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Moisutre Ingress in Honeycomb Sandwich Composite Structures – Effects & Detection

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***Abstract*— Moisture ingress in sandwich composites is an important ongoing issue that has attracted quite a lot of attention from aircraft and helicopter manufacturers, maintenance staff and researchers around the world. Most of the aero structures and components such as helicopter rotor blades and nose landing gear door are made of lightweight honeycomb composites capable of carrying high loads at minimum weight. These structures are susceptible to moisture ingress related to environmental degradation, which can have a big impact on the strength, functionality and flight safety.**

This paper outlines the effect of moisture ingress on the strength of these composite structures and development of an effective NDT technique to detect and locate these imperfections using Neutron and Gamma Radiography. The idea is to use the Gas Electron Multiplier (GEM) 2D neutron imaging technique developed by Nagoya University in collaboration with KEK, Japan for the localization of imperfections and defects. A simulation study was conducted to evaluate the feasibility of this approach and conclusions for the further development of this technique were drawn based on the results.

***Keywords*— Moisture Ingress, Sandwich Composites, NDT, Radiography, GEM**

I. INTRODUCTION

The structural failure of honeycomb sandwich composite aero structures is a major problem which has attracted attention of researchers around the world especially after the CF-18 aircraft accident during a routine mission, which resulted due to the moisture degradation of the adhesive bond. It was concluded that moisture when introduced in sandwich structure can degrade epoxy adhesives that bond the carbon sheet to the honeycomb core, resulting in disbonding. Later, thermographic inspection of a United Airlines 767 revealed that the nose landing gear door, a composite honeycomb structure, contained liquid water in approximately 7500cm^2 area [1]. This problem of accumulation of water was also detected in the rotor blades from the Mc Donnell Douglas Apache and the Boeing Chinook helicopter [2]. It was noticed that after flights in great height and humid conditions, honeycomb composite structures absorbs wet air through the micro cracks. During the then subsequent flights the wet air condensates and remains as water in the core cells. This leads to an increase in structure weight due to swelling and furthermore there is great danger of core cracking through freezing [3]. Broadly there are following two ways moisture ingress can effect composite structures:

- Modifications of the mechanical behavior due to the presence of the water in the matrix. These effects wither away as the moisture is dried down eventually.
- Residual modifications of the mechanical parameters phenomena which remain present even after the moisture is dried down [4].

So from all the previous investigations and literature review it can be concluded that composite structures tend to absorb water which can change their physical properties. The goal of this paper is to provide a better understanding of the ill effects of moisture on the adhesive bonding in honeycomb sandwich composite aero structures and develop a capable NDT method to detect it before any catastrophic failure.

II. MOISTURE INGRESS IN HONEYCOMB COMPOSITE STRUCTURES

Moisture can penetrate inside the sandwich composite structures in many ways, e.g. through edge seals, micro cracks on the surfaces, or by diffusion through the skin by Flicks law. When these moisture degraded sandwich panels, are subjected to out-of-plane loads, the core resist the shear load whereas the outer sheets the bending loads. Therefore the bonding between these two constituent structures is very important for the structural integrity of overall structure. Moisture and humidity failure in sandwich composite structures is a complex research topic as there are numerous failure modes and mechanisms.

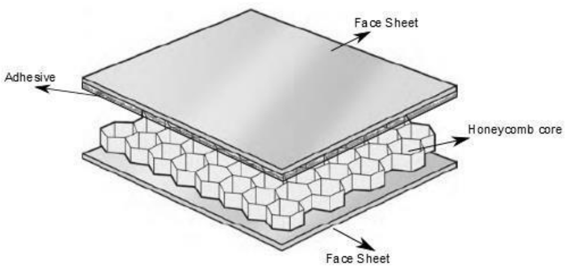

Figure 1 Honeycomb Composite Structure

The two most commonly occurred modes are cohesive failure within the adhesive material, or adhesive failure i.e. failure at the adhesive-adhered interface, as shown in the figure 2

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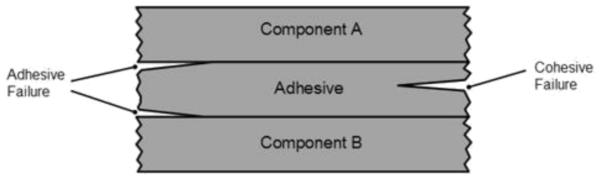

Figure 2 Adhesive and Cohesive Failures

The ingress and seepage of moisture in the sandwich panels not only degrades the strength of composite but also reduces its residual strength. Moisture and thermal spiking can also interact to cause interlaminar cracks. It is therefore of much importance to be able to measure moisture content non-destructively. To understand the moisture induced failure mechanism, it is important to understand the basic science involved with the adhesives.

Epoxy Adhesives are a class of polymer belonging to the thermoset family. They are made of long chains of molecules with smaller repetitive unit molecules called monomers. One important characteristic of thermosets polymers is the glass transition temperature (Tg). At low temperatures, polymers behave mechanically as elastic and sometimes brittle materials, with a relatively high elastic modulus. When a polymer is heated, the modulus decreases gradually up to a certain temperature where it drops sharply by orders of magnitude. The temperature at which the drop occurs is referred to as Tg. In a thermoset polymer, if the temperature is increased beyond Tg, the modulus stabilizes and elastic behavior resumes with a low modulus of elasticity. At temperatures below Tg, the decrease in polymer stiffness with increasing temperature is usually accompanied by a reduction in strength [5]. The effect of humidity is similar to the effect of temperature, i.e. it significantly decreases Tg which translates to a loss of stiffness and strength. Humidity is also responsible for the swelling of polymers, a phenomenon similar to thermal expansion.

Degradation of the polymer properties may also occur due to water contact through hydrolysis. In hydrolysis, as opposed to plasticization, irreversible chemical reactions take place between water and the adhesive. After hydrolysis, the original properties cannot be recovered. It is due to the disruption of interchain hydrogen bonds by water molecules. The molecular chains in epoxy contain polar groups, such as hydroxyls (OH) that have sufficient steric freedom to participate in interchain hydrogen bonding. These interchain bonds play a significant role in polymer stiffness below Tg. The increasing water molecules attach to the polar sites by hydrogen bonding, destroy the previous interchain bonds, and therefore plasticize the polymer.

It is understood from the literature review that the weakening of adhesive joints is due to four possible causes:

- Reversible changes in the adhesive properties leading to cohesive failure.
- Irreversible changes in the adhesive properties leading to cohesive failure.
- Stresses caused by moisture swelling of the adhesive
- Changes at all the adhesive- to- adhered interface leading to adhesive failure.

Of these four possible causes of weakening of an adhesive joint exposed to moisture, three are directly related to the adhesive: 1) plasticization, 2) hydrolysis and 3) swelling. Plasticization and hydrolysis result in a change in the mechanical properties of the adhesive material. As a result, the joint may no longer be adequate to support the intended design loads. On the other hand, swelling creates stresses when the adherends have moisture-swelling coefficients that differ from that of the adhesive material. Additional stresses in the adhesive material can lead to premature failure of the joint.

Choquese et al. [6] studied the absorption of water and corresponding changes in mechanical properties (strength and stiffness) of several reinforced thermosets used in the naval industry, including epoxy composites. They observed that temperature and pressure had an accelerating effect on diffusion but only the temperature history had an effect on the final mechanical properties. Absorption and degradation were shown to follow Arrhenius process. In addition, when the epoxy was dried after long term exposure, the degradation of the mechanical properties was accompanied by a residual weight gain and a drop in the glass transition temperature (Tg).

III. SOME OF THE METHODS TO DETECT MOISTURE IN COMPOSITES

A. Thermography

Thermographic is based on the principle of detecting radiation in infrared range of the electromagnetic spectrum (roughly 9,000–14,000 nanometers or 9–14 µm) and produce images of that radiation, called thermograms. In our case, structures that are perfectly bonded, and free from defects and inclusions have thermal characteristics such as diffusivity capacitance and conductivity uniform across the surface. Whereas regions having micro voids, defects or inclusions will change the thermal characteristics which would be well represented as a change in thermal signature on the image.

B. Ultrasound

The best way to detect water ingress in honeycomb structures is by the through-transmission ultrasonic method. It involves using two separate transducers each for transmitter and receiver placed on either side of the test specimen. When ultrasound is transmitted acoustic energy is reflected or attenuated in the structure. Through-transmission UT is used to record loss of signal amplitude, which is an indication of irregularity.

The primary technique nowadays used by aircraft maintenance staff to inspect these moisture ingress defects is ultrasonic inspection.

C. X-Ray

This techniques uses electromagnetic radiation namely X rays to view the non-uniformity inside the structure. It works on the same principle as stated above for UT that a certain amount of X-ray is absorbed by the non-

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homogeneity, which is dependent on its density and composition. In our experiment (described later) we have compared the imaging using gamma radiation to neutron radiography. Gamma radiation is much more energetic which makes it useful in radiography but hazardous to living beings.

D.Neutron Radiography

Neutron Radiography is considered as an upcoming and complementary NDT technique to conventional methods with better results and accuracy. It is based on the principal that neutrons interact with atom nucleus than the electrons spinning around it. As a result neutrons are absorbed differently than X rays and therefore neutrons are attenuated by some light materials such as hydrogen, boron and lithium but penetrate heavy materials such as titanium and lead. Neutron radiography is, therefore, suitable for a number of tasks impossible for conventional x-ray radiography. Because neutrons interact with the nucleus rather than with the electron shell, they can also distinguish between different isotopes of the same element. This makes neutron radiography an important tool in various research applications and in the field of NDT.

IV. PROPOSED MOISTURE DETECTOR BASED ON GEM (GAS ELECTRON MULTIPLIER)

We propose to use the current 2D neutron imaging set up based on Gas Electron Multiplier (GEM), developed by Nagoya University with KEK, Japan for our purpose [7].

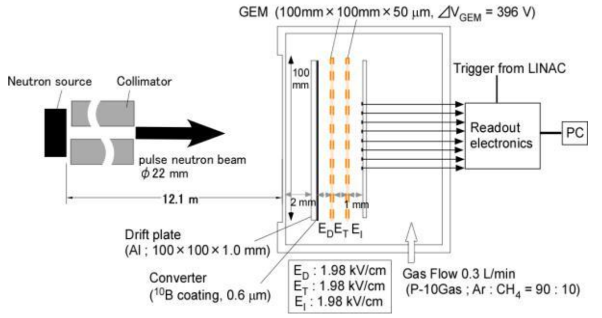

Figure 3 Experimental setup of the imaging camera with GEM

Gas Electron Multiplier electrode is a thin polymer foil, metal-coated on both sides and pierced with a high density of holes, typically 50–100 mm [8]. The large difference of potential applied between the two sides of the foil creates a high field in the holes. When electrons are released in the upper region, they drift towards the holes and acquire sufficient energy to cause ionizing collisions with the molecules of the gas filling the structure. A sizeable fraction of the electrons produced in the avalanche's front leave the multiplication region and transfer into the lower section of the structure, where they can be collected by an electrode, or injected into a second multiplying region. This avalanche is able to produce enough electrons to create a current or charge large enough to be detected by electronics.

An epithermal neutron camera based on energy-filtered imaging with GEM had already been developed by Nagoya University (see Figure 4). This technique is applicable to compact accelerator-based neutron sources.

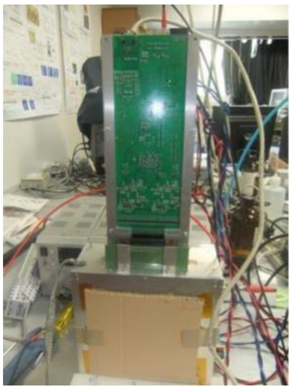

Figure 4 Epithermal Neutron Imaging Camera with GEM at Nagoya University, Japan

We think that that the voids filled with water or air would react differently as compared to the remaining structure to the incoming flux of radiation source. This change in the interaction can be exploited to sense the defects in composite honeycomb structures, or to that matter any composite defects. Since the size of these radiation particles, it can detect very small defects. The epithermal neuron camera with GEM can be used to detect and locate the defect locations. In order to use this technology the quality of the GEM and the interaction study of radiation (neutrons and gamma particles) with defects (moisture and voids) should be investigated. The first and the foremost step in this direction is to do a feasibility study of the interaction of composite with moisture defects with different types of radiation.

I. COMPUTER SIMULATION USING PHITS (PARTICLE AND HEAVY ION TRANSPORT CODE SYSTEM)

To prove the feasibility of our proposed detector system, we were required to run lab experiments. But since we need a good source of neutrons (neutron reactor) for the proposed lab test and its unavailability in our lab, we decided to prove the same by running computer simulations. We used PHITS i.e. Particle and Heavy Ion Transport code System for our purpose. It is a general purpose Monte Carlo particle transport simulation code developed under collaboration between JAEA, RIST, KEK and several other institutes in Japan. It is capable of dealing with the transport of all particles (nucleons, nuclei, mesons, photons, and electrons) over wide energy ranges, using several nuclear reaction models and nuclear data libraries. The physical processes which we should deal with in a multipurpose simulation code can be divided into two categories, transport process and collision process. In the transport process, PHITS can simulate a motion under external fields such as magnetic and gravity. Without the external fields, neutral particles move along a straight trajectory with constant energy up to the next collision point. However, charged particles and heavy ions interact many times with electrons in the material losing energy and changing direction. The second category of the physical processes is the collision with the nucleus in the material.

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In addition to the collision, we consider the decay of the particle as a process in this category. The total reaction cross section, or the life time of the particle is an essential quantity in the determination of the mean free path of the transport particle. According to the mean free path, PHITS chooses the next collision point using the Monte Carlo method. The code also has a function to draw 2D and 3D figures of the calculated results as well as the setup geometries, using a code ANGEL. Because of these features, PHITS has been widely used for various purposes such as designs of accelerator shielding, radiation therapy and space exploration. It is capable of the event generator for neutron-induced reactions in energy region less than 20 MeV. A geometric model as shown in the fig below is made in the PHITS. For the ease of geometric modeling the core is depicted as circular instead of hexagonal. This allowed efficient modeling of the honeycomb structure; however this would not have any difference in the results. A small sphere of diameter 1 cm filled with water is included in the adhesive layer, which is to be detected.

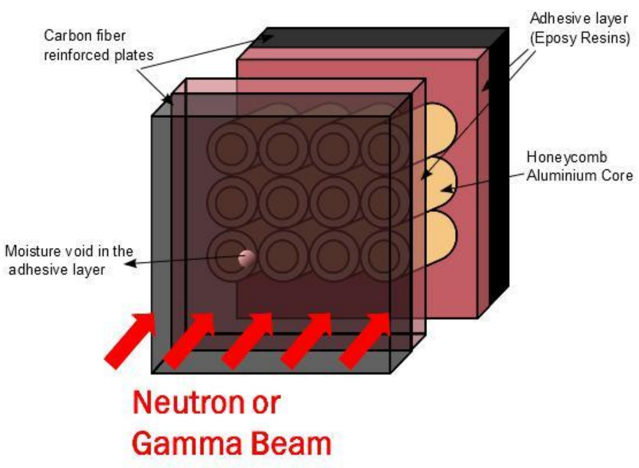


Figure 5 2d Model of the honeycomb composite structure with defect (PHITS)

VI. RESULTS

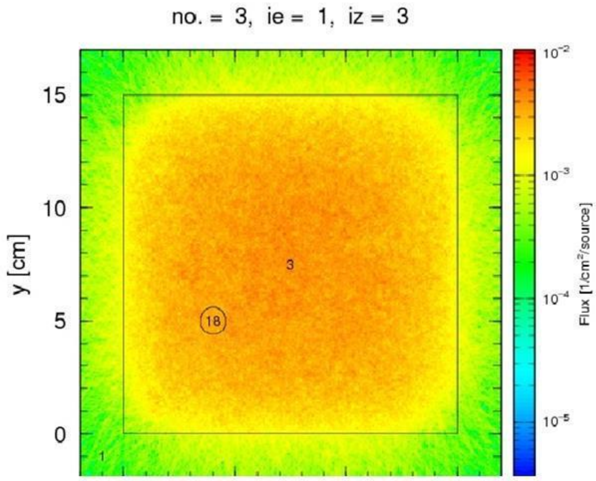
The results from the PHITS simulation are shown in Figures 6 – 9. Different energy settings and epoxy density were simulated and compared as shown in the Table 1 below. These settings were used for both the neutron and the gamma radiography.

Table 1 Result Table

S. No	Energy	Neutron Intensity	Density of epoxy	Detection of void
1	1 eV	1500x1500	2.78g/cc	No
2	50 eV	2000x2000	2.78g/cc	No
3	50 KeV	1500x1500	2.78g/cc	No
4	50 KeV	1500x1500	7g/cc	Yes

Figure 6 shows that there is no sharp attenuation in the neutrons energy during their interaction with the voids and as a result it is difficult to get a good 2D image from the epithermal neutron image sensor with GEM detector.

We tried to increase the neutron intensity, but that too didn't make any difference (see Figure 7)



6 Neutron Radiation – Moisture Void Undetected

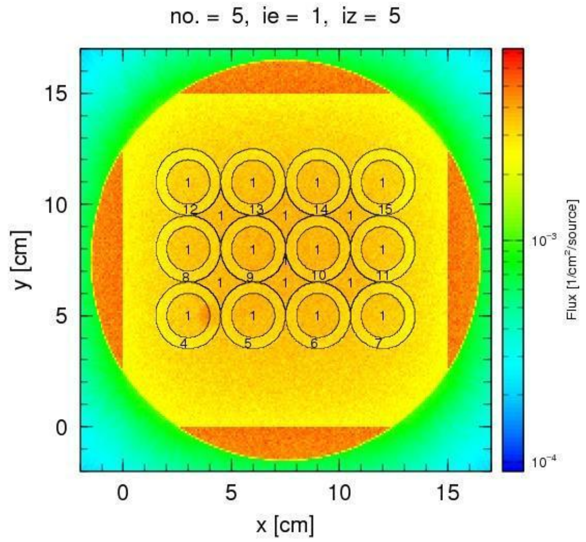


Figure 7 Neutron Radiation – Moisture Void Undetected

Figure 8 shows the void interaction with the same settings but with Gamma particles. It can be seen that gamma particles don't result in better detection capabilities either. In fact the energy attenuation is better for neutron particles than gamma particles.

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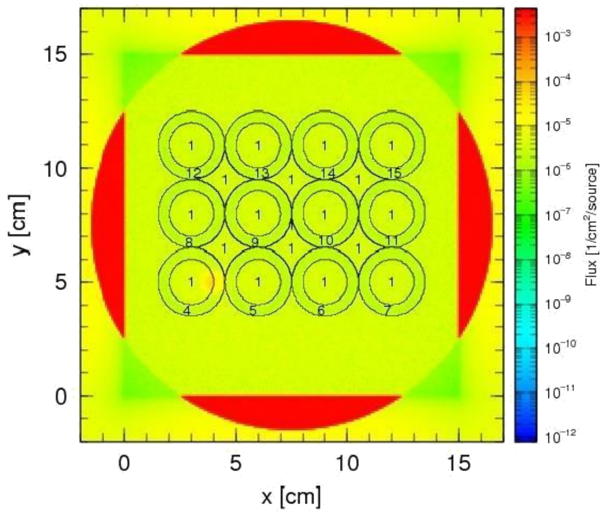

Figure 8 Gamma Radiation – Moisture Void Undetected

Figure 9 shows the effect of increasing the epoxy adhesive material density and energy of neutron. It was revealed that there is a strong effect of epoxy resin density and particle energy on the level of radiation attenuation. As it can been seen, there is a sharp contrast in the color of void to the surrounding area, which depicts larger energy attenuation.

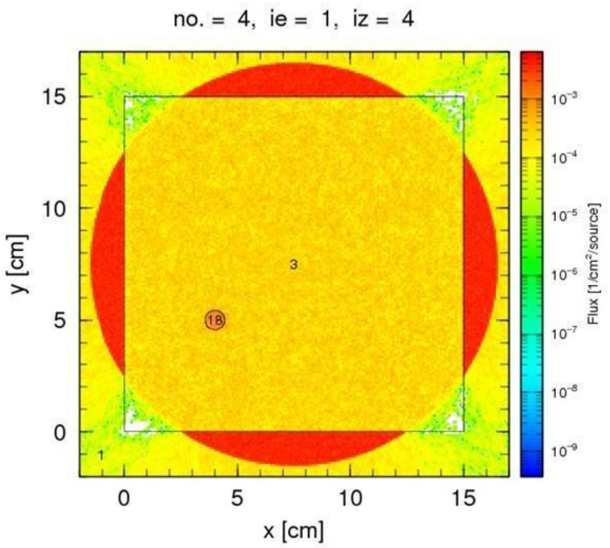

Figure 9 Neutron Radiation – Moisture Void Detected

This is probably due to the fact that neutron cross sections are better than gamma particles cross section for hydrogen particle. Neutrons can lose energy in a series of scatter events when they interact with matter such as scattering (elastic & inelastic) or capture. For hydrogen the contributors to the total cross section are predominantly elastic scatter. The Table 2 below shows the maximum fraction of energy lost, by neutron in single elastic collision with various nuclei. As it can been seen, the maximum value is for hydrogen and its isotopes, which explains the better energy attenuation.

Table 2 Neutron Cross Section (Elastic Scattering)

Nucleus	Qmax/E
^{1}H1	1.000
^{2}H1	0.889
^{4}He2	0.640
^{9}Be4	0.360
^{12}C6	0.284
^{16}O8	0.221
^{56}Fe26	0.069
^{118}Sn50	0.033
^{238}U92	0.017

**Source: Principles of Radiation Interactions, MIT*

VII. CONCLUSION

The research paper shows the feasibility of detecting moisture ingress in composite honeycomb structures using gamma and neutron particles. Neutron particles interact better than gamma particles with hydrogen particles. This is evident from the better energy attenuation as can be seen form the simulation tests.

Increasing the neutron energy density doesn't have any increasing effect on the attenuation.

There is a strong correlation between the material density of the void and its surroundings, in this case the adhesive layer. We observe that as we increase the material density of the adhesive layer, there is an increase in energy attenuation.

We conclude from this experiment, that it is indeed possible to use neutron particles for the detection and localization of moisture ingress in honeycomb composites. However, the detection capability is highly dependent on the epoxy adhesive material properties. The epithermal neutron imaging camera with GEM detectors can be used, to give a better pictorial view of the same.

Further work includes in depth study of interaction of neutron particles with different epoxy adhesives and a test experiment proving the capabilities.

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