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MOISTURE MIGRATION DURING BONDED REPAIR OF WET COMPOSITE

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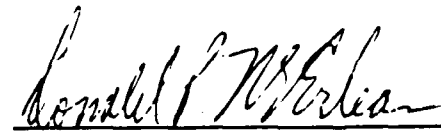
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19 ABSTRACT (Continue on reverse if necessary and identify by block number) Methods of estimating the moisture profile in composites during drying and subsequent bonded repair have been reviewed. A new method with rapid estimation of drying time based on literature values for the diffusion constant has been proposed. Methods of controlling void formation during bonding have been studied and difficulties in using standard repair techniques have been highlighted. New criteria for selection of repair adhesives to minimize void formation are proposed.					
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CONTENTS

	Page
FIGURES	iv
TABLES	iv
INTRODUCTION	1
MOISTURE ABSORPTION OF COMPOSITE MATERIALS	2
DIFFUSION OF MOISTURE WITHIN COMPOSITES	4
PREDICTION OF MOISTURE PROFILES IN COMPOSITES	6
MIGRATION OF MOISTURE DURING BONDING AT ELEVATED TEMPERATURE	7
PRESSURE IN THE BONDLINE	9
DRYING OF SUBSTRATES AND ADHESIVES PRIOR TO REPAIR	12
PARTIAL DRYING OF SUBSTRATES	12
SELECTION OF CURE CYCLE FOR ADHESIVES	15
MOISTURE IN HONEYCOMB STRUCTURES	15
CONCLUSION	16
REFERENCES	17

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FIGURES

Figure		Page
1	(i) - Theoretical Curves for Moisture Uptake ¹⁹ (ii) - Results Obtained (16) for Carbon Fiber Composite (AS3501-5) at 49°, 38°, and 27°C.	5
2	Predicted Moisture profile for carbon fiber composite (AS3501-5) saturated with moisture at 80% RH and dried at 150° for 2 hrs. Construction uses values calculated from Tables 1 and 3.	8
3	Axes used in derivation of the expression for hydrostatic pressure under a rectangular patch during adhesive bonding ²⁶	10
4	Predicted pressure distribution under a rectangular patch during adhesive bonding as predicted by Equation 12 ²⁶	11
5	Variation of predicted bondline thickness with time during bonding on a 4 in patch under a 15 psi pressure at constant adhesive viscosity as indicated ²⁶	13

TABLES

Table		Page
1	Constants for Calculation of Equilibrium Moisture Content and Diffusion Coefficient for Common Resins and Matrices (from ref 16)	3
2	Moisture Contents for Typical Resins and Composites (calculated using data from Table 1)	3
3	Values for the constant k for given fractional moisture contents in Equation 9.	7

INTRODUCTION

During bonded repair of structural composites, procedures require exposure of the composite substrate, repair adhesive and patch material to a regime of elevated temperature and pressure. The pressure program often includes a vacuum. Volatile materials in any part of the system may vaporize during this procedure and will often appear as bubbles in the liquid adhesive prior to gelation. This is the most common source of voids in the bondline which can cause significant loss of bond strength and integrity¹⁻⁵.

Formation of vapor in cavities such as preexisting voids cracks or in sealed honeycomb cells, can also result in pressures sufficient to damage areas of a structure otherwise unaffected (6).

Volatile liquids include water, organic solvents used in manufacture of adhesives and composites, organic materials absorbed by the system during exposure to paints, paint strippers, hydraulic compounds, cleaning fluids, deicing systems and other sources. The major source of volatiles has been found to be moisture and void formation in the bondline during repair of wet composite structures has been widely reported.

This review will address the problem of void formation due to exposure of the repair system to moisture. The problem of absorption of volatile, mobile species followed by their subsequent desorption and volatilization is general, however, and will only differ in values of actual diffusion constants, vapor pressures and solubilities. This review will also address the problem of entrapped moisture in cavities in the system. Investigations of problems stemming from entrapped materials other than water have not been reported.

MOISTURE ABSORPTION OF COMPOSITE MATERIALS

Composites based on organic matrices absorb significant quantities of water. While some moisture may be present as free liquid moisture in voids in the matrix, and some is physically absorbed on the composite surface, the bulk of water is present in the absorbed state throughout the organic matrix. The water is firmly bonded through hydrogen bonds to polar sections of the matrix⁷⁻¹⁰. It is likely that water is absorbed non-uniformly throughout the matrix and may exist in higher concentrations near the interface of fiber and matrix depending largely on the fiber and its pretreatment¹⁰⁻¹². The presence of moisture in the matrix results in a slight reduction in matrix modulus and also in a significant reduction in the glass transition temperature (T_g) of the matrix. This decrease in the glass transition temperature of the matrix, (which is an indicator of the maximum use temperature of a structural laminate) has resulted in interest in moisture absorption of organic matrices^{8,13-16}. Of particular significance during the repair process, the loss of rigidity of the base laminate at the cure temperature for the repair is particularly important. Care must be taken not to deform the surrounding undamaged matrix during repair by use of high cure temperatures for the adhesive, unless jigs are available for support of the structure.

Moisture that is absorbed on the surface of the composite, or that is trapped in voids or cracks which contact the surface, may be removed rapidly by local heating. However moisture within the composite, whether absorbed or trapped within the bulk of the material, can only be lost to a free surface through diffusion which is a very slow process. The diffusion rate is temperature dependent and exposure to high temperatures increased the drying rate. Even at the high temperatures however, diffusion rates are very low.

The actual weight of water which can be absorbed by the composite, depends on the resin used as matrix, on the weight fraction of resin in the composite¹⁵⁻¹⁷, on the degree of cure of the resin to a small extent^{17,18} and on the relative humidity of the surrounding environment^{15-17,19}. For most epoxy resin based matrices it has often been found that the equilibrium moisture content is not dependent on the temperature¹⁹. There have been some reports of variation of moisture content with temperature^{17, 20, 21} but it is not common and the variation of the equilibrium moisture content is small.

For the most common epoxy matrix resins, such as those based on the diglycidyl ether of bisphenol-A (eg Epon 828, DOW DER 332 or Araldite 6010) or the tetraglycidyl ether methylene p-dianiline, Araldite 0510, (eg Narmco 5208 or Magnamite 3501) the equilibrium moisture content can be assumed to be independent of temperature.

For general purposes the weight of moisture absorbed into a resin M_w is given by^(16,17) —

$$M_w = a \left(\frac{P_{\text{moist}}}{P_{\text{sat}}} \right)^b \quad (1)$$

where P_{moist} = partial pressure of moisture in surrounding environment
 P_{sat} = saturation partial pressure in the environment
 a, b = material constants

This may be expressed

$$M_w = a \left(\frac{\phi}{100} \right)^b \quad (2)$$

where ϕ = relative humidity

NADC-88023-60

Table 1 shows constants for calculation of equilibrium moisture content and diffusion constant for common resin system.

Table 1. Constants for Calculation of Equilibrium Moisture Content and Diffusion Coefficient for Common Resins and Matrices (from ref 16)

		Moisture Content		Diffusion Coefficient	
Equation		1		6	
Constant		a	b	c	D ₀
Unit				K	mm ² /sec
System					
T300/1034	Neat Resin	.00068	1	5500	2
	65% fiber vol	.00017	1	—	—
AS/3501-5	Neat Resin	.00072	1	5700	5
	65% fiber vol	.00018	1	—	—
T300/5208	Neat Resin	.00060	1	5000	.5
	65% fiber vol	.00015	1	—	—

Note 65% fiber vol is approx 25% resin wgt fraction.

The moisture content of a composite specimen M_c is directly related to the resin content of the composite (15, 22)

$$M_c = w_r M_w \quad (3)$$

Where w_r = weight fraction of resin in composite

Table 2 shows some typical values for moisture contents of some structural composites calculated using data from Table 1.

Table 2. Moisture Contents for Typical Resins and Composites (calculated using data from Table 1)

Resin System		20% RH	50% RH	80% RH
T300/1034	Neat	1.36	3.4	5.4
	65% fiber vol	.34	.85	1.36
AS/3501-5	Neat	1.4	3.6	5.8
	65% fiber vol	.36	.90	1.44
T300/5200	Neat	1.2	3.0	4.8
	65% fiber vol	.30	.75	1.20

Units: Wt %

DIFFUSION OF MOISTURE WITHIN COMPOSITES

In order to predict the moisture profile in wet composites and the effect of drying on the possibility of void formation during repair, it is necessary to describe the diffusion process mathematically. It has been shown that for diffusion in one dimension in a composite, the rate of diffusion is given by the relationship:

$$\frac{\partial C_x}{\partial T} = D_x \frac{\partial^2 C_x}{\partial x^2} \quad (4)$$

where $\frac{\partial C_x}{\partial T}$ = rate of diffusion in the X direction
 C_x = moisture content at a depth x from the surface
 D_x = diffusion constant in the X direction

This is a formal definition for a process termed "Fickian" diffusion as it is derived from the mathematical formulation of Fick's first law of diffusion which states that the flux of diffusing material is proportional to the concentration gradient.

Several studies have been reported which show that diffusion of moisture in epoxy resins is approximately Fickian for most concentrations²⁰. At high levels of moisture, a second mechanism of moisture migration has been reported^{20, 23}. It is believed that this is associated with bond rupture and the formation of microcracks in the matrix and it results in permanent damage to the composite.

Bismaleimide (BMI) resins, used as high temperature matrices are reported to have similar diffusion constants and composites based on BMI resins appear to absorb and desorb water similar to epoxy resin composites²⁴.

The diffusion constant and the equilibrium moisture content of a composite sample, can be measured by exposing a weighed sample in the form of a thin plate to an atmosphere of controlled humidity and temperature. The weight increase, expressed as a percentage, is plotted against the square root of time as shown in Figure 1. The slope of the initial linear portion of the plot and the equilibrium moisture content, M_w , are used to calculate the diffusion constant D using equation 5.

$$D = \frac{\pi m^2 h^2}{16 M_w^2} \quad (5)$$

where h = thickness of the specimen

Normally the edges of the sample are sealed using an impermeable sealant to ensure that diffusion is essentially unidirectional.

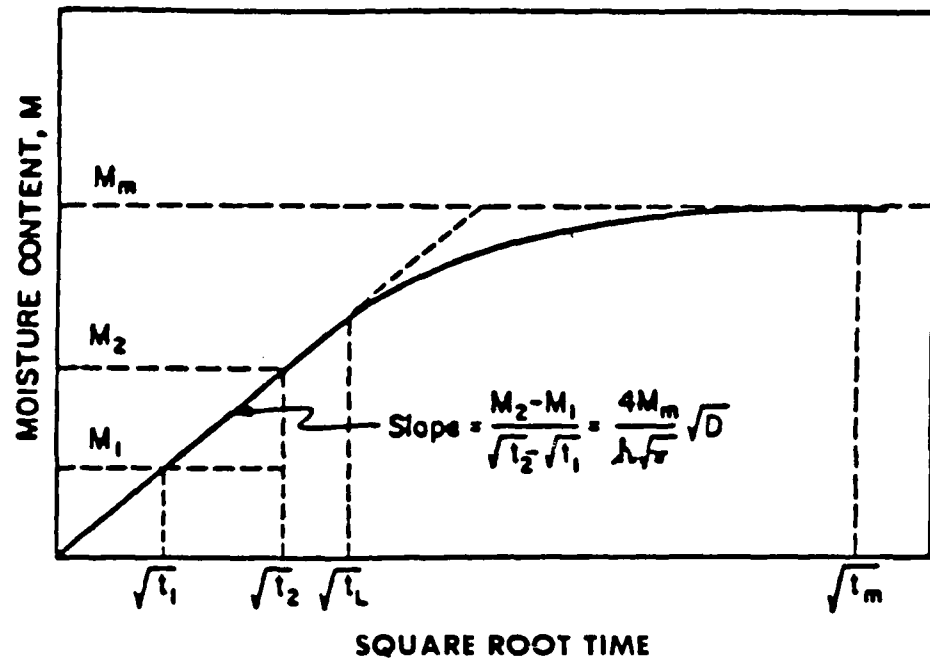


Figure 1 (i). Theoretical Curves for Moisture Uptake¹⁹.

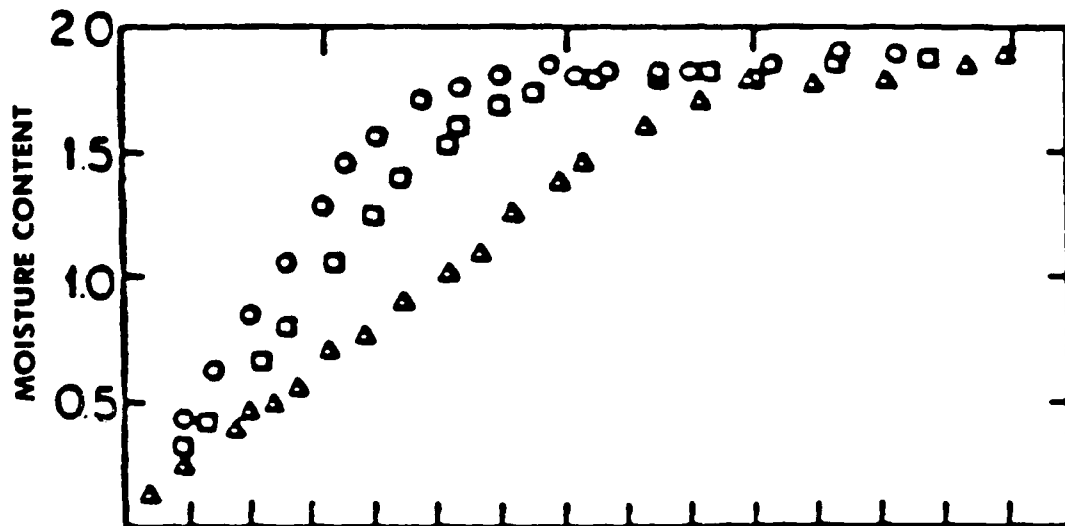


Figure 1 (ii). Results Obtained¹⁶ for Carbon Fiber Composite

Values for M_{∞} measured as a function of relative humidity can be used to determine the best fit values for the constants a and b in equation 2 and values of the diffusion constant d measured at a range of temperatures can be used to determine best fit values for the constants c and D_0 in equation 6.

$$D = D_0 \exp \left(-\frac{c}{T} \right) \quad (6)$$

$$D_x = \left(1 - \frac{\sqrt{v_f}}{\pi} \right) D_0 \exp \left(-\frac{c}{T} \right) \quad (7)$$

where T = temperature in °K

Table 1 gives values for the constants c and D_0 required to calculate diffusion constants for some commonly available composites at any resin content using equation 7.

For normal composite specimens with fibers oriented parallel to the free surface, fiber direction is not a significant variable. For other orientations with respect to the free surface the effective diffusion constant can also be found¹⁶.

PREDICTION OF MOISTURE PROFILES IN COMPOSITES

The equations which describe diffusion of moisture into and out of a thin plate from one or two surfaces exposed to constant temperature and relative humidity (or partial pressure of water) can be solved to give the distribution of moisture within the composite as function of time. The calculations tend to be complex and time consuming especially if environmental conditions change over the lifetime of the experiment. Computer programs have been written, however, to simplify the calculation procedures (2).

An approximate solution can be used to derive the concentration profile of moisture at short times within a composite which is initially at equilibrium with uniform moisture content c_0 , and is exposed to temperature and humidity conditions such that at equilibrium a moisture content c_1 is expected. The concentration as a function of time and depth from the open surface, z, is given by equation 8:

$$c(z, t) = c_1 + \left\{ 1 + \operatorname{erf} \left(\frac{z}{2 \sqrt{D_x t}} \right) \right\} \quad (8)$$

This can readily be calculated if a table of the error function is available. This equation is accurate as long as the moisture content at the center of the laminate is approximately c_0 .

A good technique for estimation of the degree to which a composite is dried by exposure to a fixed temperature and humidity is calculation of the drying depth z_d . This is defined as the depth within the laminate at which the moisture content is the mean of the initial moisture content and the equilibrium moisture content. It can be shown that the drying depth is given by

$$z_d = k \sqrt{D_x t}$$

where $k = \text{constant} = 0.95$ when $c(z, t) = (c_0 + c_1) / 2$

It can also be shown that equivalent depths to the drying depth can be calculated using equation 9 with varying fractions, f , of the moisture content difference $[c_0 + f(c_0 - c_1)]$. This is useful if it is necessary to draw the moisture profile in the composite. Table 3 shows values for the constant k associated with fractional moisture contents, f . Figure 2 illustrates the use of these values for construction of the moisture profile of AS 3501-5 saturated at 80% RH, then exposed to 150°C for 2 hours. The circulation system kept the vapor moisture concentration near zero and hence the equilibrium moisture content to zero. Initial moisture content is calculated using data in Table 1 as 41.3% and the diffusion constant at 150°C is 7×10^{-6} mm/sec.

Table 3. Values for the constant k for given fractional moisture contents in Equation 9.

f	k	z_f
0.1	.196	.031
0.25	.450	.088
0.5	.954	.19
0.75	1.626	.32
0.9	2.328	.46

Calculation for AS 3501-5 at 150°C using data from Table 1.

For circumstances where the external moisture condition changes, such as during predrying of wet composites followed by bonding with a moist, heat-cured adhesive, simple calculations such as above, are not possible. Augl² has developed a computer program suitable for calculating moisture migration and distribution during such processes. The program accepts a preliminary equilibration condition, a drying step or steps and a cure cycle for the adhesive with ramp heat stages, temperature holds and postcures. At each stage, the moisture transport from composite to adhesive and patch is calculated with an open or sealed composite back surface. The resultant moisture profile is also calculated. Input information required includes diffusion data and thicknesses and initial moisture contents of all components. Data can be calculated for circumstances using either metallic or composite patches.

MIGRATION OF MOISTURE DURING BONDING AT ELEVATED TEMPERATURE

In general, moisture will diffuse from a point of higher partial pressure of water to a point of lower partial pressure. In general, the vapor pressure of pure water, P_0 , varies with the absolute temperature, according to equation 10 (calculated from data in ref 27 using a regression analysis).

$$\log_{10} P_0 = 6.97 - \frac{2167}{T} \quad (10)$$

This may be substituted into equation 1 and rearranged to give the actual vapor pressure of moisture absorbed in the composite, P_{moist}

$$\log_{10} P_{\text{moist}} = (6.97 - \frac{\log_{10} a}{b} + \frac{\log_{10} M_w}{b}) - \frac{2167}{T} \quad (11)$$

A similar equation will describe the vapor pressure of moisture in the adhesive, provided the solubility of water is independent of the temperature and degree of reaction of the system.

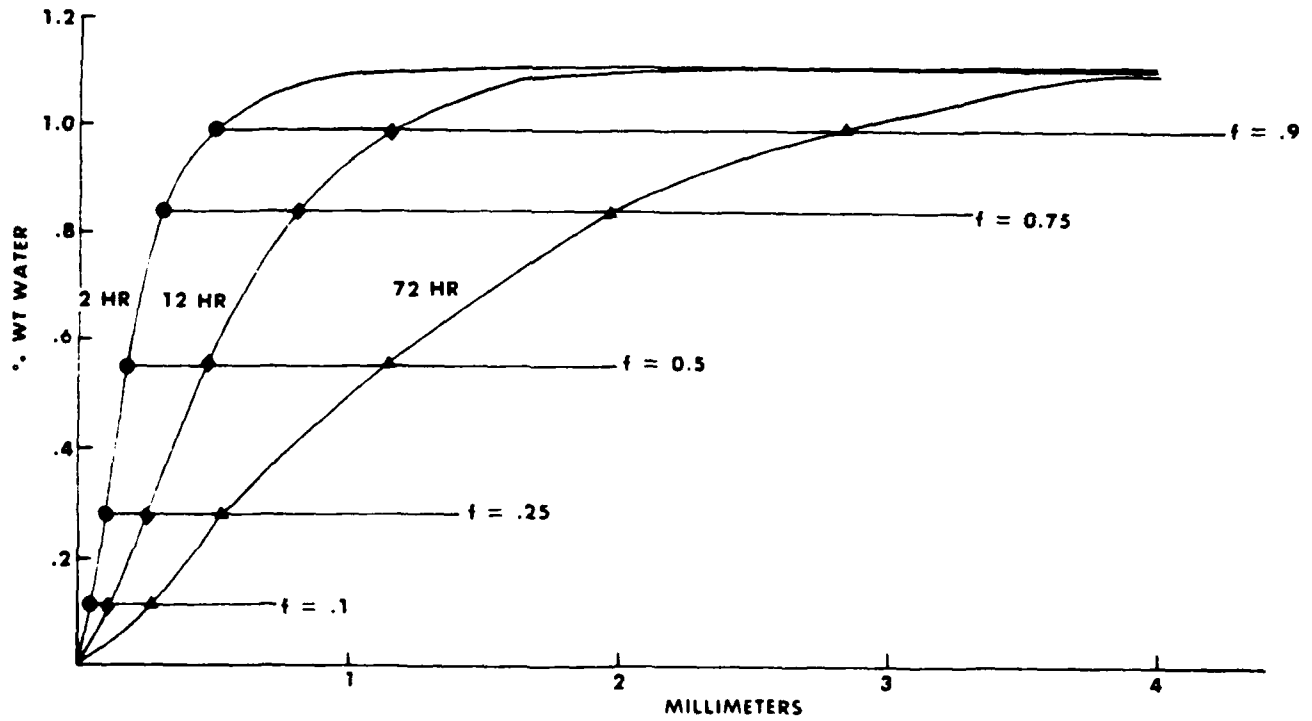


Figure 2. Predicted moisture profile for carbon fiber composite (AS3501-5) saturated with moisture at 80% RH and dried at 150° for 2 hrs. Construction uses values calculated from Tables 1 and 3.

If, in any fluid component in the system, the hydrostatic pressure falls below the the actual water vapour pressure, then a vapour-filled void may initiate and grow depending on factors such as fluid/vapor surface tension, fluid viscosity and local constraints²⁵. Consideration of this factor and using equation 11 void formation can be prevented by:

- (i) Maintaining high local hydrostatic pressure in the adhesive.
- (ii) Reducing the moisture content of the adhesive.
- (iii) Maintaining a low temperature prior to gelation of the adhesive.

Another factor which can affect void formation due to moisture is the formation of amine-hydrates by reaction of moisture with free amine in the adhesive. This may be suspected if the adhesive forms a cloudy film on the surface when exposed to moist air. this problem is usually significant only if aliphatic amines are present in the adhesive. The overall effect is to increase the maximum amount of water in the system and hence the extent of voiding which may occur²⁶. Hydrate formation can be controlled by predrying the adhesive and by limiting contact of the uncured adhesive with moist air.

Once the adhesive has gelled, void formation is less likely. In gelled resins, the local vapor pressure of water must overcome the adhesive or matrix tensile strength and surface energy to form a micro crack. This normally requires loads of 2000-5000 psi, substantially over the hydrostatic pressures prior to gelation which are typically 0-100 psi. Microcracking caused by moisture vapor pressure, will not be considered here.

PRESSURE IN THE BONDLINE

If moisture is present in the adhesive, or diffuses in from wet substrates during cure, the factor controlling void formation is the hydrostatic pressure in the bondline. A theoretical study of bondline pressure during bonding of a rigid patch to a flat substrate has been reported²⁶. Figure 3 illustrates the case studied. Here an external pressure, P_a , is applied to a patch while the edge of the patch is exposed to reduced pressure, P_o . If an external load is used the external pressure will be atmospheric pressure plus the mechanical load divided by the patch area and the edge pressure will be atmospheric. For a repair carried out in a vacuum bag, the external pressure will be atmospheric, while the edge pressure will be the vacuum bag pressure (usually zero). In order to maintain equilibrium, adhesive will flow from the center of the patch toward the edge generating a hydrostatic pressure gradient. It was shown that for a long thin rectangular patch, adhesive flowed from a peak pressure at the center of $3/2 (P_a - P_o)$ to the edge. The pressure P_x , at a distance x from the center line is given by equation 12, as is shown in figure 4.

$$P_x - P_o = \frac{6\eta}{z_t^3} \frac{dz}{dt} \left(\frac{x_c^2}{4} - x^2 \right) \quad (12)$$

where η = viscosity of the adhesive at time t
 z = bondline thickness at time t
 x_o = width of rectangular patch (short side)

This pressure distribution does not change with time until the bondline thickness becomes compatible with the surface roughness. Adhesive flow is then concentrated around the high spots of the substrate and the patch comes to rest. The pressure at the edge of the patch is distributed throughout the patch area when it is fully supported and volatization of water becomes possible.

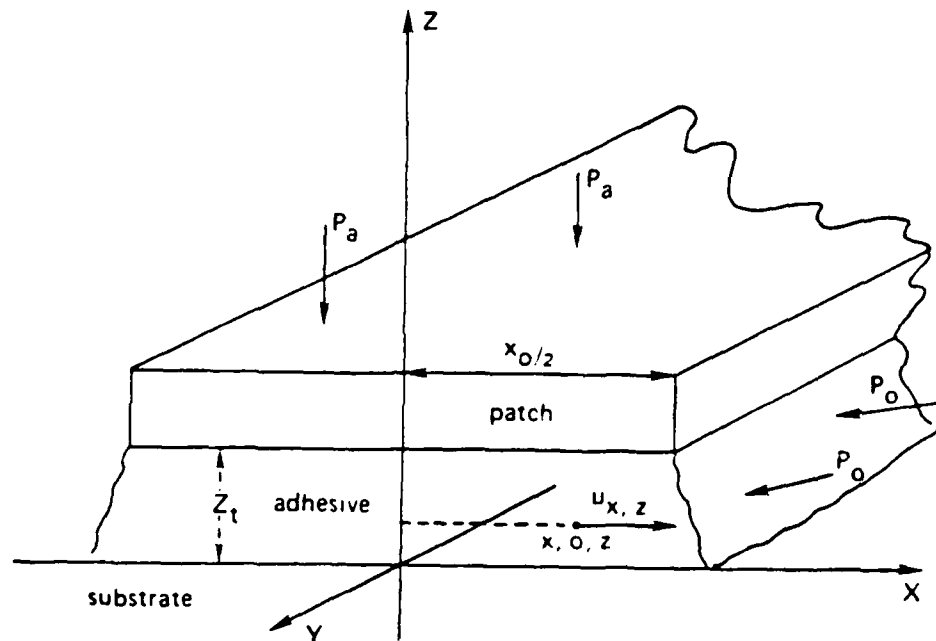


Figure 3. Axes used in derivation of the expression for hydrostatic pressure under a rectangular patch during adhesive bonding²⁶.

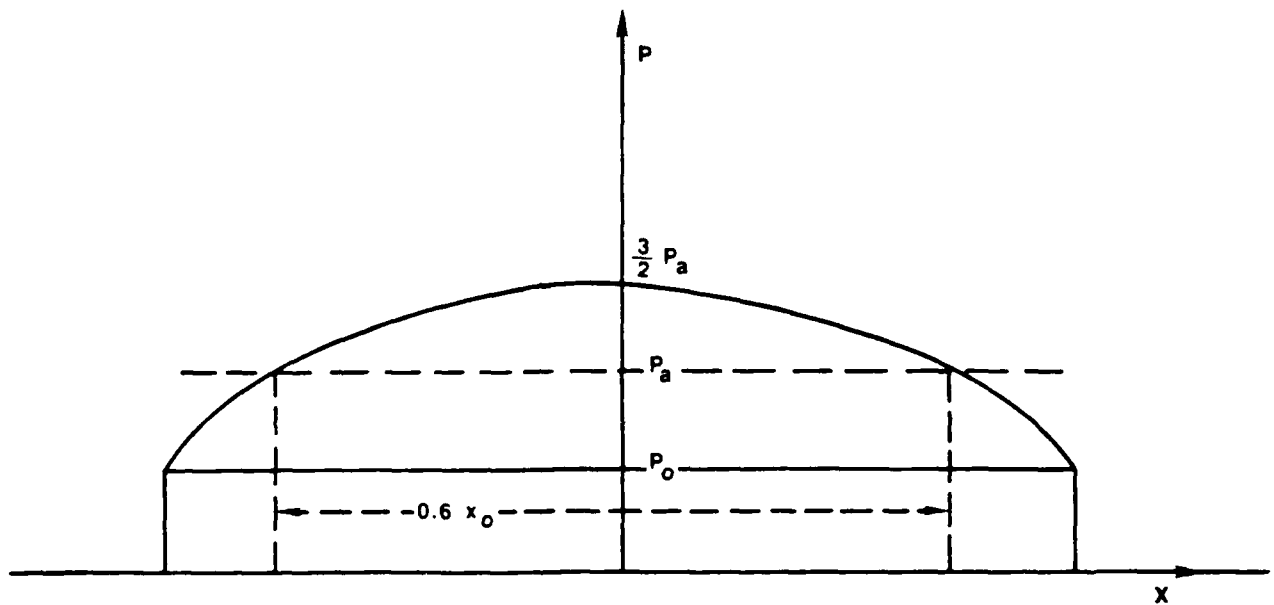


Figure 4. Predicted pressure distribution under a rectangular patch during adhesive bonding as predicted by Equation 12²⁶.

Figure 5 shows the model predictions for the variation of the bondline thickness for a rectangular patch of 4 in. width, subject to a pressure of 15 psi. The adhesive is assumed, here, to have a constant viscosity as shown. The figure illustrates the rate at which the bondline reduces to critical thicknesses indicated by the inclusion of sketches of the tricot knit cloth and dacron scrim typical of commercial adhesive supports. Any technique for controlling bondline thickness using wires or coarse beads, results in the external pressure being carried by the support and the adhesive will be uniformly at the edge pressure (P_0).

For adhesives filled with fibers, a different situation may apply. Here, as the bondline thickness decreases, part of the external pressure will be carried by the fiber bed, which acts as a spring. As the fiber bed compresses, it carries an increasing proportion of the external load and the hydrostatic pressure in the fluid due to the flow decreases correspondingly. The actual fluid flow rate also decreases markedly as the fiber fraction in the bed increases. Support of the patch by the fiber bed should be avoided if the normal hydrostatic pressure distribution is to be maintained. For some fiber systems, such as a thin random polyester mat, the fully compressed fiber bed thickness is of the order of .0002 inches. Flow in adhesives containing these materials is largely as in the unfilled case described above although the effective viscosity of the adhesive will be increased by the presence of the fiber. For open weave continuous fiber clothes, such as tricot knit fabric, the fully compressed thickness is about .005 inches and bondline thicknesses is normally controlled by the compression of the fabric. For control of void formation, it is necessary that the hydrostatic pressure in the adhesive be maintained as high as possible and consequently the process should be controlled so as not to reduce the bondline thickness close to the fully compressed thickness of the support fiber bed.

DRYING OF SUBSTRATES AND ADHESIVES PRIOR TO REPAIR

Removal of liquid water and absorbed water from the surface of a composite can readily be achieved by heating to temperatures over 212°F. Removal of the interior absorbed water, however, is much slower. Augl has calculated the time to reduce the moisture content of a 0.1 inch thick sample of composite (65% fiber) from a moisture content of 1.2% to a moisture content of 0.02% by exposing to dry air at 450°F is about 80 hours while at 350°F it is about 400 hours. Obviously complete drying is an impractical solution to the voiding problem. If drying is to be possible a method estimating the minimum time and temperature needed must be available.

PARTIAL DRYING OF SUBSTRATES

Methods for describing the moisture profile obtained by drying a composite initially at equilibrium moisture content, by exposure to an elevated temperature and reduced humidity were discussed earlier. The technique most suited to the bonding operation is that described by Augl². The computer program he developed calculates the mass of water lost from the composite and the new moisture profile. This technique has the added advantage that the computer holds this profile as input to a curing routine whereby it calculates the weight of moisture migrating out of or into the partially dried composite under conditions of bonding either a permeable (composite) or impermeable (metallic patch onto the substrate). The program, however, is unfortunately not readily transportable from the computer for which it was written (Hewlett Packard), and has not been reported to have been used for field repairs. In addition, the program assumes that the edge pressure on the adhesive (see Fig. 4) is transmitted throughout the adhesive. As described above the actual pressure in the bondline should be maintained at a higher pressure than this. Predictions of void formation by the Augl program will be conservative.

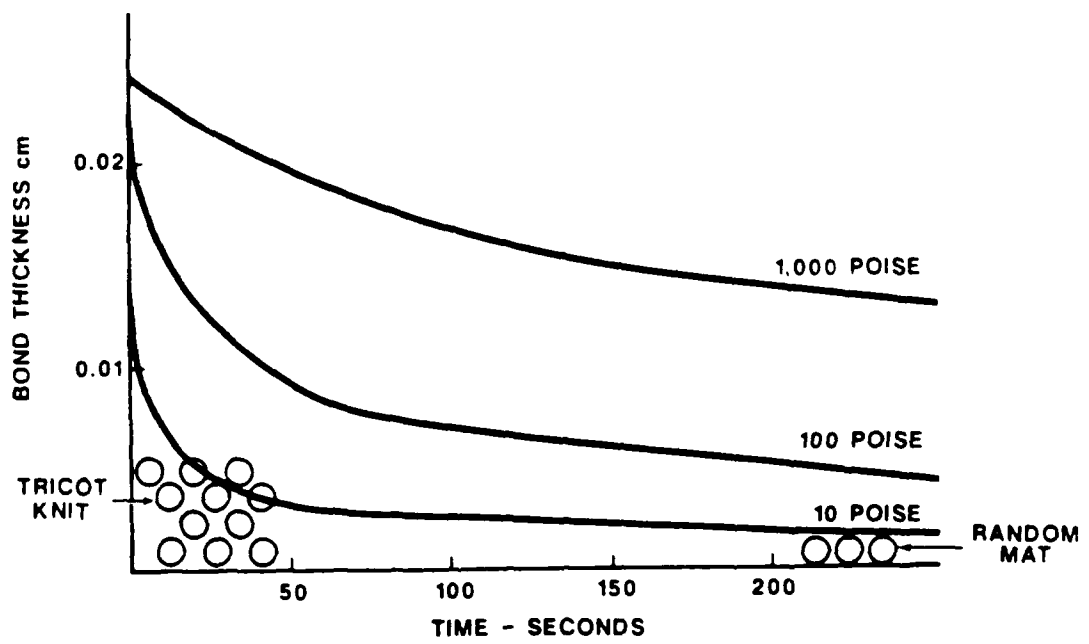


Figure 5. Variation of predicted bondline thickness with time during bonding of a 4 in. patch under a 15 psi pressure at constant adhesive viscosity as indicated²⁶.

A more practical technique for field prediction of minimum drying times is given through the drying depth concept. For this technique the nominal drying depth which would be obtained by exposing the composite to the proposed cure conditions for the adhesive is calculated using the known diffusion constant for the composite and equation 9. The time needed to obtain an equivalent drying depth times a safety factor (e.g. 2) is calculated at the highest drying temperature available. This time is then the best estimate for the shortest safe drying period available.

To use this concept the drying-depth which would be caused by application of the cure procedure to the moist laminate is calculated. For example for a moist graphite T-300 Fiberite 1034 composite to be repaired using an adhesive curing in 1 hour (3600 sec) at 120°C. The diffusion constants for this system at 105°, 120° and 150°C are respectively 1×10^{-6} , 1.7×10^{-6} , and 4.5×10^{-6} mm²/sec. The drying depth will be:

$$\begin{aligned} z_d &= 2 \sqrt{1.7 \times 10^{-6} \times 3600} \\ &= 0.156 \text{ mm} \end{aligned}$$

The component should be dried by a preliminary exposure to drying conditions to give a drying depth greater than this depth by a safe factor. For this example, taking a drying condition of 105°C and using a safety factor of two, the time necessary to dry the composite to this level give by:

$$\begin{aligned} t &= \frac{4z_c^2}{D_x} \\ &= \frac{4 (.075)^2}{10^{-2}} \\ &= 108 \text{ hours} \end{aligned}$$

At a temperature of 150°C the drying time necessary may be calculated to be 24 hours. This technique is based on the assumption that the moisture profile is rectilinear; that the moisture concentration is zero up to the drying depth and at the original moisture level from the drying depth toward the outer edge of the composite. Reference to figure 3 shows that this is not an accurate description of the profile. Application of Augl's computer program over a range of materials typical of structural composites has shown that the amount of moisture migrating into the adhesive from wet composite is considerably reduced by drying for the time recommended by the drying depth technique. Drying cycles at all temperatures resulted in approximately the same weight of moisture diffusing into the adhesive. For systems other than standard epoxy systems some other safety factors may be needed but for the systems based on epoxy resins derived from bisphenol-A or methylene dianiline, a safety factor of two appears reasonable.

It should be noted that the times recommended by the drying depth technique are still high. Generally, drying of adhesive and substrate is a slow process and not suited to military or commercial repair processes.

It is useful to assure that adhesives are dry prior to use. Most film adhesives are stored at sub-ambient temperatures in sealed containers. It is necessary to ensure that the film is brought to room temperature prior to breaking the seal to prevent condensation of water on the exposed cold adhesive. It is also necessary to prevent exposure of the film adhesive to damp conditions. Liquid two-part adhesives represent a special problem. Many amine curing agents are hygroscopic and will absorb moisture from the atmosphere rapidly, particularly during mixing. For these materials, it is advantageous to use special techniques to reduce exposure to moist air. Twin-pack systems using a removable divider to keep resin and curing agents apart prior to use are especially suited to this application.

SELECTION OF CURE CYCLE FOR ADHESIVES

The most reliable approach to reducing porosity in the adhesive bondline caused by vaporization of moisture is to reduce the temperature at which the adhesive gels, and to ensure that the adhesive flow is not significantly retarded by spacers, fillers, or fibers before gelation. This second factor implies that the final bondline thickness should be controlled precisely by choice of an appropriate cure cycle. In general, adhesives designed for manufacturing purposes are selected on the basis of a maximum operating temperature. This is usually associated with high temperature curing conditions. Consequently it is not likely that an adhesive used in manufacture will be entirely suitable for repair purposes. An ideal repair adhesive will gel in the region of 70-90°C and will have a relatively high viscosity (over 100 poise) throughout the selected cure cycle. In order to raise the upper temperature capability of the adhesive, a relatively long post-cure may be necessary in many applications. It is undesirable to require the use of vacuum bag processes to ensure that the patch conforms to the substrate and to apply the external pressure to cause the adhesive to flow during bonding. If it is necessary to use a vacuum bag for convenient field operation, it is crucial to have adequate control of bondline thickness to hold the bondline hydrostatic pressure high. It is then essential that glass spheres or coarse weave cloth (e.g. tricot knit fabric) are not used for bondline thickness control.

MOISTURE IN HONEYCOMB STRUCTURES

Repair of honeycomb structures represents a special problem. Formation of pools of liquid water within honeycomb exposed to high humidity in service has been reported⁶. This often leads to corrosion of the honeycomb which then requires repair by standard techniques, in addition to repair of mechanical damage to the component. However, in many cases, liquid water will be present in honeycomb cells in the vicinity of the physical skin damage. When this area is heated the vapour pressure of the entrapped moisture will rise according to equation 9. Values of the pressure generated by steam as a function of pressure have been tabulated²⁷. The bond strength (flatwise tension), between composite skin and honeycomb, determined for a typical moisture saturated structural adhesive at 250°F and 350°F is over 400 psi (Manufacturer's data sheets). Calculation of steam pressure from equation 10 gives pressures of 29 and 143 psi at each temperature. Steam pressure therefore, is not sufficient to damage an adequately bonded skin. Some degradation of the adhesive must also occur.

CONCLUSION

The repair of wet composites represent a serious restraint on repair procedures. Moisture existing in the adhesive will be compounded by moisture diffusing from the composite under cure conditions. If the repair procedure is inadequately controlled the trapped water will boil in the bondline causing void formation and degradation of the bond strength. Preliminary drying of the adhesive and substrates will reduce the problem by removal of accessible water but is impractical to dry the composite sufficiently to eliminate the problem completely. The best approach for safe bonding of composite is to use an adhesive and adhesive cure cycle which causes gelation to occur at a low temperature (below 90°C) and to avoid as much as possible the use of vacuum bag techniques. If a vacuum bag is required, the tight control of the bondline thickness through selection of a suitable cure cycle is essential.

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