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Moisture Ingression in Honeycomb Core Sandwich Panels

D. Cise and R.S. Lakes

Moisture ingression was studied in several composite sandwich panels, in which hydration was applied over a large surface area at the panel edges. Significant moisture ingression occurred in panels with cores of Korex (based on a substrate of a fiber pulp paper) and HRP (consisting of a woven-glass-fiber substrate with a polymer coating) of different density. Ingression was more rapid than in panels with hydration applied locally. Ingression followed an exponential pattern in time in most cases, in harmony with diffusion theory.

Keywords core, honeycomb panels, moisture, sandwich panel, water

1. Introduction

Polymer-matrix composite materials are used in many applications such as aircraft and sports equipment, just to mention a few. These materials exhibit high stiffness and strength combined with low density. Epoxy resins used in such materials absorb water from the environment. High temperature can degrade the mechanical properties of the resin, and the degradation is more severe when the resin is also exposed to moisture. Because exposure to fluctuating temperature and moisture is inevitable in aircraft applications, considerable research effort has been devoted to studying the mechanism by which epoxy resin composites absorb and transmit (ingress) moisture and the effect of moisture on their mechanical properties.

For example, epoxy-matrix materials and polymer-matrix composites absorb moisture (Ref 1), and the absorption is attributed to the matrix rather than the graphite fibers. Neat resins equilibrate (Ref 2) at higher moisture contents than the graphite-fiber composite. The graphite fibers appear to be nonabsorptive, and the epoxy matrix is the lone contributor to moisture weight gain (Ref 2). Epoxy-matrix material can absorb water up to 5% by weight (Ref 1). Fickian diffusion describes much of the ingression behavior during exposure of graphite-epoxy laminate panels to humidity or immersion in water (Ref 3-5). Water immersion of a graphite-epoxy cross-ply composite (Ref 6) for 20 days at a temperature of 343 K reduced the strength by 13% and the stiffness by 9%. Environments containing humid air can also cause loss of stiffness and strength in graphite-epoxy composite (Ref 7). Hygrothermal histories can, depending on history and polymer material type, either increase or decrease the resistance to matrix cracking (Ref 8). Moisture acts as a plasticizer of the matrix and shifts the glass transition temperature toward lower values (Ref 9). The effect is composition dependent (Ref 1) and is of concern because some composites may be used at elevated temperature. Moisture in the polymer matrix causes an increase in mechanical damping (Ref 10). Many studies have been conducted and reviewed (Ref 11) on water transport in polymer-matrix materials, but the literature on sandwich structures is sparse.

Sandwich panels made of composites contain an additional level of structural complexity. Therefore, it is considered desirable to explore their behavior experimentally. There is little published literature on moisture ingression into sandwich panels or through honeycomb cores. Experience in the commercial aircraft industry with sandwich panels in secondary structures has been generally positive. For example, spoilers in the Boeing 737 (Seattle, WA 98124-2207) aircraft have survived one million flight hours and one million landings; even so, several cases of trailing edge delamination suggest that moisture ingression can occur (Ref 1). Possible causes of ingression include negative gage pressure postcure within the core (Ref 12) which may draw moisture into the cells; ingression through cracks or other damage; and diffusion. If one were to make the primary structure of aircraft from composite materials, substantial reductions in weight and fuel costs could be achieved. Safety standards for such structures are much higher than for secondary structures; therefore, a study of long-term durability of these structures is warranted.

In a prior study (Ref 13), it was found that no observable moisture ingression occurred through an intact 1 mm thick graphite epoxy face sheet with liquid water on one side over several hundred hours. The present study was conducted to explore ingression through the honeycomb core of sandwich panels with graphite-epoxy face sheets.

2. Methods

2.1 *Humid Air Ingression*

A specimen with HRP core (Hexcel, 5794 W. Las Positas Blvd., Pleasanton, CA 94588-4083) and a graphite-epoxy matrix was used for this segment. HRP honeycomb core material consists of a woven [0/90] glass-fiber-reinforced phenolic matrix. The glass-fiber structure of HRP can offer a comparatively high modulus, but it is brittle and can crush easily. Korex (E.I. DuPont, Chattanooga, TN) honeycomb core material is an aramid-fiber-reinforced phenolic honeycomb. The phenolic resin is impregnated through the cell wall thickness. Korex is more pliable than HRP. This specimen was cut from a square specimen to a 76 mm (3 in.) diam circular specimen. Density was inferred from measurements of mass and dimensions and was determined to be 0.064 g/cm^3 (4 lb/ft^3). This is referred to as “4.0 lb HRP core” in the industry.

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The specimen was supported within a polymeric chamber supplied with humidity-controlled air, as shown in Fig. 1. The laboratory source of compressed air was found to be consistently under 5% relative humidity (RH). Stabilization procedures included exposure to this dry air. Humid conditions were produced by bubbling air through water, as shown in Fig. 1. Depending on the flow rate of air, the level of humidity could be controlled up to condensation. The air then passed through the five holes located in the upper portion of the base and ultimately out into the laboratory through the top of the assembly. Humidity in the chamber and within the specimen was monitored by miniature solid-state humidity sensors (IH-3605-A or -B, Hy-Cal Engineering, El Monte, CA). Temperature was measured via solid-state temperature sensors type LM335 (National Semiconductor, Inc., Santa Clara, CA 95052-8090) in a compact TO-92 diode package. This sensor was directly calibrated in degrees Kelvin and had a normal operating temperature range of −10 to 100 °C. A benefit to its use was that it possessed a linear output of 10 mV/K. Although it could be potentiometer-calibrated with precision, the shipped calibration was rated for accuracy within 1 °C. A current of 1 mA was used.

The output of the internal humidity sensor was recorded on an analog strip chart (Recorder 110, Gould Inc.). The hard copy was then scanned (ScanMaker IIG, Microtek) into a file on a Macintosh IIci computer (Apple Computer Corporation, Cupertino, CA). The data points were recovered by a software package (DataThief; National Institute of Nuclear Physics and High Energy Physics, Amsterdam, The Netherlands) that permitted the user to digitize these data.

2.2 *Ingression from Liquid Water Source*

A 76 mm (3 in.) square section was cut from a 12.7 mm (½ in.) thick Korex core panel of density 0.072 g/cm^3 (4.5 lb/ft^3), from a test panel supplied by Boeing Aircraft Company. The specimen was installed with temperature and humidity transducers in the center. After the sensors were sealed within the specimen, the panel was submerged in a flat tray filled with water without any prior drying or stabilization period. All sides of the core were thus exposed to water. Figure 2 shows the setup for this specimen.

The pan was open to the atmosphere, allowing evaporation; therefore the level of the water was monitored and refilled when necessary so that at least 75% of the core edges were immersed. Internal humidity was monitored daily, using a digital multimeter output (Fluke model 73; Fluke Corporation, Everett, WA). Voltage values were recorded and converted to humidity values via a spreadsheet (Excel 3.0; Microsoft Corporation, Redmond, WA).

2.3 *Direction Dependence of Ingression*

Because moisture ingression was found in these specimens, a more specific experiment was devised to investigate a hypothesis that moisture ingression within uncompromised panels depends on direction within the core. The core construction has the potential to yield ingression rates faster in the y-axis direction than in the x-axis direction, as discussed below. Moreover, Boeing Company studies into air permeability of core materials found this to be true for porous core specimens (Korex 3.0 lb) (Ref 14).

The same material used in the previous experiment was employed here. The specimens were cut from a panel with 12.7 mm (½ in.) thick, 4.5 lb Korex core and graphite-epoxy face sheets. Four square specimens, 38 mm (1.5 in.) per side, were cut with a hacksaw, and the cells in the x- and y-axial directions were counted. All four specimens had two sides sealed with epoxy to allow moisture ingression in only one direction. Specimens S1 and S2 had their y-direction sides sealed with epoxy to constrain diffusional flow in the x-direction; conversely, specimens S3 and S4 had the sides in the x-direction sealed with ep-

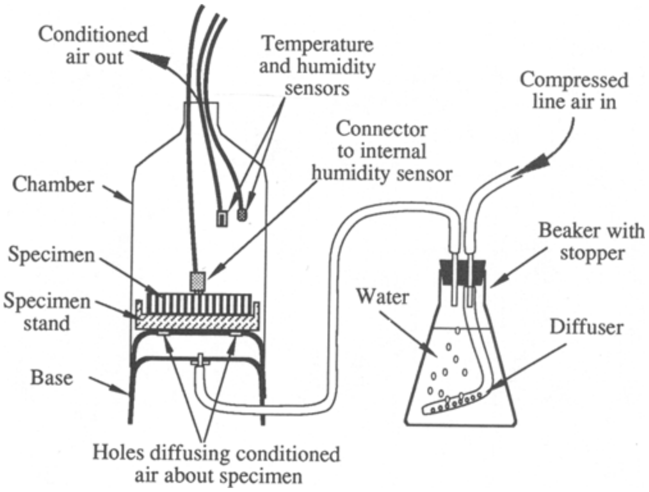

Fig. 1 Humidity-controlled chamber

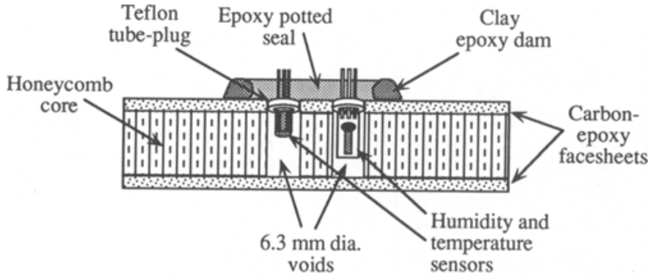

Fig. 2 Setup for submersion of 4.5 lb Korex specimen to evaluate moisture ingression in response to water over a large area

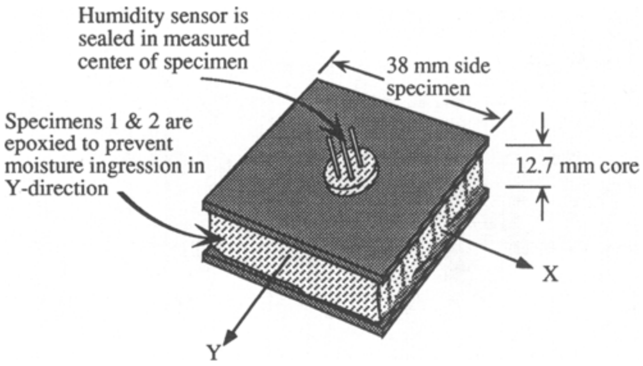

Fig. 3 Construction of unidirectional moisture flow specimen

oxy to constrain diffusional flow in the y-direction. Figure 3 shows a prepared panel section with a humidity sensor. Specimens S1 and S2 had 13 cells in the x-direction and 10 cells in the y-direction; the flow was in the x-direction. Specimen S3 had 13 cells in the x-direction and 10 cells in the y-direction; S4 had 12 cells in the x-direction and 10 in the y-direction; the flow was in the y-direction. The void of each sensor occupied approximately 3 to 4 cells in both directions.

3. Results and Discussion

3.1 *Humid Air Ingression*

During the drying and stabilization period, the interior of the sample specimen with HRP core dried from 38 to 19% RH, as shown in Fig. 4. Data were fitted by a humidity function $RH = 34.5\, e^{-t/469}$, with time t in hours and a correlation coefficient $R = 0.9979$.

After stabilization, the specimen was exposed to humid air (90 to 100% RH), and the resulting rise in internal humidity is displayed in Fig. 5. Both figures illustrate a considerable rate of ingression through this grade of HRP core and a relatively quick response to perturbations. Data were fitted by a humidity function $RH = 80.1 - 60.3\, e^{-t/158}$, with time t in hours and a correlation coefficient $R = 0.975$. The difference in the time constant for drying and that for ingression may be attributed to the difference in initial conditions or to an asymmetry in the processes of absorption and desorption.

3.2 *Ingression from Liquid Water Source*

The purpose of this preliminary experiment was to determine the degree to which 4.5 lb Korex core permits moisture ingression. Initially, the humidity dropped within the panel. However, after eight days, the humidity began to rise slowly. As seen from Fig. 6, the test panel transmitted moisture over a total experimental time of approximately 1200 h. Data were fitted by a humidity function $RH = 100 + 20\, e^{-t/395} - 100\, e^{t/3731}$,

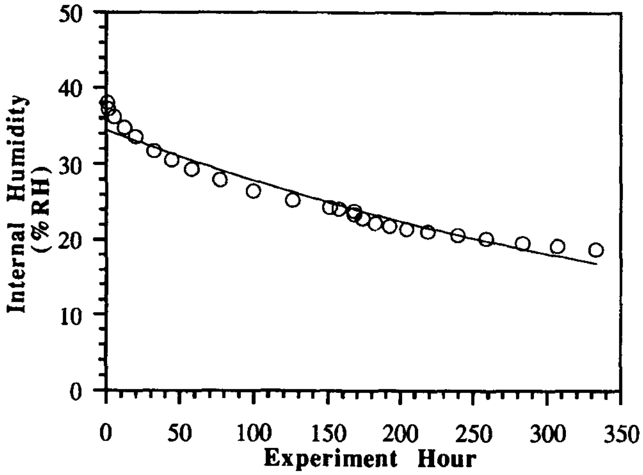

Fig. 4 Humidity versus time for drying cycle of the HRP specimen

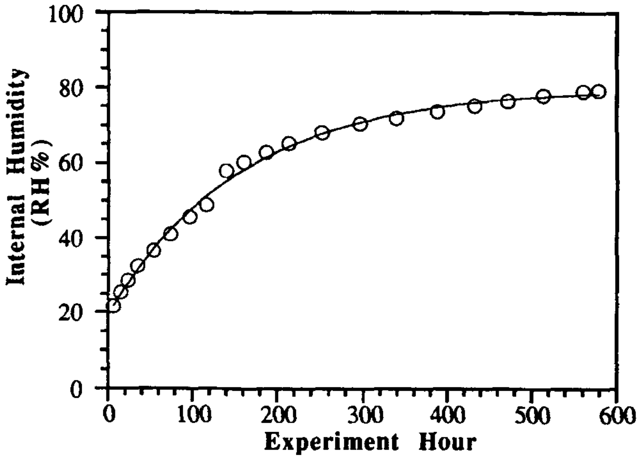

Fig. 5 Humidity versus time for moisture ingression cycle of the HRP specimen

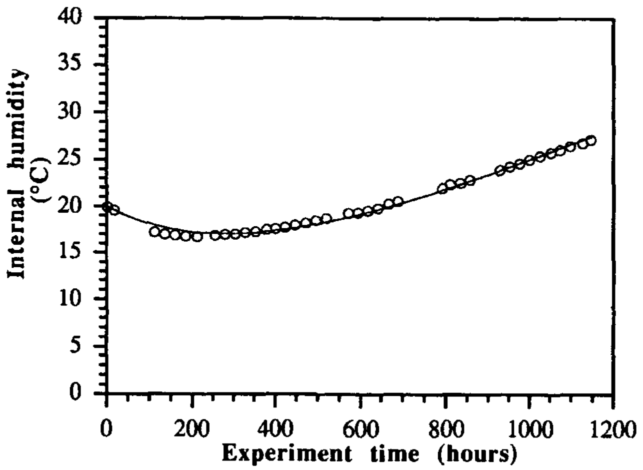

Fig. 6 Humidity versus time for a Korex 4.5 lb panel submerged in water

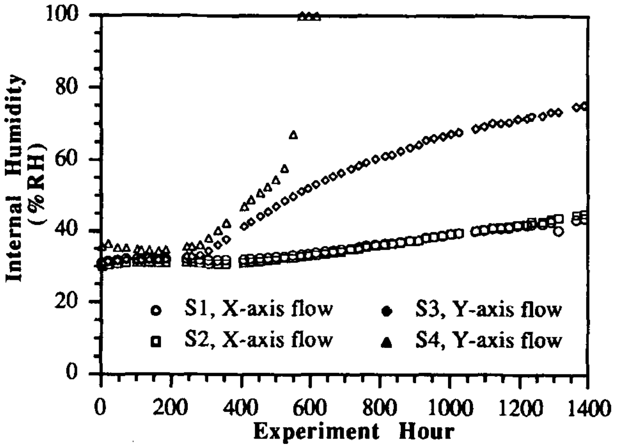

Fig. 7 Responses of four Korex 4.5 lb specimens with water access along two parallel faces. Ingression was faster in the y-direction

with time t in hours and a correlation coefficient $R = 0.996$. Again there is a difference in time constant for ingression compared with that for drying. However, because a lengthy and independent period for drying was not incorporated in this experiment, definitive conclusions cannot be drawn regarding the time constant for drying. The results indicate Korex core ingresses moisture, but slowly. Even so, ingression with this setup was much faster than in the case of a localized source of water (Ref 13). In that trial, moisture ingressing radially outward from a central point source was only marginally detectable in this sort of panel 1500 h after exposure to water. The difference in ingression rate is attributed to the difference in area exposed to water and the distances involved.

3.3 *Direction Dependence of Ingression*

Figure 7 illustrates the internal humidity of all four specimens. Specimens S3 and S4 (y-direction flow) exhibited higher rates of moisture ingression than S1 and S2 (x-direction flow). Both pairs of specimens followed similar trends until the 500 h mark. The internal humidity in specimen S4 then took a marked turn and quickly showed condensation. Given equal distances, moisture ingression depended on direction. In the y-direction, moisture ingression was faster. This can be explained through the physical aspects of the core construction (Fig. 8). There are fewer cell walls to permeate per unit distance in the y-direction. Also, the glue bonds and the double layer of core material encountered between adjacent cells transverse to the x-direction confer increased resistance to moisture flow.

3.4 *Interpretation*

Diffusion according to Fick's law for a one-dimensional continuous region gives rise to a normalized concentration $C_{\text{norm}}(t,z)$, which depends on time t and position z as follows (Ref 15):

$$C_{\text{norm}}(t,z) = 1 - \frac{1}{8\pi^2} \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)^2} \cos\left[\frac{(2n+1)\pi z}{l}\right] \exp\left\{\frac{-D(2n+1)^2\pi^2}{l^2}\, t\right\} \qquad (Eq\ 1)$$

with D as the diffusion coefficient and l as the thickness. For a cylindrical object of radius a, the time dependence is still exponential, but the dependence on radial position r involves Bessel functions J_0 and J_1.

$$C_{\text{norm}}(t,r) = \sum_{n=0}^{\infty} \left[\frac{J_0(b_n r)}{J_1(b_n a)}\right] \exp\left\{-D b_n^2 t\right\} \qquad (\text{Eq } 2)$$

with b_n as the roots of $J_0(b_n a) = 0$. Concentration has an exponential dependence on time. This is to be contrasted with the gain of weight due to diffusion, which has an initial $\sqrt{t}$ time dependence (Ref 16). The difference is due to the fact that weight gain corresponds to a spatial integral of concentration. The series expansions in Eq 1 and 2 converge rapidly; the first term dominates in most cases. Analysis of diffusion has been generalized to incorporate anisotropy of composites (Ref 16). The "time constant" τ in the first term of form $e^{-t/\tau}$, depends on both the diffusion coefficient and the square of a distance over which diffusion occurs. Interpretation of the time constants is particularly problematical for the drying phase because the distribution of humidity in the initial state of the honeycomb is not well defined.

There was a more rapid rate of ingression in S4 than in any of the other specimens. This was the first specimen prepared, and more force was used in drilling the sensor voids. For that reason it is believed that specimen S4 suffered more damage than the others during cutting and/or drilling. Following removal of the bottom and top face sheets of specimen S4, there appeared to be considerable damage from the drilling of the sensor void. Although there was a reduction in the number of intact cells between the center and the exterior, no other deformities could be seen that may cause the high ingression rates.

Ingression was faster in these specimens than in the specimen described in section 3.2. The difference is attributed to the smaller size of the present specimens, hence shorter ingression paths. Distance of ingression is important because the simple diffusion-based models predict the effective time constant to increase with the square of the distance. Nonexponential trends may be due to the small number of cells, giving rise to a discrete compartment transport phenomenon.

If one can be confident that the honeycomb core obeys classical diffusion theory, then it is possible to use measured diffusion coefficients for the sandwich constituents and perform a finite element analysis to predict the flow of moisture through the honeycomb (Ref 17). In some cases, nonFickian behavior can occur; therefore, testing of such predictions with direct experiments on the same material can be beneficial. Moreover, the quality of the adhesive joint between core and face sheet is a variable that may be difficult to model consistently. Consequently, the predictive approach and the direct experimental approach may be considered complementary. A honeycomb sandwich panel is not a continuum; therefore, the evaluation of the Fickian nature of ingression in these panels is considered to be a topic for further experiment.

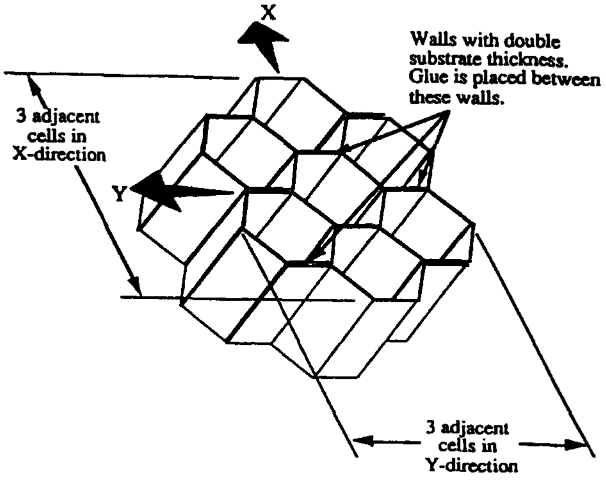

Fig. 8 Directional aspects of honeycomb structure

4. Conclusions

This article describes two methods of investigating moisture ingression in composite sandwich panels. From the study of uncompromised composite panels it can be concluded that some level of moisture ingression does occur. It is therefore recommended that sandwich panels exposed to water or humidity be sealed to prevent access of the environment to the core. The rate of ingression depends on direction. Ingression is faster when a large area of core is exposed to water than if the exposure covers a localized small area. Ingression followed an exponential pattern in time in most cases, in harmony with diffusion theory.

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