Damage Severity Prediction of Helicopter Windshields Caused by a Collision with a Small Unmanned Aerial Vehicle (sUAV)

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Small unmanned aerial vehicles (or drones) have recently been increased for various operations like parcel delivery, industrial inspection, aerial photography, and safety surveillance. Increased in sUAV traffic in future may lead to higher chance of collision between sUAV with other airspace users where mid-air collision debris might fall and endanger peoples on the ground. Finite Element Method (FEM) simulation is employed to assess damage severity caused by the sUAV collision on helicopter windshield compared to bird strike, series of collision simulation has been performed to investigate influence of different parameters like windshield thickness, windshield material type, and helicopter speed to the damage severity of the helicopter windshield. In our preliminary study, it is found the damage level in sUAV collision cause more severe damage compared to bird strike for same weight category, i.e., 1.8 kg and 3.0 kg. Study of damage severity due to sUAV collision can also be performed in future study to have better understanding on this risk. From this study, aviation airworthiness authorities have better insight on the limitation of current airworthiness, at the same time could provide information for aviation authorities to formulate regulations for operations of sUAV, helicopter, or eVTOL.

I. Introduction

The drone is expected to be operated in a large-scale in future for different operation like parcel delivery, industrial inspection, aerial photography, and safety surveillance [1]. The number of the drone is approximated to be reached 7.0 million units by years 2026 [2]. Although the small unmanned aerial vehicle (sUAV) did not have persons on board, however, it might pose a threat to other airspace users as well as upon persons and properties on the ground.

The Federal Aviation Administration [3] permits the use of sUAV without an air traffic authorization in uncontrolled airspace (Class G airspace) and up to 400 ft Above Ground Level (AGL). In addition, European Commission (EC) has published the implementing regulation European Union (EU) 2019/947 [4] for drone operation in uncontrolled airspace at the maximum altitude of 120 ft AGL. In this airspace both aviation authority allows operation of the drone with weight less than 25.0 kg to be operated without required to obtain approval from authority beforehand.

Currently, the uncontrolled airspace is primarily operated by civil aircraft, military or government, for example, the air medical emergency services and the police helicopter [5]. It is also expected in future that large size of drone like air taxi developed by the Volocopter [6] and EHang [7]; and air metro to be operated in uncontrolled airspace as mode of transportation [8] as well as for tourist and logistic purposes. Increased in sUAV traffic in future, one might

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expect the collision of manned and unmanned airspace users with the sUAV or bird might have resulted in serious consequences; such collision can be more impactful especially for drone operation in urban environment where mid-air collision debris might fall and endanger peoples on the ground [9]. Therefore, risk of drone operation in uncontrolled airspace should be analyzed carefully to maintain high level of safety in drone operation.

II. Literature Review

Commonly, helicopter is operating at the height of 400 ft susceptible to a high risk to strike with bird, data from Ilias [10] shows 70% of all bird strike cases reported occur within altitude less than 200 ft, and 95% of all strikes occur below 2500 ft, when considering worldwide traffic as shown Fig. 1. In addition, Dolbeer et. al [11] has concluded that 88% of all the bird strikes cases reported in the USA from 1990 until 2018 have occurred at altitude below than 2500 ft and around 71% of the bird strike occurred below 500 ft as shown in Fig. 2. It can be concluded the highest probability of bird-aircraft collisions is at low altitudes [12]. It was also reported around 76% of cases reported involve bird strike with large birds, as shown in Fig. 3 [10]. Fig. 4 shows area of aircraft damaged from bird strike, and it is noted that around 13% of all cases is damage to the aircraft windshield and 30% of all the accidents to the windshield is damage involve helicopters [10].

Some of the bird strike on helicopter cases which reported only cause minor damage, while some leads to fatality. In 2009, a Sikorsky UH-60M Blackhawk had involved in a collision with sUAV, where minor damage to the main rotor blade is reported [13]. In another case in 2009, a bird impacted a Sikorsky S-76C has penetrated the helicopter cockpit and caused the helicopter pilot to be disoriented, eventually makes them unable to recover from the loss of power and fall to the ground, which has killed all eight passengers, including a pilot on board [14].

Currently, EASA under Certification Specification for Large Rotorcraft (CS-29) require bird strike certification for helicopter design and construction, where the helicopter with weight more than 7,000 pounds (3,175 kg) has to be certified with 1.0 kg of bird strike at the maximum speed [15]. On the other hand, current FAA regulations developed more than 60 years ago require large aircraft windshield to be certified for bird strike with the impact of a 1.8 kg bird [16]. For helicopters that weigh above 7,000-pound (3,175 kg), the windshield must withstand a 2.2-pound (1.0 kg) bird to continue the safe flight. However, none bird strike safety regulations available for helicopters weight below than 7,000 pounds, which represent about 90% of all the US fleet, including tour, medical and police helicopters [16]. Around 45% of the bird strike reported were flocks of large birds followed by 31% of strikes from single large birds as depicted in Fig. 4. Large birds like geese, ducks, cormorants, hawks etc., have an average weight between 2.5 until 4.1 kg, which is bigger than required in certification. Aircraft airworthiness against bird strike is guaranteed by relevant regulations, however whether it is a viable for helicopter against the bird strike and sUAV collision is still unclear and need more investigations.

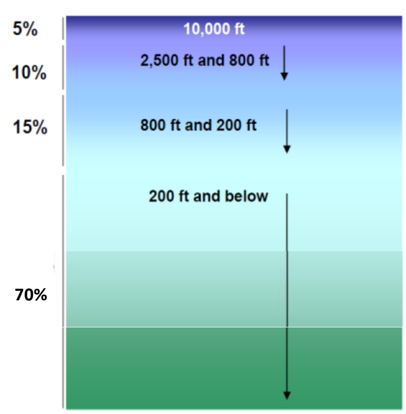


Fig. 1 Estimated percentage of bird strike per different altitude above ground level (AGL) [11, 17].

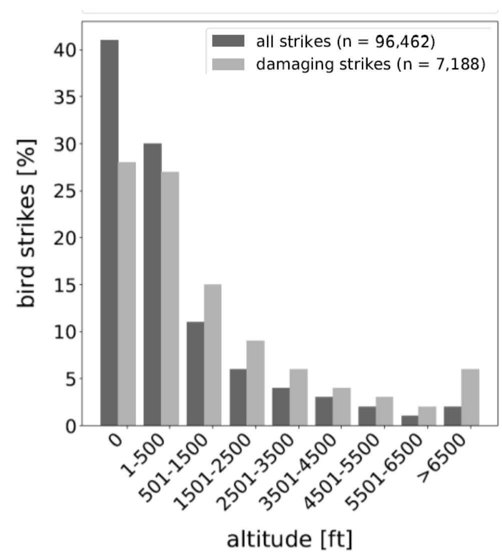


Fig. 2 Distribution of bird strikes by altitude (1990-2018) in the USA [17].

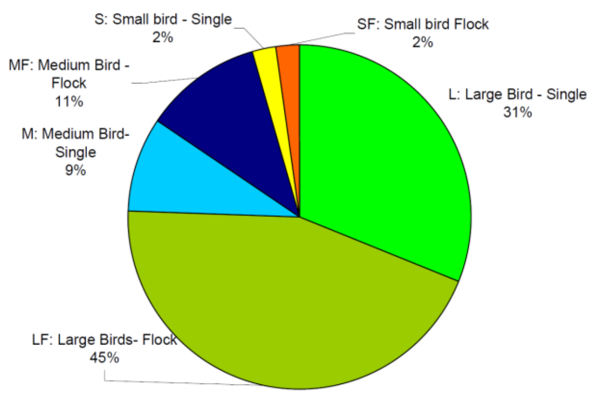


Fig. 3 Type of bird categories involved in helicopter bird strike incident reported worldwide (1998-2008) [10].

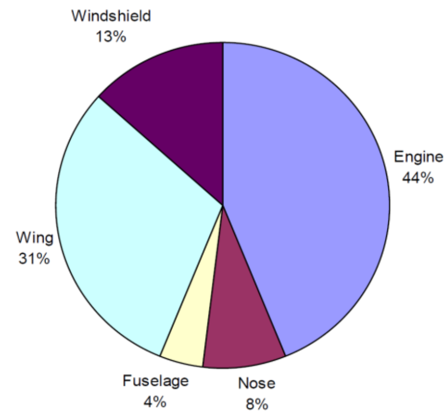


Fig. 4 Location of the aircraft which damaged from Bird Strike (1999-2008) [6].

Experimental work of drone strike on aircraft windshield has been investigated by CAAC [10], and simulation work for the same study has been conducted by Lu et. al [18]. Hedayati et. al [19] also performed bird strike simulation to identify the thickness of an aircraft windshield capable of withstanding the bird strike according to Part 29. Jonkheijm [5] has conducted a simulation of a drone strike on a helicopter windshield using the same methodology as Hedayati et. al [19] and reported windshield thickness at least 16 mm capable of withstanding 1.0 kg drone (DJI Phantom 3) impact as compared to 9 mm thickness for 1.0 kg to withstand bird strike. However, their study is limited to 1.0 kg drone size and therefore, this study intended to extend the simulation to understand damage severity caused by drone impact weight more than 3.0 kg. From this study, aviation airworthiness authorities have better insight on the limitation of current airworthiness, at the same time could provide information for aviation authorities to formulate regulations related to sUAV.

Safety Risk Management (SRM) is a strategy to identify risk in operation, where mitigation can be performed to minimized hazard or damage severity level if such risk is unavoidable. Risk criteria have been implemented for manned aircraft from available statistical data. Nevertheless, statistical data for drone operation is not yet available; therefore, two widely risk management approached can be used to control and regulate safety risks, the target Level of Safety (TLoS) approach and As-Low-As-Reasonably-Practical (ALARP) approach [20]. SRM frameworks required hazard identification, risk analysis and risk mitigation to ensure drone operation is within acceptable risk level. This study intended to analyse the risk of drone collision and investigate possible mitigation to minimize damage severity when the collision took place.

III. Simulation by FEM: Collision of Helicopter Windshield

To assess damage severity caused by the drone collision on helicopter compared to bird strike, series of FEM collision simulation has been performed. Outline of the FEM collision simulation methodology is according to the following:

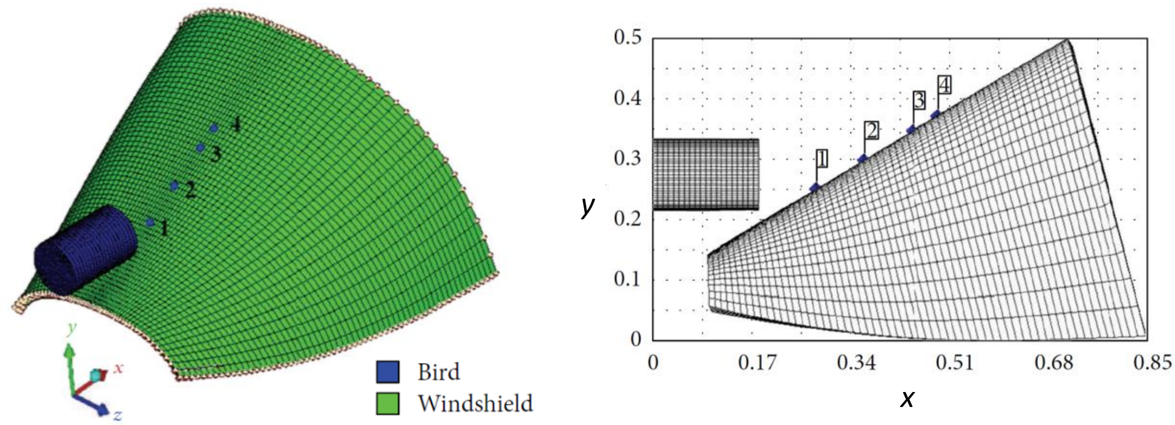
1. Firstly, is simulation of bird impact on aircraft windshield using SPH method to validate the material model of the windshield is capable to mimic actual damage and failure of the windshield. (Material: Acrylic/PMMA).
2. Secondly is to simulate bird strike and drone collision on helicopter windshield (different windshield thickness, windshield material type, and helicopter speed) using the data from the simulation in step 1.
3. Lastly, conclusions will be drawn from the simulation results in the second step by comparing windshield damage at different helicopter speeds, windshield material types, and thicknesses. Helicopter speed: 75 m/s, 80 m/s, and 85 m/s. Note that 80 m/s is cruising speed and 85 m/s is the maximum speed [21].

A. Validation of Windshield Material Model

Firstly, a simulation of bird impact on aircraft windshield using SPH method to validate the material model for Acrylic/PMMA of the windshield to mimic actual damage and failure of the windshield. The simulation results, include the displacement and the deformation of the aircraft windshield at two different impact speed of 64.4 m/s and 101.0 m/s, respectively.

Fig. 5 shows the assembly of bird and aircraft windshield for the collision simulation by the finite element method (FEM). The FEM tool is adopted to perform Dynamic/Explicit simulation using ABAQUS in this study. The aircraft windshield is made out of acrylic and using the material data as tabulated in Table 1, with a thickness of 16 mm [22]. The aircraft windshield is meshed using quadrilateral with S4R element type with a total number of 15,400 elements. Here, the element sizes for the windshield are 6.0 mm.

The SPH model of a bird in this simulation that has 8190 nodes with each node has lumped mass with a weight of 0.1221 g and positioned at an average distance of 5.5 mm between two adjacent nodes. In the FEM collision simulations, the aircraft windshield is fixed in all three axes along the edges, with the bird impacted at an initial velocity of 64.4 m/s and 101.0 m/s as the experimental work done by Li et al. [23] and Shuhua et al. [22], respectively. In the experiment by [15], the displacement measurement is taken at four locations at the aircraft windshield, as shown in Fig. 5(a) and Fig. 5(b).



(a) Assembly of bird-windshield [24] (*x*-axis is the direction of the impactor projectile)

(b) Side view of the simulation assembly (1, 2, 3, 4 are the points of measurement taken)

Fig. 5 Finite element model of bird impact on windshield [24].

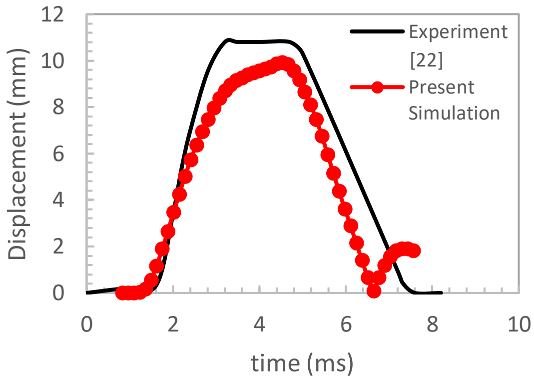
Table 1 Material properties for aircraft windshield

Material	**Density, ρ**	**Young's Modulus, E**	**Poisson's ratio, υ**	**Yield stress, σ_y**	**Failure strain, ε_f**
Acrylic [24]	1186 kg/m^3	3.2 GPa	0.40	78.0 MPa	0.067
Polycarbonate [25]	1190 kg/m^3	3.1 GPa	0.37	79.3 MPa	0.420

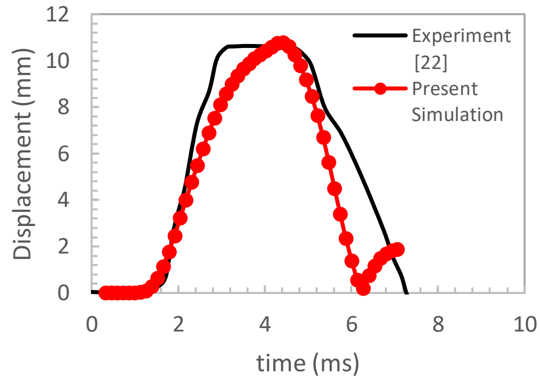
Table 2 Material properties for the simplified bird impactor [26]

Density, *ρ*	**Young's Modulus, E**	**Poisson's ratio, υ**	**Yield stress, σ_y**	**Failure stress, σ_f**	**Failure strain, ε_f**
968 kg/m^3	10.0 GPa	0.3	0.5 MPa	4.27 MPa	0.0122

The displacement of the aircraft windshield during impact was simulated by the software (see Fig. 6) at four positions and compared with the measurement from the experiment. In general, the displacement of the windshield is increased with the initiation of the impact and stable before gradually decreasing. The good correlation between the experimental and FEM simulation results also confirms that the SPH and its parameters used for the bird projectile in the simulation are appropriate.



(a) Location 1



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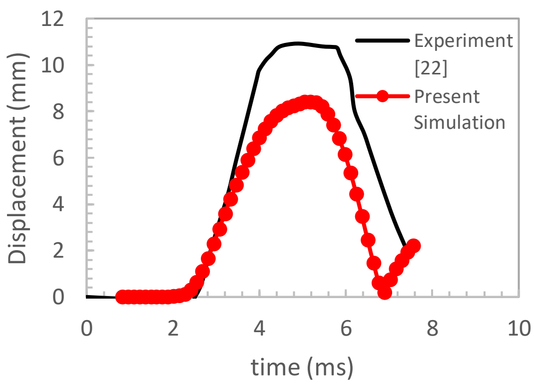
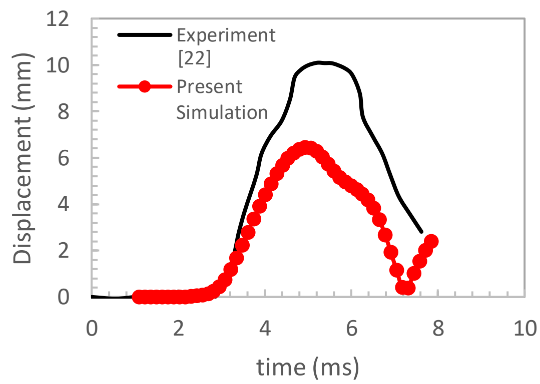


(c) Location 3

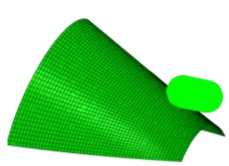
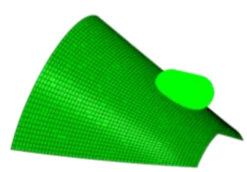
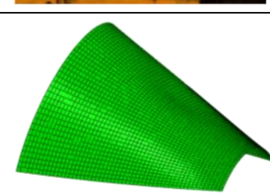
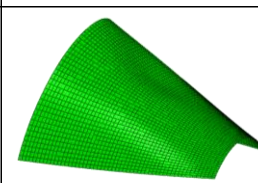


(d) Location 4

Fig. 6 Displacement versus time plots for various locations on aircraft windshield (Aircraft speed: 64.4 m/s) [24].

The deformation of the aircraft windshield during impact at the time, t=0 ms, 1.2 ms, 2.4 ms, and 3.6 ms are simulated by the software are shown in Table 3 and compared with the high-speed photographs from the experiment by Zhu et al. [22]. In general, the deformation of the windshield is increased with the initiation of the impact speed and moving backwards with the bird. The good correlation between the experimental and FEM simulation results also confirm that the elastic-plastic model and its parameters used for the aircraft windshield in the simulation can reflect the deformation of the bird after impacted very well.

Table 3 Comparison Experiment and Simulation (Aircraft Speed: 101 m/s)

Experiment [22]				
Present Simulation				
Time of impact	t = 0 ms	t = 1.2 ms	t = 2.4 ms	t = 3.6 ms

B. Simulation Setup of Bird Strike and Drone Collision on Helicopter Windshield

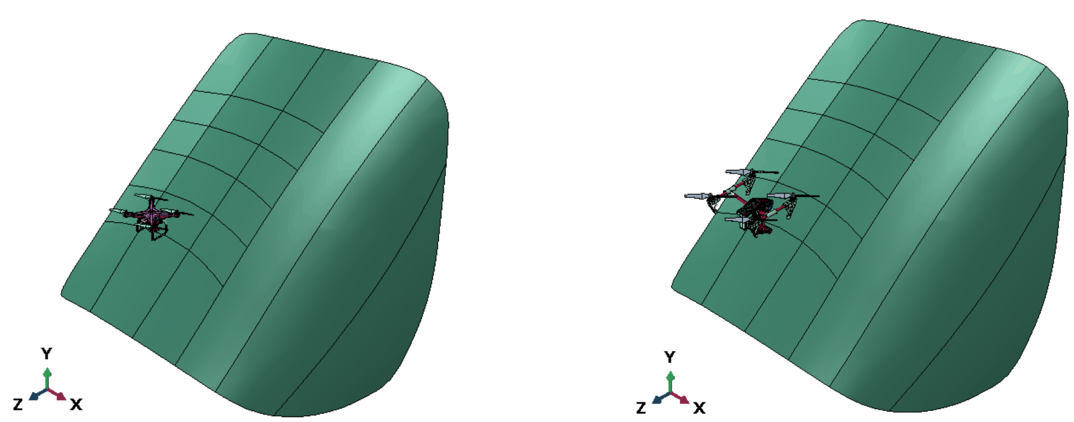
An accident report of a helicopter crash by AAIB [27] reported that A-109 windshield made from acrylic with a thickness of 3.81 mm is not certified under bird strike. Although the helicopter OEM later has improved their windshield by using Polycarbonate material and thickness of 5.0 mm [27], up to the author knowledge, no study has been conducted to investigate drone impact on the polycarbonate windshield. In this study, a FEM collision simulation is performed to investigate these two-windshield material type during the drone strike on helicopter windshield and compare it with the bird strike on helicopter windshield.

In the FEM simulation, two material of the helicopter windshield is considered, namely acrylic and polycarbonate with two different thickness of 3.81 mm and 5.0 mm, as shown in Table 4. Table 1 and Table 2 show the material properties defined in the FEM collision simulation for helicopter windshield and simplified bird impactor, respectively.

Two commercially available medium-sized and large-size drone (DJI Phantom 3 and DJI Inspire 1) with weight of 1.28 kg and 3.2 kg, respectively are chosen. Fig. 7 shows the assembly of drone (DJI Phantom 3 and DJI Inspire 1) and helicopter windshield in the FEM collision simulation. Moreover, a medium-sized and large-size simplified bird mode with the weight of 1.88 kg and 3.78 kg, respectively are chosen. Three helicopter forward speeds of 75 m/s, 80 m/s, and 85 m/s are taken into account due to most of bird strike cases reported is during en route where the helicopter flying at the highest forward speed.

Table 4 FEM Collision Simulation Parameters to Determine Damage Severity from Drone and Bird Impacted on the Helicopter Windshield

Categories	Size	Material	Windshield Thickness (mm)	Impact Speed (m/s)
Bird	Medium	Acrylic	3.81, 5.00	75.0
		Polycarbonate	5.00	75.0, 80.0, 85.0
	Large	Acrylic	3.81, 5.00	75.0
		Polycarbonate	5.00	75.0, 80.0, 85.0
Drone	Medium	Acrylic	3.81, 5.00	75.0
		Polycarbonate	5.00	75.0, 80.0, 85.0
	Large	Acrylic	3.81, 5.00	75.0
		Polycarbonate	5.00	75.0, 80.0, 85.0



(a) Assembly of Phantom 3 and Windshield.

(b) Assembly of Inspire 1 and Windshield.

Fig. 7 Finite element model of drone on helicopter windshield (only one windshield considered).

The drones (Inspire 1 [28] and Phantom 3 [29]) are made from different material types, respectively. Inspire 1 is meshed using the solid and shell with C3DR and S4R element type, respectively, with a total number of 250,400 elements. Here, the smallest element sizes for the windshield around the impact point is around 7.5 mm and increase gradually until reached the maximum element size around 20.0 mm around the edges. Here, the smallest of the element sizes for windshield is 6.0 mm and it increases gradually until they reached maximum element size of 20 mm - 30 mm around the windshield edges. The windshield is fixed in all translational directions and free rotation along the edges.

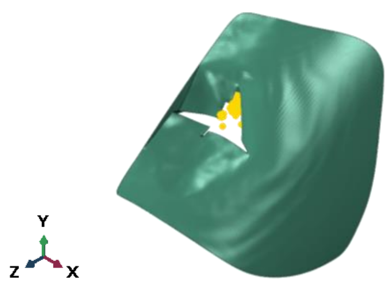
All drone parts are meshed as hexahedron with C3D8 element type except the thin-walled structures such as the main body is meshed as shell element type S4. Some minor components, such as the electronic bits, are treated as constraint masses attached to the main board of the UAV. The main body is meshed with a minimum element size of 0.75 mm and a maximum element size of 2.0 mm. The average element size of about 4.0~5.0 mm is adopted to mesh the other parts of the UAV, and the total element number for the UAV is about 104,928. The interaction behavior between the drone and engine is modeled as a general contact algorithm with a friction coefficient of 0.41 [30].

IV. Results and Discussions

In this section, the influence of helicopter forward speed, windshield material type and windshield thickness on the dynamic response and damage severity of the helicopter windshield will be presented.

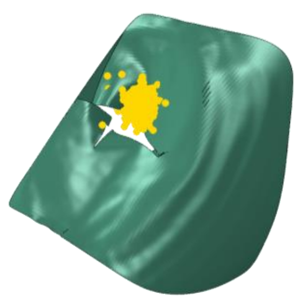
A. Effect of Different Helicopter Windshield Material Types and Thickness

The influence of windshield material type and windshield thickness on the helicopter windshield's dynamic response and damage severity level will be presented. As presented in Fig. 8, the fracture damage to helicopter windshield for the acrylic and polycarbonate windshield with the thickness of 3.81 mm and 5.00 mm, respectively, at an impact speed of 75 m/s.

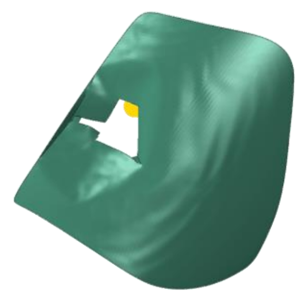


(a) Medium-sized bird: Acrylic 3.81 mm

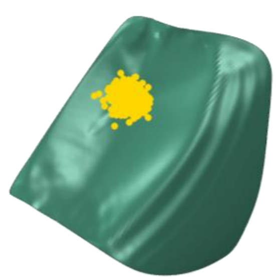
(b) Large-sized bird: Acrylic 3.81 mm



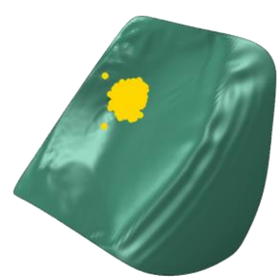
(c) Medium-sized bird: Acrylic 5.00 mm



(d) Large-sized bird: Acrylic 5.00 mm



(e) Medium-sized bird: Polycarbonate 5.00 mm

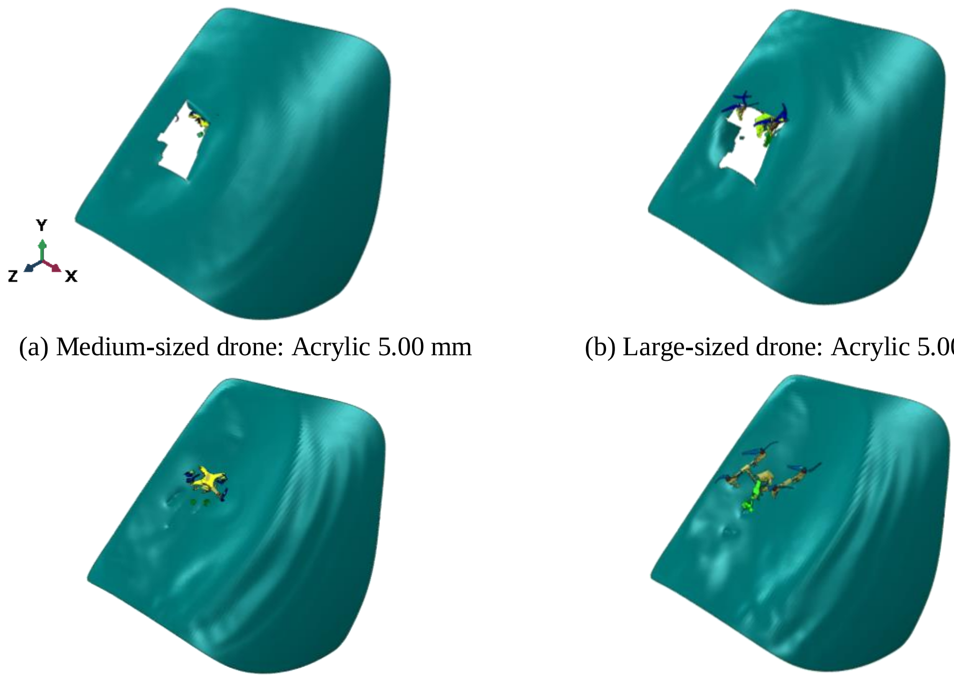


(f) Large-sized bird: Polycarbonate 5.00 mm

Fig. 8 Damage of helicopter windshield caused by the bird impact (bird speed: 75 m/s; Acrylic and Polycarbonate type).

The fracture damage to the 3.81 mm acrylic type windshield is slightly smaller compared to the 5.00 mm acrylic type windshield for both medium and large-sized bird. Furthermore, the polycarbonate type windshield shows the best impact resistance without any penetration damage compared to the acrylic type windshield for the same 5.00 mm thickness for both medium and large-sized bird at impact speed of 75m/s.

A drone has a denser and stiffer material compared to a bird, which one expected the drone's impact would result in more severe damage. As presented in Fig. 9, the fracture damage to helicopter windshield for the acrylic and polycarbonate windshield with a thickness of 5.00 mm at an impact speed of 75 m/s. The result shows clear penetration for the medium-sized and large-size drone into the helicopter cockpit as shown in Fig. 9(a) and Fig. 9(b) compared to the bird as depicted in Fig. 8(c) and Fig. 8(d), which dispersed after the penetration and dissipated the residual energy at a lower magnitude. After the penetration, such residual energy debris may result in severe damage injury to the crew and passengers on-board.



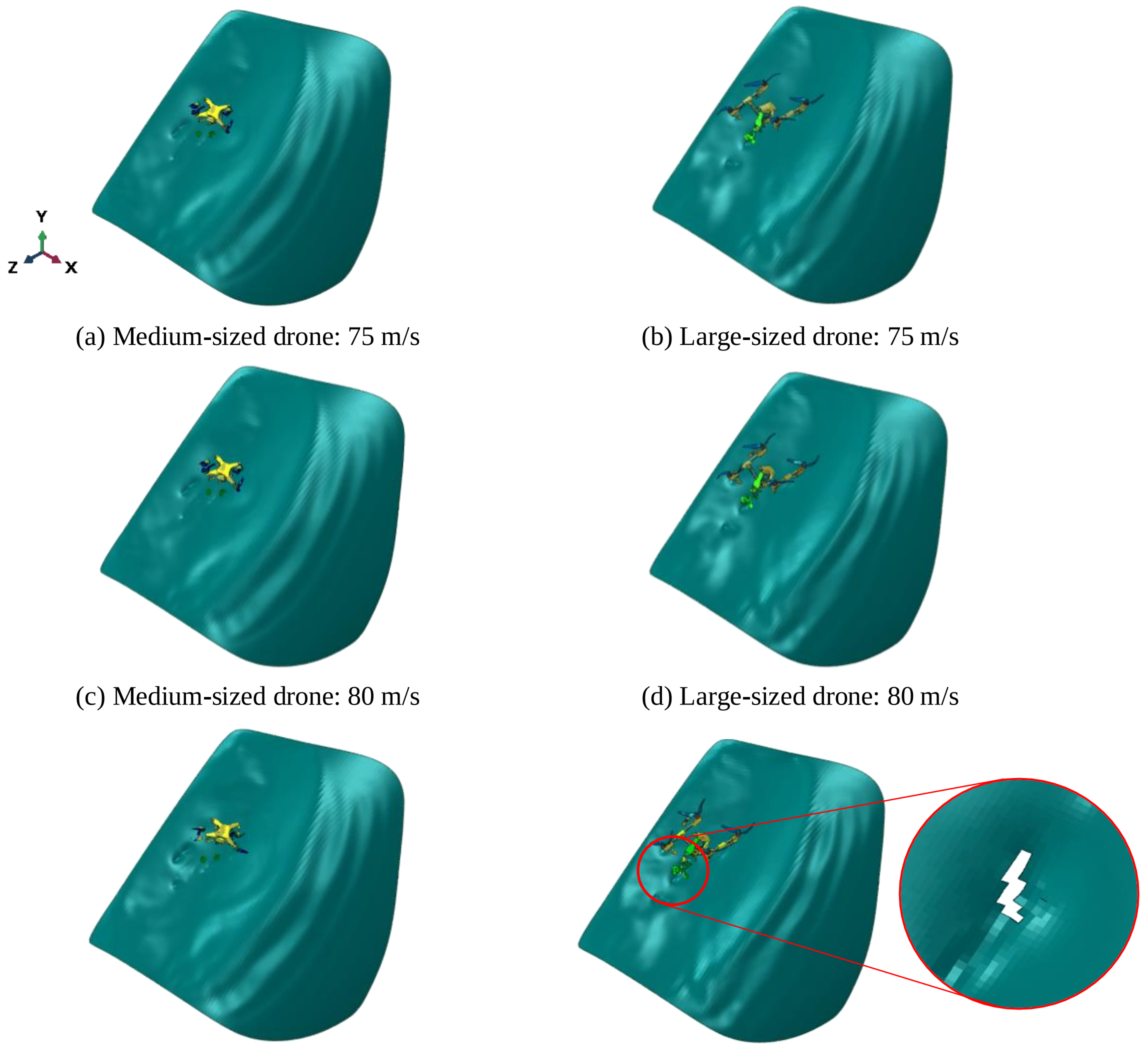
(a) Medium-sized drone: Acrylic 5.00 mm (b) Large-sized drone: Acrylic 5.00 mm

(c) Medium-sized drone: Polycarbonate 5.00 mm (d) Large-sized drone: Polycarbonate 5.00 mm

Fig. 9 Damage of helicopter windshield caused by the drone impact (drone speed: 75 m/s; Acrylic and Polycarbonate type).

B. Effect of Different Helicopter Forward Speed

As presented in Fig. 10, the damage to the polycarbonate type windshield 5.0 mm, respectively, for an impact speed of 75 m/s, 80 m/s, and 85 m/s. Similar to the impact from a medium-sized bird, the 5.00 mm polycarbonate type windshield shows good impact resistance from a medium-sized drone (approximately 1.28 kg) for all the impact speed of 75 m/s up to 85 m/s. In addition, the 5.00 mm polycarbonate type windshield under impact with a large-sized drone shows a similar trend with medium-sized drone for all speed except impact speed of 85 m/s, where fracture damage can be found as shown in Fig. 10(f) although no penetration is observed.



(a) Medium-sized drone: 75 m/s
(b) Large-sized drone: 75 m/s
(c) Medium-sized drone: 80 m/s
(d) Large-sized drone: 80 m/s
(e) Medium-sized drone: 85 m/s
(f) Large-sized drone: 85 m/s

Fig. 10 Damage of helicopter windshield (polycarbonate type windshield; drone speed: 75 m/s, 80 m/s, and 85 m/s).

V. Concluding Remarks

In our study, the dynamic response of the helicopter windshield under different impact parameters caused by collision with different drone weight categories, i.e., approximately 1.8 kg and 3.0 kg. It was found from the simulation that the 5.00 mm thickness polycarbonate type windshield provides better impact resistance compared to the acrylic type of windshield for an impact speed of 75 m/s up to 85 m/s. These results seemingly indicate the drone is still intact after impact onto the acrylic type of windshield and penetrated the helicopter cockpit, which might be resulting in serious injury to the crew and passengers on-board. Although, the polycarbonate shows better impact resistance than the acrylic type of windshield however it might still be vulnerable to the impact with a drone bigger than 3.0 kg.

It should also be noted that this study conclusion is obtained based on the preliminary numerical analyses. Therefore, experimental work can be performed to further validate the damage severity due to drone collision from this study better to understand the damage severity from the drone collision. Damage severity to the helicopter main rotor hub can be considered in the future as this hazard contributes to a lot of accidents due to bird strike. This study provides an insight into the damage severity from drone collision under current airworthiness, which aids the aviation authorities to formulate regulations for sUAVs. At the same time, the study could provide information to design the helicopter windshield for helicopter and eVTOL in the future.

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