Research Article

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Influence of hydrothermal aging on the mechanical performance of foam core sandwich panels subjected to low-velocity impact

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Abstract: The effect of hydrothermal aging on the impact resistance of foam core sandwich panels is studied in this study. The sandwich panels with glass fiber-reinforced skins and polyurethane foam core were fabricated and then were treated with different hydrothermal aging conditions. The moisture absorption characteristic of the composite skins was evaluated. A modified Fickian formulation was proposed to predict the moisture absorption behavior of composite skins. The low-velocity impact resistance of the aged sandwich panels was determined at three different impact energies. The impact responses including contact force, deflection, and dissipated energy of the sandwich panels with and without hydrothermal aging were analyzed. The macroscopic and microscopic damage morphologies were observed by visual inspection and scanning electron microscope methods, respectively. The damage mechanism of the aged panels was revealed. Results indicate that the impact resistance of aged sandwich panels is degraded, and the performance degradation is larger with increasing aging temperature. Compared to the panel without hydrothermal aging, the reduction of the contact force is 35.69%, and the increase of the deflection is 71.43% for the aged panel at 70°C aging temperature. The fiber/matrix interfacial cohesive performance is degraded resulting from the hydrothermal aging.

Keywords: sandwich panel, hydrothermal aging, impact resistance, damage mechanism

1 Introduction

In recent decades, composite sandwich panels have been widely used in many fields such as aerospace, ship-building, automobile industry, and wind turbine blades due to superior properties in terms of high bending stiffness to weight, good corrosion resistance, simple fabrication, multifunction integration, high anti-impact, and vibration performance [1–5]. Moreover, the effect of hybrid composite, shape, and size of composite structure on the low-velocity impact performance have attracted attention from researchers [6–10]. However, sandwich panels suffer from severe environment such as exposure in hydrothermal condition or immersion in water, which can reduce the mechanical performance of sandwich panels including tensile, compressive, and flexural properties [11–13]. Therefore, the research on the influence of hydrothermal aging has been a crucial issue for more security and wider application of the sandwich structures.

The water inevitably permeates the foam core sandwich panels, which are in the hydrothermal environment. In general, the water exists in free or bound form in the sandwich panels. The moisture absorption characteristics of composites have been studied by many researchers [14–17]. Popineau et al. [14] studied the water absorbed by an epoxy resin through gravimetry. Based on the free and bound components of water considered separately, they found that the moisture absorption of the epoxy resin achieves a good, overall, empirical agreement with the classic Fickian model. The effects of seawater on foam core composite sandwich lay-ups were investigated by Li and Weitsman [15]. The weight gains, expansional strains, and performance degradation of foam materials due to extended exposure were evaluated. Furthermore, the influences of seawater on the fracture behavior of foam materials and on skin/core interface performance were investigated experimentally and numerically. In the study of Katzman et al. [17], the moisture diffusion experiments on a sandwich material made of graphite-epoxy face

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sheets and a foam core were conducted and a multilayer diffusion model applicable to sandwich structures was established. The results revealed that the skins can retard the moisture diffusion into the foam core but they do not prevent the foam core from absorbing moisture.

The degradation of composites performance can be interpreted by two aging mechanisms. One is the physical aging in terms of swelling and plasticization, and another is the chemical aging including curing reaction and hydrolysis [18,19]. The effect of hydrothermal aging on composites can be affected by temperature and water content. The aging process is generally accelerated by high ambient humidity and temperature experimentally [20–23]. The effects of hydrothermal aging on the mechanical properties of composite sandwich panels have been reported in many literatures [24–30]. Joshi and Muliana [24] evaluated the influence of transient moisture diffusion on the deformation of the sandwich panel consisting of fiber-reinforced laminated face sheets and polymeric foam core using finite element analysis. The results showed that the overall long-term deformation of sandwich panel is increased and is attributed to the viscoelastic foam core without moisture degradation. The deformation of the sandwich panel is more aggravated resulting from the transient moduli of the foam core degrading with moisture concentration. Degradation of mechanical performance of foam core sandwich panels exposed to high moisture and immersed into seawater was experimentally investigated by Avilés and Aguilar-Montero [25]. Testing showed significant reduction in the flexural stiffness and strength of the laminated skins, only minor tensile stiffness and strength decreased for the foam core. Compared to the degradation of the interfacial skin/core fracture toughness of sandwich panels exposed to elevated moisture, the degradation of sandwich panels immersed in seawater was more serious. The moisture absorption and mechanical degradation of glass fiber-reinforced vinyl-ester sandwich panels with polyurethane foam core were studied by Manujesh et al. [27]. The moisture uptake behavior of the prepared specimens was tested, and the induced performance degradation in terms of flatwise and edgewise compressive strength and flexural strength was evaluated. Their study indicated that the foam core shear strength, skin bending strength, flatwise and edgewise compressive strength of sandwich panels are all decreased resulting from the effects of hydrothermal aging. The influences of hydrothermal aging on the mechanical properties of sandwich panels in terms of flexural performance and flatwise and edgewise compressive properties have been reported by above literatures. As revealed by researches [31–35], the

sandwich panels are inherently sensitive to localized damage (matrix cracking, delamination, skin/core debonding, local core crushing, etc.), resulting from transverse loading such as low-velocity impact. Hence, the effect of hydrothermal aging on the impact mechanical performance of sandwich panels is also worth studying. This study mainly focuses on the degradation of the impact resistance of foam core sandwich panels exposed in a long-term hydrothermal environment.

The moisture absorption characteristics of composites and the influence of hydrothermal aging on the impact performance of foam core sandwich panels were investigated in this study. First, sandwich panels consisting of glass fiber-reinforced laminated face-sheets and polyurethane foam core were manufactured by vacuum-assisted resin injection (VARI) process. Second, the sandwich panels and face-sheet composites were treated with different hydrothermal aging conditions and the moisture absorption property of the face-sheets was evaluated. Third, the low-velocity impact tests on the sandwich panels after 30 days aging time were carried out at three different impact energies. The impact mechanical responses including contact force, deflection, and absorbed energy were compared. The microstructures of the damaged skins with and without hydrothermal aging were observed by scanning electron microscopy (SEM), and the damage mechanism of sandwich panels with hydrothermal aging was revealed.

2 Materials and methods

2.1 Materials

In this study, the laminated face-sheets were made of plane weave glass fabrics and vinyl ester resin. The resin matrix can be cured at room temperature mixed with the accelerating agent dimethylaniline and the hardening agent methyl ethyl ketone peroxide. The resin, accelerating agent, and hardening agent were purchased from Harbin, China. The weight ratio of 100:1:0.15 was applied to mix the resin and the hardening and accelerating agents. The two-dimensional orthogonal plane weave glass fabric cloth with a surface density of 600 g/m^2 and single layer thickness of 0.3 mm was provided by Tongxiang Mentai Reinforced Composite Material Company in Tongxiang, China. For both the face-sheets of all specimens, they are stacked with eight layers of weave glass fabrics. The polyurethane foam with a density of 75 kg/m^3 was applied as the core, which was 10 mm in thickness in this study.

Figure 1: Sandwich panels manufactured by the VARI process.

2.2 Specimen manufacturing

The foam core sandwich panels were fabricated by the VARI method, which is convenient and practical for the thermosetting resin composites used in this study. Figure 1 shows the schematic of the VARI process. The specimen manufacturing process can be described as the following. First, a glass plate was fixed on a table as the workbench. Second, the sandwich panel and one layer of release cloth at each side of the panel were placed on the glass plate. The plane weave glass fabrics and the polyurethane foam core were arranged according to the desired lay-up. Third, to help the resin flow quickly, one layer of diversion net covered the whole structure. Then, the whole structure was sealed in a vacuum bag with the help of sealant tape because, in vacuum environment, the air is exhausted out, and then the resin is infused into the gap between fibers. To make the resin flow uniformly, two delivery pipes were bonded at the entrance and the exit of the structure, respectively. Finally, the resin mixture was injected to the structure. The system was cured with a vacuum level of 600 mbar for 24 h at room temperature.

2.3 Hydrothermal aging treatment

Samples were aged in a climatic chamber (SY/GS, Xi'an, CHINA) that can provide the temperature and humidity at the same time. The climatic chamber is illustrated in Figure 2. In this study, four different temperatures, 25, 40, 55, and 70°C, were investigated with the same relative humidity of 85%, respectively. To evaluate the moisture absorption behavior of the samples, the hydrothermal aging duration was up to 30 days, and the samples were examined every day. To assess the hydrothermal aging on the degradation of impact resistance, the samples with the aging time of 30 days were used, and at least five samples

were taken out from the chambers at each temperature for the low-velocity impact testing.

2.4 Low-velocity impact testing

The low-velocity impact tests on the sandwich panels with and without aging treatment were carried out by the Instron Dynatup CEA5T 9250HV (Instron, Norwood, MA, USA) testing machine at room temperature, which is shown in Figure 3. The test system consists of three parts: the pneumatic clamping fixture, a drop hammer device, and a data acquisition system. Based on the American

Figure 2: Climatic chamber for hydrothermal aging.

Figure 3: INSTRON 9250HV impact testing machine.

Society for Testing and Materials D5420-2010 standard, the manufactured sandwich panels were cut with the dimensions of 100 mm × 100 mm using a diamond saw blade-cutting machine. The hemispherical projectile with 16.9 kg in mass and 12.7 mm in diameter was used in the testing. The impact energy of 10, 16, and 20 J are loaded on different aged samples, resulting in a low-velocity impact behavior of the sandwich panels. The contact force was recorded by a load cell located just above the projectile head, and the displacement was determined by a laser detector. The impact-absorbed energy can be analyzed based on the data acquisition system. After the impact testing, the damage modes of damaged samples were identified by visual inspection and SEM (Hitachi S-4300, Tokyo, Japan) methods. The microdamage morphology of the face-sheets was observed in the damaged region of sandwich samples.

3 Results and discussions

3.1 Moisture absorption characteristics

The moisture absorption behavior of composites generally includes two stages, namely the permeation and diffusion of the water molecular and the hydrolysis reaction of the resin matrix. Generally, the weight of sample increases due to the diffusion of the water molecular, and then the moisture sorption gradually reaches saturation, and the weight is nearly stable during the first stage. With time increasing, the hydrolysis reaction of little resin occurs, and the weight of sample is reduced in the second stage.

The second law of Fickian behavior can be applied to interpret the moisture absorption behavior of composites [16,17]. The moisture absorption ratio depends on the concentration gradient of water and the diffusion coefficient. Due to the thickness of composites is much less than the length and width, the moisture absorption ratio can be written as follows:

$$\frac{dM}{dt} = -D_x \frac{dC}{dx}, \quad (1)$$

where M is the weight of sample, C is the concentration of water, and D is the diffusion coefficient.

The diffusion of water is determined by its concentration gradient; hence, the Fickian formulation can be replaced by

$$\frac{M(t)}{M_m} = 1 - \exp \left[-7.3 \times \left(\frac{Dt}{h^2} \right)^{0.75} \right], \quad (2)$$

where M_m is the moisture absorption ratio when the sample is in moisture absorption equilibrium. h is the thickness of sample.

The diffusion coefficient D in above formula can be calculated as follows:

$$D = \pi \left(\frac{h}{4M_m} \right)^2 \left[\frac{(M_{t_2} - M_{t_1})^2}{t_2 - t_1} \right], \quad (3)$$

where M_{t_1} and M_{t_2} are moisture content at times t_1 and t_2 , respectively.

The diffusion coefficient D of composite face-sheets at different temperatures can be calculated, and the values are summarized in Table 1. Then the moisture absorption ratio of samples at 25, 55, and 70°C are determined. The moisture absorption ratio of composite face-sheets based on the experimental results and numerical analysis are plotted in Figure 4. It can be seen that the moisture absorption characteristic of composites shows the Fickian behavior at different temperatures. The moisture absorption ratio is linear increased versus to the aging time at initial phase. Then the moisture absorption ratio increases slowly until reaching the saturation level. After moisture equilibration, the moisture absorption ratio is decreased because of the hydrolysis reaction of the resin

Table 1: Diffusion coefficient and the equilibrium moisture content at different temperatures

Temperature (°C)	Diffusion coefficient ($10^{-6} \text{ mm}^2/\text{s}$)	Equilibrium moisture content (%)
25	3.24 ± 0.08	6.66 ± 0.14
55	27.3 ± 0.82	5.98 ± 0.19
70	49.7 ± 2.19	5.33 ± 0.26

Figure 4: Moisture absorption ratio versus aging time curves based on experimental results and numerical analysis: (a) 25°C, (b) 55°C, and (c) 70°C.

matrix. The moisture absorption ratio of samples reaches saturation after 25 days aging at 25°C, and the hydrolysis reaction is nearly not found because of no weight loss after moisture equilibration. At room temperature, the composite structure is not damaged due to no hydrolysis reaction, the integrity of samples is not affected, and thus nearly no new cracks are formed. The moisture absorption behavior of samples mainly shows the permeation and diffusion of water molecular through original defects while the time of moisture equilibration is just 5 days for 55 and 70°C samples. Thus, it can be concluded that the moisture absorption ratio of composites can be accelerated by temperature, which is in consistent with the results in Yang et al. study [36]. Moreover, the moisture absorption characteristic is no longer in agreement with the Fickian curves after moisture absorption saturation, especially for the 70°C samples. The weight of samples is reduced resulting from the hydrolysis reaction of resin matrix in this phase, and the moisture absorption characteristic is generally known as the un-Fickian behavior.

Based on the diffusion coefficient at 25, 55, and 70°C summarized in Table 1, the diffusion coefficient versus time curve is drawn in Figure 5. The relationship between parameter diffusion coefficient D and aging temperature T can be thus determined, and the formulation is given by

$$D = 7 \times 10^{-7} \times e^{0.0636T}. \quad (4)$$

The formulation indicates that there is an exponential relationship between the diffusion coefficient and temperature. Substituting equation (4) into equation (3), the modified Fickian behavior formulation appropriate for plane weave glass fabrics composite laminates can be acquired as follows:

$$\frac{M(t)}{M_m} = 1 - \exp \left\{ -7.3 \times \left[\frac{7 \times 10^{-7} \times e^{0.0636T} \times t}{h^2} \right]^{0.75} \right\}. \quad (5)$$

To verify the availability of the modified Fickian moisture behavior formulation, the plane weave glass

Figure 5: Diffusion coefficient versus to temperature curve in hydrothermal aging process.

fabrics composite laminates treated at 40°C hydrothermal aging conditions were also carried out. The moisture absorption ratio versus aging time curve based on the experimental results and the numerical analysis calculated by modified Fickian formulation is shown in Figure 6. It can be indicated that the numerical analysis based on the modified Fickian formulation agrees well with the experimental results in the first stage of composite moisture absorption behavior.

3.2 Effects of hydrothermal aging on impact resistance

3.2.1 Effects of hydrothermal aging on the impact responses

The typical impact responses of sandwich panels in terms of contact force, displacement, and absorbed energy are shown in Figure 7. It can be seen that all sandwich panels are not penetrated. For the panels subjected to 10 J impact energy, the force–time curves show that only one peak force is recorded except the 70°C aged panel. Consistent with the damage morphology discussed above, one peak contact force indicates that the front face-sheet is not penetrated by the projectile, the main damage modes include matrix cracking, local fiber breaking beneath the projectile and some foam core crushing. For the panels suffering 16 and 22 J impact energies, there are two peak forces on the force–time curves except the panels without hydrothermal aging, which indicates that serious damage is induced into the sandwich panels with hydrothermal

Figure 6: Moisture absorption ratio versus aging time curve based on the experimental results and the modified Fickian formulation.

aging, and the front face-sheets are penetrated. For the sandwich panels with front face-sheets penetrated, the contact force–time curves can be divided into two parts, which agrees with the damage morphology observed in sandwich panels. The first part of the force–time curve indicates that the projectile penetrates the front face-sheet, and the first peak force appears in this process. The second part mainly includes the contact between the projectile and the foam core, and the interaction between the broken front skin and the foam core. The second peak force is formed in this stage, and the rear face-sheet plays a major role in supporting the impact loading after the breaking of the front face-sheet and the local compression crushing of the foam core. In general, compared to the reference panel, the contact forces of the aged panels are decreased, and the contact peak force is smaller with increased aging temperature for the three impact energies. For the force–displacement curves, it is apparent that the maximum deflections of the samples with hydrothermal aging are all larger than the samples without hydrothermal aging. Moreover, the maximum displacement and the residual deformation are larger with increasing aging temperature. For the impact-absorbed energy, there is almost no difference between the samples with different aging temperatures for the three impact energies. The absorbed energy of the reference samples is the smallest, and a little more impact energy is released in the rebound phase compared with the aged samples.

Based on the experimental data, the maximum forces, displacements, and the absorbed energies are summarized in Table 2. The maximum contact force can be a mechanical parameter indicating the impact resistance of sandwich panels, a larger contact force suggests a better

Figure 7: Typical impact responses (force–time, force–displacement, and energy–time) of the sandwich panels for the three impact energies: (a) 10 J, (b) 16 J, and (c) 22 J.

loading support capability [33,34]. For the 10 J impact energy, the peak force of the panel without hydrothermal aging is the largest and is 3.44 kN, whereas the value reduces to 2.42, 2.24, 1.95, and 1.68 kN for panels with hydrothermal aging at 25, 40, 55, and 70°C, separately. For the 16 J impact energy, the peak force of the reference panel 3.73 kN decreases to 2.73, 2.54, 2.25, and 1.96 kN for panels with 25, 40, 55, and 70°C aging temperatures, separately. The same trend of the maximum force is indicated for the 22 J energy, and the peak force can decrease from 3.98 kN of the reference panel to 2.56 kN of the panel with 70°C aging temperature. Moreover, it can be seen that the degradation of the peak force is larger with increasing aging temperature, and the degradation can reach 35.69% for the 70°C aging temperature at 22 J impact energy. Thus,

the impact resistance of foam core sandwich panels is degraded due to hydrothermal aging, and the high aging temperature can aggravate the impact performance degradation. The maximum displacement can be another mechanical parameter to assess the impact performance, better impact resistance of sandwich panels produces smaller deflection attributing to the higher bending stiffness [33,34]. The maximum displacements of specimens with hydrothermal aging are larger than that of the reference specimen throughout the three impact energies. In detail, for the 10 J impact energy, the maximum displacement of the reference sample is 5.46 mm, whereas the values are 6.64, 8.23, 9.42, and 12.16 mm at 25, 40, 55, and 70°C aging temperatures, respectively. The displacement of the reference panel 8.11 mm increases to 9.62, 11.06, 11.92, and

Table 2: Impact mechanical parameters for sandwich panels with and without hydrothermal aging

Energy (J)	Parameters	25°C – 0 days	25°C – 30 days	40°C – 30 days	55°C – 30 days	70°C – 30 days
10	Ultimate force (kN)	3.44	2.42	2.24	1.95	1.68
	Displacement (mm)	5.46	6.64	8.23	9.42	12.16
16	Ultimate load (kN)	3.73	2.73	2.54	2.25	1.96
	Displacement (mm)	8.11	9.62	11.06	11.92	13.78
22	Ultimate load (kN)	3.98	2.92	2.74	2.45	2.56
	Displacement (mm)	10.08	12.25	13.70	14.72	17.28

13.78 mm for the panels with aging temperature increasing at 16 J impact energy. Compared with the panel without hydrothermal aging, the maximum displacement has an increase of 21.53, 35.91, 46.03, and 71.43% for the panels with 25, 40, 55, and 70°C aging temperatures at the 22 J impact energy, respectively. Similarly, the increase of the deflection is larger with higher aging temperature, which indicates a weaker mechanical performance of the foam core sandwich panel. Therefore, the hydrothermal aging makes a negative effect on the impact performance of foam core sandwich panels and high aging temperature can make a larger degradation. Most of the impact energy is absorbed through various failures caused in the samples, including matrix cracking, fiber breaking, delamination, face-sheet/core debonding, and foam core crushing [31,35]. As shown in Table 2, compared with the changes of maximum contact force and displacement, the difference of absorbed energy is small for testing samples with and without hydrothermal aging treatments. It should be noted that the absorbed energy of the reference sample is a little smaller than that of the samples with hydrothermal aging. It also can be seen that it takes less time to dissipate the impact energy for the panels without hydrothermal aging than the aged panels. Moreover, the time to reach the absorbed energy is the largest for the panels with 70°C aging temperature throughout the studied energies. The results also indicate that the impact performance is degraded for the panels with hydrothermal aging, and the degradation is the largest for the panel with 70°C aging temperature.

The fiber/matrix interfacial micromorphology of sandwich panels with and without hydrothermal aging is shown in Figure 8 using the SEM technology. It can be seen that there is a lot of residual resin on the fiber surface in the panel without hydrothermal aging, which indicates a good interface cohesive performance between the fiber and matrix resin. Although there is much less residual resin

on the fiber surface in the panels with hydrothermal aging compared to the no aged panel, which reveals the weak fiber/matrix interfacial cohesive performance. The diffusion of water molecular along the fiber/matrix debonding interface and the hydrolysis reaction of resin make a negative effect on the fiber/matrix interfacial cohesive performance in hydrothermal aging environment. Consistent to the conclusion shown in studies [25,26], the resulted weaker interface performance makes the fiber/matrix debonding behavior easier, and the overall mechanical properties of aged panels are degraded.

Based on the analysis of the damage morphology and the impact responses, it can be concluded that the impact resistance of foam core sandwich panels is degraded resulting from hydrothermal aging and the degradation is larger with aging temperature increasing. As indicated in the researches [21,26], the movement of water molecular is accelerated with elevated temperature; thus, the diffusion of water molecular into the defects of sandwich panels is easier. Moreover, the hydrolysis reaction of the matrix resin is aggravated with high aging temperature and more plate quality is lost. Resulting from the complete diffusion of water molecular and hydrolysis reaction of matrix with elevated temperature, initial defects such as matrix cracks and face-sheets/core debonding are aggravated, and new damage relative to matrix cracking and fiber/matrix debonding is induced. Thus, the mechanical performance of the sandwich structures with hydrothermal aging is degraded. The same conclusions are also revealed in the studies [25,27]. The impact resistance of the aged sandwich panels is degraded, resulting in the larger damage regions and the reduction of loading carrying capacity and the resistance to deformation. The mechanical performance degradation of sandwich panels with elevated temperatures is larger owing to the more aggravated diffusion of the water molecular and hydrolysis reaction of

Figure 8: Fiber/matrix interfacial micromorphology of sandwich panels with and without hydrothermal aging.

the matrix. Therefore, the degradation of the impact resistance is larger for the sandwich panels with increasing hydrothermal aging temperature.

3.2.2 Effects of hydrothermal aging on the damage morphology

The typical damage morphology of the front surfaces of three different energies impacted sandwich panels with and without hydrothermal aging is plotted in Figure 9.

Generally, there is a little damage occurring on the surfaces of sandwich panels without hydrothermal aging throughout the three studied energies. However, large failure areas are induced into the aged sandwich panels with high aging temperatures for all impact energies. For the reference panels, damage gradually occurs with impact energy increasing, and the front face-sheets of all sandwich panels are not penetrated; moreover, only a little fiber breaking is found on the front skin of the panel suffering 22 J impact energy. For the sandwich panel with hydrothermal aging at 25°C, although the damage on the

Figure 9: Typical damage morphology of front surfaces: natural aging – 30 days, 25°C – 30 days, 40°C – 30 days, 55°C – 30 days, and 70°C – 30 days.

front surface of the panel subjected to 10 J is not evident, serious fiber breaking has appeared at high impact energies, even a circular indentation of about the projectile diameter, and a cavity are formed for the 22 J-impacted sandwich panel. It is obvious that catastrophic damage regions around the impact location are recorded on the surfaces of the sandwich panels with 40, 55, and 70°C aging temperatures for all impact energies, a clear circular indentation and a cavity are found for each panel. For all sandwich panels, delamination is also found around the failure regions. Overall, larger damage is induced with impact energy or aging temperature increasing. For the sandwich panels treated with the same hydrothermal aging, the fiber breaking region is propagated, the indentation depth is increased and the cavity is extended with impact

energy increasing. The same conclusion can be drawn for the sandwich panels with different aging temperature treatments at the same impact energy.

The damage morphology of the impacted sandwich panels in a cross-section view is also plotted in Figure 10. For detail, the typical damage modes (fiber breaking, cracking, core crushed, and cavity) are shown in Figure 11. For the reference sandwich panel suffering. For the reference sandwich panel suffering 10 J impact energy, there is little damage on the cross-section. Fiber breaking occurs with impact energy increasing. Moreover, a clear indentation and some crushed foam core are found for the panel subjected to 22 J energy, whereas the front face-sheets are not penetrated for all panels at different impact energies. For the panels subjected to 10 J energy at 25, 40, and 55°C aging

Figure 10: Cross-section damage morphology of sandwich panels 25°C – 0 days, 25°C – 30 days, 40°C – 30 days, 55°C – 30 days, and 70°C – 30 days.

Figure 11: Typical damage modes: (a) without aging at 16 J and (b) 70°C – 30 days at 22 J.

temperatures, fiber breaking and foam core crushing are found, and the front skins are also not penetrated, whereas for other sandwich panels, especially the panels with high aging temperature and impact energy, the damaged skin immerses the foam core and large crushed foam core is found around the impact location as the front skin is penetrated. The diameter of the failure regions is about 12 mm, which is close to the diameter of the projectile. Moreover, the foam core crushing can extend to the rear face-sheet. In general, with impact energy increasing, the damage is aggravated for panels at the same aging temperature. Compared to the panels without hydrothermal aging throughout the three impact energies, the damage region is larger for panels with hydrothermal aging, and the damage is also aggravated with increasing aging temperature.

The damage morphology observed in the impacted sandwich panels reveals that the damage is aggravated with impact energy or increasing aging temperature. As the studies [34,35] show, the damage including matrix cracking, fiber breaking, delamination, and foam core crushing is propagated with impact energy increasing. Thus the integrity of sandwich panels is destroyed, and the impact resistance is degraded. As a result, larger damage regions in extent and depth are observed in the impacted sandwich panels. For the influence of hydrothermal aging, the researches in earlier studies [25–27] indicate that the mechanical performance of sandwich panels, especially bending strength and stiffness, is degraded owing to the damage caused by the diffusion of water molecular and the hydrolysis reaction of the resin matrix. As the mechanical properties of the laminated face-sheets and foam core are degraded, the damage region is enlarged, and the penetration depth is increased in the sandwich panels with hydrothermal aging. With increasing aging temperature, the diffusion of water molecular and the hydrolysis reaction of

the matrix is accelerated, the impact performance is more degraded, and the damage is larger.

4 Conclusion

The moisture absorption characteristics and the low-velocity impact resistance of foam core sandwich panels with hydrothermal aging at three different impact energies were studied. The following conclusions can be drawn:

(1) The moisture absorption characteristic of composites is well in agreement with the Fickian behavior until the moisture saturation. To predict the moisture absorption characteristic of composites with different hydrothermal aging temperatures, a modified Fickian behavior formulation is established, and the moisture absorption behavior until the moisture saturation is described with good accuracy.

(2) Compared to the panels without hydrothermal aging, the impact performance of the panels with hydrothermal aging is degraded and the degradation is larger with increasing aging temperature. For the 22 J impact energy, the loading bearing capacity can decrease from 3.98 kN of the reference panel to 2.56 kN of the aged panel with 70°C aging temperature, and the increase of the deflection can reach 35.69%. It is caused by the degradation of brittleness of resin. Therefore, the damage is concentrated at the central region.

(3) With impact energy and increasing aging temperature, the damage induced in the panels is aggravated. The front face-sheets are not penetrated in most of the panels without hydrothermal aging or at the lower impact energy, other front face-sheets are penetrated and large crushing form core occurs. With increasing aging

temperature, the diffusion of water molecular and the hydrolysis reaction of matrix are aggravated, more defects are generated, and the impact resistance of foam core sandwich panels is larger degraded. Damage morphology indicates that the resin becomes more brittle in hydrothermal aging environment, which makes the sandwich plate show a poor performance in a low-velocity impact.

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