論 文 の 内 容 の 要 旨

論文題目　The study of layerwise hybrid laminates for lightning strike applications
（耐雷用ハイブリッド積層板に関する研究）

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Carbon fibre reinforced plastics (CFRPs) have played an important role in the aviation industry with outstanding properties, such as high specific strength, adjustable mechanical properties, corrosion resistance, and ease of moldability. These properties have made CFRPs good substitutes for metallic materials for aircraft, for example, aluminium. Utilizing CFRPs also contributes to lower greenhouse gas emissions and higher fuel efficiency. Conventional CFRPs are made of Carbon fibres with a high strength, but insulating epoxy resin. The conductivity of CFRP with epoxy resin (CF/Epoxy) obtained only from the carbon fibres, not the resin. This results in anisotropic and non-uniform conductivity compared to metallic materials. This dielectric property has made CFRPs vulnerable to lightning strikes. Especially in thunderstorm clouds, lightning can happen frequently and cause damages to the aircraft. The lightning strikes can cause structural damages and disturb the radio system; sometimes such attacks cause lethal accidents due to critical part failure, such as fuel tanks. To prevent such incidents, aircraft manufacturers employ a lightning strike protection (LSP) system, which provides conductive paths for the lightning current to flow away from the aircraft body to prevent damage. This system requires multiple layers of materials to prevent the corrosion of metals and CFRPs. This complexity, in turn, obstructs the aim to lighten the weight of aircraft. To seek alternatives, researchers have put their efforts into finding new technologies of LSP, for example, conductive coatings, conducting nanoparticles. The method of incorporating conducting nanoparticles into epoxy resin gains interest from researchers, but it comes with the territory of agglomerations and percolation threshold. They could not yield uniform conductivity above their mixing limit.

As alternatives, conducting polymers can provide a promising solution to the

current problem as well as providing intrinsic LSP. Polyaniline (PANI) has gained interests among scientists since it possesses several advantageous properties, such as ease of polymerization, low cost, availability, and tuneable conductivity. Our research group has been working on PANI-based materials and provided several options for PANI-based resin. Many of them have been tested to be effective against lightning strike. This proved that CFRP with PANI-based resin (CF/PANI) has high electrical conductivity; however, I would like to know the possibility of this material whether its strength can be improved without compromising the weight. This is because the strength of CF/PANI is much less than that of CF/Epoxy and this may be dangerous in practical application. Therefore, this thesis aims to use conventional CF/Epoxy for their superior strength and add a number of CF/PANI layer on top to provide the structure with high resistance against lightning strikes without an increase of weight.

The product of this combination is introduced as layer-wise hybrid laminates; both laminae were fabricated layer-wisely and combine two different laminae as a hybrid laminate. These layer-wise hybrid laminates (CF/Hybrid) are expected to provide both structural strength by CF/Epoxy and electrical conductivity by CF/PANI. This thesis put efforts to verify the characterisation by using mechanical tests: four-point bending test, interlaminar shear strength test, and fracture toughness test in mode one and two.

For lightning strike preparation, the electrical conductivity in through-thickness direction was measured. There were altogether 3 cases of CF/Hybrids which were varied by CF/PANI and CF/Epoxy to obtain 8 layers of laminate: CF/Hybrid-4P4E, CF/Hybrid-2P6E, and CF/Hybrid-1P7E where the number before P represents the number of CF/PANI layers and the number before E represents the number of CF/Epoxy layers. The tests were conducted on both sides of the specimens due to different properties. The bending strength of hybrid laminates were in range of 194 MPa to 328 MPa on CF/PANI side and in range of 554 MPa to 684 MPa on CF/Epoxy side. The ILSS tests were conducted in the same manner. The ILSS were in range of 33 MPa to 53 MPa on CF/PANI side and in range of 37 MPa to 53 MPa on CF/Epoxy side. For ILSS, the results on both sides are not distinguished because the maximum shear planes were in CF/Epoxy layers. The interlaminar fracture toughness tests were conducted on both CF/PANI and CF/Epoxy sides except fracture toughness test mode I. The results show obvious differences between CF/PANI and CF/Epoxy and CF/Hybrids fall either between or higher than CF/Epoxy. This is because the interfaces were strengthened by the adhesive film. Conductivity of the specimens in this study varies from 0.49 S/cm to 0.78 S/cm.

After confirming that the CF/Hybrids have sufficient strength as well as high electrical conductivity, the CF/Hybrids were inspected using non-destructive inspection

(NDI) before testing against lightning strike.

Simulated lightning strike tests were conducted with modification from the standard SAE ARP-5412B. The specimen was fixed to a picture-frame-type copper jig, which was attached to the ground of the impulse current generator. The specimen was held by the base plate and cover frame at all edges by screw-clamping. Lightning current was applied at the centre of the specimen surface, where the gap between the tip of the discharge probe and the surface of specimen is 2 mm. Additionally, several observation methods were employed to help clarify the lightning strike phenomena: high-speed cameras, and a thermography camera. After the test, damages were evaluated and analysed.

These results have indicated that to achieve the coexistence of structural strength and electrical conductivity, at least 4 layers of CF/PANI should be incorporated on the top of CF/Epoxy. This is because the experimental results of CF/Hybrid-4P4E have proven the highest potential to withstand lightning strikes both mechanically and electrically. In terms of mechanical properties, although other specimens showed higher strength due to higher number of CF/Epoxy layers, higher number of CF/PANI layers indicates higher strength as well as effectiveness to withstand lightning strike damages. By comparing damages visually, CF/Hybrid-4P4E obviously shows less damages compared to other cases. When observing the phenomena during lightning strike, CF/Hybrid-4P4E shows the potential to conduct lightning current quickly. In high-speed cameras, the pyrolysis could, which was generated from resin burnt, expanded steadily as a sphere shape from the centre. This means the lightning moved steadily within the CF/PANI layers unlike the case of CF/Hybrid-7P1E that they could generated in a cross shape due to fast flow of lightning current. The thermography images also confirm this trend. Within the same period of time, the surface temperature of the CF/Hybrid-4P4E panel decreases considerably faster than others (less high temperature area). The other method that confirms this result is residual strength test. The residual strength of CF/Hybrid-4P4E shows residual ratio, which defines as the ratio of residual strength to its pristine strength, of 0.71 while others are more than 2.0. This meant that the CF/PANI of other cases delaminated and did not contribute to the strength, so the CF/Epoxy parts bear all the load and resulted in high strength ratios.

This thesis has introduced the concept of layerwise hybrid laminates using both CF/PANI and CF/Epoxy to achieve the coexistence of electrical conductivity as well as structural strength without compromising additional weight. This structure can cover each disadvantage and bring about possible application as LSP for aircraft. This concept has been built on simple methods and has a potential to apply with different materials or structure to accomplish synergistic results.