Journal of Engineering and Applied Sciences 14 (19): 6971-6981, 2019
ISSN: 1816-949X

Numerical Analysis of Bird Strike Resistance of Helicopter Composite Rotor Blade

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Abstract: The rotor blade made with composite material should be designed to fully sustain the bird-strike. This analysis proved the structural integrity of the leading edge of the rotor blade made with composite material. To apply the analysis of bird-strike, the debris of the bird was assumed to be fluid and applied as a Euler element after the collision, since, there is a big difference among material property of the leading edge of the rotor blade, solidity and property of matter of bird-strike. The analysis showed that the design of the rotor blade pre-resistant structure had sufficient strength and safety factor for the impact of birds. The results of the bird-strike analysis of composite blade are assessed to be sufficiently reliable and may be evaluated to replace the test with various analysis conditions. Structural integrity of the rotor blade can be assessed by applying various load conditions different current modelling methods in the future.

Key words: Bird-strike, rotor blade, Euler element, composite bladem, solidity, structural integrity

INTRODUCTION

Aircrafts should be designed and manufactured to make safe flight and to survive in the environment easily disturbed by external factors such as bird-strikes. Bird-strikes threatening the security of aircrafts have continued for a century and now it has been a prerequisite step for aircraft development to verify stability for bird-strikes. To resolve this factor, many of aircraft manufacturer's attention is being directed to simulation technology in the field of product development.

As in Fig. 1, bird-strikes caused the malfunction of two engines that resulted in the emergency landing in Hudson River. Bird-strikes have been the cause of significant damage to aircraft and rotorcraft structures and the loss of life it has tried for stakeholders of many airports to reduce population of birds around the area in order to reduce accidents. In addition, aircraft manufacturers have been requested to conduct bird-strike test and design pre-resistant structure for the impact of bird-strikes.

In an effort to protect passengers and flight attendants from the impact of bird-strikes, the regulatory agencies including Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) announced regulation measures in helicopter functions which can resist in the impact of bird-strikes. For example, 14 CFR 29.631 of FAA regulation requires that rotary wing aircrafts have to be in A category (which is the most highly regarded safety certification standards of assuring continued flight in case of malfunctioning) which means that aircraft can safely fly and land after bird-strikes. However, getting such kind of certification for bird-strikes is time-consuming and expensive process, since, it is the only way to use actual parts for certification test to see, if

Fig. 1: Hudson River emergency landing, US airway (Anonymous, 2009)

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it can resist the impact of bird-strikes. And the certification tests commonly reiterated, since, the parts can be broken frequently and required replacement for each newly designed process.

One of studies from previous researchers (Georgiadis *et al*., 2008) conducted the experiment on model verification process and design efficiency for bird-strikes on trailing edge and (Yulong *et al*., 2008) conducted the experiment on the similarity rule of aircraft structure in accordance with the load of bird-strikes based on dimension analysis and similarity theory.

Guida *et al*. (2011) showed the accuracy of method of bird-strikes on solid target and compared to the results of bird-strike simulation. Heimbs (2011) researched detailed information on general summaries of bird-strike analysis, software, modeling methods, impact geometry, weight and velocity.

The study of Ivancevic and Smojver (2011) focused on damage modeling of composite parts of aircraft structure to propose the damage estimation step and proved the finite element model by copying the aircraft wing flap. Guo *et al*. (2012) applied Smoothed Particle Hydrodynamics (SPH) method to prove that the standard requirements for impact resistance of vertical wing cannot be met in case of collusion. Washburn *et al*. (2013) analyzed that 97% of the most frequent wild animals attack to aircrafts is from birds as a result of study on wild animal attack on the civil helicopters in the US.

Hu *et al*. (2016) developed the coupling model for Smoothed Particle Hydrodynamics (SPH) to access the outcome of structural cracks on cockpit of helicopters and proved it by an experiment. Heimbs *et al*. (2017) successfully showed the examples copying the resistance of searchlight and externally installed equipment on military helicopters.

In this analysis, theories of bird-strike analysis by Aribitray Lagranigian Eulerian (ALE) method to be reviewed and by copying the actual structure of composite material rotor blade to have actual bird-strikes on the leading edge of the blade and see, if there is a fracture on the structure confirm the failure index distribution in visual way. In addition, the strength applied by bird-strikes can be calculated based on the test value of bird-strikes on the different type of aircraft. By conducting precise bird-strikes simulation, it is able to save a lot of time and cost also, it allows the efficient and adequate design. As a result, it can be proved by one test after the bird-strike on the subject material.

MATERIALS AND METHODS

Theory

Hydrodynamic theory: To put it simply, it can be regarded that this bird-strikes is as an eruption of water which hit by the target subject. This can be divided into two steps, initial impact and steady stream. The early stage of Hugoniot pressure can be provided from the Eq. 1 and the stagnation pressure can be calculated by Bernoulli and Eq. 2:

$$\text{Hugonoit: } P_{shock} = \rho_0 v_{shock} v_{impact} \quad (1)$$

$$\text{Stagnation pressure: } P_{stagnation} = \frac{1}{2}\rho_0 v^2_{impact} \quad (2)$$

These two kinds of pressure are very important, since, Hugoniot pressure provides the maximum value for the impact and when the stream of impact stabilized, stagnation pressure provides the expected value. Also, it has to be reminded that the pressure is nothing to do with the size of projectile, since, the mass is not variable of pressure equation. As in Eq. 1, the density of birds perceived to be remain same regardless of its size and kinds and the Hugoniot pressure is decided based on the velocity of bird and aircraft. Bird-strikes can be divided into 4 progressive processes as in Fig. 2.

It is easy to calculate the required variable for calculating stagnation pressure. Whereas Hugoniot pressure can be varied by the velocity of bird and aircraft and the impact velocity itself can be varied by impact velocity. Bird-strikes can be divided into 4 progressive processes as in Fig. 2.

As in Fig. 2 shows the impact process of fluid on rigid body can be divided into 4 steps. To simplify the issue, the subject getting impact will be regarded as a rigid body and the behavior of it by impact pressure will be ignored. The solidity of birds will also be ignored and regarded as complete fluid with a shape of cylinder (D refers to Diameter, L refers to Length) and the fictional force on the impact surface will be ignored. Impact process, the early stage of compression wave generated and transferred to other direction. Releasing process, particles of bird-strike around the area released in all directions. Stagnation process, particles of bird-strike streams in fixed flow direction. Termination of impact, all particles of bird-strike reach to the surface of the target and pressure go down to “0”.

The shock wave on the contact surface of birds and structure at the early stage of bird-strikes. When the shock wave goes forward to the inside of the bird, the maximum shock pressure around the surface of shock wave created can be calculated by the law of conservation of mass and momentum and it can usuallycalled as Hugoniot pressure. After the creation of shock wave, it advances to the inside of the bird and along with that the release wave which created the free surface of the bird also goes into the center of the bird (Fig. 2). This release wave is reducing the shock wave, so that, the shock wave

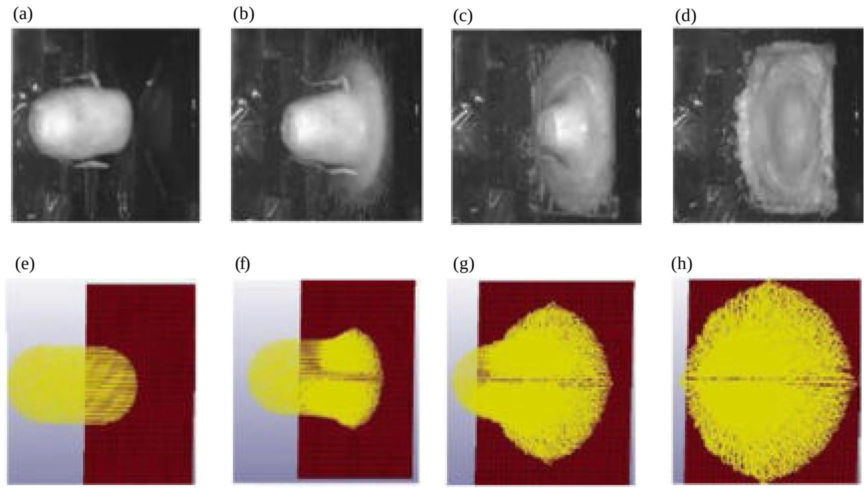

Fig. 2: a-d) Bird-strike progressive process (Bianchi)

instantly created and vanished at the early stage of bird-strike. After this kind of decreasing process, the impact process becomes the stagnation process. The creation of this stagnation process can be decided on the compared value of length for the diameter of cylinder inferred from the bird. Wilbeck showed that the critical value for compared value of length for the diameter of cylinder to have the stagnation process can be calculated based on the assumption that the fluid should be water (Guo *et al*., 2012). According to his result, the compared value of length is more than around 2, the stagnation process can be created in any pressure velocity.

During previous decreasing process, the release wave is getting weak and the shock velocity is also decreasing. In the impact on the subsonic speed, the shock wave is becoming weak and disappeared and after that the stagnation process is started. The pressure distribution can be measured by the experiment or calculated the approximately by applying the potential flow theory.

The entire time from the start of the impact and to its end will be regarded as the time to stream the length of the cylinder with impact velocity. The other useful information relating the bird as water is the state equation which applied to the relation with pressure and density of birds. Few equations are applicable and the most commonly applied equation is the polynomial expression as:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3,\ \mu = \rho/\rho_0 - 1 \quad (3)$$

The coefficient is early stage of density ρ_0, sound velocity on water and experiment invariable k.

Arbitrary Lagrangian Eulerian (ALE) method for bird modeling: One problem when modelling the bird as finite element is that the distortion of finite element due to large deflection of the bird is getting worse and as a result, the calculation will be possible afterwards. As a countermeasure of this problem, the rezoning method can be applied to create the adequate finite element again but it takes much time and efforts.

Recently, Lagranigin-Eulerain coupling method is commonly applied that movement of the bird analyzed by Euler element which can reflect large deflection without distortion of the element and the structure can be modelled utilizing previous finite element and finally analyze by relating two parts. In Euler algorithm, the element is fixed on the space and the substance streams between the elements, so, the distortion due to the large distortion cannot be created, Euler algorithm widely applied not only to analysis of the fluid behavior also to analysis of the solid behavior.

Therefore, studies on arbitrary Lagrangian-Eulerian method which combines the advantage of Euler and Lagrange algorithm on the bird-strike accompanying large distortion is actively conducted. Dytran is recently, developed the commercial program providing this algorithm. As stated above, the weight calculation by the bird-strike was the important analysis variables before but the definition of bird behavior is emerging subject of study at the moment.

The model of sequential progress of travel process of node by random time Lagrangian element shape function and advection process by Euler element can be applied to analysis Fluid Structure Interaction (FSI). As such, the reference area is required to facilitate the mesh for

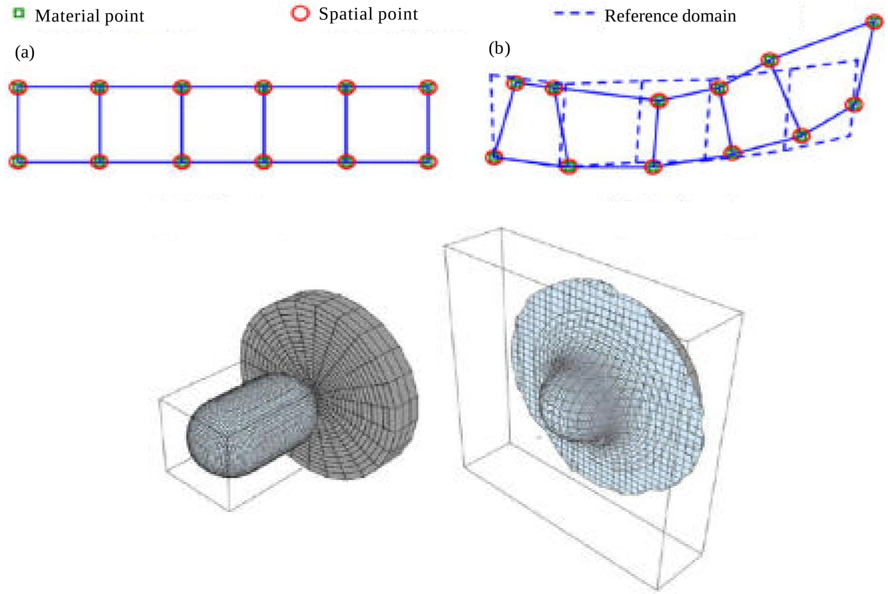

Fig. 3: Arbitrary Lagrangian Eulerian (ALE) method (Kim, 2016): a) At time t_1 and b) At time t_2

Table 1: FAR-bird-strike test requirements

Categories (Parts)	Requirements
23	The aircraft in commuter category has to sustain without penetration of 2.0 lb bird-strike on max approach flap speed
25	The aircraft has to sustain without penetration of 4.0 lb bird-strike on equivalent speed of cruising speed @ sea surface height
27	There is no requirement for bird-strike
29	Safe flight and landing have to be possible after 2.2 lb bird-strike of V_{ne} or V_h

calculation of each space and material area in relation with ealerian and Ladrangian method. As shown in Fig. 3, the reference area is independent from the material element and similar to the space area of Eulerian method. But it can move randomly with independent velocity w in space area. If the material velocity is v, ALE area will be Eulerian area when $w = 0$ and when $w = v \neq 0$ it will be Lagrangian area. In general, the material derivative function or the total time derivative function of linear unfunctional can be shown as Eq. 4:

$$\frac{df}{dt} = \frac{df}{dt}[D_h]\{L_h\}T = q^* \tag{4}$$

From Lagranigian perspective, the convection area will be disappeared, since, there is no relative velocity between mesh and material. But the material streams based on the fixed mesh from Eulerain perspective, the variable u in the convection area is replaced with material velocity v. In case of ALE equation, variable u is the relative velocity between material and mesh and same as v-w. Therefore, the differential governing equation has to be modified partly and reflect the random velocity on the reference area to apply ALE method.

In general, there are two types to calculate ALE equation. First, calculating ALE equation which completely combined. The weakness of this method is that it only allows to calculate for a single material from a single element. Second, dividing each calculation process into two consecutive status. By doing, so, Lagrangian process which material and mesh move together firstly, conducted and then calculate the result from mapping from Lagrangian and to reference area. This allows to simplify the calculation by diving fully combined ALE equation into two steps. So, it allows that Lagranigian and Eulerian steps are independently conducted. This algorithm is more efficient in general than calculating fully combined ALE equation. But it can be less accurate by dividing governing equation and it should be noted that most part of advection algorithm can ignore the rapid grade of result at the second step (Table 1).

Bird-strike requirement: With a growing importance of flight safety along with improvement of aircraft performance, the airworthiness which evaluate the safety factors in aircraft development, modification and operation stages is the stepping stone to ensure flight safety. To smoothly run businesses, it is required to identify and reflect risk factors at the early stage of development of aircraft. As in Fig. 1, the Federal Aviation Administration (FAA) is categorizing aircraft as FAR part 23/25/27/29 in order to adequately define the airworthiness requirements matrix per each aircraft types.

Table 2: FAR-bird-strike test requirements

Aircraft models	Development (Year)	Bird-strike verification
UH-1H	1959	X
BO-105	1967	X
UH-60	1974	X
AS365	1975	X
AW109C	1976	X
BK117	1979	X
S76C	1990	X
MD902	1992	X
EC135	1994	X
Bell430	1995	O
KA-50	1995	O
MI-28	1996	O
EC635	1998	X
EC155	1999	X
S76C++	2006	X
NH-90	2007	O
KA-52	2008	O
Bell429	2009	X

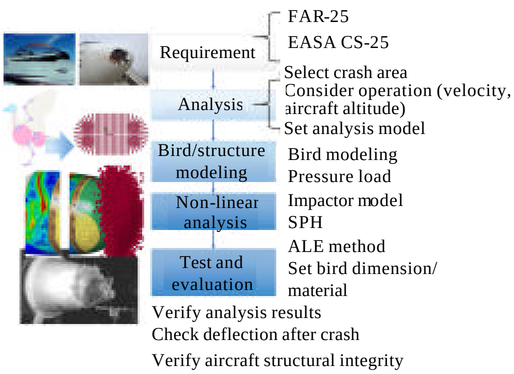

Fig. 4: Bird-strike analysis and test procedure

Table 2 shows the resistance of bird-strike on wind shield of helicopters which developed all around the world. There was no bird-strike requirement for helicopters developed prior to mid 1990's but it shows after mid 1990's. It can be inferred that there was a growing awareness of flight risk for bird-strike, since, bird-strike requirement stipulated on FAR in 1996 even it was only civil regulations. After 1996, helicopters, EC625 and Bell 429 certified part 27 which not stipulated the bird-strike requirement and EC155 certified part 29 but exempted from the bird-strike requirement.

Analysis procedure of the bird-strike analysis: Bird-strikes can have severe impact on the aircraft safety with flying high speed. In accordance with CFR25.571/JAR 25.631/FAR-25, EASA CS-25 or equivalent regulations it is required to secure structural integrity and modification of aircraft safety for bird-strikes on radome, external equipment such as wing structure of aircraft. General process of bird-strike analysis is in Fig. 4. It needs to set the requirement based on types of aircraft. Once the requirements are set, the area of bird-strikes and impact condition based on operation requirement. After that, modelling subject of design as finite element and input the applied weight and boundary condition. Since, it is nonlinear analysis it can take much more time for bird-strike analysis than linear analysis. Lastly, the structural integrity will be proved by setting off birds or equivalent gelatin to the developed target structure.

Table 3: Bird-strike condition

Object	Condition
Blade	
Type	Multi spar composite blade
Radius	R = 7.9 (m)
RPM	Ω = 272 (rpm)
Speed	v = 225 (m/sec)
Bird	
Weight	w = 2.2 (lbs)
Diameter	D = 3.5 (in)
Height	t = 7.0 (in)
Density	$\rho = 930$ (kg/m^3)
Bulk modulus	$E_{bulk} = 2.2e9$

FE modeling of the bird-strike analysis

Composite rotor blade configuration: The composite material blade structure can be divided into three configuration information, the upper and under cantilever which support centrifugal force, transition segment which rapidly changes form and lastly airfoil section. Figure 5 shows the cross section of composite material of blade based on designated position. To conduct two dimensional analysis, it consists of unidirectional spar, box, foam core and skin made of composite material. At the frontal part of box, the unidirectional glass fiber is deployed which can support primary load of blade. In case of skin, it can be possible to optimize the stacking sequence of composite material but the diameter is relatively thin. So, this will follow the general stacking procedure for production convenience.

Bird properties: There are many kinds of birds in nature and depends on its kind, the density and size can be varied. Chickens are generally, used for bird-strikes experiment which can be easily procured. The measurement of chicken density was conducted by multiple researchers. Especially, wilbeck was presented 900~950 kg/m^3 as its value. The 950 kg/m^3 of chicken density value is usually used for bird-strikes analysis.

Bird-strike analysis condition: The size, weight and density of the bird have to be set to conduct bird-strikes analysis. The collision position rotor blade has to be set also. The collision speed has to reflect the speed of helicopter and bird. The condition of bird-strikes is as in Table 3.

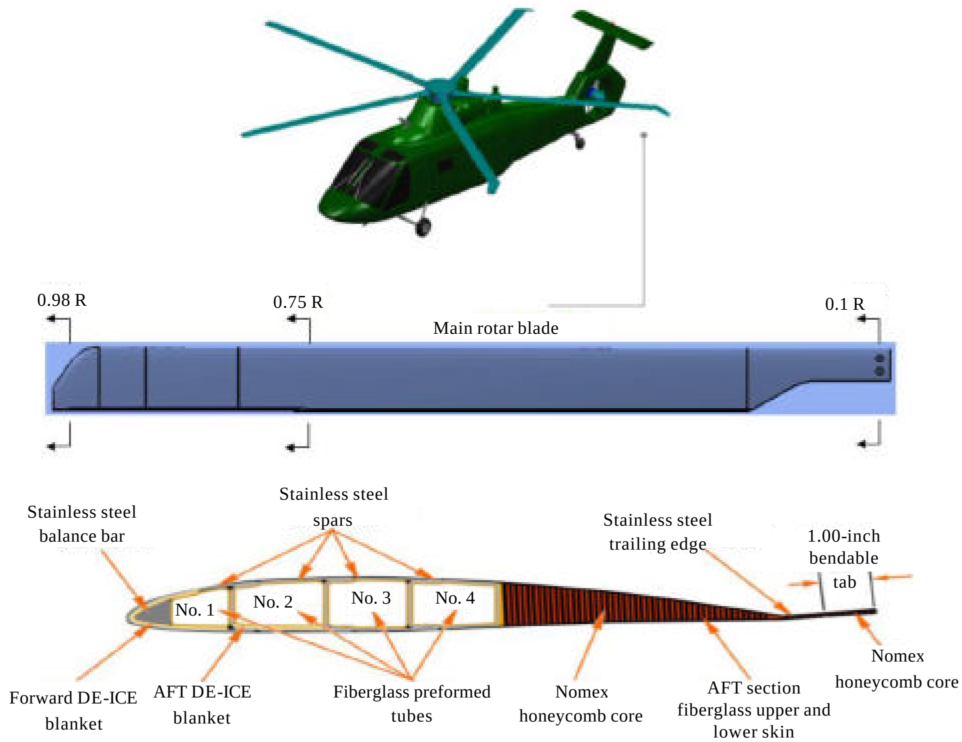

Fig. 5: Rotor blade configuration

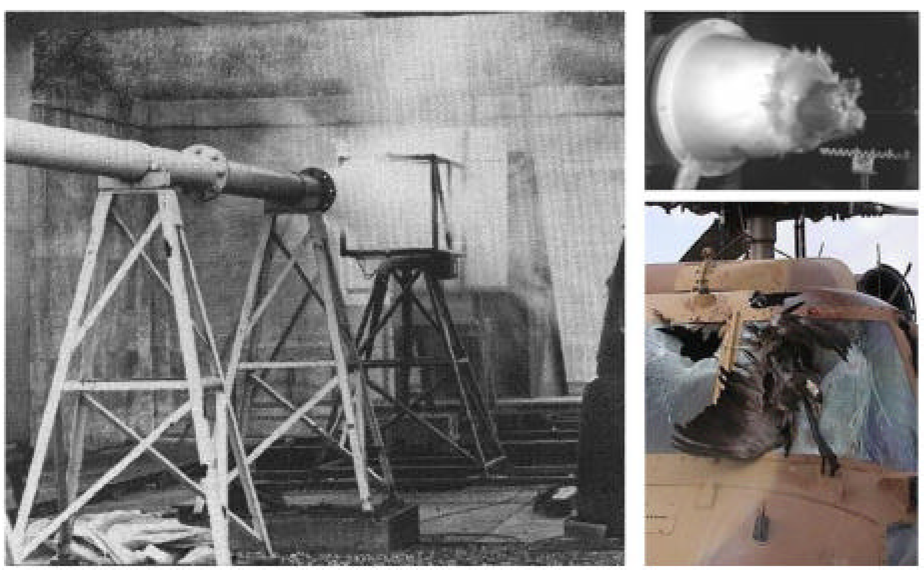

Fig. 6: Bird-strike test configuration

Bird-strikes is applied 2.2 lbs which stated on FAR 29.631. The configuration of bird is modeled as cylinder shape and applied bulk modulus to provide fluid ductility. The collision position is set between 0.75~0.98 R of entire blade as in Fig. 5 and 6.

FE modeling of the bird and composite rotor blade: The blade modelling to conduct bird-strikes analysis is as in Fig. 7 and 8. The blade consists of composite and metal materials and applied a property of matter of Table 2. Euler mesh is the area which bird stays as fluid after the

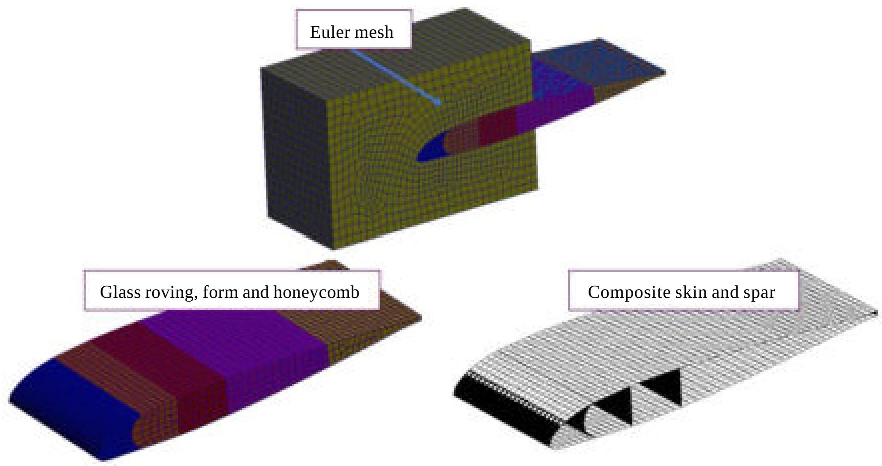

Fig. 7: Blade FE modeling

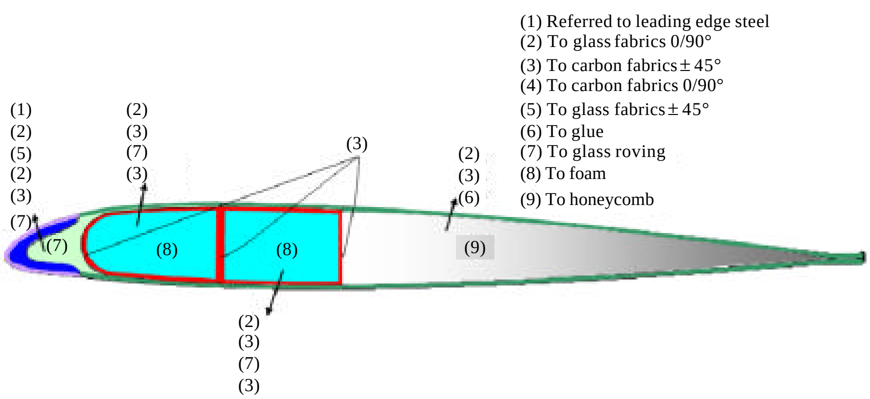

Fig. 8: Composite blade material distribution

collision on the blade. It is inconvenient to make grid for setting fluid area. One of characteristics of Lagrange-Euler analysis method, it can be possible to calculate fast, accurately and efficiently.

Bird-strike analysis results

Structure criteria of bird-strike analysis: Since, the blade made of composite material, the stability can be evaluated based on the failure criteria of composite material. The failure criteria can include Tsai-wu, Tsai-Hill, max. Stress and max. Strain.

In this analysis, the Tsai-Hill was facilitated which is considered as the most conservative criteria with consideration of the characteristics of aircraft structure. Tai-Hill is the criteria which is revising and improving Hill-criteria which designed for applying von-Mises criterion on anisotropic material. It is relatively the most conservative result among the lamina criteria, since, longitudinal and transverse stress was applied as quadratic interaction type:

$$\left(\frac{\sigma_L.SR}{\sigma_{LU}}\right)^2-\left(\frac{\sigma_L.SR}{\sigma_{LU}}\right)\left(\frac{\sigma_T.SR}{\sigma_{LU}}\right)+\left(\frac{\sigma_T.SR}{\sigma_{TU}}\right)^2+\left(\frac{\tau_L.SR}{\tau_{LU}}\right)^2<1 \quad (5)$$

$$M.S = SR\text{-}1>0$$

SR refers to Strength Ratio. The strength ratio when the result of Eq. 5 is 1, the margin of safety can be calculated. Figure 6 shows the analysis process of bird-strikes on composite material of blade. When the margin of safety from Eq. 6 is positive value, if can be decided whether the design can be applied.

RESULTS AND DISCUSSION

Bird-strike analysis results: Figure 9 shows the impact procedure of bird onto the blade. By conducting the experiment, the Euler area can be modified by measuring the area of bird's debris. The condition of experiment

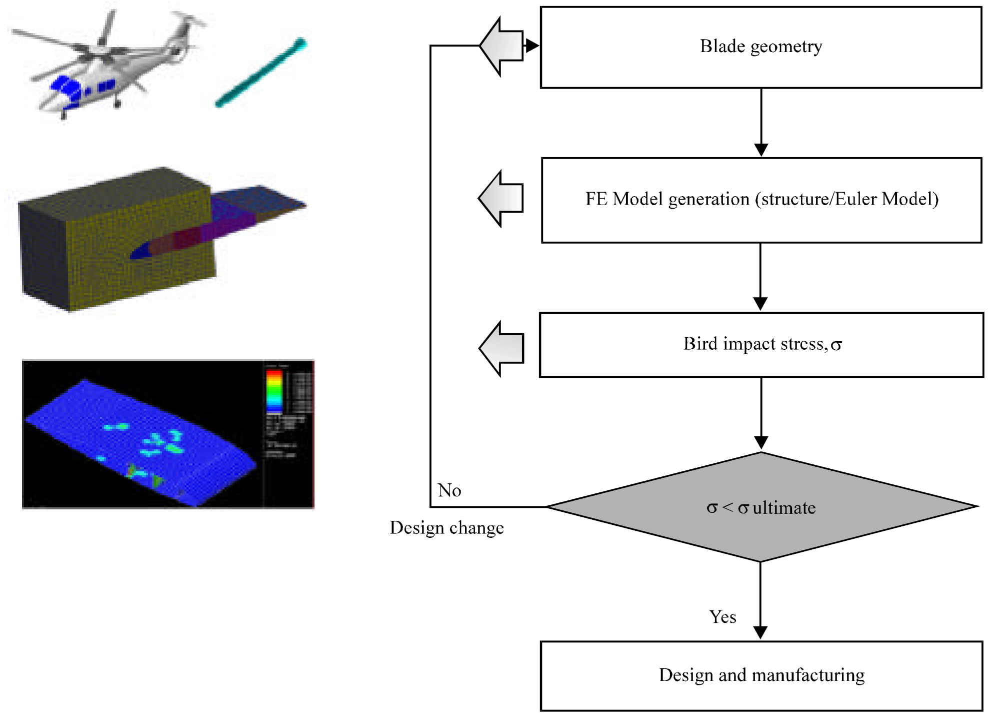

Fig. 9: Bird-strike numerical analysis procedure

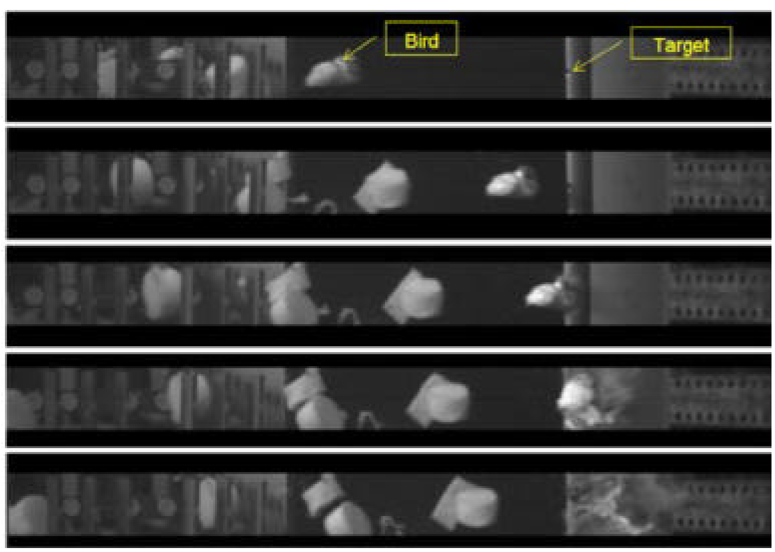

Fig. 10: Impact procedure of composite blade and bird (Eren *et al*., 2017)

presented that the end part is free area and the other part is fixed area. The result of experiment well shows from early impact by Hugonoit pressure through the stagnation process.

As in Fig. 10, bird-strikes experiment is conducted on the position where the maximum speed created on the blade radius. The rectangle area is the Euler area where birds are spreading as fluid after strike. The shape of bird model reflecting the result of previous studies was a capsule which shaped as cylinder connected with hemisphere on the front and back. The weight of bird was 2.2 lb.

The impact position of bird-strike is budging area of frontal part of blade and it was designed for bird to fly in parallel in order to minimize the impact of bird-striker and reduce loss of delivering energy. After bird-strikes,

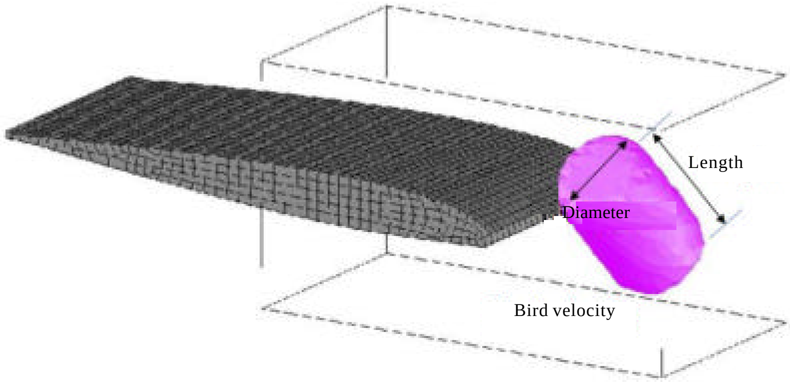

Fig. 11: Impact location of bird and composite blade

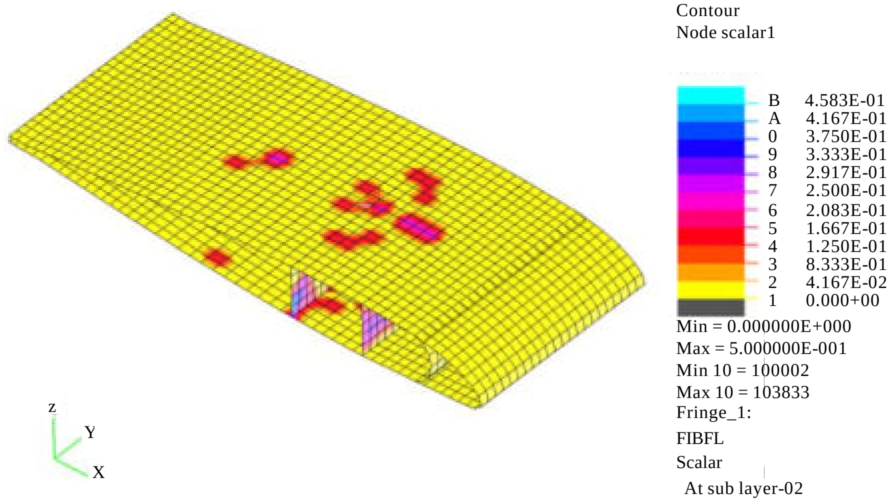

Fig. 12: Bird-strike analysis results with max failure index

Table 4: Analysis results in various conditions

Load case	Configuration	Length/Diameter	Velocity (m/sec)	Tsai-fill failure index	Margin of safety
1	Hemispherical	1	127.5	0.2505	2.99
2		2	127.5	0.1126	7.87
3		1	197.2	0.3617	1.76
4		2	197.2	0.2002	3.99
5		1	255.0	0.3726	1.68
6		2	255.0	0.4583	1.18

failure-index can be calculated with blade Eq. 5 which applying Tasi-Hill failure criteria designed based on composite material failure criteria failure-index is a reciprocal of strength ratio. As shown in Table 4, the analysis was performed by setting the speed and size of the bird as variables. As stated on Fig. 11 and 12, max failure-index calculated as in 0.4583. This failure-index is the strength ratio. The safety margin as 1.18 and it was accessed that the structure integrity had been secured (Fig. 11).

Bird-strike load calculation: In this paragraph, the data which conducted bird-strikes experiments on other types of blade was calculated with Eq. 6 in linear way. The impact of bird is in proportion to weight a square of speed and a square of impact time:

$$F_{Bird} = F_{Test} \cdot (m_{bird}/m_{test}) \times (\nu_{bird}/\nu_{test})^2 \times (t_{blade}/t_{test\ blade}) \quad (6)$$

In this equation, F_{test} is the weight of bird-strike conducted in the experiment previously, m_{bird} is the weight

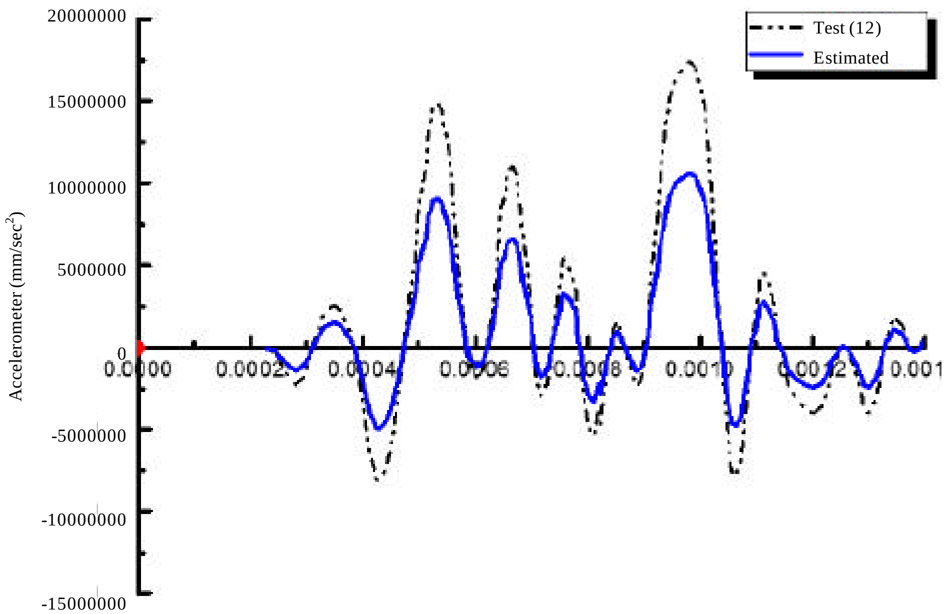

Fig. 13: Impact load estimate of composite blade and bird

of bird, m_{test} is the weight of bird conducted in the experiment, v_{bird} is the speed of bird, v_{tes} is the speed of bird conducted in the experiment, t_{blade} is blade profile thickness, t_{test} is blade profile thickness. Figure 13, the maximum strength measured by the experiment of Agusta Westland company was 1730 N. The weight of bird-strikes can be expected in linear way when applying Eq. 6. The impact on the blade was calculated as in 1060 N by Eq. 6. This impact result can be facilitated in the design process of fastener which adjusting the balancing of end part of rotor blade.

CONCLUSION

In this analysis, bird-strikes experimented on the leading edge of blade the copy of actual structure to see whether there is any facture in order to access the resistibility of bird-strike on the rotor blade made of composite material. And the failure index calculated and the failure index distribution could be visually confirmed.

The requirement for the structure of leading edge of blade made of composite material was not to allow the penetration of structure inside in case of bird-strikes. As a result of bird-strikes, it shows that designed structure of leading edge has sufficient strength and safety factor.

The results of the bird-strike analysis of composite blade are assessed to be sufficiently reliable and may be evaluated to replace the test with various analysis conditions. Structural stability of the rotor blade can be assessed by applying various load conditions, different current modelling methods in the future. This kind of analysis achieved the reduction of the cost and time for development allowing the optimum design of rotor blade prior to prototype test.

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