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Design and Analysis of Composite Sandwich Panel against Impact Loads for Airborne Radome

Prasanna Kumar K[1], Ilavarasu S[2], Mandeep Singh[3]& Maruthi Kumar[4]

[1]P G Scholar, The Oxford College of Engineering, Bengaluru.
prasannakmrk@gmail.com

[2]Scientist-F, Centre for Airborne Systems (CABS), DRDO, Bengaluru.
s.ilavarasu@gmail.com

[3]Scientist-D, Centre for Airborne Systems (CABS), DRDO, Bengaluru.
mandeepaero@gmail.com

[4]Asst. Prop., The Oxford College of Engineering, Bengaluru.
maruthi.auto18@gmail.com

ABSTRACT: Radome is a structural weatherproof enclosure or cover that protects radar system from environment. Radome should be designed in such a way, not to attenuate electromagnetic signals transmitted but also to have high mechanical strength against bird impact loads and aerodynamic loads.

Radome has designed for loads against impact with 4 lb bird. E-glass fiber laminates are used for skin and aramid honeycomb is used as core material. The core and face sheet thickness are decided based on the EM performance and Structural Strength point of view. Hyper mesh, LS-Dyna and CST Microwave software are used for analysis. Face sheets are represented by shell elements where as solid elements are used for core representation. Orthotropic material model and equivalent material properties are used for simulation. Bonding between laminates and core is achieved using modelling a layer of film adhesive with penalty based tie-break contacts. Smooth particle hydrodynamics (SPH) approach is used for bird model (4-pound bird with 150 m/s velocity). Hashin failure criteria was used for explicit dynamic (Bird Strike Simulation) FE Analysis. The bird fails to penetrate through the sandwich composite specimen. The EM performance of Radome is simulated using CST Microwave software and the same are measured experimentally in the Planar near field measurement facility (PNFM).

Keywords: Radome, Antenna, SPH, Bird Strike, Impact Analysis, EM Performance.

1. INTRODUCTION

Aeronautical structures always fly with a risk of impact by the foreign objects generally known as bird strike, mostly during takeoff and landing. The impacts may cause a small damage to structure or can lead to a catastrophic failure based on the intensity of energy transferred during impact. According to a survey bird strike alone will account for a loss of $1.2 billion to aircraft industry worldwide. The International Civil Aviation Organization (ICAO) reported 65139 bird strikes during 2011-14. Federal Aviation Authority (FAA) counted 177269 strikes between 1990 & 2015, growing 38% in last seven years from 2009 to 2015. As per FAA 61% of strikes occur below 30meters and only 8% of strikes happen above 900m.

A Radome as an airborne structural component can be made with class of materials of interest for bird strike but these materials should allow electromagnetic radiations without any attenuation. Always a healthy competition exists between mechanical and electrical performances; concession depends on the application area and operating environment. In the stealth technology, the radar performances are very important in order to be the superior. The performance of radar system is directly influenced by the radome design [2]. The low power, high performance radars functioning today are sensitive to specious signals and side-lobe reflections. Repair or damage to radome directly affects the radar resolution and efficiency. Hence, the radome is designed to meet both the mechanical and the electrical requirements [3]. In fact, a little addition of filler material or paint of thickness 12 to 15 mil will change the performance of radar system and reduces the radar system signal efficiency. It is important that FAA advisory circular 43-14 states “all repairs to a Radome, no matter how minor, must return the Radome to its original or properly altered condition, both electrically and structurally”. The purpose can be best served by non-metallic components. The non-metallic components must withstand the high aerodynamic loads and bird impacts. Composites are the best category of materials to fulfill the above needs, since the use of composites is likely increasing in aeronautical industry.

2. DESIGN AND ANALYSIS

The design phase involves the finalization of material, thickness, manufacturing process, no. of laminates and orientation of laminates. The factors that influence the selection of materials are mechanical properties and EM performances. The dielectric constant and loss tangent of the material have direct influence on EM characterization. Material with low dielectric constant will result a good EM performance [6]. Since we are designing an airborne quality, mechanical properties also play a vital role.

Radar system is a dual band operating system; it is decided to design a sandwich structure of A-type as per MIL standards [12]. Sandwiching of a low di-electric core between two high dielectric laminates. A Specimen of 1m × 1m flat panel is considered for the simulation and analysis. Radar system housings are generally meant to transfer radiating signals, non-metallic will be the best choice. Since composites will serve both mechanical and electro-magnetic means, they are chosen as materials. Structure's primary requirement is to withstand the impact loads, carbon, glass, aramid and quartz were the option to choose. Carbon is eliminated due to its conducting nature. Even though aramid & quartz have low dielectric constant and good impact strength, E-Glass is chosen as fiber laminate for reinforcement. The high moisture absorption property of aramid & quartz limits their use over E- Glass [2] [6]. The moisture pickup may increase the impact strength but reduces the mechanical properties hence aramid and quartz are not chosen as materials for radome. Mechanical and Electrical properties of reinforcement materials are given in table 1.

Reinforcement material	**Tensile Modulus, GPa**	**Tensile strength, Mpa**	**Dielectric constant, (ε_r)**	**Loss tangent (δ dB)**	**Moisture absorption, %**
Carbon	160	2750	NA	NA	2.0 - 2.5%
Aramid	41	560	4.1	0.019	1.9 - 4%
E-glass	36	450	4.2	0.015	1.2 - 2%
Quartz	29	720	3.6	0.017	1.2 - 1.6%

Table 1: Mechanical and Electrical properties of reinforcement materials.

The thermoset resins are the best suitable for the radome fabrication. Polyester, epoxy and vinyl ester are the resins, which are being mostly used in the industry. Availability, cost, fabrication easiness and their mechanical and electrical properties made them to consider for the radome fabrication. Epoxy is chosen as a matrix material for the reinforcement of E-glass fiber since epoxy is widely used as radome material [7]. The mechanical properties of epoxy are comparatively better than the polyester; low dielectric constant of epoxy is an added advantage for selection. The E-glass/epoxy prepregs are used in the fabrication of the radome. Mechanical and Electrical properties of Resins are given in table 2.

Resin	**Tensile Strength, MPa**	**Tensile Modulus, GPa**	**Compression Strength, MPa**	**Flexural Strength, MPa**	**Di-electric Constant, (εr)**
Polyester	40-85	1.3-4.5	140-410	205-690	4.0-4.5
Epoxy	40-85	2.1-5.5	150-825	1000-1500	2.6-3.4

Table 2: Mechanical and Electrical properties of Resins.

The strength to weight ratio of a sandwiched composite is always more because of the core. Various types of foams and honeycomb structures are used as core materials. Rohacell (PMI foam), PVC foam, Clocell foam, Plessey foam and Nomex honeycomb are available for the radome fabrication [2]. All foam and honeycomb materials are having good strength to weight ratio, selection is done based on the application, strength requirements, electrical properties and moisture absorption property. Aramid Honeycomb is having good mechanical properties and low dielectric constant. Honeycombs are susceptible to moisture pickup; hence, they are used with a moisture protection layer during fabrication when chosen as core material for radome.

The EM simulations are carried out to find out the thickness of core and skin, which will match better with the free space impedance of 377Ω resulting in an ideal transmission. Based on EM simulation results, for A-type sandwich the skin thickness is finalized to 1.5mm, core thickness is considered to be 25 mm. A specimen of A-sandwich is manufactured, with reticulation process. E-Glass (BD Fabric of 260 gsm) prepregs are stacked in an order [0, +45, 90, -45] for both top and bottom skin. Nomex honeycomb with cell size ⅛" and density 80Kg\m^3 is used as core material. 6 plies of 0.25mm thick are used for skin laminate in A-sandwich. Vacuum bagging at 3bar pressure for 15 min and autoclave curing at 180ºc for 4hours is followed during fabrication process [8]. The fabricated specimen is used experimentally to measure the antenna patterns in the planar near field chamber. The material allowable and material properties used are tabulated in table 3.

Material	P (kg/m3)	Ex (Gpa)	Ey (Gpa)	Ez (Gpa)	Gxy (Gpa)	Gyz (Gpa)	Gzx (Gpa)	μxy	μyz	μzx
GFRP	2200	20	20	2	3	0.8	0.8	0.12	0.04	0.04
Nomex HC	80	0.0004	0.0004	0.0039	0.00093	0.00093	0.00186	0.05	0	0

Table 2: Material Properties for Impact Test.

FE Model was created using Hyper mesh, shell elements are used to define the skin and solid elements are used to represent core. The constrains are in all Translational (Ux, Uy and Uz) and all rotational (Rx, Ry and Rz) degrees of freedom. The impact analysis is carried out using LS Dyna. Smooth Particle Hydrodynamics (SPH) method is used to model the bird for impact analysis, in conjunction with the certification standard required by the FAA [11]. The properties of bird used for impact was tabulated in table 4.

Sl No	Parameters Governing the Impact Response of Bird Strike	Assumptions or Values Chosen
1	Bird Mass	1.82 Kg
2	Bird Geometry	Cylindrical Shape
3	Bird Density	938.5 kg/ m^3
4	Bird material	Hydrodynamic fluid

Table 3: Properties of Bird.

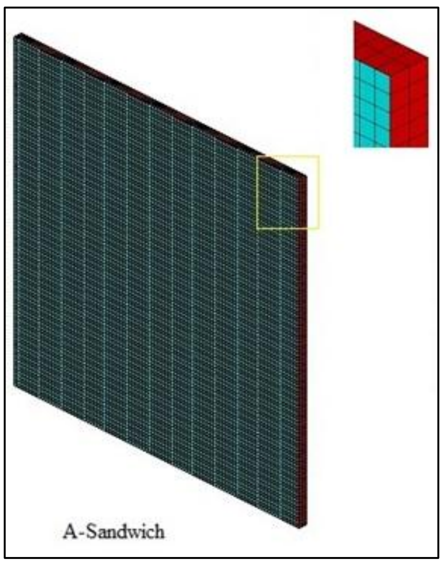

Fig 1: FE model of A-Sandwich Specimen.

LS DYNA material model "MAT_126" [13] is used to describe the honeycomb material properties for impact analysis. The honeycomb allowables are taken from open source. "MAT_058, Mat Laminated Composite Fabric" [13] is used for GFRP skin. This model uses Hashin's failure initiation criterion and accounts for the following modes: fiber rupture in tension, fiber buckling or kinking in compression, matrix cracking under transverse tension and shearing, matrix crushing under transverse compression and shearing. To model the bonding between the Bird and Face sheets a penalty based Automatic Node To Surface [14] contact interface is defined. To model the bonding between the core and Face sheets a penalty based Automatic Surface To Surface Tiebreak [14]. Contact interface is defined. The contact tiebreak allowable (interface layer shear and normal strength) are taken from open literature. As per FAR25, the impact of bird to the specimen was simulated at a speed of 150m/s.

Transmissivity and reflectivity of A-type sandwich specimen is simulated in EM Simulation tools (CST). Analysis is carried out by imposing periodic boundary conditions there by assuming as an infinite sheet, hence refraction and multi path effects are nullified [3] [10]. The experimental validation of the specimens is carried out at Planar Near Field Measurement (PNFM) chamber.

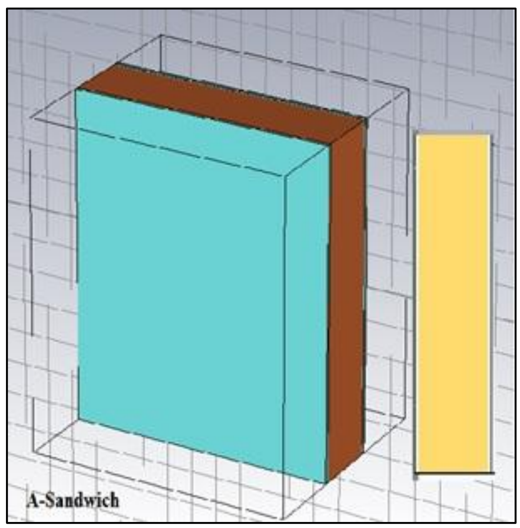

Fig 2: A-Sandwich Specimen subjected to EM Simulation.

3. RESULTS AND DISCUSSION

The EM simulations carried out to find the optimal thickness of core and skin that will match better with the free space impedance. Better performance will be achieved with a core thickness of 20mm and skin thickness of 0.25mm. The results may be acceptable from electrical point but it will not take the aerodynamic and impact loads. Hence, we need to select thickness in such a way that, it has to withstand aerodynamic loads and impact loads with minimum deviation from the ideal EM performances.

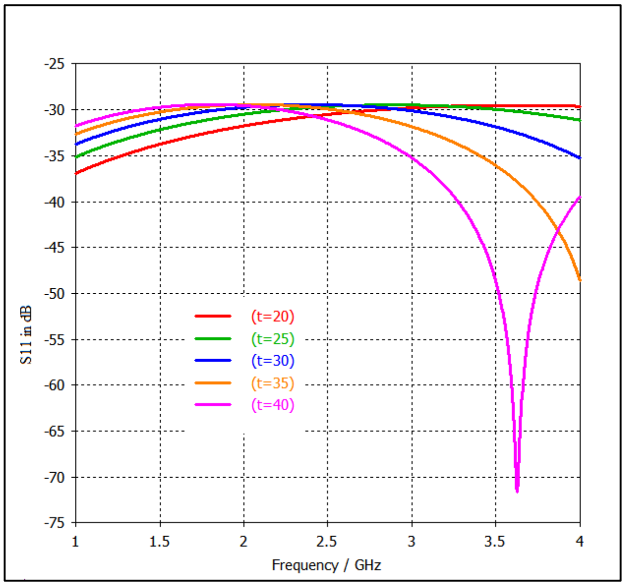

Fig 3: Core Thickness Study on EM Performance.

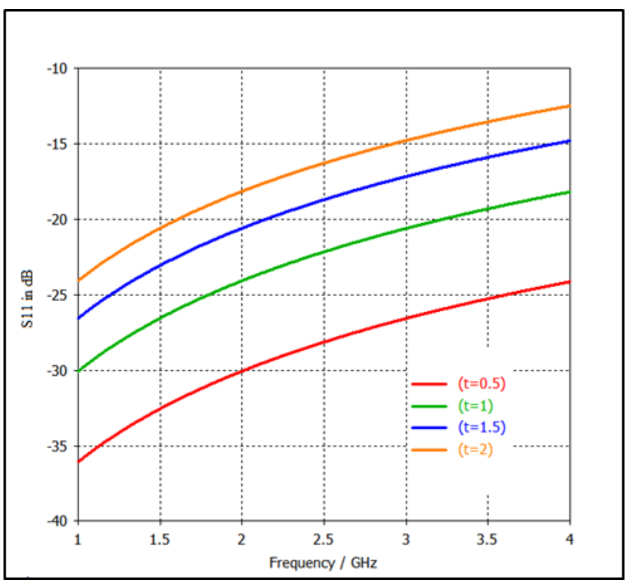

Fig 4: Skin Thickness Study on EM Performance.

3.1 Bird Impact Results

A-type sandwich specimen with a skin thickness of 1.5mm and a core thickness of 25mm simulated against an impact at a speed of 150m/s.

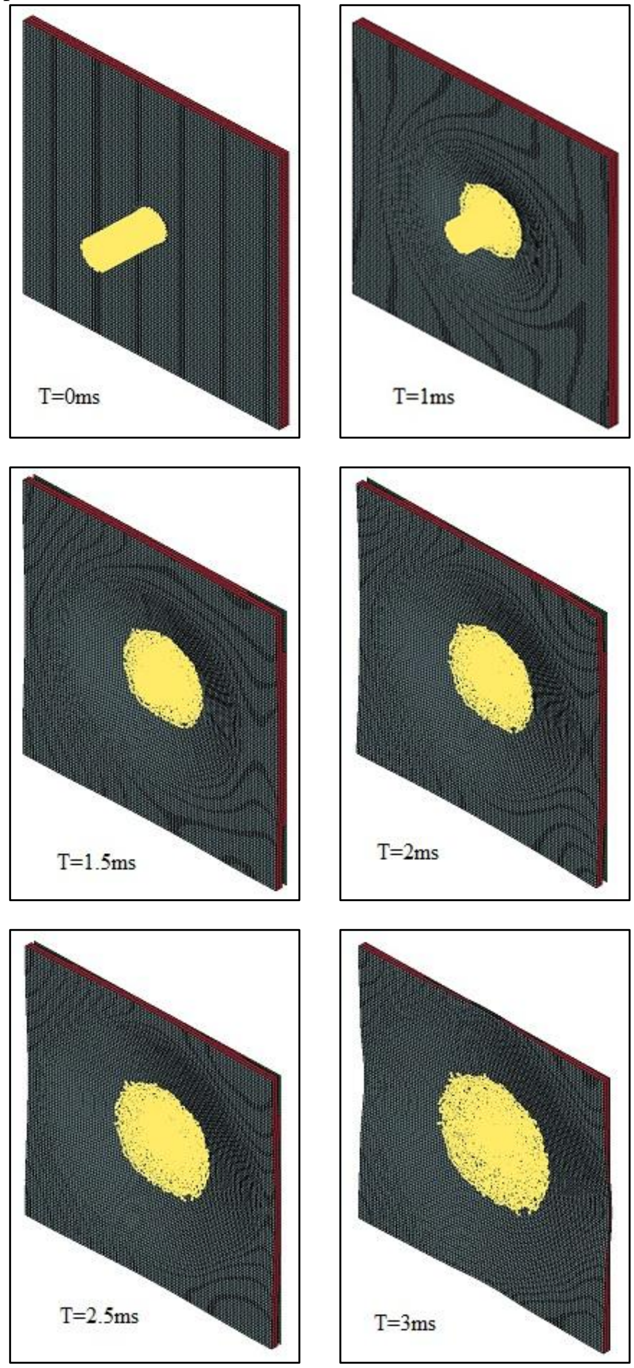

Fig 5: Bird Impact on A-Type Sandwich Specimen at different Time Intervals.

The duration of impact is calculated using the squash time formula, the ratio of length to velocity of bird. The bird is formulated with a diameter of 0.112m and a length of 0.224m [1] [4]. The squash time of bird is, $T = \frac{L}{V}$= 1.49 mili seconds. The kinetic energy transferred to the sandwich panels during the impact of 4lb bird at a speed of 150m/s is given by

$$\mathrm{K.E} = \frac{1}{2}\mathrm{mv}^2$$

$$= \frac{1}{2}*1.82*150^2$$

$$= 20475 \text{ J.}$$

The calculated impact duration is 1.49 mili seconds but the time taken by the bird to completely disintegrate by the simulation is 2.4 mili seconds, given by the bird velocity plot. This is because the projectile or bird slows down during the impact [5]. The different stages of the bird impact on A-Sandwich specimen is given in Fig 5.

At T=0 mili seconds, there is just a contact between bird and specimen. As the bird impacted on to the target surface, the front surface particles of bird are brought to rest immediately. This creates a high pressure at the bird/target interface leading to generation of shock wave. The pressure at the interface is given by the equation 1[1] [9].

$$P = \rho_o c_o V_o \qquad (1)$$

Where, ρ_o is bird density, c_o is shock wave velocity and V_o is initial bird velocity.The shock wave created by the initial impact of bird will travel back in the direction of length of the bird. The particles present adjacent are brought to rest. Shocked region behind the wave are subjected to high magnitude pressures, this pressure is called as Hugoniot pressure given by equation 2 [9].

$$P = \rho_p V_{sp} V_o \left[\frac{\rho_T V_{ST}}{\rho_p V_{sp} + \rho_T V_{ST}}\right] \qquad (2)$$

Where, ρ_p is bird density, V_{SP} is shock wave velocity of bird, V_o is initial velocity of bird, ρ_T is density of target, V_{ST} is shock wave velocity of target. This stage is represented by T=1ms.

In Fig 5, the steady state condition can be represented when time T=1.5ms and T=2ms. At this stage, Bird particles start accelerating radially outward forming a release wave due to the high-pressure gradient. The radial pressure present in the bird is relieved by the release wave. Many reflections of the release wave lead to an establishment of steady state condition. The stagnation pressure during the steady state is given by equation 3 [1] [9].

$$P = k\rho_o V_o^2 \qquad (3)$$

Where, ρ_o is bird density, V_o is initial velocity of bird and k=0.5 for incompressible fluid. At time T=2.5ms, pressure decay takes place. This is the last stage of impact process. The termination takes place at the end of this process. When the particles velocity is completely radial then the pressure decays completely leading to the end of impact process. This process is represented by T=2.5ms and T=3ms.

Fig 6 shows the velocity plot of bird for A-Sandwich panel. The bird velocity is gradually decreasing and approaches to zero at 2.4 mili seconds. All the energy of the bird is transferred to the target panels at a time duration of 2.4 mili seconds.

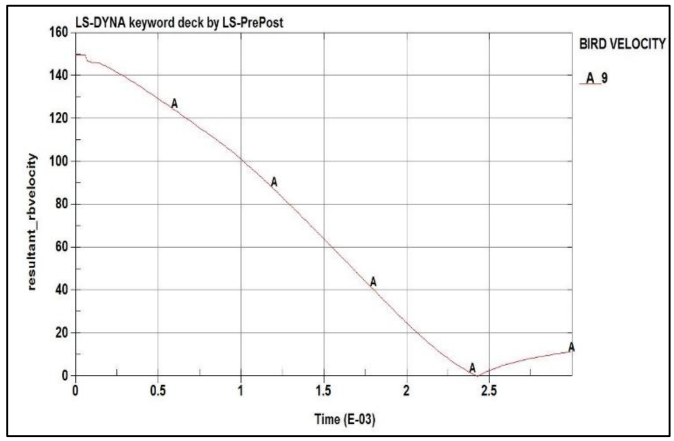

Fig 6: Bird velocity during impact of A-Sandwich Panel.

Fig 7 shows the Kinetic Energy plot of bird. Theoretically during impact all the kinetic energy of the bird is transformed to the target specimen. The deformation of the specimen will absorb all the kinetic energy of bird. If the specimen is not designed to take energy by deformation, then the energy will be utilized to fracture the specimen thus satisfies the conservation of energy [1]. In actual practice, all the kinetic energy of bird is not completely transferred to the target specimen, some of the energy is converted in the form of sound and heat [5].

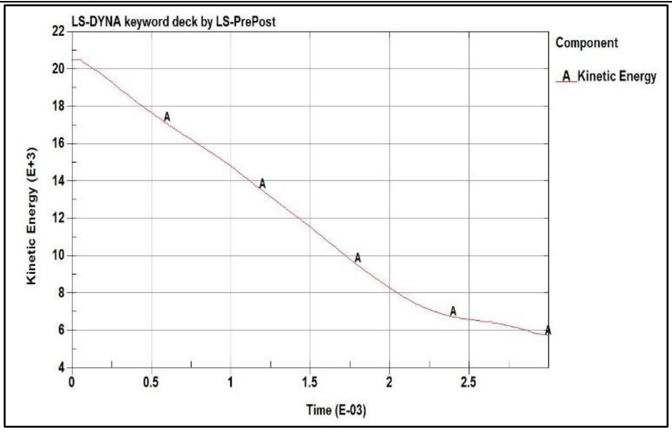

Fig 7: Kinetic Energy of the bird for A-Sandwich Panel.

Fig 8 represents the total energy and hourglass energy present in A-Sandwich panel. The hourglass energy for the system constitutes the distortion energy. If the distortion energy of particles of the system is more than the particles wont deform properly leading to a failure. Hence, for a system the hourglass energy should be low [14]. For A-Sandwich panel the hourglass energy is very low compare to the total energy present in the system.

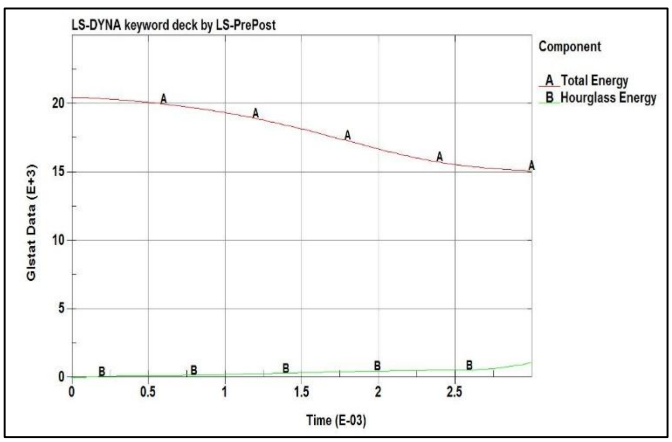

Fig 8: Total Energy and Hourglass Energy of A-Sandwich Panel.

The following are the observations for the impact of 4lb bird at a speed of 150m/s.

a) No penetration observed.
b) No fragments of secondary projectiles formed.

For A-Sandwich panel top skin and core developed cracks whereas bottom skin doesn't have any crack. The specimen of A-Sandwich is capable of withstanding the impact of 4lb bird at a speed of 150 m/s during the flight as per FAR 25 requirements. The specimens successfully absorb the energy created during the impact of bird.

3.2 Electromagnetic Characterization Results

The simulated results of electromagnetic parametric values for A-Sandwich specimen are plotted in Figs 9 and 10. The return loss (energy loss reflected by radome) and Insertion losses (energy loss due to absorption and reflection) of simulation results of A-Sandwich panel are shown below.

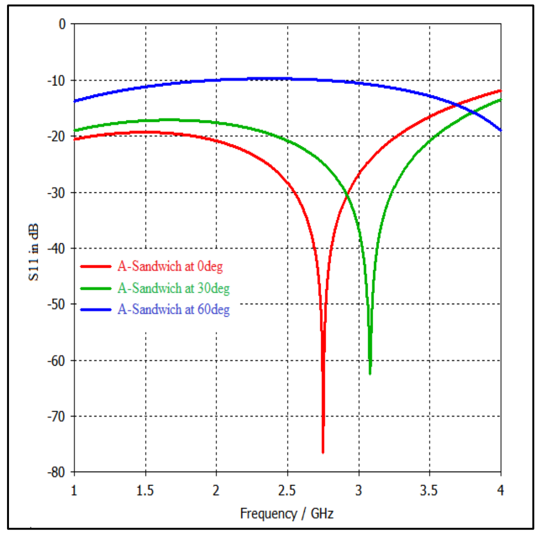

Fig 9: Return Losses of A-Sandwich panel at different angle of incidence.

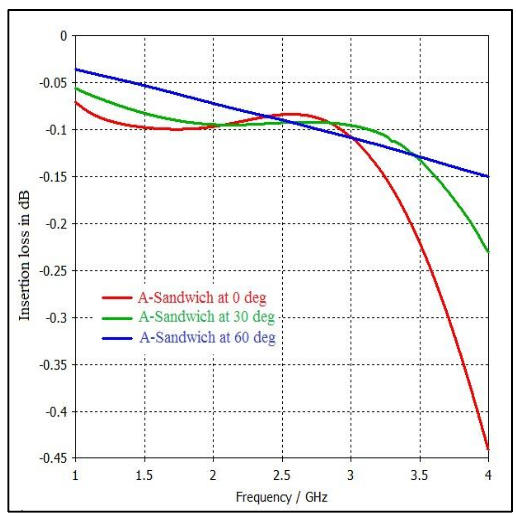

Fig 10: Insertion losses of A-Sandwich panel at different angle of incidence

The S_{11} parameter constitutes the return losses of specimen, is plotted against operating frequency. The return losses for the specimen at lower incidence angels is low and it increases with increase in angle of incidence. As the frequency increases, for lower incidence, the losses increase and for higher incidence the losses decreases. As per general practice the return losses should be kept less than -10db in order to achieve maximum transmission rates.

The insertion loss of the specimen is plotted against frequency of operation. The insertion losses are less for lower incidence and high for higher incidence. The insertion losses are found to be between 0db to -1db, which is necessary for maximum transmissibility.

4. Experimental Results

The fabricated Samples (1m X 1m) of A-type sandwich is tested for its performance in the anechoic chamber. An S-band 3x3 element linear array is used to excite the radome and its performance is validated by measuring the antenna pattern with and without radome. From the measured antenna patterns, it is observed that the A-Sandwich radome designed exhibits negligible impact on antenna patterns. The antenna pattern, sidelobe levels, boresight error etc., are almost comparable to that of patterns without radome.

5. CONCLUSION

A specimen with size 1m x 1m is fabricated as per the design. Honeycomb core of thickness 25mm is sandwiched between two GFRP face sheets of thickness 1.5mm to produce A-type Sandwich specimen. A-Sandwich Specimens withstand the impact loads generated during the impact of a 4lb bird at a speed of 150m/s as per FAR 25 Regulations. The energy generated during the impact was successfully transferred to the sandwich panels without causing any rupture.

Electromagnetic Characterization simulations is carried out to measure the radome performances in terms of free space impedance matching. The performance of A-type Sandwich specimen in terms of return losses and insertion losses are measured. The performance of A-Sandwich panel is better at low frequency and low incidence angles. Anechoic chamber measurements showed that the A-type Sandwich specimen pattern is comparatively same with pattern of antenna without radome.

A-Sandwich specimen withstand the impact of 4lb bird at a speed of 150m/s. No secondary projectiles were observed. For low incidence angles, A-Sandwich specimen has a less return loss and less insertion loss. Hence A-sandwich performance is better in the frequency range of 1-4 GHz. A-Sandwich design can be used for construction of radome which houses the radar system being operated at a frequency range of 1GHz to 4GHz.

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