Effects of moisture accumulated into the adhesively bonded composite structures on their bondline mechanical strengths are investigated through a series of comparative experiments. Those composite structures include a honeycomb sandwich structures fabricated by the cocure and the precure processes. Mass of moisture accumulated into the closed cells of the honeycomb sandwich panel specimens has been calculated. A pressure due to the vapor expansion in each cell of the sandwich panel has also been obtained for the minimum repair pressure to be applied to the laminate patched area by vapor pressure–temperature relations from the thermodynamic steam table, the ideal gas state equation and two vapor pressure equations. The bondline strengths of the laminated skins on the flat surface of honeycomb have been compared by the flatwise tension test and climbing drum peel test for dry, wet and repair-after-wet specimens, respectively.

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1. Introduction

The absorbed water in polymeric composite materials has significant influences on the physical and chemical properties of composites as well as final structural/functional performance of composite structures especially in their long-term utilization for aircraft usage [1–5]. The primary and secondary composite structures used in state of the art aircraft usually experience the repeated absorption/desorption of water in a wide range of humidity and temperature during the service life. This type of non-mechanical hygroscopic variation is considered to be closely related to the long-term durability as well as the short term static strengths of the composite structures, especially when the water absorption is accompanied with high variations of temperature and/or mechanical load variations during the service usage of aircraft. Also the moisture absorbed in the structure tends to depress the glass transition temperature by plasticizing the polymer network in the composite structure. As a result of the reduced glass transition temperature induced by water absorption, the initial service temperature range of the aircraft can be restricted severely by early loss of mechanical performance at lowered maximum service temperature. Accordingly, for the applications of high performance composite materials in aircraft environments, the composite structures have been strongly required to satisfy the hot-wet mechanical properties designated in the design specifications, where the structures are tested after being exposed to moisture at high temperatures for specified time [6].

A change in moisture content and/or temperature usually induces hygro-thermal forces as well as dimensional changes in the composite body. In addition, the thermal stresses produced during the cooling process of composite structure after cure at elevated temperature could be so combined with those hygro stresses induced by moisture absorption [7,8]. The resulting hygro-thermal and mechanical stresses combined together with each other may become sufficiently large enough to induce the earlier failure of the composite structures and thus should not be neglected in modern design analysis and lifetime estimation. Furthermore, the recursive changes of internal stresses due to water absorption/desorption processes may induce fatigue damage in the inter/intra-laminar regions as well as bonded interphases/interfaces of composite structures influencing long-term durability and performance of the structure [9]. Also, in the field of composites for aircraft applications utilizing electromagnetic characteristics of structures, the water absorption is one of key issues that should be addressed. Especially in honeycomb sandwich radome structure fabricated with glass fiber reinforced skin and honeycomb core, the absorbed and accumulated water can strongly influence the aircraft safety since the dielectric properties and the electromagnetic characteristics of these functional and safety-related composite
structures can be easily deteriorated by the moisture absorbed in the structure.

Since the structural safety or integrity of honeycomb sandwich structures highly depends on the bonding properties between the honeycomb surface and skin substrates and furthermore the bonding properties depend on its curing method applied, a comparative experimental evaluation of the bondline strengths for cure methods is required.

For the fabrication of composite sandwich structures for aircraft usage using autoclave, there are two different cure methods. One is to cure a sandwich structure layer on the condition that smoke is generated in one time operation so that energy for cure is economically saved. The other is to cure first several parts separately on the different autoclave schedules and later assemble the trimmed parts again into a final structural form in room temperature and cure it in the autoclave. By the energy saving merits for cocure method, it is being newly applied to the fabrication of some parts, which have been fabricated by precise method. In case of fabricating sandwich structures with relatively thin prepreg skins by cocure method, the prepreg may have possibility of being a little pushed into the honeycomb cell by the autoclave pressure so that the cured surface has a kind of surface defect after cure called as a telegraphing phenomenon. Due to this telegraphing phenomenon it is expected that the edgewise-compressive buckling strength of the cocured honeycomb sandwich structure can be lowered than that of the mother composite material. In case that these damaged sandwich parts contain accumulated water in the honeycomb cells, the internal vapor pressure is generated by the accumulated water in the cells.

It is well known that most of all polymeric composites absorb moisture to some extent and its absorption rates or saturated amounts are different from each other and strongly depend upon the matrix materials rather than fibers. While when the composite sandwich structures especially fabricated with Nomex honeycomb core are exposed to the wet environmental conditions, moisture diffused and/or transferred by capillary phenomenon through micro-cracks, interface disbonds, delaminated skins and voids can be so severely accumulated into the structures that the original purpose of adoption of sandwich structures to utilize their merit and cure it in the autoclave. By the energy saving merits for cocure method, it is being newly applied to the fabrication of some parts, which have been fabricated by precise method. In case of fabricating sandwich structures with relatively thin prepreg skins by cocure method, the prepreg may have possibility of being a little pushed into the honeycomb cell by the autoclave pressure so that the cured surface has a kind of surface defect after cure called as a telegraphing phenomenon. Due to this telegraphing phenomenon it is expected that the edgewise-compressive buckling strength of the cocured honeycomb sandwich structure can be lowered than that of the mother composite material. In case that these damaged sandwich parts contain accumulated water in the honeycomb cells, the internal vapor pressure is generated by the accumulated water in the cells. It is possible that the cure process significantly affects the thermal and mechanical behaviors as well as the integrity of the

In this study, skin–honeycomb bondline characterization of sandwich structures will be investigated from the viewpoints of cure methods and moisture absorption. Also such mechanical tests as flatwise tension/compression test [21,22] (abbreviated as ‘FTT/CFT’ in followings) and climbing drum peel test [23] (abbreviated as ‘DPT’ in followings) will be performed for the cocured/precured honeycomb sandwich specimens before and after moisture absorption.

In this study the vapor pressure will be estimated via thermodynamic steam table, ideal gas state equation, and two vapor pressure equations (Appendix A) in order to obtain the minimum weight or repair pressure that should be applied to the external patch to avoid subsequently occurring damages during repair.

2. Experimental

2.1. Preparation of specimens

In order to compare structural performance between cocured and precured honeycomb sandwich panels, carbon/epoxy plain woven fabric composites, specified by McDonnell Douglas (Now, merged by Boeing Co., USA) as DMS 2224 [19] (Type 2, Class W, Grade 4, Hextol Co., USA), and DMS 1974P (type 3, class 2, grade A, thickness of 12.7 mm (0.5 in.), density of 80.1 kg/m³ (5 lbs/ft³)) Nomex honeycomb with hexagonal cells are used for skin and core materials of the sandwich panels, respectively. Also DMS 2177 [20] (American Cyanamid Co., USA) adhesive film is used to bond the skin and core materials for the cocure and/or precure bonding of composite structures. It is possible that the core process significantly affects the thermal and mechanical behaviors as well as the integrity of the
sandwich structures. Since the amount and quality of the fillet formation on which the structural strength depends highly can be changed by the selection of cocure or precure process for the fabrication of sandwich structures, the experimental approach is required to check its dependency upon the process selection.

In the precure process, the primary cure is conducted by curing composite prepreg for the skins with cure temperature and applied pressure of 177 °C (350 °F) and 586.1 kPa (85 psi), respectively. Then, the secondary cure is followed with cure temperature of 121 °C (250 °F) and applied pressure of 310.3 kPa (45 psi), respectively, to prevent distortion or deformation of parts during secondary bonding. On the other hand, in the cocure process, the sandwich structures are cured at 177 °C with applied pressure of 310.3 kPa to suppress the undesired deformation and core crush. Two and three plies of woven DMS2224 prepregs are used for skins of DPT and FTT specimen, respectively, with curing temperature of 177 °C and applied autoclave pressure of 586.1 kPa. The DMS 2177 adhesive films are placed on both top and bottom of Nomex honeycomb sheet with height of 12.7 mm. Then, the prefabricated composite skins are placed on the top of them. The honeycomb sandwich panel is cured up to 121 °C with cure temperature increment rate of 2.78 °C/min (5 °F/min) and hold at that temperature for 2 h in the autoclave as shown in Fig. 1.

During the cure process, vacuum is applied on the part from the beginning of cure to the end of cure. It is expected that the strength and stiffness of the honeycomb sandwich panels are highly dependent on interfacial characteristics between skin and core materials. These interfacial characteristics can be also influenced by both cure process and surface condition of the skins. In order to evaluate the effect of surface roughness of skins on the bondline strength of precure specimens, two types of specimens are prepared. One type of specimens are fabricated with composite skins sanded on the adhesion side with Grit #320 sand paper (3 M Co., USA) and the other type of specimens are fabricated with the skins unsanded but MEK (Methyl Ethyl Ketone) cleaned. The composite skin and honeycomb sheets are vapor degreased and cleaned with MEK prior to bonding. The abbreviations, “CO”, “SP” and “NSP” are assigned to the initial part of specimen names to indicate that the specimens are fabricated with cocure process, precure process with sanded composite skins and precure process with unsanded composite skins, respectively. Also “FT” and “DP” are assigned to specimen names for FTT and DPT specimens, respectively. And “W” and “WR” are assigned to the last part of specimen names to indicate that the specimens are immersed and wet in water bath of 70 °C (for 40 days) for moisture absorption and exposed to hot air of 177 °C for 2 h just after the moisture absorption to simulate repair condition, respectively. The shapes and dimensions of referred specimens used in this study are shown in Table 1 and Fig. 2.

2.2. Moisture absorption of honeycomb sandwich structures

The moisture absorption behavior of honeycomb sandwich structure is monitored by measuring the weight gain of specimens immersed in water bath with time intervals. The weight of immersed specimens are measured with AP210-0 electronic scale with ±0.0001 g measuring error range (OHAUS Co., USA) after the specimens are removed from water bath and excessive water vapor is removed by blowing compressed air to the specimens. As soon as mass of specimen is measured, it is put into the reservoir again for the succeeding absorption of moisture. An appropriate guide is used to fix the location of the floating sandwich specimens in the middle of water reservoir. The required time needed from putting-out and putting-in of the specimen is restricted to be within 1 min to avoid loss of measuring accuracy. The DPT and FTT specimens have been immersed in hot water reservoir of 70 °C for 40 days and the hygroscopic mass changes of the specimens are measured to observe the hygroscopic behavior and the accumulated average mass of water in each cell. As soon as moisture absorption in the water reservoir is finished, mechanical tests for bondline strength evaluation are performed to study the effect of moisture absorption on the bondline strength. Finally some untested but wet specimens are placed to simulate the repair condition in hot oven chamber at the temperature of 177 °C for 2 h to observe influence of internal vapor pressure in honeycomb cells on the bondline characteristics of interface between skin and core materials. The diagram schemes of all tests are shown in Fig. 3a. Fig. 3b is drawn to show that for the cocure specimen, moisture is first absorbed by diffusion to the saturated state in the wall of cells and from this saturated state moisture begins to accumulate as water in the cells. Mass of saturated moisture in the wall of cells and the net mass accumulated water in the saturated cells will be measured experimentally to estimate the internal vapor pressure occurred when repair is being done.

2.3. Mechanical strength evaluation

Bondline strengths of cocured and precured honeycomb sandwich specimens have been evaluated using FTT/FCT and DPT specimens. The tests are conducted according to the ASTM procedures [21–23]. SFM-30 universal testing machine system (10.3-ton max. capacity, United Calibration Co., USA) is used for the mechanical tests. Five consecutive tests have been conducted for each case and the results are represented in an average value. The failed surfaces of the tested specimens are observed to see the bondline

---

**Table 1** Dimensions and cure conditions for moisture absorption test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Width × length × (thickness or ply numbers)</th>
<th>Cure condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>7.62 cm × 7.62 cm × (2 plies)</td>
<td>177 °C, 586.075 kPa</td>
</tr>
<tr>
<td></td>
<td>7.62 cm × 7.62 cm × (3 plies)</td>
<td></td>
</tr>
<tr>
<td>Nomex H/C</td>
<td>5.08 cm × 5.08 cm × (1.27 cm)</td>
<td>–</td>
</tr>
<tr>
<td>Adhesive</td>
<td>5.08 cm × 5.08 cm × (1 film)</td>
<td>177 °C, 310.275 kPa</td>
</tr>
<tr>
<td>DPT H/C</td>
<td>7.62 cm × 22.86 cm × (1.27 cm)</td>
<td>Ccocure/precure condition</td>
</tr>
<tr>
<td>Upper skin</td>
<td>7.62 cm × 22.86 cm × (2 plies)</td>
<td></td>
</tr>
<tr>
<td>Lower skin</td>
<td>7.62 cm × 30.48 cm × (2 plies)</td>
<td></td>
</tr>
</tbody>
</table>

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**Fig. 1.** Autoclave cure cycles for cocure/precure laminate or sandwich panels.
failure modes. The dimensions of specimen, crosshead speed of test machine and the peeling speed are presented in Table 2.

3. Results and evaluation

Fig. 4a shows the force–displacement diagram resulting from FTT test for the cocure and precure specimens. For the cocure specimen with a relatively well-formed fillet at the skin–honeycomb interface where the epoxy resin from the carbon/epoxy prepreg and the epoxy component from adhesive are mixed together in a melted form and cured at the same time in an autoclave, the largest tensile bondline strength is obtained compared to the other cases, i.e., precure-sanded and non-sanded specimens. It is notable that even though the cocured specimens have the largest tensile bondline strength, the stiffnesses for the cocured ones have lower value than for the precure-sanded specimens. Since the cocured specimens have some possibility of micro-buckling damages at the skin–honeycomb interface due to unbalanced compressing forces acting on the normal surface induced by telegraphing phenomenon during the cure process, the tensile bondline stiffness can be lower than precure sanding case. Intuitively it is clear that the skin–honeycomb interface due to unbalanced compressing forces acting on the normal surface induced by telegraphing phenomenon during the cure process might result in a decrease in the stiffness of the cocured specimen.

Fig. 4b shows the peeling force–deformation diagram resulting from DPT test for the cocure and precure specimens. For the peeling torque per unit width required to peel out the skin from the one edge of the specimen, cocured specimens have the largest peeling torque which corresponds to the energy required to propagate the separating line at the crack tip. Also for the cocured specimen, due to the well-formed fillet at the interface along the honeycomb cell boundaries, fluctuations with very sharp saw-tooth shape can be shown in the peeling force–deformation curve. The cocured specimen has the highest average amplitude of fluctuation and can be thought to have better fillet formation than precure case. While for the precure-sanded specimen where the fillet formation is relatively incomplete to the cocure case, saw-tooth shape of the fluctuation becomes smoother with small average amplitude and no fluctuation is found in the precure non-sanded specimen.

Fig. 5 shows Fractography for the three specimens shown in Fig. 4b. In case of cocure specimen shown in Fig. 5a, clear cohesive failure mode, which is desirable for the adhesively bonded structures, can be observed along the honeycomb cell boundaries where the melted adhesive is locked into the micro scratches and cured in a mechanical bonding manner. Also cohesive failure mode is observed in a local zone as shown in Fig. 5b but in the remained zone failure of adhesive at the fillet due to relatively incomplete fillet formation for the precure-sanded specimen compared to the cocure case can be found. But it is notable in the precure-sanded specimen that the fillet formation is thought to be enough to transfer the load across the fillet along the cell boundaries. In addition, in the precure non-sanded specimen, clear and complete disbond of the laminate skin from the adhesive layer represents an interfacial failure mode with no failure at fillet. Three distinct failure modes are observed that cohesive failure with preferable fillet formation is dominant for cocure specimen, adhesive failure with insufficient fillet formation for precure-sanded specimen, interface failure with insufficient fillet formation for precure non-sanded specimen.

Fig. 6a shows mass percent (%) of moisture absorbed into the components with which Nomex honeycomb sandwich panel is fabricated in order to estimate the total mass of moisture diffused into the honeycomb sandwich panel at saturated state without accumulation of moisture inside the sandwich panel specimen. The used components (2ply laminate, 3ply laminate, Nomex honeycomb, 1ply film type adhesive cured at 177 °C) are well dried in the oven and put into the 70 °C water for moisture absorption test. It is shown that in the moisture absorption curve, each component reaches at its saturated state after about 400 h but each amount of moisture absorbed depends on materials. Especially, due to the large net area of wall of cells for Nomex honeycomb, the M% of Nomex honeycomb has the largest value. The moisture content, M%, is defined as the percentage (%) ratio of the mass of absorbed moisture into the dry body to the mass of the dry body. Also it is observed that the cure 1ply adhesive film absorbs more water than the 2 or 3ply laminate skins. Fig. 6b represents the mass of moisture per unit area of the each component.

The moisture absorption behaviors of the 3-type DPT sandwich specimens in the 70 °C water such as M% and the net mass of absorbed water are shown in Fig. 7.

As seen in Fig. 6, the full saturation time from which no more water is absorbed into each component can be selected as about 400 h without loss of generality. But the sandwich specimens are observed to keep absorbing the water even after the saturation time of 400 h for components. Considering the reach of saturated state for the components after 400 h, the mass increased from the saturation time can be thought as the mass of accumulated in the honeycomb cells in DPT specimens. Comparing the moisture absorption behaviors for the cocure and precure specimens, it is noticeable that cocured sandwich specimen absorbs moisture in a linearly increasing manner to the saturation time of the components (400 h) and after the saturation time accumulation into the honeycomb cells looks like beginning. The linearity of moisture
absorption curve seems to result from the fact that the sealing at the skin–honeycomb bondline interface by adhesive layer is so perfect and well formed that the specimen absorbs moisture mainly not by the capillary effect driven by the micro-disbonds or cracks at the interface, but by the moisture diffusion mechanism governed by well known Fickian equation [24,25]. Due to their relatively incomplete and weak bonding characteristics of the precured specimens, severe fluctuations in the moisture absorption curves in Fig. 7 can be found because of the in- and out-flow of water through the locally debonded interfacial areas in the specimens during the air-blowing step taken just before the mass measurement of the specimen to eliminate the attached water drops on the edge surfaces of honeycomb sandwich specimens. It should be noted that even if a similar air-blowing step is taken to the cocure specimen to eliminate the water drops before mass measurement, no fluctuation in the curve is found. This means that the air-blowing step does not give large mass measuring errors. Even with these fluctuations in the precure specimens, gradual increase of the mass can be seen during the moisture absorption. Also it is naturally accepted that precure specimens tend to absorb more amount of water than the cocure specimens in the moisture absorption curves. As mentioned before, due to the cocure specimen’s superior sealing property by the fillet at the skin–honeycomb interface, amount of absorbed moisture is much smaller than the precure specimens. In general autoclave cure process for the honeycomb...
sandwich structures, application of vacuum is necessary for the quality control of the structure and is maintained to the end of the cure. It is reported that honeycomb cells in the structure remain the vacuum state even after the cure is finished [26]. In this paper the vacuum state in the cells after cure for cocured specimens is assumed to remain even after the saturation time of 400 h but a little weakened by the generation of partial vapor pressure in the cells at 70 °C. Then this vacuum state can be thought to accelerate the sandwich structure to absorb more water than precure specimens even after 400 h. While for the precure specimen with less complete bonding than cocure specimen, after 400 h the rate of water accumulation becomes less than that of cocure case since the leakage of vacuum through weak interface bonding.

Mass of purely accumulated water in the cells which is assumed to start to accumulate from the saturation time (400 h) of the components until the end of the moisture absorption test can be calculated as explained in Appendix A. The mass of purely saturated moisture in each component of the cocure specimen can be estimated using the results obtained in Fig. 6. Finally it is subtracted from the total mass of the water measured at the end of the moisture absorption test to obtain the mass of purely accumulated water. It is assumed that the saturated moisture absorption% for each component is independent of the cocure or precure method adopted to cure the component of the sandwich specimens.

If the average inside volume of one cell, average mass of water accumulated in one cell and temperature of the cell are determined at the time \( t \), the vapor pressure in the cell can be easily estimated by the thermodynamic steam table. From the determined values of the saturated mass per unit area of each component in the Fig. 6 and the mass of the moisture at the end of moisture absorption in the Fig. 7, the accumulated mass of water in the inner volume of one cell is obtained as about 0.000610 g/cell (see Appendix A).

Also considering that the wall thickness of cell is 0.1 mm and the ratio of cross-sectional area of the cells to the rectangular area of sandwich specimen is about 0.0695, the inner volume of one cell in average value can be determined as 0.155197 cm³/cell.

The same composite materials as the damaged structure are used as repair materials. Assuming the carbon/epoxy prepreg for 177 °C cure is used as patch material, the same cure temperature is used for cure of repair patches. Since the vapor at temperature of 177 °C is at super heated state, the vapor pressure can be obtained from the thermodynamic steam table [27] as about 775 kPa (7.65 atm). From the Fig. 8 for vapor pressure–temperature curve for the given by the steam table, it can be known that super heated state begins from 167 °C. In addition, the vapor pressure at saturated temperature region given by List [28] is given by

\[
\log_{10}(p_v) = A_1 \left( \frac{T_s}{T} - 1 \right) + A_2 \log_{10} \left( \frac{T}{T_s} \right) + A_3 (10^{(1 - T/T_s)} - 1) + A_4 (10^{(T_s/T_s - 1)}) + \log_{10}(P_0),
\]

(1)

where the saturation vapor pressure, \( p_v \), which is a function of temperature, \( T \), and \( A_1 = -7.90298, A_2 = 5.02808, A_3 = -1.3816 \times 10^{-7} \),
When a composite sandwich structure is damaged, the damaged area is usually repaired by the portable curing equipment called as ‘Hot-Bonder’ which uses hot rubber blanket put on the patched reinforcing composites for cure as seen in Fig. 9a. Fig. 9b represents that in case the structure containing moisture are repaired by hot blanket, compensating mass or minimum repair pressure on the blanket is need to resist the vapor pressure which pushes skin upward and results in local debonding of the normal skin around the patches.

Flatwise tensile test has been performed at room temperature on the cocure and precure specimens as shown in Fig. 10. The specimens are treated in various environmental conditions; dried (\(_D\)), wet (\(_W\)), repair conditioned after wet (\(_W, R\)) states. It is shown that the cocure specimens (CO-) have higher tensile strengths than the precure specimens (SP-, NSP-) in both corresponding comparisons of dried and wet cases, respectively. Also sanded precure specimens (SP-) have superior tensile strength values to the nonsanded precure cases (NSP-). It should be noted that even though the cocured specimen keeps the highest strength when in dried condition, numerical values of specimens are treated in various environmental conditions; dried (\(_D\)), wet (\(_W\)), repair conditioned after wet (\(_W, R\)) states. It is shown that the cocure specimens (CO-) have higher tensile strengths than the precure specimens (SP-, NSP-) in both corresponding comparisons of dried and wet cases, respectively. Also sanded precure specimens (SP-) have superior tensile strength values to the nonsanded precure cases (NSP-). It should be noted that even though the cocured specimen keeps the highest strength when in dried condition, numerical values of 

\[ P = \rho RT \]  

where \( R \) is specific gas constant for superheated water vapor, \( \rho \) is density of water vapor and \( T \) is Kelvin temperature. For a given condition, numerical values of \( R = 0.46189 \) kJ/kgK, \( \rho = m/V = 3.9369 \) kg/m\(^3\) and \( T = 177 \) °C (=450.15 K) are used. The vapor pressure at superheated state can also be calculated from the equation given by Redlich and Kwong [29] as

\[ P_h = \frac{N g T}{V - N_R} \frac{a_R N^2}{T^{1/2} V(V + N_R)} \]  

where \( N = 3.37 \times 10^{16}, \quad a_R = 39.7 \times 10^{-48} \) Pa m\(^6\) K\(^{1/2}\) molecule\(^2\), \( b_R = 3.51 \times 10^{-25} \) m\(^3\) molecule, and \( k_B = 1.3805 \times 10^{-23} \) J/K is Boltzmann constant. This equation is named as ‘Redlich–Kwong eq.’ in Fig. 8 where the superheated vapor pressure at 177 °C is estimated as \( P = 851.5 \) kPa (=8.40 atm).

When the damaged and moisture accumulated composite honeycomb sandwich structures are to be repaired by hot blanket cure process using composite prepregs or laminated patches, it is notable that the honeycomb cell pressure at repair temperature of 177 °C (=350 °F) is about four times higher than that of 121 °C (=250 °F) with the same amount of accumulated water quantity in the honeycomb cell. These two temperatures are known as representative cure temperatures for repair process as well as initial fabricating cure process of most composite structures. When selecting relatively high curing temperature, it is required that optimal repair conditions be maintained to prevent an additional occurrence of damages induced by vaporization of the accumulated water near the damaged zone of the sandwich panel by balancing the internal vapor pressure of the cells with the external weight or corresponding pressure applied on the wider repair area than the patch area in the repair process of the honeycomb structures. Namely, it is notable that at the repair temperature of 177 °C, the internal vapor pressure increases by 10% if the accumulated water quantity in the cell increases by 10% because the internal pressure and the superheated vapor (=water) quantity has a linear relationship as shown in the ideal gas equation and Redlich–Kwong equation in the Fig. 8. The figure shows that vapor pressure in the cell increases in a nonlinear way in the saturated vapor temperature zone up to 167 °C, while it increases almost linearly in the superheated vapor temperature zone after 167 °C. Specifically, if temperature increases by 10% from 121 °C and 177 °C, the pressure increases as much as 42.7% by the List equation for saturated status and 10% by ideal gas equation for superheated status, respectively.

When a composite sandwich structure is damaged, the damaged area is usually repaired by the portable curing equipment called as ‘Hot-Bonder’ which uses hot rubber blanket put on the patched reinforcing composites for cure as seen in Fig. 9a. Fig. 9b represents that in case the structure containing moisture are repaired by hot blanket, compensating mass or minimum repair pressure on the blanket is need to resist the vapor pressure which pushes skin upward and results in local debonding of the normal skin around the patches.

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\[ A_4 = 8.1328 \times 10^{-3}, \quad E_2 = 11.344, \quad E_2 = -3.49149, \quad T_r = 373.16 \text{ K}, \quad P_0 = 101.325 \text{ kPa}. \]  

This equation is also plotted to compare with the result of the thermodynamic steam table, for which two results are close together and the maximum difference is within 4% at 167 °C. The equation given by List is named as ‘List eq.’ in the Fig. 8.

Another method to estimate the vapor pressure for superheated state is by ideal gas state equation. Since the accumulated water in the cell becomes superheated at repair temperature of 177 °C, it is reasonable to assume that the partial pressure by air is negligible and steam follows the behavior of ideal gas. Then by ideal gas state Eq. (1), the vapor pressure can be estimated as \( P = 818.55 \) kPa (=8.08 atm) which is calculated higher than the former method, steam table method.

\[ \frac{P - P_0}{P_0} = \frac{\rho V}{N g T} \]  

where \( \rho = 0.46189 \) kJ/kgK, \( V = 3.9369 \) kg/m\(^3\) and \( T = 177 \) °C (=450.15 K) are used. The vapor pressure at superheated state can also be calculated from the equation given by Redlich and Kwong [29] as

\[ P_h = \frac{N g T}{V - N_R} \frac{a_R N^2}{T^{1/2} V(V + N_R)} \]  

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When the damaged and moisture accumulated composite honeycomb sandwich structures are to be repaired by hot blanket cure process using composite prepregs or laminated patches, it is notable that the honeycomb cell pressure at repair temperature of 177 °C (=350 °F) is about four times higher than that of 121 °C (=250 °F) with the same amount of accumulated water quantity in the honeycomb cell. These two temperatures are known as representative cure temperatures for repair process as well as initial fabricating cure process of most composite structures. When selecting relatively high curing temperature, it is required that optimal repair conditions be maintained to prevent an additional occurrence of damages induced by vaporization of the accumulated water near the damaged zone of the sandwich panel by balancing the internal vapor pressure of the cells with the external weight or corresponding pressure applied on the wider repair area than the patch area in the repair process of the honeycomb structures. Namely, it is notable that at the repair temperature of 177 °C, the internal vapor pressure increases by 10% if the accumulated water quantity in the cell increases by 10% because the internal pressure and the superheated vapor (=water) quantity has a linear relationship as shown in the ideal gas equation and Redlich–Kwong equation in the Fig. 8. The figure shows that vapor pressure in the cell increases in a nonlinear way in the saturated vapor temperature zone up to 167 °C, while it increases almost linearly in the superheated vapor temperature zone after 167 °C. Specifically, if temperature increases by 10% from 121 °C and 177 °C, the pressure increases as much as 42.7% by the List equation for saturated status and 10% by ideal gas equation for superheated status, respectively.

When a composite sandwich structure is damaged, the damaged area is usually repaired by the portable curing equipment called as ‘Hot-Bonder’ which uses hot rubber blanket put on the patched reinforcing composites for cure as seen in Fig. 9a. Fig. 9b represents that in case the structure containing moisture are repaired by hot blanket, compensating mass or minimum repair pressure on the blanket is need to resist the vapor pressure which pushes skin upward and results in local debonding of the normal skin around the patches.

Flatwise tensile test has been performed at room temperature on the cocure and precure specimens as shown in Fig. 10. The specimens are treated in various environmental conditions; dried (\(_D\)), wet (\(_W\)), repair conditioned after wet (\(_W, R\)) states. It is shown that the cocure specimens (CO-) have higher tensile strengths than the precure specimens (SP-, NSP-) in both corresponding comparisons of dried and wet cases, respectively. Also sanded precure specimens (SP-) have superior tensile strength values to the nonsanded precure cases (NSP-). It should be noted that even though the cocured specimen keeps the highest strength when in dried initial state but if attacked by moisture absorption (wet) and heat attacked by repair condition (\(_R\)), its initial tensile strength could be severely deteriorated to the lowest point of 75% decrease as
shown in Fig. 10. This means when repair process should be applied to the moisture-attacked composite sandwich structures, the drying step of the moisture is very important to avoid unexpected loss of structural integrity by the neighboring areas near damaged repair zone. Also in actual manufacturing precure process for the bonded composite structures, non-sanded laminate skins are never used.

For the precured specimens with sanded skins, the pop-up phenomenon caused by debonding due to high internal pressure build up in the honeycomb cells is observed in the skins of sandwich panel. The precured specimens did not show any noticeable deformation in the skins because the weak bond between skin and core materials caused leak of internal pressure in cells from the initial stage. These phenomena are actually observed in the field repair procedures at composite repair shop of Korean Air.

For the cocured specimens, the skins of sandwich panel are slightly bulged and no sign of debonding between skin and core materials is observed showing high bondline adhesion. These phenomena are indirectly noted in Fig. 11 showing the results of DPT test. Similar to the results shown in Fig 10, the cocured specimens have the highest peeling torque per unit width and precured specimens with unsanded skins have the lowest peel torque per unit width. The precured specimens with sanded skins have the peel torque per width 20% less than that of cocured specimens. It is also shown in the figure that the peel torques per width of moisture-absorbed specimens are slightly smaller than those of dry specimens.

Fig. 12 shows the results of flatwise compression tests of specimens in Fig. 10 and Nomex honeycomb core. The cocured specimens showed superior in stiffness and strength over precured specimens. The precured specimens showed a little influence of bondline adhesion and moisture absorption. For the cocure specimens, the reduction of strength is expected due to telegraphing. However, the formation of better filleting compare to that of precured specimens must have compensated the strength reduction. The small reductions of strength and stiffness of Nomex honeycomb are obtained with moisture absorption.
4. Conclusions

In this study, the effect of several aspects such as cocure/precure process differences, moisture absorption and repair temperature on the structural integrity of Nomex honeycomb sandwich structures widely used in the aircraft structures has been considered through mechanical drum peel and flatwise tensile tests. The several results are extracted as follows:

1. Most desirable fillet formation resulting from the chemical mixing and bonding of prepreg resin and adhesive is observed to have the largest bondline strength in cocured honeycomb sandwich structure. Cocured sandwich structure tends to absorb moisture in a linearly increasing manner with no fluctuation. While precured sandwich structure absorbs in an increasing manner but with large fluctuation resulting from the in- and out-leakage of moisture through micro debonding of interface due to weak bonding.

2. The moisture absorbed and accumulated into the honeycomb sandwich structure can severely reduce the peeling resistance, bondline tensile/compressive strengths at the interface between composite laminate skin and honeycomb surface. Honeycomb sandwich structure has the highest bondline strengths when cocured even in wet environmental conditions. Especially when repair condition is applied to the sandwich structure, cocured structure shows better structural stability than precured one.

3. When water is accumulated in the sandwich structure and it is found, then this structure is to be repaired as soon as possible. Cautions to avoid subsequent debonding of skin near repair zone, resulting from the internal vapor pressure in cells of undamaged zone near damaged-and-being repaired zone, must be given during the curing process for repair of honeycomb sandwich structures. The vapor pressures have been calculated to be high enough to induce debonding of skins at the repair temperature from the thermodynamic steam table, ideal gas state equation and vapor pressure equations suggested by List and Redlich–Kwong, respectively. Also these vapor pressure values can be used to obtain the value of minimum weight balance (or repair pressure) that should be put or applied on the repair areas to avoid debonding of skins induced by the vapor pressure during repair process of damaged and moisture accumulated honeycomb sandwich composite structures.

Appendix A. Calculation of water vapor pressure in a honeycomb cell by ideal gas equation and vapor pressure equation

1. Saturated mass of moisture absorbed into each element consisting of honeycomb sandwich panel.
   - Areal density of Nomex honeycomb (H/C): 0.4857 g/(2 in. × 2 in.) = 0.01882091 g/cm².
   - Areal density of 1 ply adhesive: 0.0012277 g/cm².
   - Areal density of 2-ply woven laminate: 0.0524 g/(7.462 cm × 7.395 cm) = 0.00094958 g/cm².

2. Saturated mass of moisture absorbed into cocure DPT specimen with no accumulation (see Fig. 7).
   - Total mass of moisture in laminate with area of two 2-ply woven fabric laminate skins (9 in. × 12 in.) = 63 in.² × (6.4516 cm²/in.²) = 0.0094958 g/cm² = 0.38596 g.
   - Total mass of moisture in adhesive with area of 2 × (9 in. × 3 in.) = 54 in.² × (6.4516 cm²/in.²) = 0.0012277 g/cm² = 0.042771 g.
   - Total mass of moisture in H/C with area of 9 in. × 3 in. = 27 in.² × (6.4516 cm²/in.²) = 0.01882091 g/cm² = 3.27847 g.
   - Total saturated mass in cocure DPT specimen with no moisture accumulation in cells = 0.38596 g + 0.38596 g + 3.27847 g = 4.05039 g.

3. Final mass of moisture absorbed into cocure DPT specimen (see Fig. 7) = 4.8596 g.

4. Accumulated mass of moisture in the 9 in. × 3 in. honeycomb sandwich panel = 4.8596 g – 4.05039 g = 0.80921 g.

5. Average number of cells per unit area of honeycomb sandwich panel = 49.125 cells/in².
   - Number of cells in cocure DPT specimen = (9 in. × 3 in.) × 49.125 in.² = 1326.375 cells.

6. Average mass of moisture accumulated in each cell, m = 0.80921 g/1326.375 cells = 0.000610 g/cell.

7. Inside volume of one cell (V).
   - Average volume of cells: 0.5 in. × 9 in. × 3 in./1326.375 cells = 0.01017812 in.³/cell = 0.00016678945 cm³/cell.
   - Wall thickness of Nomex honeycomb cell = 0.1 mm.
   - Ratio of area of cross-sectional area of wall to the area of one unit cell = 0.0695.
   - Inside volume of unit cell considered the wall thickness 0.1 mm, V = 0.16678945 cm³/cell × (1–0.0695) = 0.155198 cm³/cell.

8. Vapor pressure induced by the moisture (n = 0.000610 g) accumulated in a cell of inside volume V = 0.155198 cm³ can be estimated in terms of temperature T by thermodynamic steam table, ideal gas state Eq. (2) and two vapor pressure Eqs. (1) and (3).

References