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Cheol-Won Kong[a], Gi-Won Nam[a], Young-Soon Jang[a] & Yeong-Moo Yi[b]

[a] Structures and Materials Department, Korea Aerospace Research Institute, Daejeon, Korea

[b] Korea Aerospace Research Institute, Daejeon, Korea

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NOTE

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Cheol-Won Kong[a]*, Gi-Won Nam[a], Young-Soon Jang[a] and Yeong-Moo Yi[b]

[a]*Structures and Materials Department, Korea Aerospace Research Institute, Daejeon, Korea;* [b]*Korea Aerospace Research Institute, Daejeon, Korea*

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Composite sandwich panels with face sheets made of carbon/epoxy fabric and carbon/epoxy uni-directional prepreg were tested. The sandwich cores made by aluminum honeycomb and foam were cured with the face sheet at 180 °C. The aluminum core sandwich failed at the 40% failure strain of the face skin in the compression test. On the other hand, the foam core sandwich failed at the 100% failure strain of the face skin in the compression test. In the case of the aluminium core sandwich, nonhomogenous load distributions and fiber contents may affect the lower failure strain. Therefore, the specific compression strength of the foam core was 72% higher than the compression strength of the aluminum core. Failure mode analysis of sandwich panels made of aluminium honeycomb cores shows that shear failure leads to final failure. However, the specific flexural strength of the sandwich panels with aluminum cores had a slightly higher value than that of the sandwich panels with foam cores. Because the sandwich panel with aluminium cores had higher critical stress for the face wrinkling than the sandwich panel with foam cores due to higher compression modulus of aluminium cores than foam cores.

Keywords: sandwich panel; honeycomb; foam; strength; compression test; flexural test

1. Introduction

Composite sandwich structures are used in aerospace structures and the strength of composite sandwich structures with aluminum honeycomb cores or foam cores is important for the design of aerospace structures. The selection of a sandwich core depends on strength, stiffness, cost and manufacturing skill. Compatibility of the skin and core material is shown to play an important role in the buckling behavior of sandwich structures.[1] The strengths of composite sandwich structures are investigated.[2–6] The failure modes of composite sandwich skin are analyzed.[7] A study on the strength of sandwich panels with aluminum honeycomb cores or foam cores is conducted.[8]

We conducted strength tests for sandwich panels with different cores. Two kinds of tests were done. One is edge compression, the other is flexural testing. Typically, we also conducted compression tests for sandwich panels with holes and analyzed the failure mode of sandwich panels with aluminum honeycomb cores.

*Corresponding author. Email: kcw@kari.re.kr

2. Edge compression test

2.1. Specimen preparation

To fabricate the composite sandwich specimens we used aluminum honeycomb cores or foam cores. The face sheets were made of carbon-epoxy fabric or uni-directional prepregs. The adhesive film between the face sheets and the core was used. Table 1 shows the material properties of the face, the core, and the adhesive film. X is the strength in the fiber direction, Y is the strength in the transverse direction, subscripts T and C represent tension and compression, respectively.

The directions of the aluminum core were of two kinds. One is the L direction (Ribbon direction) and the other is W direction as shown in Figure 1. The foam core is made of polymethacrylimide.

The length of the specimen was 250 mm and the width of the specimen was 50 mm. Points 20 mm from the bottom and 20 mm from the top were all fixed by fixture as shown in Figure 2. The loading condition was 0.5 mm/min. Zero degree of the face sheet's stacking sequence was the loading direction.

2.2. Results

We tested the compression strength of composite sandwich specimens with different honeycomb cores or different stacking sequences. Each of the averaged failure loads is summarized in Table 2.

Table 1. Material properties.

Woven fabric (Carbon/epoxy)	E_1 = 62 [GPa], E_2 = 61 [GPa], G_{12} = 4.3 [GPa], ν_{12} = 0.11, X_T = 757 [MPa], X_C = 707 [MPa], Y_T = 704 [MPa], Y_C = 594 [MPa], S = 86 [MPa], t_{ply} = 0.19 mm
Uni-directional prepregs (Carbon/epoxy, Type I)	E_1 = 152 [GPa], X_T = 2120 [MPa], X_C = 1680 [MPa], t_{ply} = 0.14 mm
Uni-directional prepregs (Carbon/epoxy, Type II)	E_1 = 138 [GPa], X_T = 2400 [MPa], X_C = 1670 [MPa], t_{ply} = 0.14 mm
AL core	E_1 = 8.27 [MPa], E_2 = 1.31 [MPa], E_3 = 1276 [MPa], G_{12} = 0.0001 [MPa], G_{23} = 117 [MPa], G_{13} = 296 [MPa], ν_{12} = 0.75, ν_{23} = 0.0001, ν_{13} = 0.0001, t_{core} = 25.4 mm
Foam core	E = 180 [MPa], G = 70 [MPa], t_{core} = 30 mm
Adhesive film	Lap shear 34.5 [MPa], Flatwise tensile 8.3 [MPa], Peel performance 3.57 [kg/cm]

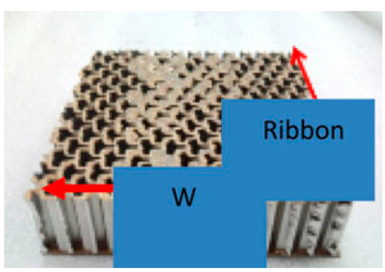

Figure 1. Direction of aluminum core.

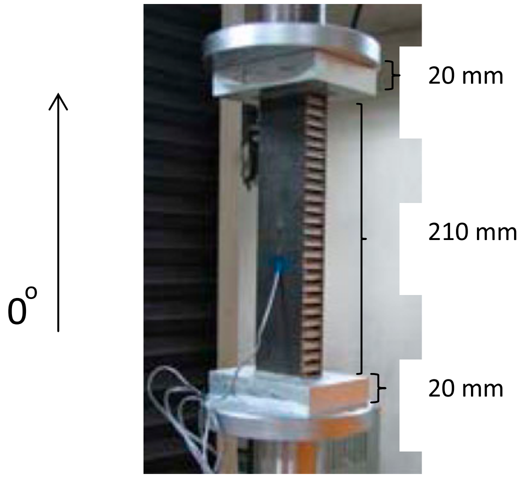

Figure 2. Edge compression test.

2.2.1. Sandwich panels with carbon fabric and aluminium honeycomb core

In the case of sandwich panels with $[0]_{4T}$ for face sheets and 0° for W direction of the aluminum honeycomb cores, the failure load was 17,611 N. In the case of sandwich panels with [0/45/45/0] for face sheets and 0° for W direction of aluminum honeycomb cores, the failure loads was 19,923 N. The strength of [0/45/45/0] for face sheets was 13% higher than that of $[0]_{4T}$ for face sheets. One of the reasons is that the shear strength of [0/45/45/0] was higher than that of $[0]_{4T}$.

2.2.2. Sandwich panels with uni-directioal carbon prepreg (Type I) and aluminium honeycomb core

In the case of sandwich panels with $[60/{-60}/0]_s$ for face sheets and 0° for W direction of the aluminum honeycomb cores, the failure loads was 13,044 N. In the case of sandwich panels with $[60/{-60}/0]_s$ for face sheets and 0° for L direction of aluminium honeycomb core, the failure loads was 14,700 N. The strength of 0° for L direction of aluminium honeycomb core for face sheets was 12% higher than that of 0° for W direction of the aluminium honeycomb core. The L-direction stiffness of the aluminium honeycomb core was 8.27 MPa and the W-direction stiffness of the aluminium honeycomb core was 1.31 MPa. The stiffness of the aluminium core affected the strength of the sandwich panels.

2.2.3. Sandwich panels with uni-directioal carbon prepreg (Type II) and aluminium honeycomb core

In the case of the sandwich panels with $[60/{-60}/0]_s$ for face sheets (Type II) and 0° for W direction of the aluminum honeycomb cores, the failure loads was 16,003 N. In the case of the sandwich panels with $[60/{-60}/0]_s$ for face sheets (Type I) and 0° for W direction of the aluminum honeycomb cores, the failure loads was 13,044 N. The strength of Type II face sheet was 22% higher than that of type I because the strength of Type II fiber was higher that of Type I fiber and the stiffness of Type II fiber was lower that of Type I fiber.

Table 2. Failure load of edge compression test.

	Type	Face sheet	Average value [N]	Standard deviation [N]
Case 1	$[0]_{4T}$ for face sheets and 0° for W direction of the aluminum honeycomb cores	Woven fabric	17,611	2617
Case 2	[0/45/45/0] for face sheets and 0° for W direction of aluminum honeycomb cores	Woven fabric	19,923	1725
Case 3	$[60/-60/0]_s$ for face sheets and 0° for W direction of the aluminum honeycomb cores	UD (Type I)	13,044	853
Case 4	$[60/-60/0]_s$ for face sheets and 0° for L direction of aluminium honeycomb core	UD (Type I)	14,700	774
Case 5	$[60/-60/0]_s$ for face sheets and 0° for W direction of the aluminum honeycomb cores	UD (Type II)	16,003	1441
Case 6	$[60/-60/0]_s$ for face sheets and foam cores	UD (Type II)	36,211	2038

2.2.4. Sandwich panels with uni-directioal carbon prepreg (Type II) and foam core

In the case of sandwich panels with $[60/-60/0]_s$ for face sheets and foam cores, the failure loads was 36,211 N. The failure load of the sandwich panels with foam cores was 226% higher than that of the sandwich panels with aluminium honeycomb cores and face sheets which are $[60/-60/0]_s$ stacking sequence. However, the weight of the sandwich panels with foam cores were 31.5% heavier than that of the sandwich panels with aluminium cores. Therefore, the specific compressive load of the sandwich panels with foam cores, 14,955 [N/kg], was 72% higher than that of the sandwich panels with aluminum cores, 8693 [N/kg]. The failure strain of sandwich panel with foam core was 10,927 $\mu\varepsilon$ in compression, the failure strain of sandwich panels with aluminum core was 4271 $\mu\varepsilon$ in compression. The failure strain of sandwich panels with foam cores was same as the failure strain of the face sheets, but the failure strain of sandwich panels with honeycomb cores was lower than the failure strain of the face sheets. In the case of the aluminium core sandwich, nonhomogenous load distributions and fiber contents may affect the lower failure strain. Failure mode analysis of sandwich panels made of aluminium honey comb cores shows that shear failure leads to final failure. In the case of sandwich panels with foam cores, the flatness of cores keeps the skin in homogenous load distribution. Figure 3 shows the failure mode of the sandwich panels with the aluminium core or the foam core. Skin failures were the major failure modes for both the aluminium core and the foam core. In Chapter 3, the failure modes for the sandwich panels with honeycomb cores were discussed.

3. Compression test for composite sandwich panels with holes

3.1. Specimen preparation

The fabrication method was same for the edge compression test. The length (L) was 180 mm and the width (W) was 200 mm, as shown in Figure 4. The loading condition was 0.5 mm/min in the u direction. The face sheet was carbon fabric and the stacking sequence was $[0]_{8T}$. The boundary condition was same as that of the edge compression test. Points 20 mm from the bottom and 20 mm from the top were all fixed by fixtures and only the loading direction was free.

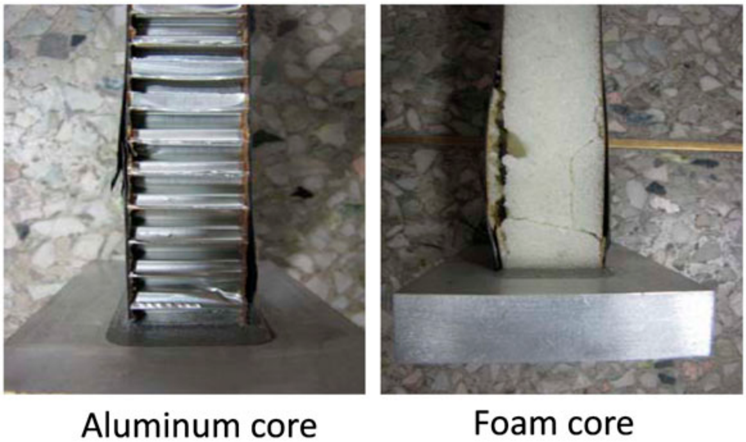

Figure 3. Failure mode of edge compression test.

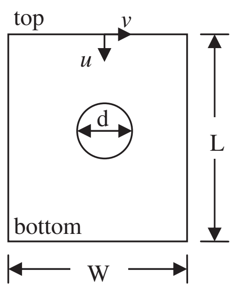

Figure 4. Sandwich panels with holes.

3.2. *Analysis for failure mode*

Finite element modeling using ANSYS SHELL 91 element was performed for d = 40 mm. The failure load was 48.5 kN in the test. The linear buckling load was 1030 kN in analysis. Therefore, static analysis was performed with 48.5 kN compression load for the load input of the failure analysis. The in-plane shear stress was 64 MPa which was near the shear strength, 86 MPa, as shown in Figure 5. The locations of shear stress concentration are marked. The shear stress of sandwich plate with a hole was higher than that of sandwich plate without hole. Therefore, the global failure strength of sandwich plate with a hole was lower than that of sandwich plate without hole. Figure 6 shows the failure location of the specimen. The final failure takes place at the location apart from the hole before the stress concentration near the hole leads to the final failure.

The failure mode shows that the shear failure leads to final failure in cases of sandwich panels with aluminum honeycomb cores, similar to the edge compression test discussed in Chapter 2. Figure 7 shows the effect of hole size on compressive failure load. Type I is the case of the aluminium honeycomb core and Type II is NOMAX 1/4 honeycomb core. However, the failure load did not depend on different kinds of cores because the shear failure of the face sheets leads to final failure in the case of the

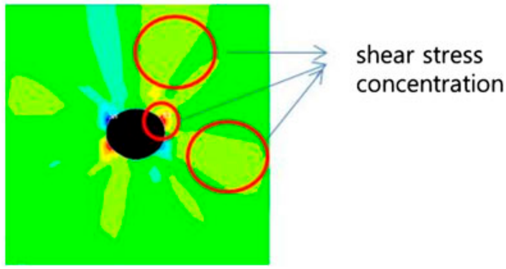

Figure 5. Shear stress contour.

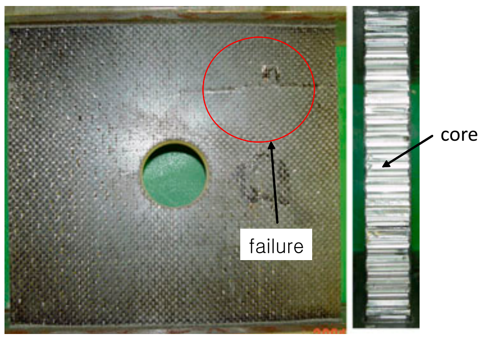

Figure 6. Failure of the specimen.

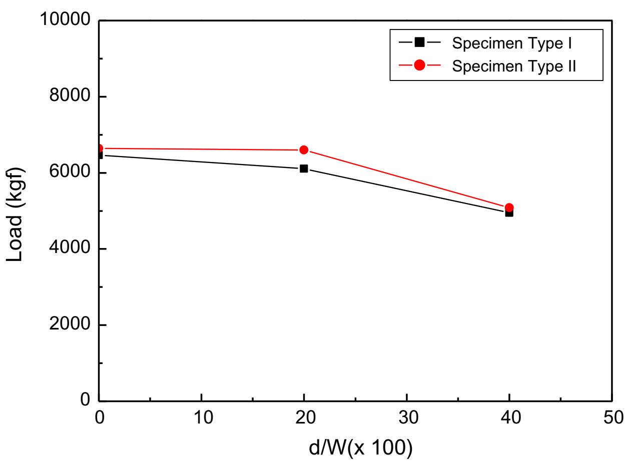

Figure 7. Effect of hole size on compressive failure load.

honeycomb cores. The failure load of sandwich panels with holes that had $d/W = 0.4$ was 33% lower than that of sandwich panels without holes. The failure load of sandwich panels with holes that had $d/W = 0.2$ was 5% lower than that of sandwich panels without holes.

4. Flexural test

4.1. Specimen preparation

The fabrication method was the same as that used for the specimen for the edge compression test. The length was 600 mm and the width was 60 mm. The loading condition was 2 mm/min, as shown in Figure 8.

We tested the flexural strength of composite sandwich specimens with different honeycomb cores or different stacking sequences. Each of the averaged failure loads is summarized in Table 3.

4.2. Results

4.2.1. Sandwich panels with carbon fabric and aluminium honeycomb core

In the case of sandwich panels with $[0]_{4T}$ for face sheets and 0° for W direction of the aluminum honeycomb cores and length direction, the failure load was 30,733 N. In the case of sandwich panels with [0/45/45/0] for face sheets and 0° for W direction of aluminum honeycomb core and length direction, the failure load was 34,751 N. The strength of [0/45/45/0] for face sheets was 13% higher than that of $[0]_{4T}$ for face sheets.

4.2.2. Sandwich panels with uni-directioal carbon prepreg (Type I) and aluminium honeycomb core

In the case of sandwich panels with $[60/-60/0]_s$ for face sheets and 0° for W direction of the aluminum honeycomb cores and length direction, the failure was 29,949 N. In the case of sandwich panels with $[60/-60/0]_s$ for face sheets and 0° for L direction of the aluminum honeycomb cores and length direction, the failure was 34,114 N. The strength of 0° for L direction of aluminium honeycomb cores for face sheets was 14% higher than that of 0° for W direction of the aluminium honeycomb cores, similar to the results of the compression test.

4.2.3. Sandwich panels with uni-directioal carbon prepreg (Type II) and aluminium honeycomb core

In the case of sandwich panels with $[60/-60/0]_s$ for face sheets and 0° for W direction of the aluminum honeycomb cores, the failure was 28,400 N. In the case of sandwich panels with $[-30/30/90]_s$ for face sheets and 0° for L direction of the aluminium honeycomb cores, the failure was 36,221 N. In the case of sandwich panels with $[0]_{6T}$

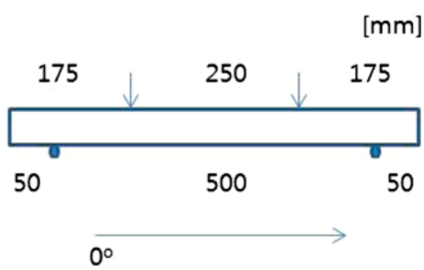

Figure 8. Flexural test.

Table 3. Failure load of flexural test.

	Type	Face sheet	Average value [N]	Standard deviation [N]
Case 1	$[0]_{4T}$ for face sheets and 0° for W direction of the aluminum honeycomb cores	Woven fabric	30,733	764
Case 2	[0/45/45/0] for face sheets and 0° for W direction of aluminum honeycomb core.	Woven fabric	34,751	529
Case 3	$[60/-60/0]_s$ for face sheets and 0° for W direction of the aluminum honeycomb cores	UD (Type I)	29,949	1372
Case 4	$[60/-60/0]_s$ for face sheets and 0° for L direction of the aluminum honeycomb cores	UD (Type I)	34,114	862
Case 5	$[60/-60/0]_s$ for face sheets and 0° for W direction of the aluminum honeycomb cores	UD (Type II)	28,400	657
Case 6	$[-30/30/90]_s$ for face sheets and 0° for L direction of the aluminium honeycomb cores	UD (Type II)	36,221	3881
Case 7	$[0]_{6T}$ for face sheets and 0° for W direction of the aluminum honeycomb cores	UD (Type II)	32,095	1607
Case 8	$[60/-60/0]_s$ for face sheets and foam cores	UD (Type II)	35,162	794
Case 9	$[-30/30/90]_s$ for face sheets and foam cores	UD (Type II)	45,109	549

for face sheets and 0° for W direction of the aluminum honeycomb cores, the failure was 32,095 N. The strength of Type I face sheets in case 3 had slight higher value than that of TYPE II face sheets in case 5. The strength of the sandwich panels with $[-30/30/90]_s$ for face sheets and 0° for L direction of the aluminium honeycomb cores was 27% higher than that of the sandwich panels with $[60/-60/0]_s$ for face sheets and 0° for W direction of the aluminium honeycomb cores.

This means that if a cylindrical fuselage was made of $[60/-60/0]_s$ for face sheets and 0°, which is the length direction of the cylindrical fuselage, for W direction of the aluminium honeycomb cores, the strength of the circumferential direction is 27% higher than that of the longitudinal direction, as shown in Figure 9.

4.2.4. *Sandwich panels with uni-directioal carbon prepreg (Type II) and foam core*

In the case of sandwich panels with $[60/-60/0]_s$ for face sheets and foam cores, the failure was 35,162 N. In the case of sandwich panels with $[-30/30/90]_s$ for face sheets and foam cores, the failure was 45,109 N. The weight of the sandwich panels with foam cores were 31.5% heavier than that of the sandwich panels with aluminium cores. If we compare the failure load divided by specimen weight for flexural testing with the failure load for compression test, the results are as follows. The specific flexural

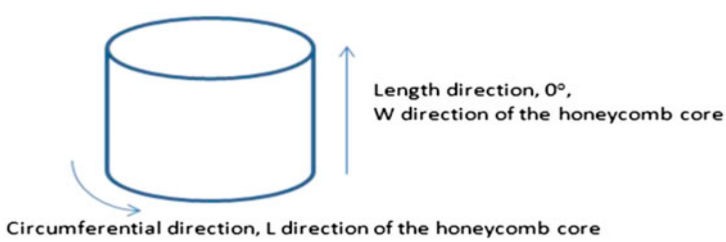

Figure 9. Composite cylindrical fuselage.

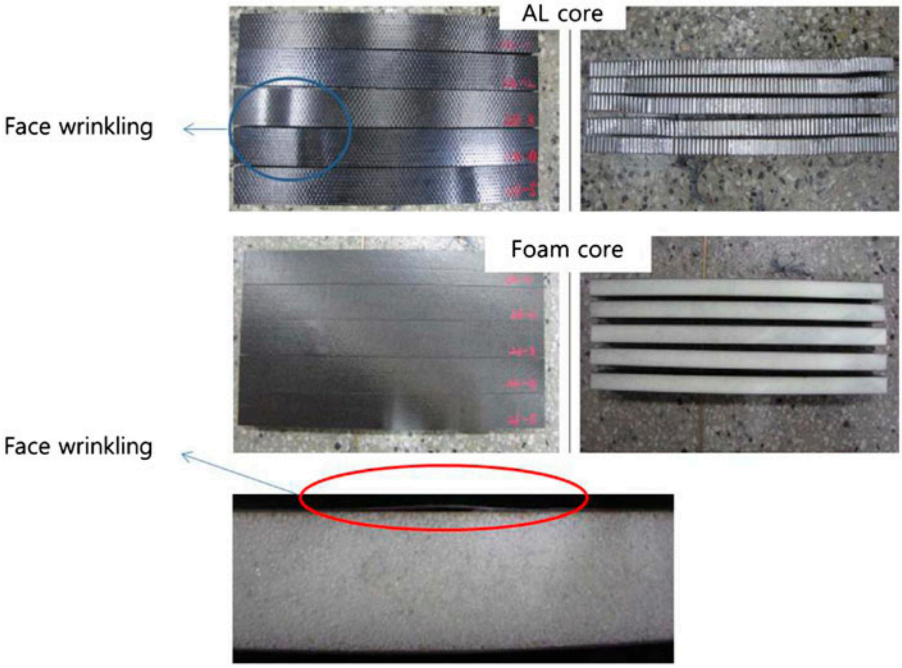

Figure 10. Failure mode of flexural test.

strength of sandwich panels with aluminum cores was 7% higher than that of the sandwich panels with foam core for both $[60/-60/0]_s$ and $[-30/30/90]_s$ unlike the comparison for the specific compression strength. Therefore, in the case of the flexural test, nonhomogenous fiber contents of the sandwich panels with aluminium honeycomb cores only slightly affect the strength. Instead, it is reasonable to assume that the core compression modulus affect the critical stress for the face wrinkling. The compression modulus of the aluminium core was higher than that of the foam core in Table 1. Therefore, the sandwich panel with aluminium cores had higher critical stress for the face wrinkling than the sandwich panel with foam cores. Face wrinkling was the major failure mode of sandwich panels under flexural test, as shown in Figure 10. The failure mode of face wrinkling was affected by the core compression modulus under flexural test. Skin failures, on the other hand, were the major failure modes under compression test in Chapter 2 and 3. The flatness of cores affected the failure mode and strength under compression test. Therefore, the relative strength between the aluminum core sandwich and the foam core sandwich was different according to the loading directions.

5. Conclusions

We conducted strength tests for sandwich panels with different cores. The compressive strength or flexural strength of 0° for L direction of aluminium honeycomb cores for face sheets was 12–14% higher than that of 0° for W direction of the aluminium honeycomb cores.

The aluminum core sandwich failed at the 40% failure strain of the face skin in the compression test. On the other hand, the foam core sandwich failed at the 100% failure strain of the face skin in the compression test. Therefore, the specific compressive strength of the sandwich panels with foam cores was 72% higher than that of the sandwich panels with aluminum cores. In the case of the aluminium core sandwich, nonhomogenous load distributions and fiber contents may affect the lower failure strain.

Failure mode analysis of sandwich panels made of aluminium honeycomb cores shows that shear failure leads to final failure. In the case of sandwich panels with foam cores, the flatness of cores keeps the skin in homogenous load distribution. We conducted strength tests for sandwich panels with different cores.

However, the specific flexural strength of the sandwich panels with aluminum cores had a slightly higher value than that of the sandwich panels with foam cores. Because the sandwich panel with aluminium cores had higher critical stress for the face wrinkling than the sandwich panel with foam cores due to higher compression modulus of aluminium cores than foam cores. Therefore, the flexural deformation can be said to hardly affect the strength comparison relative to two kinds of cores. In the design of composite sandwich panels, the loading direction should be considered for the selection of the core including manufacturing cost, weight, and strength.

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