Mechanical Properties of Honeycomb Prepared from Aromatic Polyimide Film

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SYNOPSIS

Aromatic polyimides have many advantages such as low thermal expansion coefficient, good electrical insulation, and self-extinguishing properties. We tried to use polyimide film for honeycomb structure. Polyimide honeycomb core and sandwich panel were prepared from polyimide film, i.e., UPILEX R, and adhesive by the expansion method. Mechanical properties, i.e., compressive, crushed, shear, and flexural strengths, were evaluated for this core and panel. Compressive and crushed properties increased largely with the density of the honeycomb, whereas shear and midspan flexural properties did not vary so much with the density, because these failures occurred in the adhered interface. Strong adhesion is required for improving the latter properties. © 1993 John Wiley & Sons, Inc.

INTRODUCTION

Honeycomb is constituted of many hexagons that are prepared by adhering films. This structure is very light in weight, and the volume ratio of air is ~99%. Honeycomb core is ordinarily used in sandwich construction by adhering to aluminum panel, GFRP, or CFRP on both sides. This honeycomb sandwich construction can also be regarded as a set of "I-beam" in the microscopic viewpoint, namely, the facing panels correspond to props supporting both ends of the I-beam. The honeycomb sandwich constructions have many advantages such as low weight, high strength, excellent resistance to impact damage, and effective heat-exchange.[1] The honeycomb sandwich constructions have been applied to various fields of manufacturing industries, such as aircraft construction.[2] Steel honeycomb and glass-fiber-reinforced phenolic honeycomb are practically used as a heat shielding panel of the space capsule.[3,4] CFRP and Kevlar, and aluminum are used as facing and core materials, respectively, in the parabolic antenna of a communications satellite.[5] The materials adopted for these applications are required for the high modulus of elasticity and strength and good electric insulation properties over a wide range of temperature. The materials used for parabolic antenna of a communications satellite are especially required for a low thermal expansion coefficient to keep excellent smoothness of the surface over the range of 25–300°C.[5] Aromatic polyimide film is better in some of the above properties than are those materials. We tried to apply this film for honeycomb core and facing. Compressive, shear, and flexural tests were conducted for this honeycomb core and panel.

PREPARATION OF POLYIMIDE HONEYCOMB

Materials

UPILEX R film[6] was supplied by Ube Industries Ltd. (Tokyo, Japan) and was adopted for core and facing materials of honeycomb. Several mechanical properties of UPILEX R film are shown in Table I. Polyimide-type adhesive was also supplied by the same company and is the mixture of soluble polymer, polyimide oligomer, and 1,4-dioxane as solvent in the ratio of 1:1:8 by weight.

Preparation of Polyimide Honeycomb Core

We adopted an expansion method for preparing polyimide honeycomb core and sandwich panel. The

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Table I Mechanical Properties of UPILEX R[6]

Properties	UPILEX R
Tensile strength	0.27 GPa
Elongation at break	130%
Tensile modulus of elasticity	3.27 GPa

Table II Honeycomb Core and Sandwich Panel Prepared in This Study

Sample Name	Width Coated with Adhesive (mm)	Cell Size (mm)	Thickness of Facing Film (μm)
125R-7	5.0	7.0	125
75R-18	12.7	18.0	75
75R-9	6.4	9.0	75
75R-7	5.0	7.0	75
75R-4	2.8	4.0	75

process of preparing honeycomb core is explained as follows for a 7 mm cell size as an example: Adhesive is applied on a film in the width of 5 mm at the interval of 15 mm. Adhesive is applied on the other film with 10 mm shifting. Solvent in the applied adhesive is evaporated by keeping it at 90°C for 20 min. Subsequently, polyimide sheet is cut in width approximately corresponding to the thickness of the honeycomb core, and these films are stuck alternatively. The films are adhered at 300°C for 15 min under pressure of 0.4 MPa. After removing pressure, stuck films are held at 300°C for 30 min. The assembly is cut so as to have the thickness expected and the cut surface is polished up. Successively, the assembly is expanded by applying tension

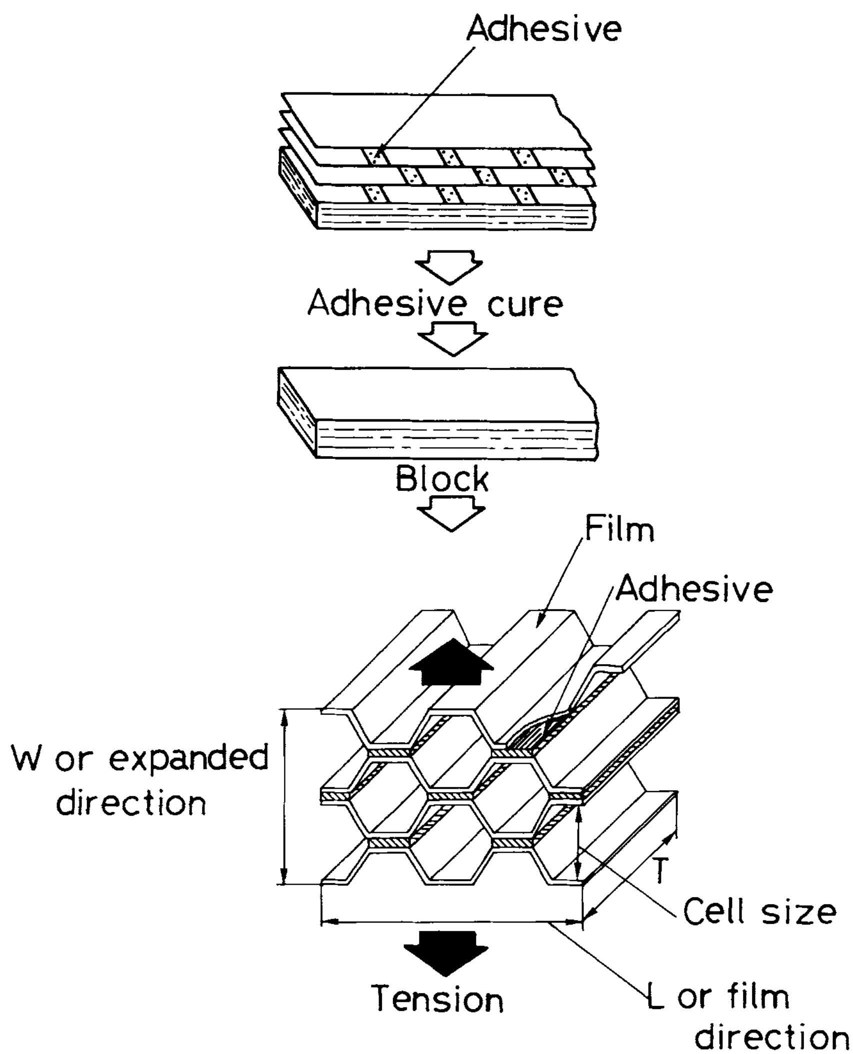

Figure 1 Process for preparing polyimide honeycomb.

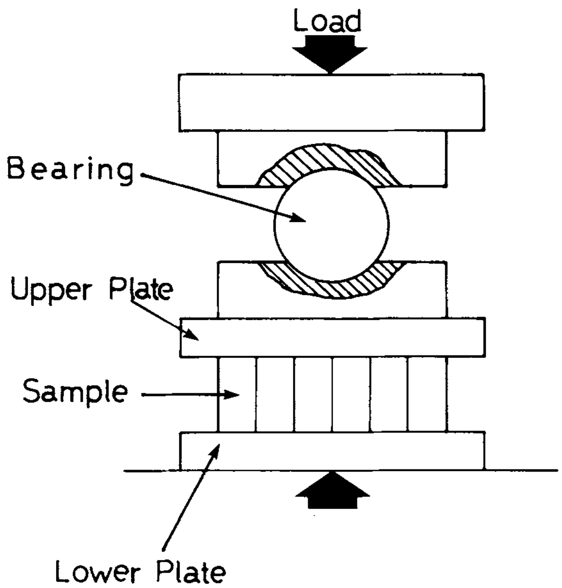

Figure 2 Apparatus for compressive test of sandwich panel.

perpendicular to the film direction and kept at 300°C for 20 min.

In the honeycomb core, the "L direction" means the film direction; the "W direction," the one perpendicular to the film direction; and cell size, the distance between two faces next to each other as shown in Figure 1.

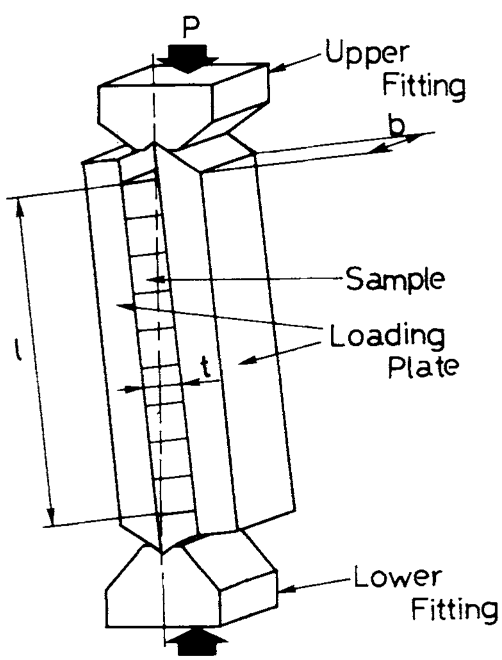

Figure 3 Arrangement of apparatus and test specimen for shear test.

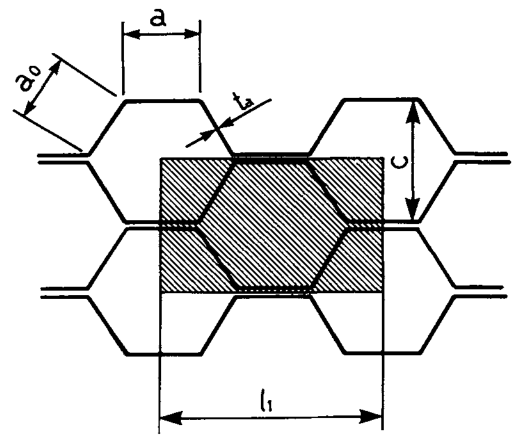

Figure 4 Symbols for honeycomb core.

Additionally, the names of samples prepared in this study indicate the thickness of the film used and cell size, e.g., 125R-7 means that the thickness of the film used is 125 μm and 7 indicates cell size in mm. The film adopted for core and facing in a sample has the same thickness. The honeycomb cores and panels that were prepared are described in detail in Table II.

Preparation of Honeycomb Sandwich Panel

The above-described adhesive was applied to one side of the surface of the film. After evaporation of the solvent, the facing film was adhered to the honeycomb core under the same conditions as described above. The same process was conducted for the other side of the honeycomb. We adhered films so as to prevent such permanent deformation such as wrinkles and hollow.

EVALUATION OF POLYIMIDE HONEYCOMB

Methods of evaluation of the honeycomb are shown in JIS A 6931[7] and MIL STD 401B.[8] JIS A 6931 is concerned only with a paper honeycomb core for the panel. MIL 401B is very popular and has been applied to aluminum honeycomb, which is the most popular honeycomb. In this study, the latter method was adopted mainly for evaluation of polyimide honeycomb. Five specimens were provided for each test and the values obtained were averaged.

Compressive Test

This method is concerned with the determination of compressive and crush strengths of honeycomb

Table III Measured and Calculated Densities for Honeycomb Core

Sample Name	Measured Density ρ_1 (kg/m^3)	Cell Size C (mm)	Length of Adhered Surface a (mm)	Calculated Density ρ_2 (kg/m^3)	Errors of Density[a]	Thickness of Adhesive (mm)
125R-7	67.52	6.8	6.98	66.40	−1.6	0.15
75R-7	39.38	6.4	6.71	39.92	1.4	0.05
50R-7	28.20	6.7	6.61	26.46	5.8	0.14

[a] $(\rho_2 - \rho_1)/\rho_1 \times 100$ (%).

core and sandwich panel. Compressive strength means the maximum load in compression, and crushed strength, the load when honeycomb core is folded. The size of the test specimen is 50 × 50 mm in cross section and 12 mm in thickness. The apparatus for this test is schematically shown in Figure 2. The speed of the plate movement is 2 mm/min. Compressive strength is obtained from the following equation:

$$\sigma_{co} = \frac{P_c}{S} \tag{1}$$

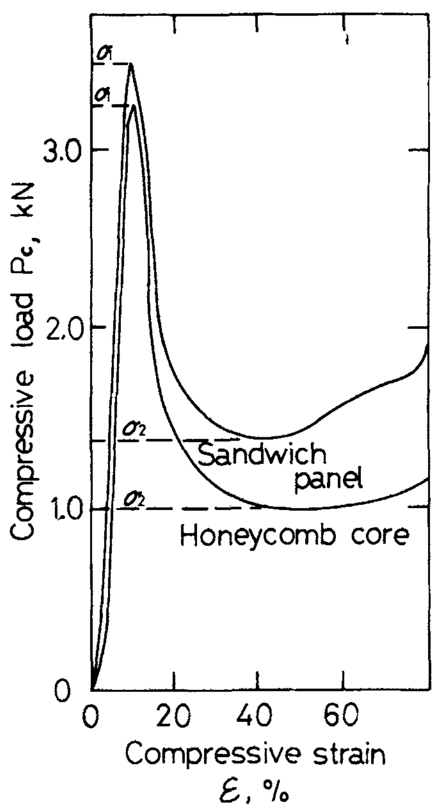

Figure 5 Typical stress–strain curves in compressive test: σ_1, compressive strength, σ_2, crushed one.

where σ_{co} is the compressive strength; P_c, the maximum load; and S, the cross section area of the specimen.

Shear Test

This method is concerned with the determination of shear strength parallel to the plane of the sandwich panel and the shear modulus of elasticity. The size of test specimen is 150 × 50 mm and 14 mm in thickness. Epoxy resin adhesive was applied to both faces of a sandwich panel, and those were bonded with two steel plates at 90°C for 90 min. The test was conducted by forcing the loading plates as shown in Figure 3. The speed of the head movement is 2

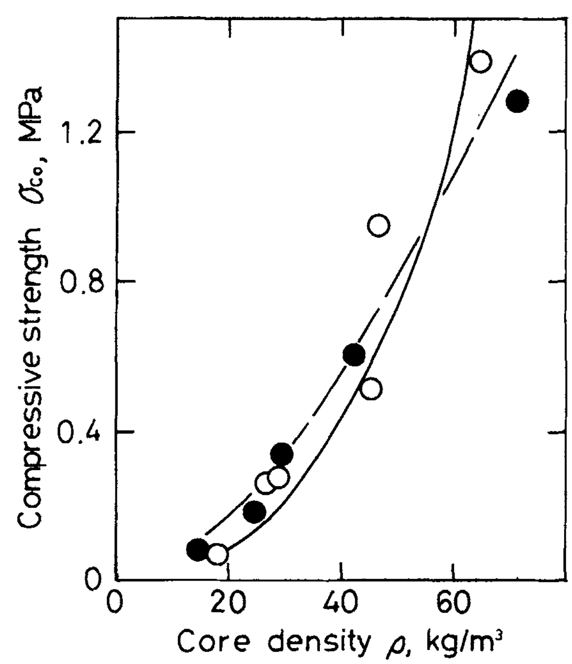

Figure 6 Density dependence of compressive strength: (○) honeycomb core; (●) sandwich panel. In the case of the sandwich panel, the weight of the face panels is subtracted from total one when ρ is calculated.

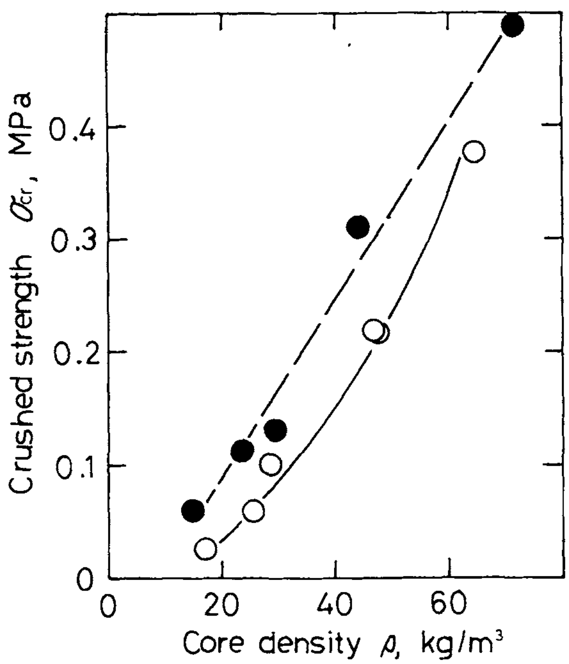

Figure 7 Density dependence of crushed strength: (○) honeycomb core; (●) sandwich panel. The same treatment as in Figure 6 is taken into consideration for the ρ value.

mm/min. Shear strength is obtained from the following equation:

$$\tau = \frac{P}{lb} \tag{2}$$

where τ is the shear strength; P, the load at maximum strength; l, the length of the specimen; and b, the width of the specimen. Shear strain is obtained from eq. (3):

$$\gamma = \frac{r}{t} \tag{3}$$

where r is the movement of one loading plate with respect to the other one at maximum strength, and t, the thickness of the specimen.

Midspan Load Flexural Test

This method is concerned with the determination of facing strength and core shear strength. The size of specimen is 200 × 75 × 16 mm, and the span length is 150 mm. The facing strength is obtained from eq. (4):

$$\sigma_f = \frac{P_f a_l}{2f(t+e)b} \tag{4}$$

where P_f is the flexural load at maximum strength; a_l, the length of the span; e, the thickness of the core; b, the width of the sandwich; and f, the thickness of the facing film.

Flexural stiffness of sandwich panel D is obtained from eq. (5):

$$D = \frac{P_f a_l}{48\left(w_l \frac{P_f A_l}{4N}\right)} \tag{5}$$

where w_l is the midpoint deflection at maximum strength, and N, the shear stiffness obtained from eq. (6):

$$N = \frac{G(t+e)^2 b}{4e} \tag{6}$$

where G is the shear modulus of elasticity obtained from the shear test.

Calculation of Density

Mechanical properties of the honeycomb core are believed to depend upon the kind of material and

Table IV Compressive Properties of Polyimide Honeycomb Core and Sandwich Panel

	Honeycomb Core			Honeycomb Sandwich Panel		
Sample Name	Density (kg/m³)	Compressive Strength (MPa)	Crushed Strength (MPa)	Density (kg/m³)	Compressive Strength (MPa)	Crushed Strength (MPa)
75R-7	42.7	0.52	0.22	42.0	0.61	0.31
75R-9	28.5	0.27	0.10	29.0	0.35	0.13
75R-18	18.1	0.07	0.02	14.5	0.09	0.06
125R-7	65.7	1.39	0.38	71.5	1.28	0.49
125R-9	42.8	0.96	0.22			
125R-18	27.1	0.26	0.06	23.8	0.19	0.11

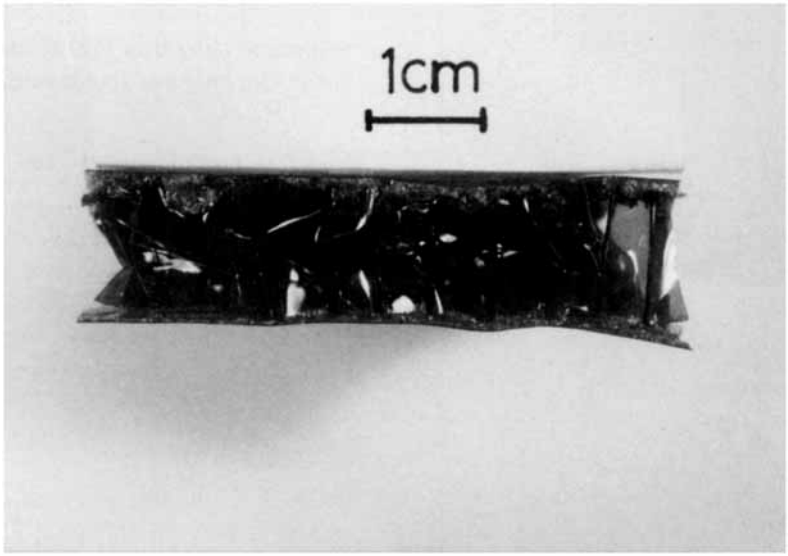

Figure 8 Appearance of compressive failure in the sandwich panel.

density.[9] Mechanical properties of polyimide honeycomb were evaluated as a function of density. We will take into account the shadowed portion in Figure 4 for calculation of density of the honeycomb core, which is incompletely hexagonal. The length of the adhered surface is not equal to the other surface, i.e., a is slightly different from a_0 in Figure 4. These lengths were measured practically. The length

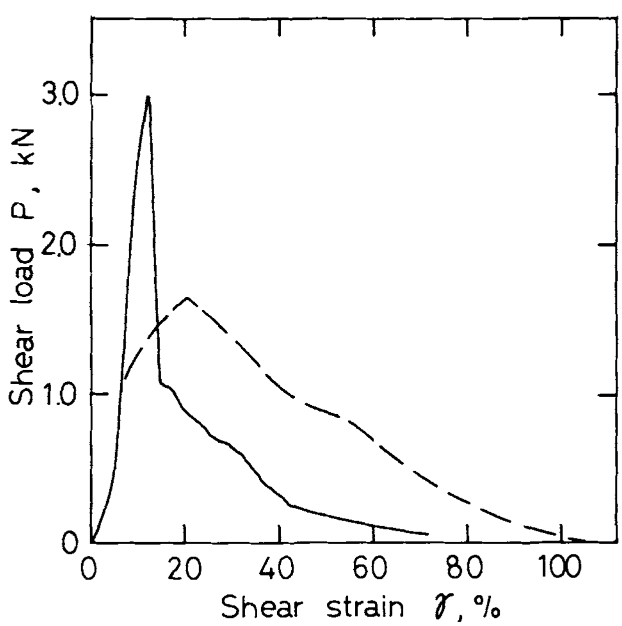

Figure 9 Example of load-strain curve in the shear test (75R-7): (——) L direction; (----) W direction.

of the shadowed portion l_1 is calculated by assuming that the angle between two sides is 120°:

$$l_1 = 2a + 2 \times \frac{c}{2} \times \tan 30.$$

$$= 2a + \frac{c}{\sqrt{3}} \qquad (7)$$

where c is the cell size, and a, the length of the adhered surface.

The volume of the shadowed portion V can be expressed as follows:

$$V = cl_1e = c\left(2a \frac{1}{\sqrt{3}}\right)e \qquad (8)$$

The length of the nonadhered surface a_0 can be expressed as follows:

$$a_0 = 4 \times \frac{c}{2} \times \frac{1}{\cos 30°} = \frac{c}{\sqrt{3}} \qquad (9)$$

The length of film in the shadowed portion l_f can be expressed as follows:

$$l_f = 4a + 4a_0 = 4\left(a + \frac{c}{\sqrt{3}}\right) \qquad (10)$$

The weight of the film and adhesive in the shadowed portion W_m can be expressed by

$$W_m = 4\left(a + \frac{c}{\sqrt{3}}\right)t_r\rho_r e + a\rho_a t_a e \qquad (11)$$

Table V Shear Properties of Polyimide Honeycomb Sandwich Panel

	L Direction			W Direction	
Sample Name	Density (kg/m^3)	Shear Modulus of Elasticity (MPa)	Shear Strength (MPa)	Shear Modulus of Elasticity (MPa)	Shear Strength (MPa)
125R-18	23.2	6.00	0.23	2.32	0.09
125R-9	48.7	11.12	0.39	4.50	0.24
125R-7	67.3	9.85	0.73	5.11	0.44
75R-7	32.2	8.18	0.45	4.09	0.23

where ρ_r is the density of the polyimide film; t_r, the thickness of the polyimide film; ρ_a, the density of the adhesive; and t_a, the thickness of the adhesive.

The thickness of adhesive t_a can be easily calculated from the weight of the adhesive coated. The density of honeycomb core ρ can be expressed as follows: Calculated and measured values of the density are shown in Table III. The agreement between them is fairly good. Therefore, the density of honeycomb cores was hereafter calculated according to eq. (12). The density of the honeycomb sandwich panels is easily calculated by using a similar equation:

$$\rho = \frac{4\left(a + \frac{c}{\sqrt{3}}\right)t_r\rho_r e + a\rho_a t_a e}{c\left(2a + \frac{c}{\sqrt{3}}\right)e} \qquad (12)$$

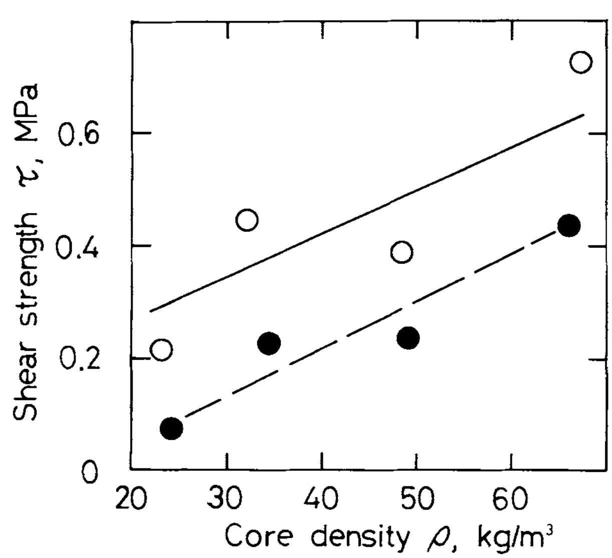

Figure 10 Density dependence of shear strength in the sandwich panel: (○) L direction; (●) W direction.

RESULTS AND DISCUSSION

Compressive Properties

Figure 5 shows the load-strain curve obtained from compressive test of the honeycomb core and sandwich panel. When compressive load is applied to the honeycomb core, the core is crushed down, keeping almost constant stress from the first buckling to bottoming out by bending of all core walls. The effective stroke to bottom out is 65% of core thickness in this case, whereas this stroke is 75% in case of aluminum honeycomb.[9] The effective stroke for the polyimide sandwich panel is 25%. This difference would depend upon the film thickness adopted.

Compressive and crushed strengths were plotted against the density of honeycomb cores and sandwich panels, as shown Figures 6 and 7, respectively. (See also Table IV.) The appearance of compressive failure is shown in Figure 8. The relations shown in Figures 6 and 7 are very similar to ordinary honeycomb cores, such as the aluminum one. In the case of the sandwich panel, the weight of the facing film is always subtracted from total one when ρ is calculated, because the principal comparison of core and panel constructions is important. Compressive strength is not improved at all by changing the core to the sandwich structure. The same tendency is observed in crushed strength. These results come from the weak adhesion strength between the honeycomb core and the facing film. In fact, the peel strength between the films of UPILEX R is in the range of 10–35 N/25 mm.[10]

Shear Properties

Figure 9 shows the load-strain curve obtained from shear test in a flatwise plane of polyimide sandwich

Figure 11 Typical failure in shear test.

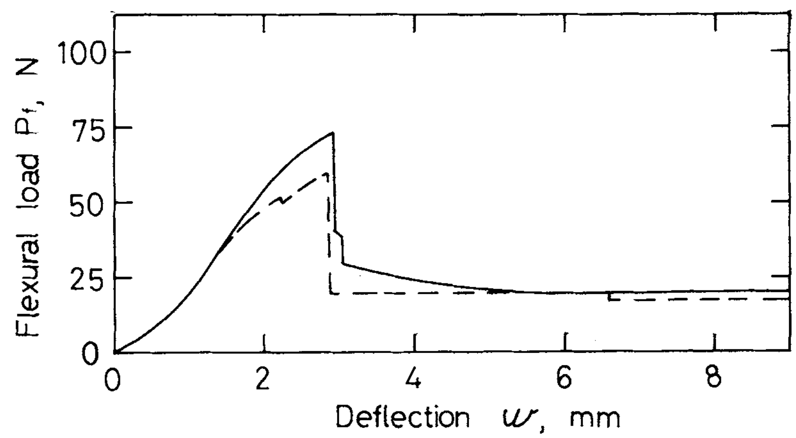

Figure 12 Example of load-deflection diagram in the flexural test (75R-7): (——) L direction; (----) W direction.

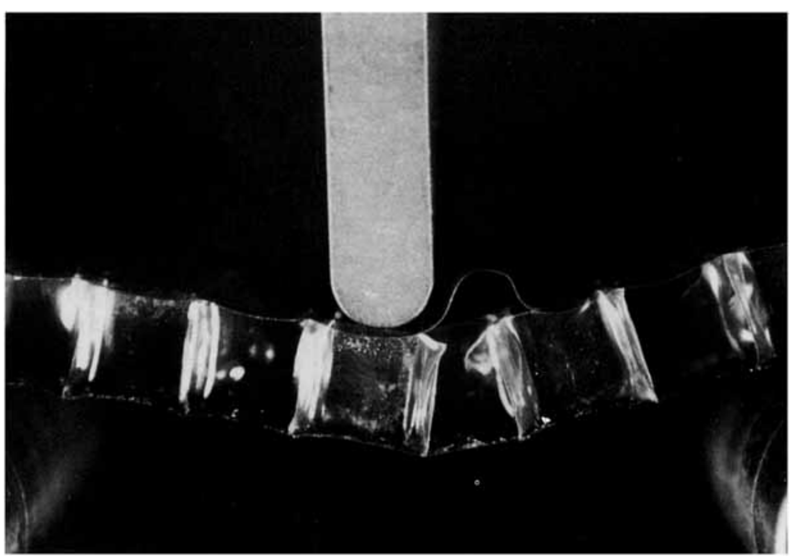

Figure 13 Typical failure in flexural test.

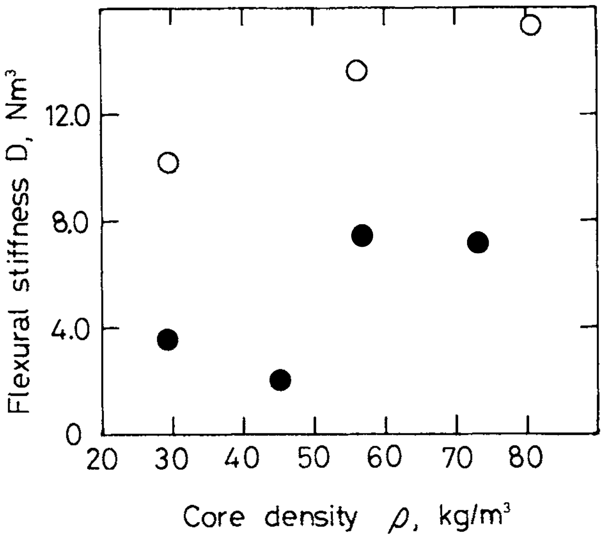

Figure 14 Density dependence of flexural stiffness in the sandwich panel: (○) L direction; (●) W direction.

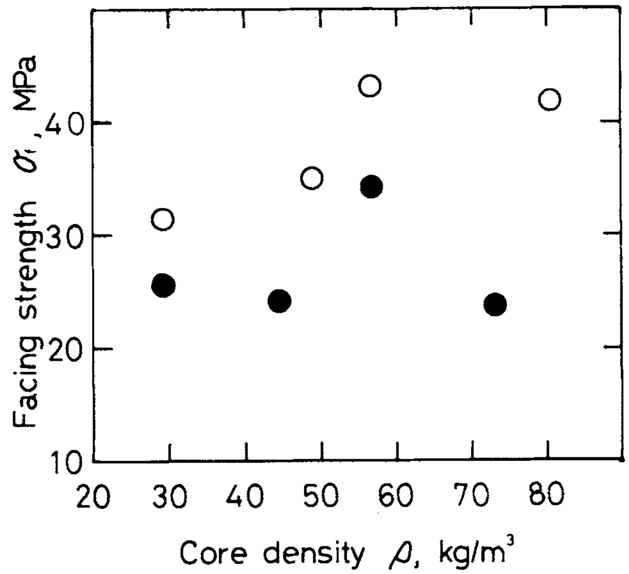

Figure 15 Density dependence of facing strength in the sandwich panel: (○) L direction; (●) W direction.

panel. The maximum shear strength in the W direction is equal to approximately half of that in the L direction. Shear strength in the L direction suddenly decreases, but that in the W direction slowly decreases, after reaching the maximum strength. The average shear strengths, shear modulus of elasticity, and densities in the sandwich panel are summarized in Table V. Figure 10 shows the density dependence of shear strength in the sandwich panel. The shear strength slightly increases with the density of the sandwich panel. This fact implies that the density or cell size is not very important for shear strength, because the failure always occurs in the adhered interface between core and facing film, as shown in Figure 11. Shear strength in the W direction is equal to approximately half of that in the L direction. This difference can be understood from Figure 1, namely, the direction of adhered surface between core films is parallel to the L direction.

Midspan Flexural Properties

Figure 12 shows the load-deflection curves obtained by the midspan load flexural test. Flexural load suddenly decreases after reaching the maximum flexural load. Figure 13 shows the typical failure in a flexural test. Figures 14 and 15 show the density dependencies of flexural properties. Facing strength and flexural stiffness were calculated according to eqs. (5) and (6), respectively. The average facing strength, flexural stiffness, and density in the sandwich panel are summarized in Table VI. The density dependence of these properties in the sandwich panel is very small, like that of shear properties. This is because flexural failure always occurs in the adhered interface between core and facing films, as shown in Figure 13. Improvement of adhesion properties or development of a new strong adhesive is required

Table VI Flexural Properties of Polyimide Honeycomb Sandwich Panel

		L Direction		W Direction	
Sample Name	Density (kg/m^3)	Flexural Stiffness ($N\ m^2$)	Facing Strength (kPa)	Flexural Stiffness ($N\ m^2$)	Facing Strength (kPa)
125R-18	29.5	10.20	31.4	3.45	25.8
125R-9	56.2	13.72	43.1	7.42	34.5
125R-7	80.3	15.70	41.6	7.03	23.6
75R-7	45.3		34.8	1.94	23.9

for this aromatic polyimide film in order to obtain polyimide honeycomb having excellent mechanical properties.

CONCLUSION

Polyimide honeycomb was prepared by the expansion method. Fundamental properties such as compressive, flexural, and shear ones were determined for the honeycomb core and sandwich panel mainly according to MIL STD 401B. We tried to correlate these properties with the density. However, the density dependence of these properties was small except for compressive properties. This is because the adhesion strength between the films is weak.

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