STRENGTH OF COMPOSITE SANDWICH JOINTS UNDER HYGROTHERMAL CONDITION

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1. Introduction

Composite sandwich structures are effective to carry the bending and compressive loads since they have high flexural stiffness and buckling resistance compared to conventional monocoque skins [1]. Thanks to the excellent mechanical properties, the composite sandwich structures have been used for aircraft structures like the control surfaces and doors. Recently much effort has been consistenly made to adopt the sandwich structures to the primary structures of aircraft. One of the problems is, however, difficulty in joining the parts. Their weakness against moisture has also been one of the hurdles to be used for primary structure because the strength of composite sandwich is sensitive to environmental factors such as temperature and humidity.

Many papers have addressed the sandwich structures in terms of the failure modes, mechanical properties, buckling, wrinkle, fatigue, and manufacturing methods in analytical and experimental methods [2~6]. These studies have mainly focused on the mechanical characteristics of the sandwich themselves. However, the joint in sandwich structure is not such a simple problem which is related only to the mechanical characteristics of the sandwich themselves. The joint strength of the sandwich are connected with fasteners, inserts, potting materials and interfaces between the components.

Bozhevolnaya et al. [7, 8] showed that stress concentration due to material discontinuity caused by potting material can be minimized by reducing the potting material progressively. Bunyawanichakul et al. [9] presented experimental results and related numerical model of pull-out tests of potted inserts. They showed demonstrated the importance of pre-stress and identified the different types of damages. Song et al. [10] installed an insert in sandwich panels and conducted pull-out and shear tests. They experimentally investigated the effects of the core height and density, face thickness and the clearance between the face and insert on the joint strength. Zabihpoor et al. [11] developed a new design for bolted joints in composite sandwich structures with foam core. They also showed that the interface angle between the solid laminate and the foam core plays an important role on the failure. Sharma et al. [12] examined the influence of rigid inserts on the static behavior of sandwich panels made of high density foam core. In addition, possible failure modes and the maximum load corresponding to the failure mode were analyzed. Feldhusen et al. [13] proposed practical configurations of sandwich joints after studying various joining methods. Raghu et al. [14] conducted pull-out tests for honeycomb sandwich panel and confirmed that the strength under pull-out loading changes considerably depending on the cell size and potting area. Heimbs et al. [15] investigated the mechanical behaviors of three different corner joints and two different potted insert joints. They conducted shear tests and bending tests of the corner joints and pull-out tests of the threaded inserts to study the failure mechanisms.

In spite of many existing papers, the studies dealing with the effect of hygrothermal environment on the strength and failure of sandwich joint are very limited. By the way, there have been demands from the aircraft industries for the detail information about the failure of sandwich joints in high temperature and humidity. In this study, the composite sandwich joints designed for a Korea indigenous aircraft were experimentally investigated with a focus on the effect of test environment on the strength and failure. Two test environments are examined including elevated temperature-wet (ETW) and room temperature-dry (RTD) conditions.

Two kinds of loading including pull-out and shear are tested.

2. Specimen Preparations

A total of 96 sandwich joint specimens of sixteen different types, depending on the configuration and environmental conditions, were tested. The dimensions of the pull-out and shear specimens are 120 × 120 (width × length, unit: mm). The specimen details are shown in Table 1.

Table 1 Specimen details

ID	Test condition	Insert/ Joint type	Face Type	Core		Compound type
				Type	Height (mm)	
P01/ S01	RTD	Blind, Floating	Carbon Fabric	Nomex™	25.4	Magnobond 6398
P02/ S02	ETW	Blind, Floating	Carbon Fabric	Nomex™	25.4	Magnobond 6398
P03/ S03	RTD	Blind, Floating	Carbon Fabric	PMI foam	20	Magnobond 6398
P04/ S04	ETW	Blind, Floating	Carbon Fabric	PMI foam	20	Magnobond 6398
P05/ S05	RTD	Potting/ Hole	Glass Fabric	Nomex™	9.53	EC-3500 B/A
P06/ S06	ETW	Potting/ Hole	Glass Fabric	Nomex™	9.53	EC-3500 B/A
P07/ S07	RTD	Potting/ Hole	Carbon Fabric	PMI foam	11	Epocast 1618 D/B
P08/ S08	ETW	Potting/ Hole	Carbon Fabric	PMI foam	11	Epocast 1618 D/B

※ RTD: Room Temperature/Dry condition
※ ETW: Elevated Temperature/Wet condition

The face sheets were manufactured by carbon/epoxy fabric (G3-500-3k-PW/5276-1, CYTEC) and a glass/epoxy (CYTEC, MXB7701-7781-B4) fabric tapes. A Nomex™ honeycomb (Hexcel) and a PMI foam (Rohacell®) were used for the sandwich core. All specimens were cured in an autoclave by Korea Aerospace Industries Ltd (KAI). The configurations of the joints are shown in Fig. 1.

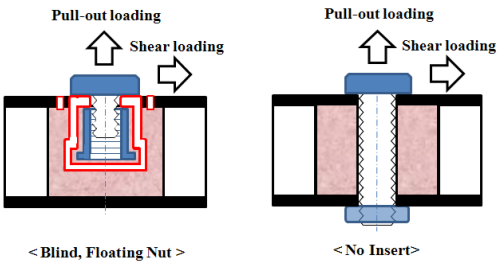


Fig. 1. Configurations of joints; insert type (left) and potting type (right)

The joint specimens for the ETW test were first dried in an oven and then exposed to the 71℃ and 85% RH (Relative Hunidity) environment in a chamber. The moisture contents were checked according to ASTM D5229. The moisture contents are assumed to be in saturation when the difference of the moisture content in the specimen between any two adjacent measuring points becomes less than 0.05% of the weight of the dried specimen.

3. Experiment

Fig. 2. Test set-ups for pull-out (left) and shear (right) in the ETW condition

The test set-ups for pull-out (left) and shear (right) tests are shown in Fig. 2. In the pull-out test, an upper plate with a circular cut-out of 80 mm diameter supports the specimen against the pull-out loading. The load is applied to a fastener vertically connected to the insert through the center of the hole. To constrain the specimens in the shear test, three steel guide blocks are used. Shear loading was also applied to a fastener by a shear plate. In the shear test, the ribbon direction of the core was set to be parallel to the loading direction.

A universal material testing machine, Instron 5582, was used for these tests. The loading speed was 1.27 mm/min. The machine provides a chamber for the tests at high temperatures of 82℃.

The detailed procedure of the ETW test is as follows:

1. Keep the specimen in the environmental chamber at 71℃ and 85% RH until the saturation of moisture content is reached.
2. Place the specimen in the test chamber.
3. Heat the chamber to 82℃ within 5 minutes.
4. Hold the temperature at 82℃ for 2 minutes.
5. Start the loading and test.

4. Results and Discussion

4.1. Failure in RTD condition

The test results for the sandwich joint under pull-out load in RTD environment were reported in [16]. In this paper, some of those results are quoted to be

compared with ETW results. In RTD condition, a total of 48 sandwich specimens of 8 different types were tested under pull-out and shear loading. The typical load-displacement curves and failure modes of the joints P01 and P03 are shown in Figs 3 and 4, respectively. In the case of joint P01, failure progress is identified in four different regions. The regions “1”, “2”, “3”, and “4” in Fig. 3 represent the core shear buckling (1), core crushing (2), debonding of lower face from potting (3), and upper face failure (4), respectively. Despite the core shear buckling at region 1, any remarkable reduction of carried load in load-displacement is not observed. Region 2 between the first peak and the maximum load peak is the process where the core shear buckling and compressive failure (crushing) develop progressively. When the lower face is separated from potting at the region 3, a sharp drop of sustained load appears with a sound. It means that the structure substantially lost the load carrying capability at that point. Even after the drop at region 3, however, the structure carries some amount of load to another peak at region 4. Between the regions 3 and 4, the pull-out load is mainly supported by the bending rigidity of the upper face. Reaching the peak at the region 4, the potting part penetrates the upper face and the structure is completely destroyed.

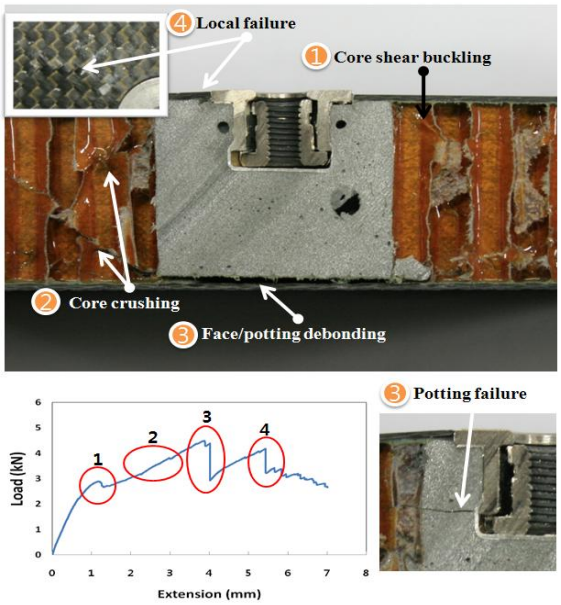


Fig. 3. Failure and load-displacement curve of joint P01 and under pull-out loading [16].

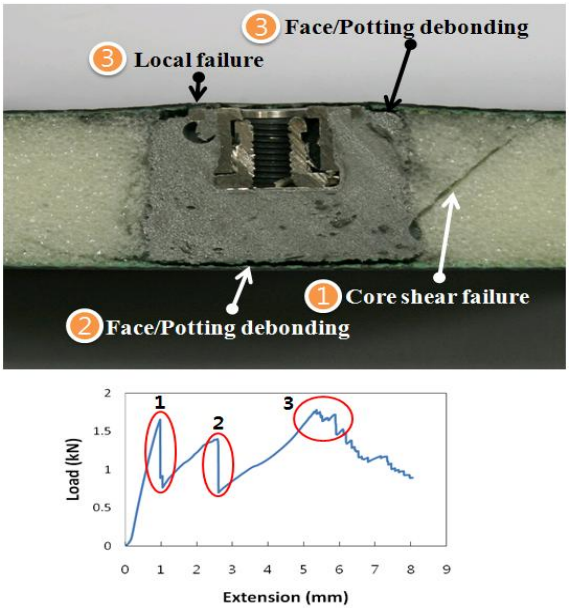


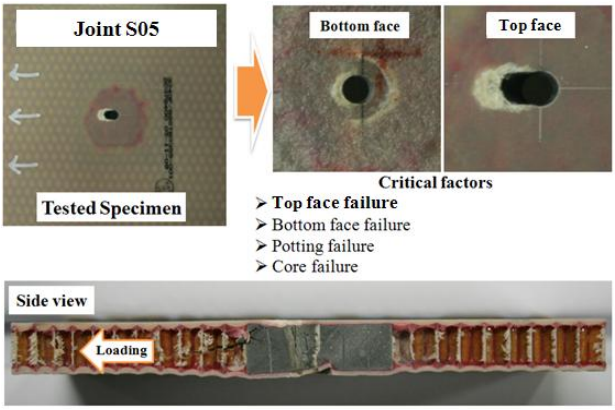
Fig. 4. Failure and load-displacement curve of joint P03 and under pull-out loading [16].

When a foam core is used for the sandwich, three peaks appear in load-displacement curve which correspond to the core shear failure (first peak), debonding of lower face from potting (second peak) and upper face failure (third peak), respectively. The curve is different from that of the joint P01 (Nomex core) at the first peak. In the joint P01, load reduction after the first peak is negligible. In the joint, P03 using foam core, however, the load instantaneously and radically drops after the first peak which comes from core shear crack through the thickness as shown in Fig. 4.

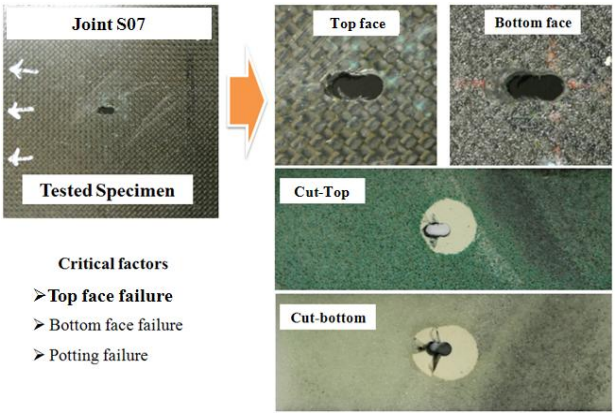
The failure in the joints P05 and P07 using Nomex honeycomb core and PMI foam core without insert, also proceeds in three different steps. The joint P05 with glass/epoxy fabric faces and Nomex core experiences a similar failure behavior as the joint P01. The joint P07 with carbon/epoxy fabric faces and PMI foam core shows a similar failure behavior as the joint P03. However, the final failure modes in the joints P05 and P07 are quite different compared to those of the other insert joint specimens. The head of the bolt and the nut hold the upper and lower faces to prevent the debonding between faces and the potting material until the final failure. When the maximum peak load is reached, potting failure occurrs and the nut penetrates into the lower face.

The main difference of the shear test results from those of the pull-out test is that the first peak of the

load-displacement curve always becomes the maximum load, which means that the first peak load can be defined as the failure load and design allowable as well. The representative failure modes for the joint S05 and S07 are shown in Fig. 5.



(a) Joint S05



(b) Joint S07

Fig. 5. Representative failure of joints S05 and S07 in RTD condition

4.2 Failure in ETW condition

Failure in the ETW test of the joint P02 is shown in Fig. 6. Unlike the test results in RTD environment which shows the upper face failure and debonding of lower face from potting, the joint P02 in ETW condtion shows the insert emerging out of the sandwich structure. The failure mode is attributed to the degradation of the constituents of the sandwich due to the absorbed moisture. It necessarily causes the reduction of failure load.

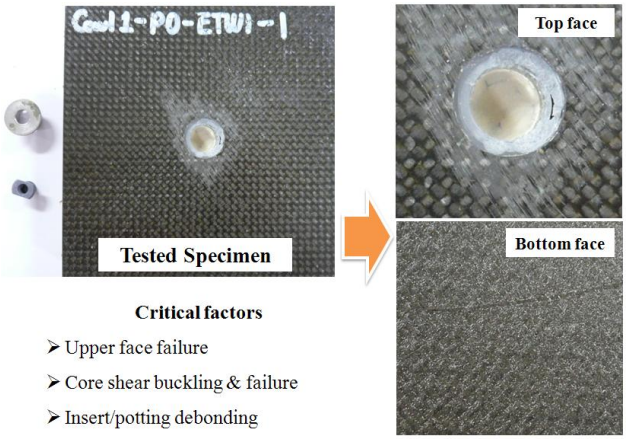


Fig. 6. Failure of joint P02 in ETW condition

In the joint P04 which uses the same insert joint as the joint P02 but adopts the foam core, however, the insert is not separated from the potting. It only shows the upper face failure around the hole (Fig. 7.). Furthermore, when compared with the failure of the joint P03 in RTD condition, the debonding of the lower face from potting happens the first without core shear failure. The failure of the joints with potting in ETW condition appears similar to the failure in RTD condition. The failure of the joints in ETW condition under shear loading is also similar to the one in RTD condition.

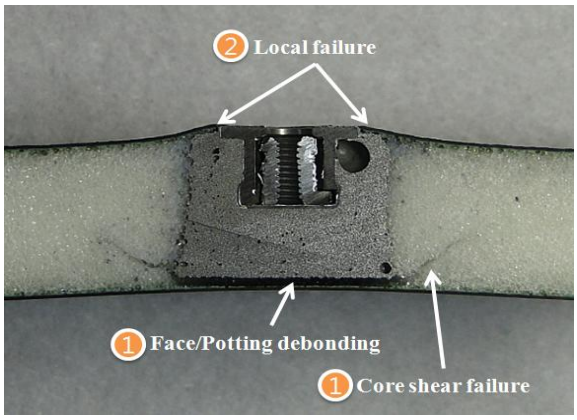


Fig. 7. Failure of joint P04 under pull-out loading in ETW condition

4.3 Strength Degradation

Under the pull-out loading, the core shear buckling (when Nomex honeycomb is used) or the core shear failure (when PMI foam core is used) are always observed. They cause a permanent deformation to the sandwich core. The failure load should be

defined as the loads corresponding to the shear buckling or shear failure. Unlike the pull-out test results, the joints under shear loading do not show the reduction of the carried load before the maximum load is reached. Accordingly, the failure load is identified to be the maximum load that the joint can carry in all joint types.

In Figs 8, 9, and 10, the failure (first peak) loads and the ultimate loads from the pull-out loading, and the failure loads from the shear loading were compared in the RTD and ETW environment. As confirmed in the figures, the failure loads of the pull-out test in ETW condition decreased from the minimum of 8.4% to the maximum of 54.4%. Furthermore, the failure load of shear test in ETW condition is decreased with the maximum of 59.1%. However, in the case of the ultimate loads for the pull-out test in ETW condition, an exceptional case is found in the joint P03.

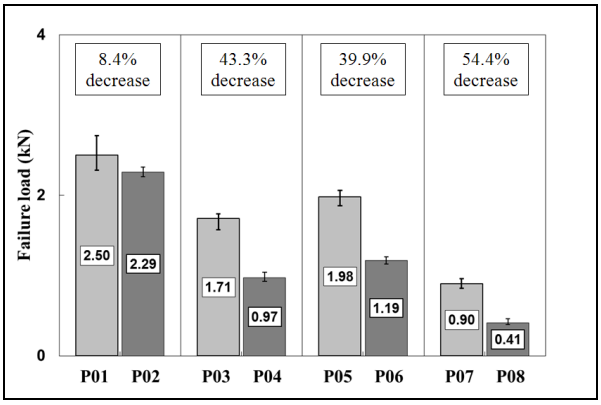


Fig. 7. Effect of ETW condition on failure load in the pull-out test

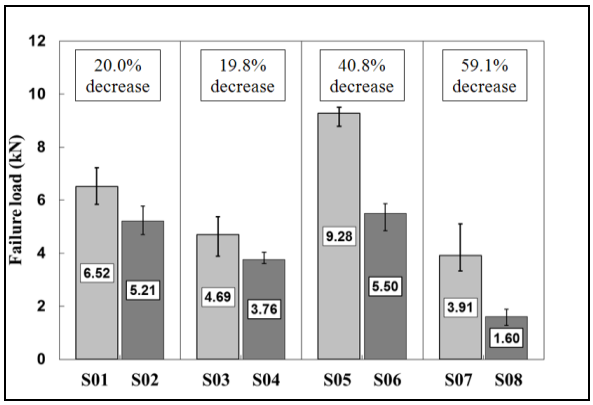


Fig. 8. Effect of ETW condition on failure load in the shear test

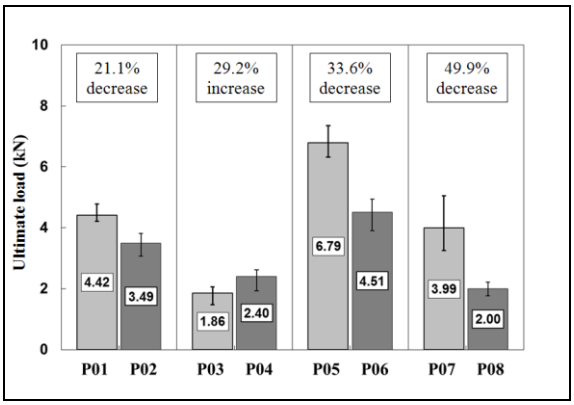


Fig. 9. Effect of ETW condition on ultimate load in the pull-out test

5 Conclusions

The experimental results showed that failure loads of joints under pull-out loading with the Nomex honeycomb core were dominated by core shear buckling, while joints with the PMI foam core were dominated by core shear failure. In the shear test, failure loads of the joints relied on contact between the insert flange the the face (in the case with insert), and the bearing strength of the face (in the case without insert). The ultimate pull-out and shear strength of sandwich joints appeared to be smaller in ETW (elevated temperature and wet) condition than at RTD (room temperature and dry) condition with an exception of one case, which was the PMI foam insert joints.

Acknowledgement

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