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A study on the bonding strength of co-cured T800/epoxy composite–aluminum single-lap joint under out-of-plane compressive pressure condition

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In this paper, the bonding strengths of co-cured T800 carbon/epoxy composite–aluminum single-lap joints with and without additional pressures in the out-of-plane direction were investigated to simulate the stress condition at the interface between the composite layers and the aluminum liner of a Type III pressure vessel made by the filament winding process. All test specimens were fabricated by autoclave vacuum bag de-gassing molding under controlled forming pressures (absolute pressures of 0.1, 0.3, and 0.7 MPa including vacuum). A special device which can impose uniform additional pressures on the bonding part of the single-lap joint specimen was designed. Additional pressures were applied and, subsequently, the bonding strengths of the composite–aluminum single-lap joint specimen were estimated. After the three different additional pressures (absolute pressures of 0.1, 0.3, and 0.7 MPa) were applied to each of the specimens, the effects of the additional pressures on the bonding strengths of the co-cured single-lap joints were evaluated.

Keywords: co-cure bonding; winding tension; single-lap joint; forming pressure; additional pressure

1. Introduction

Fiber-reinforced composite materials have been widely used in automobile, aerospace, and military industries as replacements for existing metals because of their excellent mechanical properties such as high specific strength, modulus, and damping capacity [1]. For applications in mechanical structures, the bonding between these composites and other materials has become an important issue [2]. The composites have been joined mainly by two methods: mechanical joining and adhesive bonding. Adhesive bonding has many advantages; for example, loads can be distributed on a relatively wide area and no holes are needed to join parts [3]. Co-cure bonding is a type of bonding method which uses the excessive resin of composite prepregs during the curing process.

The filament winding process was developed to efficiently mass produce cylindrical composites structures such as fuel tanks. Accordingly, the process controls, material behavior, and mechanical performances of filament wound structures and so on have been studied extensively. It is well known that the filament winding process has some shortcomings such that the properties of the complete products are significantly affected by the processing conditions

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[4]. Winding tension is one of the major factors in a fabrication process [5], so in the case of composite structures fabricated by the filament winding process, it can change the strength and stiffness of the composite structures. Especially, for the case of the Type III hydrogen pressure vessels, comprised fibrous composites and a metal liner, fabricated by the filament winding process, the winding tension of the fibrous composites has a significant effect on the pressure vessel's quality since the fibrous composites support most of the loads [6]. The winding tension generates pressures in materials to help consolidate the pre-wound composite layers consecutively. In other words, the winding tension is closely related with the forming pressure of the composite layers [7]. Therefore, the pressure induced by the winding tension is considered to affect the bonding strength between the composites and the aluminum liners.

In this paper, in order to estimate the bonding strength of a Type III hydrogen pressure vessel, co-cured single-lap joints were fabricated under various pressures (0.1, 0.3 , and 0.7 MPa including vacuum) and their bonding strengths were measured by imposing out-of-plane pressures, which were the same as the forming pressures, on the bonding parts of the specimens. The forming pressures of co-cured single-lap joints were determined by referring to the results of a previous study [7,8]. Four specimens were fabricated according to each forming pressure and the bonding strengths of the joints were measured through a tensile test. The test results were compared with those without additional pressures to confirm whether or not the pressure induced by the winding tension during the filament winding process influences the bonding strength. These results are to be used in the design of Type III hydrogen pressure vessels made of T800 carbon fibers. The originality of this paper is to provide the method for simulating the pressure condition of filament winding structure with a simple single-lap joint specimen. In general, measuring the bonding strength of a tubular joint is difficult so a special rig is essential. By using the presented additional pressure device various pressure conditions caused by a thermoforming process can be simply simulated.

2. Specimen preparation and experimental setup

2.1. Additional pressure device

A special device that can impose uniform additional pressures (0.1, 0.3, and 0.7 MPa) in the out-of-plane direction on the bonding part of a specimen was designed to estimate the effects of the pressures on the bonding strength of the T800/epoxy composite–aluminum co-cured single-lap joint. This additional pressure device consisted of an epoxy block, a steel jacket, a contacting plate, and a control screw, as shown in Figure 1(a) and (b). After the bonding part of the co-cured single-lap joint specimen was placed in an empty space of the device, additional pressures were applied, respectively, by pressing the contacting plate to the bonding part of the specimen by fastening the screw (Figure 1(b) and (c)). The additional pressures were measured by two strain gages, which were attached to both sides of the epoxy block. Strains of the epoxy block generated by the fastening of the control screw were measured and averaged during experiments. For accurate strain measurements, the strains of the epoxy block, which corresponded to the additional pressures, were calculated by using a stress–strain curve that was obtained from specimens made of epoxy materials. Table 1 shows the strains corresponding to the additional pressures, respectively.

2.2. Specimens

A unidirectional carbon/epoxy prepreg (MCU200 ns, Hankuk Carbon, Korea) and aluminum (AL 6061-T6) were used for the fabrication of the specimens. The composites specimens (2 mm thickness, bonding width 25 mm, and bonding length 20 mm) were fabricated by

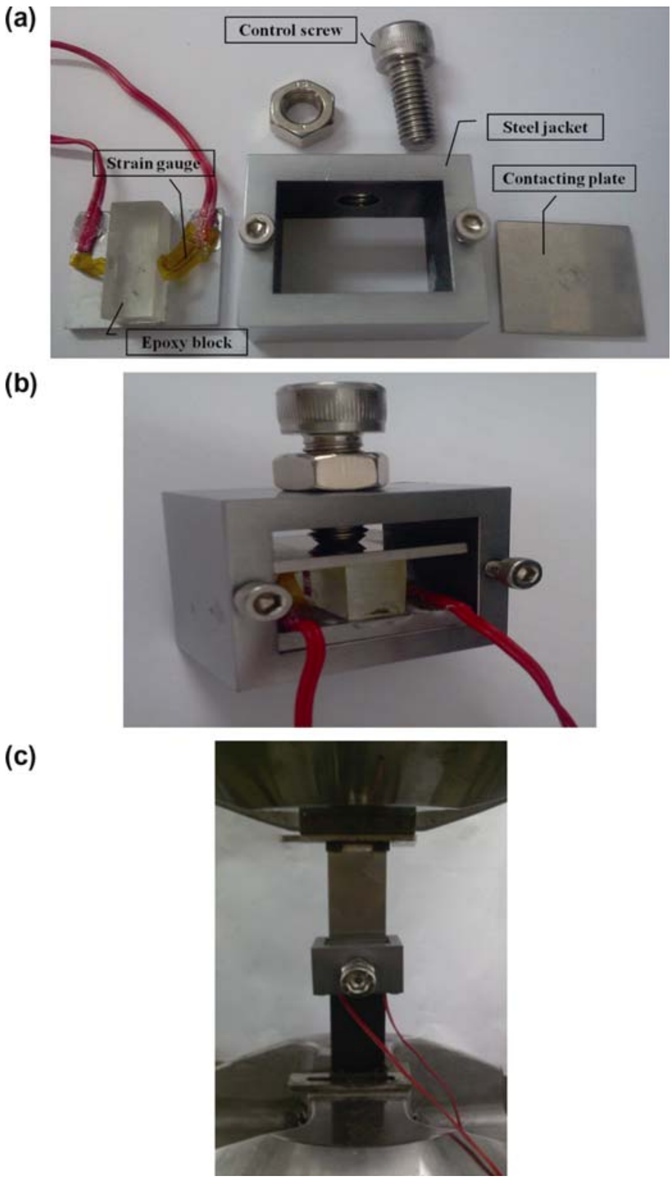

Figure 1. Additional pressure device: (a) component details of the additional pressure device, (b) additional pressure device, and (c) specimen attached by the additional pressure device.

Table 1. Strains corresponding to additional pressures.

Additional pressure (MPa)	Strain
0.1	−0.00019
0.3	−0.00057
0.7	−0.00135

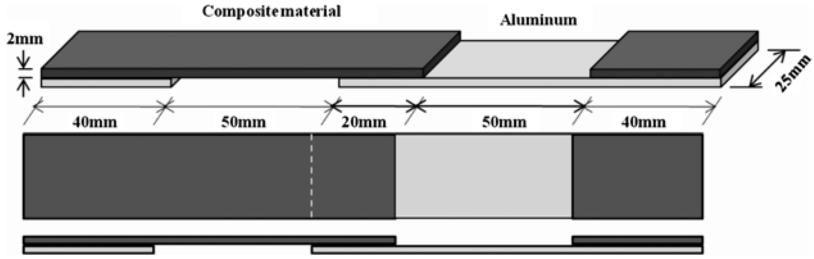

Figure 2. Shape of the co-cured single-lap joint specimen.

Table 2. Mechanical properties of T800 carbon/epoxy composites.

Mechanical properties	Value
E_1	161.3 GPa
E_2, E_3	8.820 GPa
G_{12}, G_{13}	5.331 GPa
G_{23}	2.744 GPa
v_{12}, v_{13}	0.33
v_{23}	0.45
X_t	2300 MPa
Y_t	30 MPa
Density	1.580 kg/m^3

stacking 12 prepregs at 0° angle after polishing the aluminum surfaces, as shown in Figure 2. All the aluminum surfaces were uniformly polished with #220 abrading papers. The average surface roughness (R_a) of the specimen was measured by a stylus type roughness gage (Mitutoyo SJ-201) and the value was 0.79 µm. The stacking angle (0°) was determined by considering the actual winding pattern of the hydrogen pressure vessel and the stress distribution generated in it [9]. The major mechanical properties of the composite materials (MCU200 ns) are presented in Table 2 [10]. All test specimens were fabricated by a vacuum bag de-gassing molding process in an autoclave using the recommended curing cycle; the curing temperature rises to 135 °C in 70 min and then remains there for 100 min. The forming pressures were 0.1, 0.3, and 0.7 MPa including vacuum. The tensile tests were carried out based on ASTM D1002-01 and D5868-01.

Tabs fabricated with the counterpart materials were attached using an epoxy adhesive (DP-460, 3 M) at the both ends of a specimen to minimize the bending moment generated by misalignment. The bonding strengths of the co-cured single-lap joint specimens were measured. Tensile tests were carried out with and without the additional pressures (0.1, 0.3, and 0.7 MPa) using a universal testing machine (MTS 810, USA).

3. Tests results

3.1. The bonding strength according to the forming and additional pressures

Two types of tensile tests results of the co-cured single-lap joints with and without the additional pressures for forming pressures of 0.1, 0.3, and 0.7 MPa are presented in Tables 3–5. In the tests with additional pressures, the additional pressures were set to be the same as the corresponding forming pressures.

Table 3. Bonding strengths of co-cured single-lap joints with and without additional pressures at the forming pressure of 0.1 MPa.

No.	Without additional pressure Strength (MPa)	With additional pressure Strength (MPa)
1	3.39	6.60
2	3.14	5.73
3	3.13	5.80
4	3.03	6.84
Mean	3.17	6.24
SD	0.15	0.56

SD: standard deviation

Table 4. Bonding strengths of co-cured single-lap joints with and without additional pressures at the forming pressure of 0.3 MPa.

No.	Without additional pressure Strength (MPa)	With additional pressure Strength (MPa)
1	7.79	10.20
2	5.99	10.62
3	7.75	10.52
4	5.08	11.63
Mean	6.65	10.74
SD	1.34	0.62

SD: standard deviation

Table 5. Bonding strengths of the co-cured single-lap joints with and without additional pressure at the forming pressure of 0.7 MPa.

No	Without additional pressure Strength (MPa)	Without additional pressure Strength (MPa)
1	6.34	11.18
2	5.41	9.66
3	6.65	10.51
4	5.23	10.37
Mean	5.90	10.43
SD	0.69	0.62

SD: standard deviation

The generated pressure in the filament wound structure increases with the number of winding and then saturates [7] as illustrated in Figure 3(a). To simulate this pressure condition (0.1, 0.3, and 0.7 MPa), the co-cured single-lap joint was thermoformed under the same saturated pressure as the filament winding structure. To maintain this pressure condition after the curing process, the additional pressure device was applied to the bonding part during the tensile test as illustrated in Figure 3(b).

Meanwhile, in order to check the accuracy of the additional pressures, which were imposed on the specimens via a control screw during the tensile tests, the strains measured by the strain gages were observed. Figure 4 shows the strain variations of the epoxy block during the tensile tests with additional pressures (0.1, 0.3, and 0.7 MPa). ‘FP’ and ‘AP’ stand

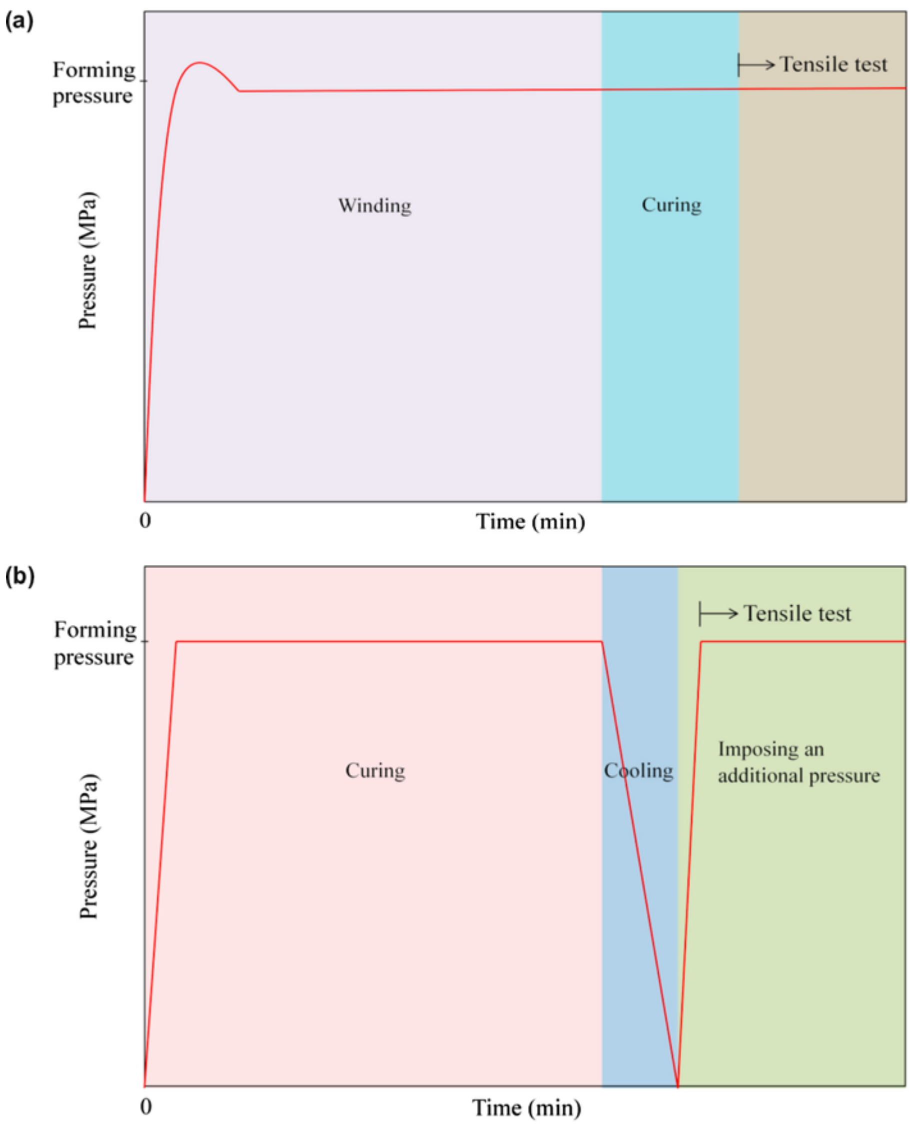

Figure 3. The pressure variation during forming and tensile testing for the cases of (a) filament winding process and (b) vacuum bag de-gassing process.

for the forming pressure and the additional pressure, respectively. As shown in Figure 4, the generated strains were relatively stable for the whole duration of the tensile test.

By using the measured stains, the actual additional pressures imposed on the bonding part of the specimen were calculated by the simple Hooke's law (Equation [1]) and the results are listed in Table 6.

$$\sigma = E\varepsilon \tag{1}$$

where σ is the generated additional pressure, E is the Young's modulus of the epoxy block, and ε is the generated strain. The Young's modulus (E) of the epoxy block was measured by

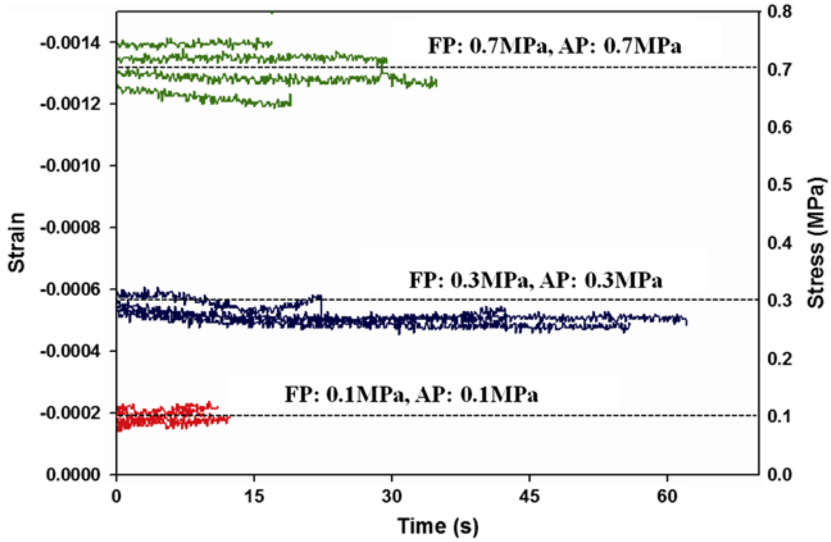

Figure 4. Generated strains at the joint during the test.

Table 6. Generated additional pressures acting on the specimens.

	No.	Average strain	Actual additional pressure (MPa)
FP: 0.1 AP: 0.1 MPa	1	−0.00017	0.09
	2	−0.00017	0.09
	3	−0.00019	0.10
	4	−0.00021	0.11
			SD: 0.01
FP: 0.3 AP: 0.3 MPa	1	−0.00056	0.29
	2	−0.00051	0.27
	3	−0.00051	0.27
	4	−0.00049	0.26
			SD: 0.01
FP: 0.7 AP: 0.7 MPa	1	−0.00120	0.62
	2	−0.00135	0.70
	3	−0.00141	0.73
	4	−0.00128	0.66
			SD: 0.05

a tensile test with a ‘dog bone’ type tensile specimen made of epoxy. From the test result, it was found that the overall strain variations were not significant, having about 10% error, which means that there was almost no loosening of the control screw during the test, and, therefore, the test results could be regarded as reasonable data. The representative stress–strain curves for the single-lap joint specimens with and without the additional pressures are shown in Figures 5 and 6. All the test results are summarized in Figure 7. The strains presented in the figures were the nominal strains, which were calculated by the measured displacement divided by the original bonding length. The test results reveal that the additional pressures greatly affected the bonding strengths of the co-cured single-lap joints, even though they were cured under the same forming pressure. And the bonding strengths increased when the

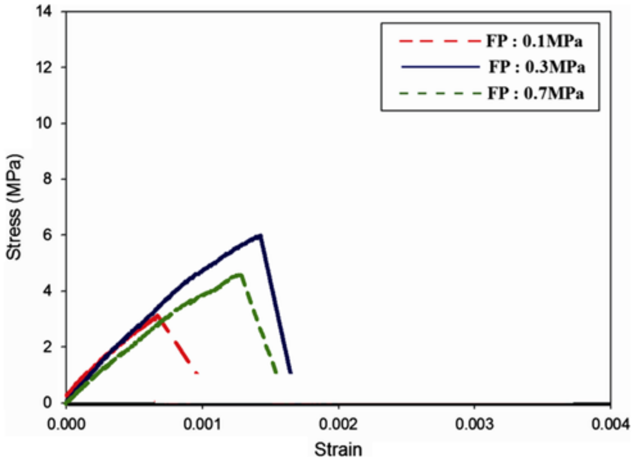

Figure 5. Representative stress–strain relationships without additional pressure.

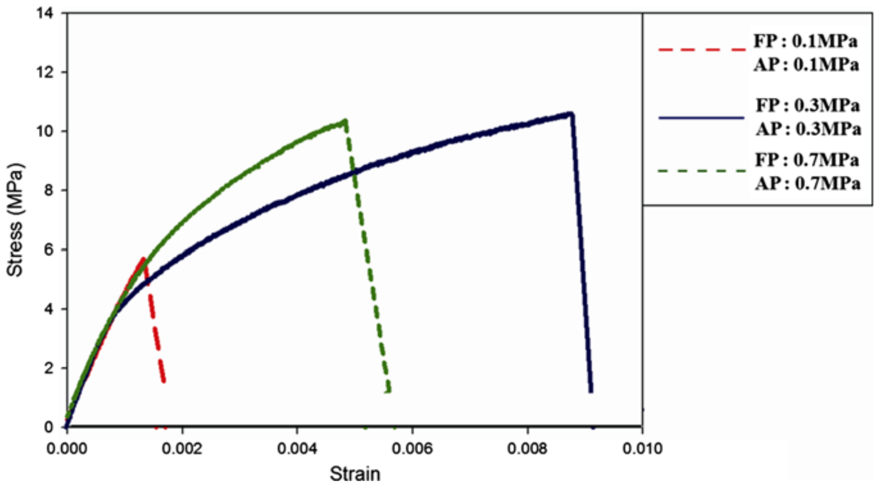

Figure 6. Representative stress–strain relationships with additional pressure.

forming pressure increased to 0.3 MPa and then it became almost saturated, as shown in Figure 7, which means that the forming pressure did not affect the consolidation of the composite laminate and the bonding layer over a certain pressure (0.3 MPa). And the fact that the forming pressure did not affect the consolidation also implies the limited effect of the winding tension of the filament winding process on the bonding strength between the composite layer and a liner. According to the test results, the bonding strengths of the T800/epoxy composite–aluminum co-cured single-lap joints with additional pressures were approximately 1.8 times higher than those of the cases without additional pressures. This result is similar to the result of a previous study [11], suggesting that an appropriate level of additional pressure can enhance the bonding strength of the pressure vessel. These results are expected to be useful in the design of a hydrogen pressure vessel.

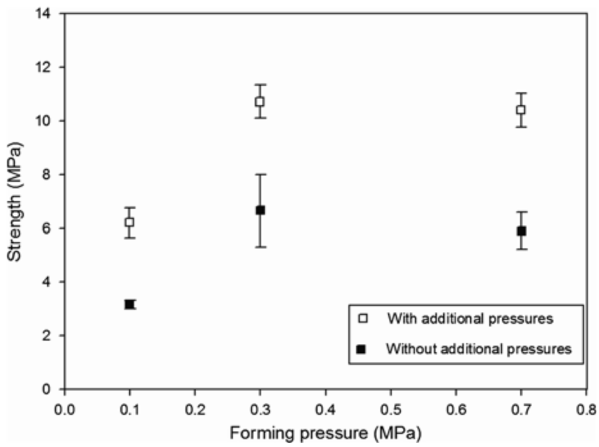

Figure 7. Bonding strengths according to forming and additional pressures.

3.2. Fracture surface observation

The micrographs of the bonding parts after failure are shown in Figure 8. Figure 8(a) and (b) shows the bonding parts for the lowest bonding strength (FP 0.1, AP 0.1 MPa), whereas Figure 8(c) and (d) shows those for the highest bonding strength (FP 0.3, AP 0.3 MPa). In the former case, there were little residual composites on the aluminum surface of the specimen because the epoxy resin could not be distributed effectively on the co-cured bonding part due to the relatively low forming pressure. Moreover, the peel stress generated at the bonding part was not sufficiently suppressed because of the low additional pressure (0.1 MPa), ultimately resulting in the low bonding strength of the specimen. In contrast, in the latter case, the epoxy resin was distributed properly on the aluminum surface during the curing process and

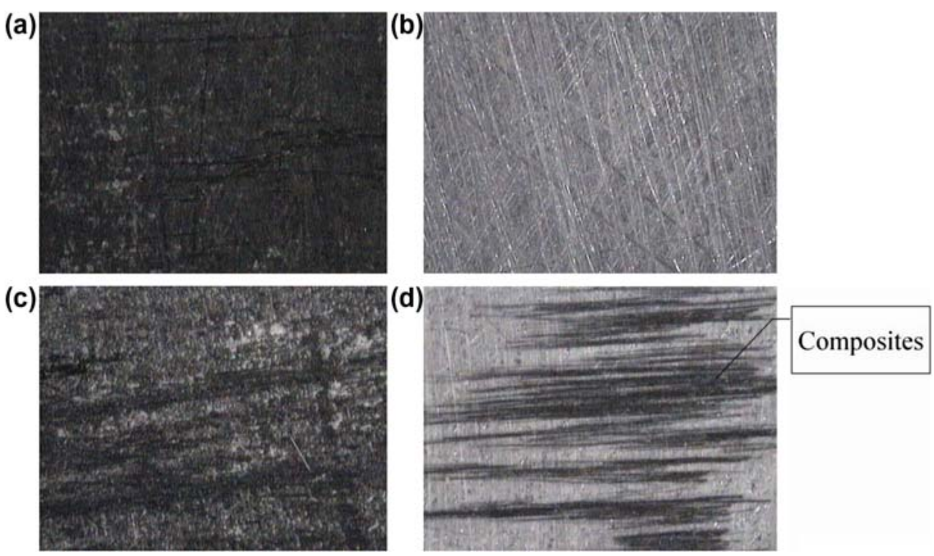

Figure 8. Micrographs of the cross sections of the co-cured single-lap joints; (a) composite surface (FP: 0.1, AP: 0.1 MPa), (b) aluminum surface (FP: 0.1, AP: 0.1 MPa), (c) composite surface (FP: 0.3, AP: 0.3 MPa), and (d) aluminum surface (FP: 0.3, AP: 0.3 MPa).

the composites were effectively consolidated on the polished aluminum surface, ultimately enhancing the bonding strength. The peel stress at the bonding part was also appropriately suppressed by the high additional pressure (0.3 MPa). It was confirmed experimentally that the bonding strength can be increased with appropriate levels of forming and additional pressures. However, the bonding strength was not linearly proportional to the forming or additional pressure and did not increase above a certain level of forming pressure.

4. Conclusion

In this paper, composite–aluminum single-lap joint specimens, which were fabricated by vacuum bag de-gassing molding, were simulated as filament winding structures with winding tension and their bonding strengths were evaluated. The winding tension generated pressures on the materials, which consolidated the pre-wound composite layers consecutively. Since the pressure induced by the winding tension was considered to have an effect on the bonding strength between the composites layers and the aluminum liner in a Type III pressure vessel, the bonding strengths of co-cured single-lap joints were measured according to the forming pressure by tensile tests after fabricating the specimens under the determined forming pressure conditions. Because the pressure generated in the composite layer by the winding tension is difficult to estimate, the forming pressures of the single-lap joint specimens were set to 0.1, 0.3, and 0.7 MPa based on a previous study [7,8].

And for the simulation of the actual pressure vessel fabricated by the filament winding process, the additional pressures (0.1, 0.3, and 0.7 MPa), which were the same as the forming pressures, were imposed on the specimens in the out-of-plane direction to estimate the bonding strengths, and then the results were compared with the results of the cases without application of additional pressures.

The experimental results revealed the followings:

(1) To indirectly evaluate the bonding strength of the composites–aluminum liner in the Type III hydrogen pressure vessel fabricated by the filament winding process, a co-cured single-lap joint was prepared. A special device imposed a uniform pressure on the bonding part of this joint, and this pressure condition simulated the stress condition at the interface between the composite layer and the aluminum liner of the filament-wound structure.
(2) The bonding strengths of the T800/epoxy composite–aluminum co-cured single-lap joints with the additional pressures were approximately 1.8 times higher than those of specimens without the additional pressures.
(3) Bonding strength was not linearly proportional to the forming or additional pressure and the bonding strength saturated at a certain level, even though the forming pressure and additional pressure were increased beyond a certain level (0.3 MPa).

Consequently, it was indirectly confirmed that the consolidation induced by the winding tension influenced the bonding strength. This study is expected to be useful in the design of a Type III hydrogen pressure vessel fabricated by the filament winding process.

Acknowledgments

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References

[1] Lee DG, Suh NP editor. Axiomatic design and fabrication of composite structures: applications in robots, machine tools, and automobiles. New York (NY): Oxford University Press; 2006.
[2] Reinhart TJ, editor. Engineered materials handbook. Metals Park (OH): ASM International; 1987.
[3] Vinson JR, Sierakowski RL editor. The behavior of structure composed of composite materials. Norwell (MA): Kluwer Academic; 2008.
[4] Yoon SH, Kim JY, Hwang TK. Experimental investigation on relationship of winding process variables and mechanical properties for filament wound composites. J. Korean Soc. Propul. Eng. 1999;3:56–65.
[5] Cohen D. Influence of filament winding parameters on composite vessel quality and strength. Composites Part A. 1997;28:1035–1037.
[6] Cai Z, Gutowski T, Allen S. Winding and consolidation analysis for cylindrical composite structures. J. Compos. Mater. 1992;26:1374–1399.
[7] Hahn HT, Kempner EA, Lee SS. The stress development during filament winding of thick cylinders. Compos. Manuf. 1993;4:147–156.
[8] Banerjee A, Sun L, Mantell SC, Cohen D. Model and experimental study of fiber motion in wet filament winding. Composites Part A. 1998;29:251–263.
[9] Son DS, Chang SH. Evaluation of modeling techniques for a Type III hydrogen pressure vessel (70MPa) made of an aluminum liner and a thick carbon/epoxy composite for fuel cell vehicles. Int. J. Hydrogen Energy. 2012;37:2353–2369.
[10] Kim CU, Hong CS, Kim CG, Kim JY. Optimal design of filament wound type 3 tanks under internal pressure using a modified genetic algorithm. Compos. Struct. 2005;71:16–25.
[11] Park MG, Cho SK, Chang SH. A study on the variation of in-plane and out-of-plane properties of T800 carbon/epoxy composites according to the forming pressure. J. Korean Soc. Compos. Mater. 2010;23:61–66.