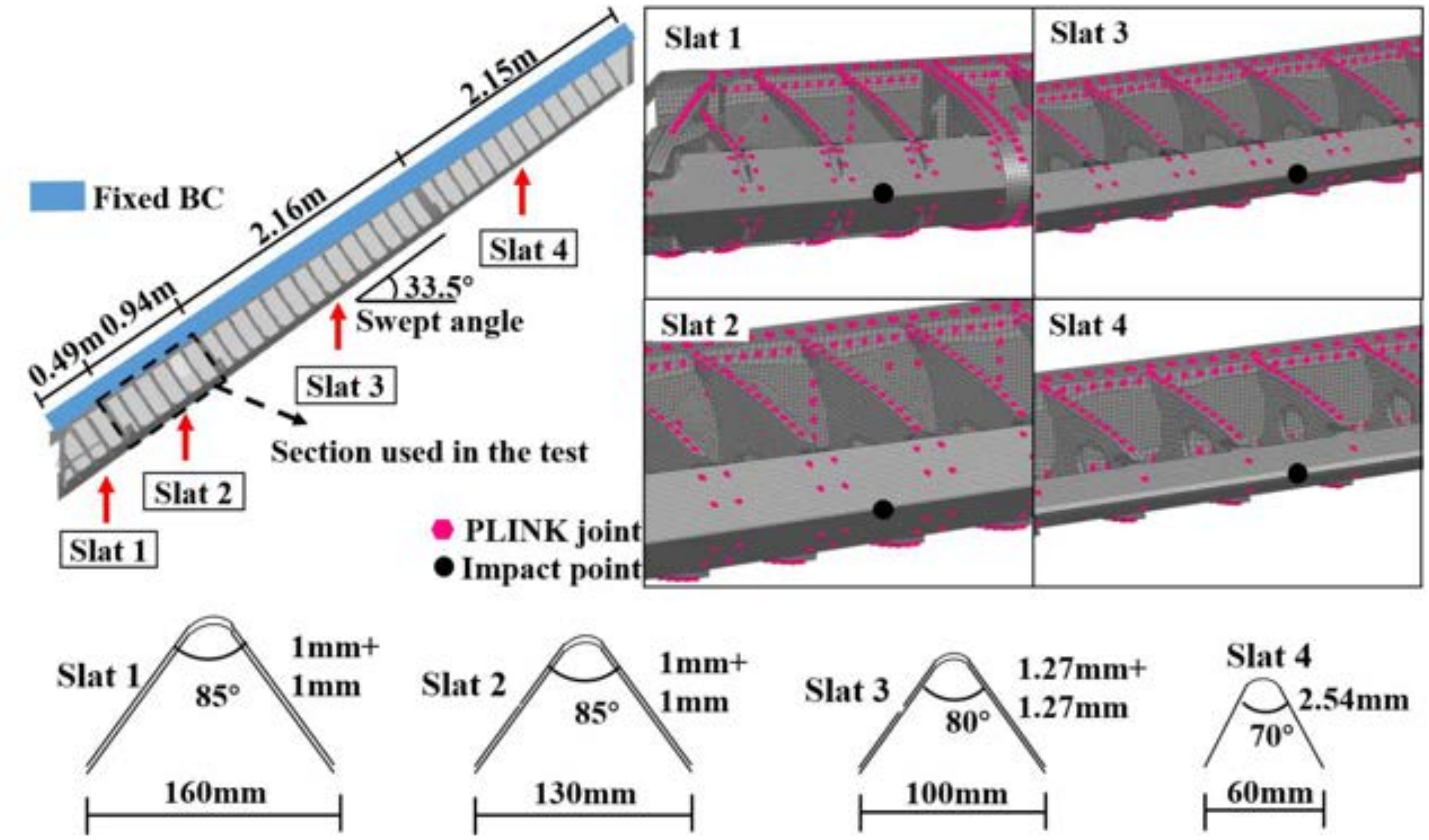
Uncertainty of precise drone posture



PART.4 Discussion of Different Impact Scenarios

Discussion of Different Impact Scenarios

horizontal stabilizer leading edge FE model



The structure was about 5.74 m long and can be divided into four sections

The whole FE model contained 318,333 shell elements and 3194 PLINK elements.

Fixed boundary conditions were applied on the upper and lower edges of the front spar

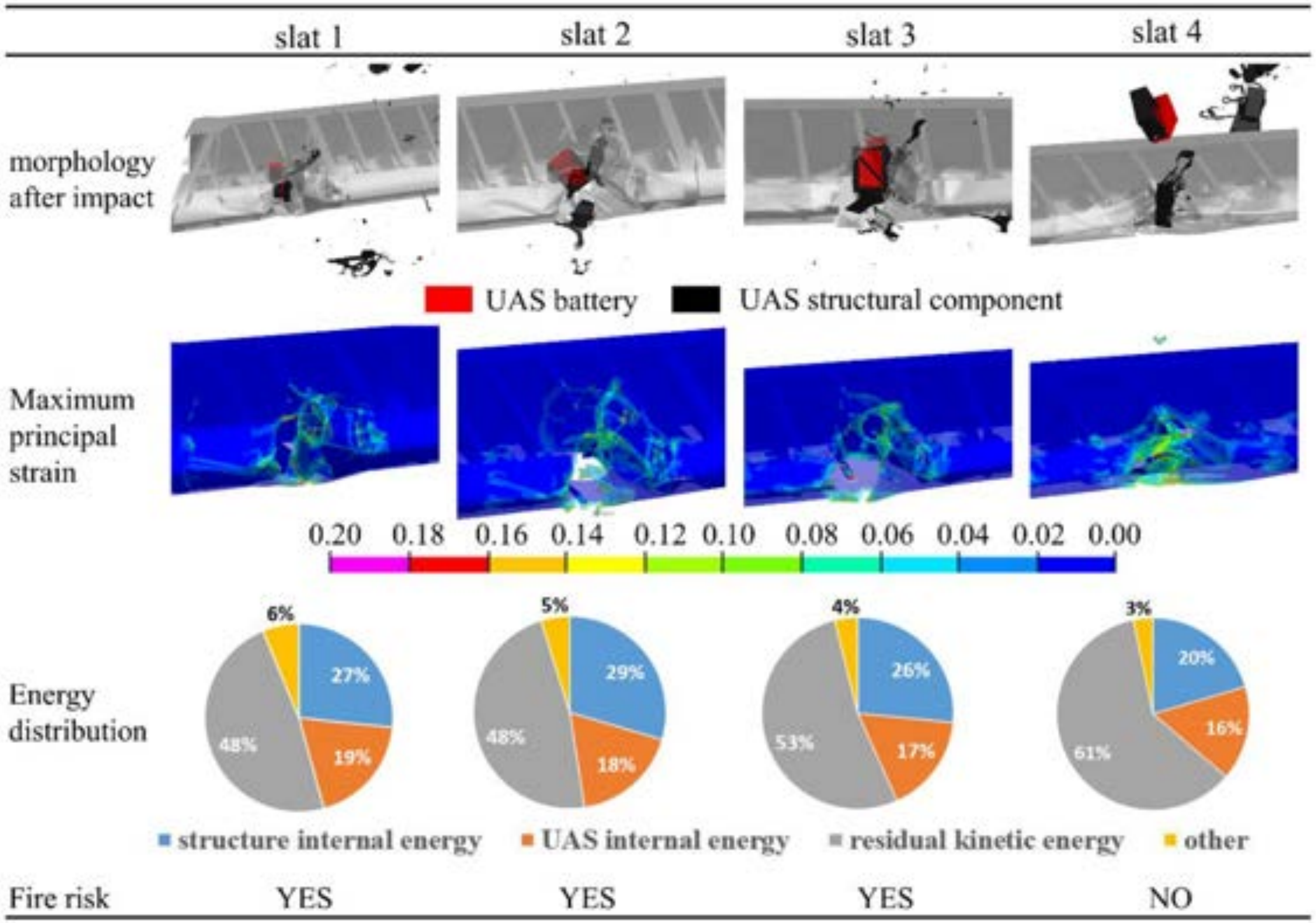
Discussion of Different Impact Scenarios

Different impact locations

Drone projection areas on the leading edge at different impact points

Impact point	Projection area [cm^2]	Projection area [%]	Mass in projection area [kg]	Mass in projection area [%]
Slat 1	358.4	83.9%	2.707	79.0%
Slat 2	341.3	79.9%	2.529	73.8%
Slat 3	295.6	69.2%	2.172	63.4%
Slat 4	190.5	44.6%	1.577	46.0%

Results



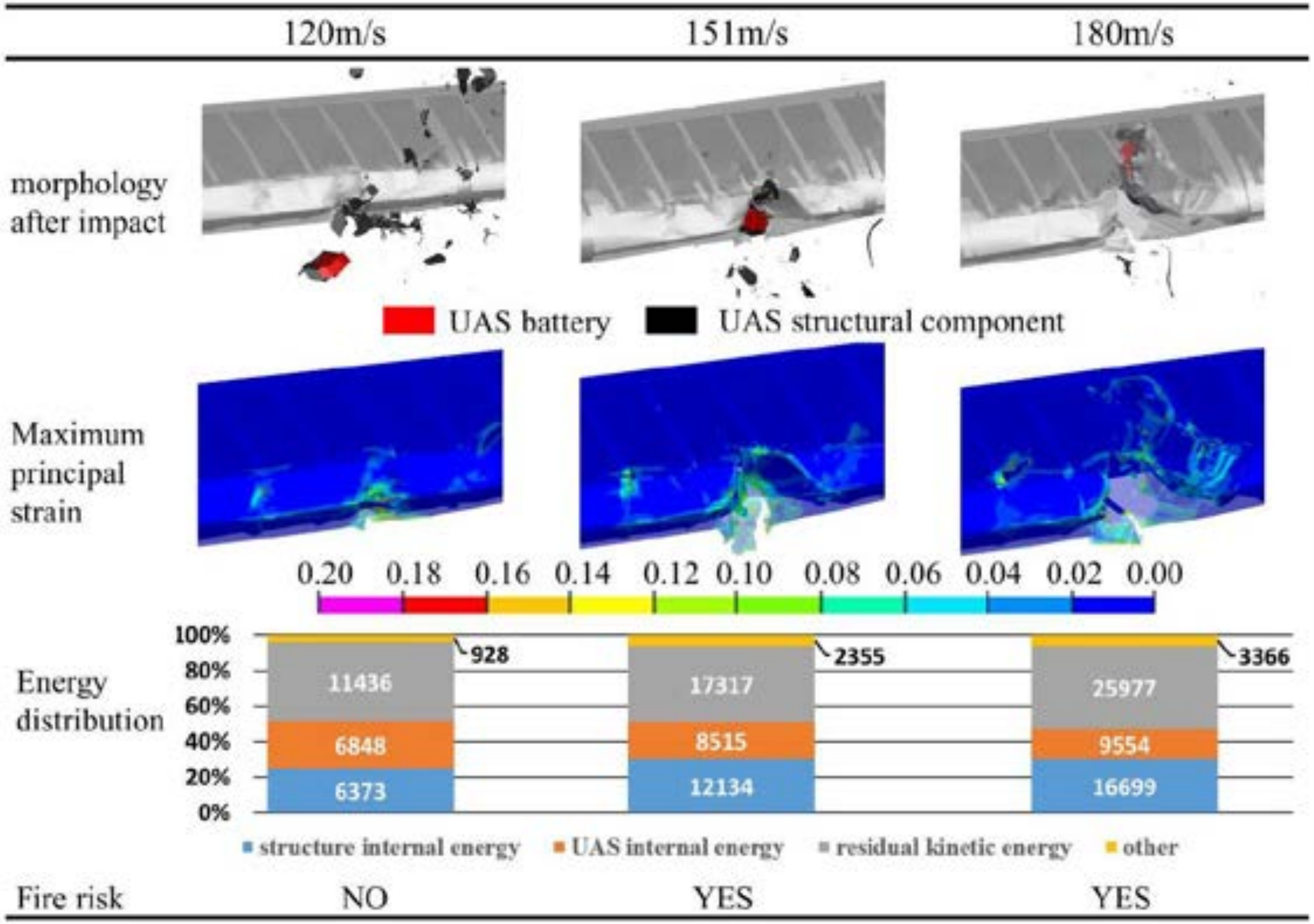
Discussion of Different Impact Scenarios

Different impact locations

Velocity-attack angle relationship of the airliner

Velocity [m/s]	Attack angle [°]	Projection area [%]	Mass in projection area [%]
95	15°	78.4%	76.4%
126	10°	80.9%	78.2%
155	4°	78.7%	78.2%

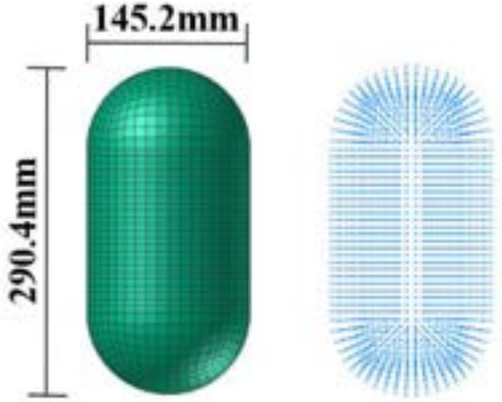
Results



PART.5 **Comparison with Bird Strike**

Comparison with Bird Strike

Bird model



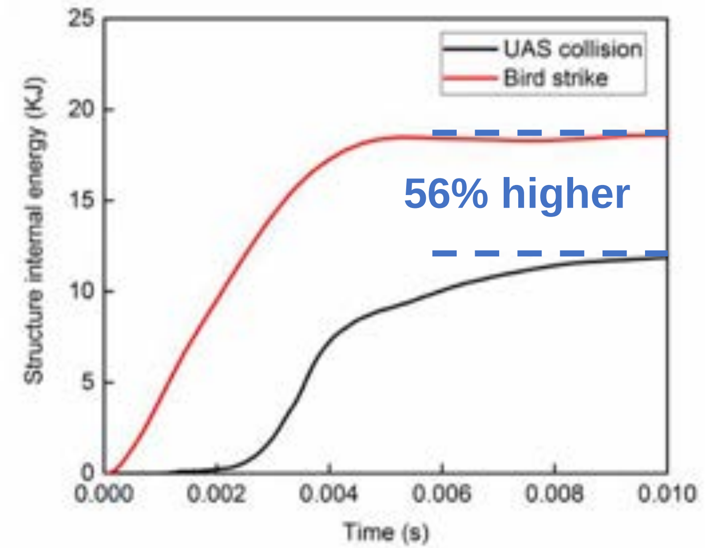
Murnaghan EOS

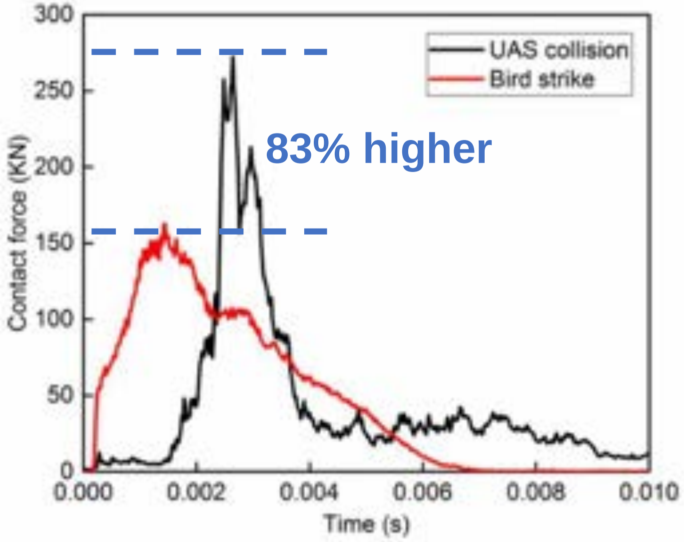
$$p = p_0 + B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right]$$

***B* = 128 MPa**
***γ*=7.99**

Results

Damage characteristics of UAS collision and bird strike （150m/s）





PART.6 Conclusion

Conclusion

- The impact behavior simulated by the FE model was in acceptable agreement with test data and the simulation methodology is proved to be an efficient way to reduce certification costs.
- The commercial airliner cannot complete the flight safely when a UAS airborne collision happens at its cruising speed.
- Some anti-bird strike designs were proved to be not so efficient against UAS airborne collision, new design principles should be considered.
- UAS collision would cause more serious consequences than bird strike at the same mass level, Relevant airworthiness standards should be drafted.

THANK YOU

ANY QUESTIONS?

- This wrok was funded by **Airworthiness Certification Center of CAAC** and **Shanghai Aircraft Airworthiness Certification Center of CAAC**
- All the drones used were supplied by **SZ DJI Technology Co., Ltd**

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