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Basic mechanical properties of balloon-type TEEK-L polyimide-foam and TEEK-L filled aramid-honeycomb core materials for sandwich structures

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Abstract—The objectives of this study are to investigate the basic mechanical properties of TEEK-L polyimide-foam of a balloon type and TEEK-L filled aramid-honeycomb core-materials for sandwich structures and to compare their mechanical properties with those of AIREX R82 and ROHACELL WF foam core-materials. Compression, tension, and plate-shear tests provided their stress–strain relationships, elastic modulus, and strength. The test results are compared and discussed. The major results obtained are: (1) Filling the aramid honeycomb cells with TEEK-L can improve the basic mechanical properties of an aramid-honeycomb core-material, in particular making them higher than the values expected from the principle of superposition for compression tests and equal to the values expected from superposition for plate-shear tests. (2) The basic mechanical properties of the TEEK-L filled aramid honeycomb are superior to those of AIREX R82 110 and equivalent to those of ROHACELL WF 110, where the three materials have equal densities. (3) The basic mechanical properties of TEEK-L are inferior to those of AIREX R82 60 and ROHACELL WF 51, when materials with equivalent densities are compared. (4) TEEK-L filled aramid honeycomb has high potential as a new core material for aerospace sandwich structures.

Keywords: Sandwich core materials; TEEK-L polyimide foam; balloon type; TEEK-L filled aramid honeycomb; compression test; tension test; plate-shear test; mechanical properties; principle of superposition.

1. INTRODUCTION

The use of sandwich structures, which consist of a plastic foam core material and two skins of laminated composite materials, has grown for the structural

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members of aircraft and rockets in recent years. A family of ROHACELL foams made of PMI (polymethacrylimide) [1–5] and that of AIREX foams made of PEI (polyetherimide) [5–7] have been used for this purpose.

Unlike the above examples, TEEK foam materials made of polyimide resins have been cooperatively developed by NASA and Unitika Ltd. for use in the TPS (thermal protection system) for cryogenic tanks to reduce vehicle weight for the X-33 program and RLV (reusable launch vehicle) program [8–12]. TEEK was named by the capital letters of the collaborators' names from NASA and Unitika. These materials have excellent characteristics for environmental stability against cold air, heat, flame, and moisture, as well as for sound insulation, formability, impact-load resistance, and so on. Nowadays two groups of TEEK are available in the market. One group is TEEK-H series (LaRC-IA: 4,4′-oxydiphthalic anhydride/3,4′ oxydianiline) and the other TEEK-L series (3,3′,4,4′-benzophenone-tetracarboxylic acid dianhydride/4,4′-oxydianiline) [8, 10, 12]. The characteristics of both series of TEEK were summarized in Refs [12, 13]. TEEK-H has excellent hydraulic stability but is rather expensive. TEEK-L has fair hydraulic stability and is less expensive.

Weiser *et al.* presented the process of filling honeycomb core materials with TEEK-H [9]. Meanwhile, Showa Aircraft Industry Co. Ltd. has developed an original technology for filling honeycomb cells with the foam of balloon-type TEEK and is now in a patent application. The initial purpose of filling honeycomb cells with TEEK-H or -L was to improve the heat insulation capability of a honeycomb core-material, though the core weight was increased. In addition, a TEEK-filled honeycomb has the potential to improve the elastic modulus and strength in comparison with the original honeycomb core-materials, and is expected to be excellent new core-materials of light weight with high heat resistance.

Since TEEK foam core-materials are entirely new, only a little data on the basic mechanical properties of TEEK-H and -L foams and TEEK-H filled aramid honeycomb materials have been published. Weiser *et al.* presented the tensile strength and compressive modulus and strength of TEEK-H [8, 9], the flatwise compressive modulus and strength of TEEK-L [8], and the flatwise compressive modulus and strength of TEEK-H filled aramid honeycomb [9]. Veazie *et al.* [10] reported the flatwise tensile and compressive strength of TEEK-H. Resewski and Buchgraber [11] showed the compressive strength of TEEK-H and TEEK-H filled honeycombs as a function of temperature. However, there are no data about the shear properties of these materials, though these shear properties are very important in designing sandwich structures. Moreover, the basic mechanical properties of TEEK-L foam materials and TEEK-L filled aramid honeycomb core materials have not been reported in the literature, except for only one example [8] of the compressive modulus and strength of a TEEK-L foam.

An aramid honeycomb core-material filled with TEEK-L also has a potential to be an excellent light core material for less-expensive aerospace sandwich structures. In order to explore this possibility, the mechanical properties of TEEK-L and honeycombs filled with TEEK-L as new core-materials should be investigated. Furthermore, the comparison of mechanical properties with those of AIREX R82 and ROHACELL WF is also important from the viewpoint of practicality evaluation for aerospace sandwich structures.

This study selected two kinds of sandwich core-material as subject materials, TEEK-L polyimide foam of a balloon type and an aramid honeycomb filled with TEEK-L of this type. The objectives are as follows: (1) to investigate the basic mechanical properties of TEEK-L, an aramid honeycomb, and the TEEK-L filled aramid honeycomb, (2) to clarify the improvement of the elastic modulus and strength of the aramid honeycomb by filling with TEEK-L on the basis of the principle of superposition, (3) additionally to investigate the basic mechanical properties of AIREX R82 and ROHACELL WF, (4) to compare the mechanical properties obtained for TEEK-L and the TEEK-L filled aramid honeycomb with those of AIREX R82 and ROHACELL WF, and (5) to examine the possibility of TEEK-L filled aramid honeycomb for a core material of aerospace sandwich structures.

2. MATERIALS, SPECIMENS AND TESTING PROCEDURE

2.1. Materials

TEEK-L foam core-materials available in our country can be classified into two kinds according to their cell types. One is called a neat resin type. The cells are closed like those of AIREX R82 and ROHACELL WF. With this type, TEEK-L cannot be filled into honeycomb cells, so it was not considered in this study. The other is called a balloon type, of which cells consist of spherical balloons bonded with an adhesive binder. TEEK-L of this type can be filled into the honeycomb cells in the manner that TEEK-L balloon powders with a polyimide binder are filled into the honeycomb cells and cured by heating. TEEK-L of this type is the focus of this study and from here is briefly called TEEK for simplicity. As described above new core materials used in this study are of two kinds, TEEK-only and TEEK-filled aramid honeycomb, shown in Fig. 1.

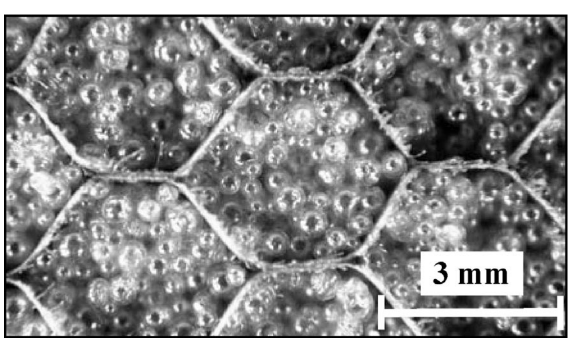

Figure 1. TEEK-filled aramid honeycomb.

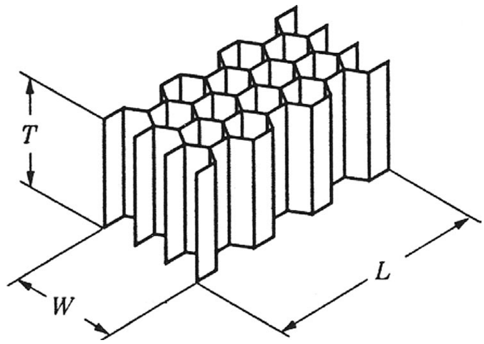

Figure 2. Honeycomb directions.

Seven kinds of sandwich core-materials were tested, including TEEK, the aramid honeycomb (AHC), TEEK-filled aramid honeycomb (TEEK + AHC), AIREX R82 60, 110, and ROHACELL WF 51, 110. The nominal densities of the materials are 72 kg/m^3 (4.5 pcf = pound/feet^3) for TEEK, 48 kg/m^3 (3 pcf) for the aramid honeycomb, and 110 kg/m^3 (7 pcf) for the TEEK-filled aramid honeycomb. In order to discuss the effect of filling aramid honeycomb cells with TEEK, equal densities for TEEK-only and TEEK-filled into the aramid honeycomb cells are desirable. Since these values are 72 and 62 (= 110 − 48) kg/m^3 respectively, both values are fairly close. AIREX R82 60, 110, ROHACELL WF 51, and 110 were selected as the comparison materials. The nominal densities of AIREX R82 60, 110 are 60 and 110 kg/m^3, respectively, and those of ROHACELL WF 51 and 110 are 51 and 110 kg/m^3, respectively. This study classifies TEEK-only, AIREX R82 60, and ROHACELL WF 51 as materials with equivalent densities, though their densities are 72, 60, and 51 kg/m^3, respectively. Meanwhile, the TEEK-filled aramid honeycomb, AIREX R82 110, and ROHACELL WF 110 have nominally equal densities, i.e. 110 kg/m^3.

The aramid honeycomb directions are defined by T for the thickness direction, L for the ribbon direction, and W for the expanded direction, i.e. perpendicular to the ribbon direction, as shown in Fig. 2. The nominal cell size is 3.2 mm (1/8 in).

2.2. Specimens and testing procedure

Specimen configurations and testing procedures were based on ASTM standards. Static tests were conducted with an Instron 4505 material testing machine. Compression and tension specimens and test methods were designed in accordance with ASTM C 365 and C297, respectively. Figure 3 shows the specimen configuration common to compression and tension tests. This flatwise compression and tension testing was used by Weiser *et al.* [8, 9], Veazie *et al.* [10], and Resewski and Buchgraber [11] also. In a compression test, a specimen was compressed between the anvil and loading table. Figure 4 illustrates a tension test. The upper and lower surfaces of a tensile specimen were bonded to metallic loading blocks with an adhesive. Tensile load was given as shown in Fig. 4. Plate-shear tests were based on ASTM

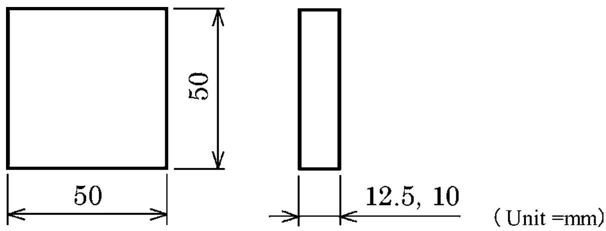

Figure 3. Specimen configuration common to compression and tension tests.

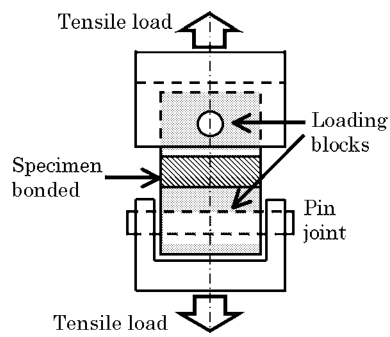

Figure 4. A tension test.

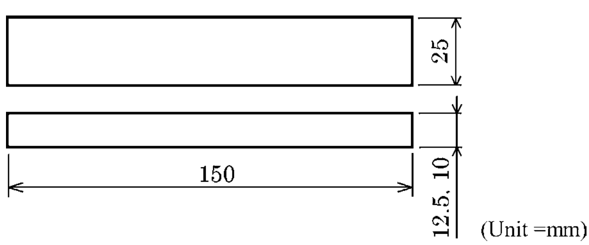

Figure 5. Specimen configuration for plate-shear tests.

C273. Figure 5 shows the specimen configuration for plate-shear tests. Figure 6 shows a plate-shear test. The front and back surfaces of a specimen were bonded to the metallic loading plates. The specimen and the fixtures were assembled as shown in Fig. 6. The shear force was applied to the specimen by a tensile load on the pin joints of the loading plates.

The nominal specimen thickness is 12.5 mm for TEEK, the aramid honeycomb, and the TEEK-filled aramid honeycomb, and 10 mm for AIREX R82 and ROHACELL WF. The loading speed for the cross-head of the testing machine was selected to be 1 mm/min for all compression tests, 0.5 mm/min for all tension tests, 0.5 mm/min for plate-shear tests on TEEK, AIREX R82 60, 110, and ROHACELL WF 51, 110, and 0.25 mm/min for plate-shear tests on the aramid honeycomb and TEEK-filled aramid honeycomb. The loading speeds were chosen to conform to the referred ASTM standards. The strain was calculated from the cross-head displacement with a correction based on a load–displacement relationship that was

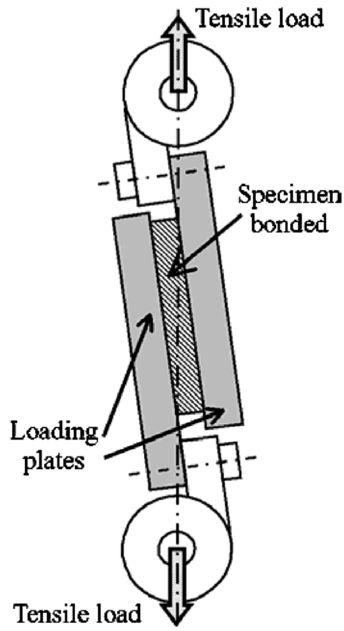

Figure 6. A plate-shear test.

measured with no specimen for a compression test and measured for an aluminum-alloy dummy specimen for tension and plate-shear tests. All mechanical tests were conducted in ambient air.

3. TEST RESULTS AND DISCUSSION

The stress–strain relationships in Figs 7–10 and 12–13 shown later are represented by a typical example in each case for simplicity. In Tables 1 to 3, the total number of tests in each case is called the sample size and the mechanical properties are listed by the mean and coefficient of variation (CV) in %, i.e. (sample standard deviation) $\times$ 100/mean, where CV is used as an index of data scatter.

3.1. Compression test results

Table 1 shows the test results for compressive mechanical properties, i.e. the compressive elastic modulus and strength of TEEK, the aramid honeycomb (T direction), the TEEK-filled aramid honeycomb (T direction), AIREX R82 60, 110, and ROHACELL WF 51, 110. The compressive strength of TEEK is defined by the stress corresponding to 10% strain (deflection), because TEEK did not show a peak stress in its stress–strain relationships. This definition is used in JIS K 7220: 1999 (ISO 844) and Weiser *et al.* [8]. However, 50% deflection also was used by Weiser *et al.* [9] and Veazie *et al.* [10], and 70% used by Resewski and Buchgraber [11]. For other materials it is defined by the first peak stress.

Table 1.
Compressive mechanical properties

		TEEK		AIREX R82 60		ROHACELL WF 51		Aramid honeycomb		TEEK + AHC		AIREX R82 110		ROHACELL WF 110	
		Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %
Sample size	—	5	—	3	—	2	—	5	—	5	—	3	—	2	—
Density	kg/m^3	75	1.8	69	2.0	57	1.4	49	2.0	95	1.8	97	0.57	130	2.1
Compressive modulus	MPa	8.1	9.8	20	3.5	27	7.2	101	4.7	150	5.1	43	3.1	150	17
Compressive strength	MPa	0.33	6.6	0.89	3.1	0.82	2.9	2.0	2.3	2.9	3.2	1.6	2.1	3.1	0.48

3.1.1. Comparison of compression test results. Figure 7 shows the compressive stress–strain relationships of TEEK, AIREX R82 60, and ROHACELL WF 51. The compressive elastic modulus and strength of TEEK are lower than those of AIREX R82 60 and ROHACELL WF 51, as shown in Fig. 7 and Table 1. In Fig. 7, the stress of TEEK increased gently beyond the elastic range, while the stresses of AIREX R82 60 and ROHACELL WF 51 increased slightly or remained almost constant after reaching peak values.

Figure 8 presents the compressive stress–strain relationships of the TEEK-filled aramid honeycomb, AIREX R82 110, and ROHACELL WF 110. The compressive elastic modulus and strength of the TEEK-filled aramid honeycomb are higher than those of AIREX R82 110 and equivalent to those of ROHACELL WF 110, as illustrated in Fig. 8 and Table 1. There is a sharp peak in the stress–strain relationship of the TEEK-filled aramid honeycomb due to wrinkling from the top or bottom edge of the honeycomb cell walls, but only a very small peak for AIREX R82 110 and ROHACELL WF 110. The stress after the peak value remains constant over a wide range of strain for AIREX R82 110 and ROHACELL WF 110. Table 1

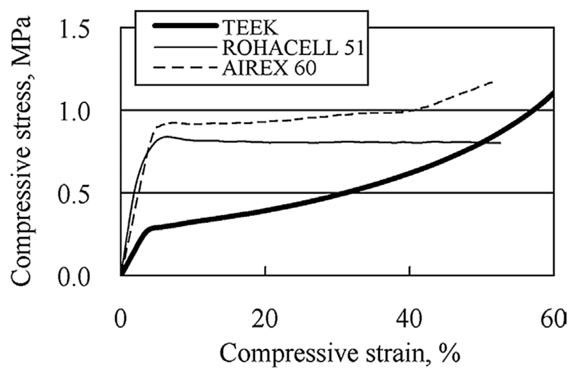

Figure 7. Typical examples of compressive stress–strain relationships of TEEK, AIREX R82 60, and ROHACELL WF 51.

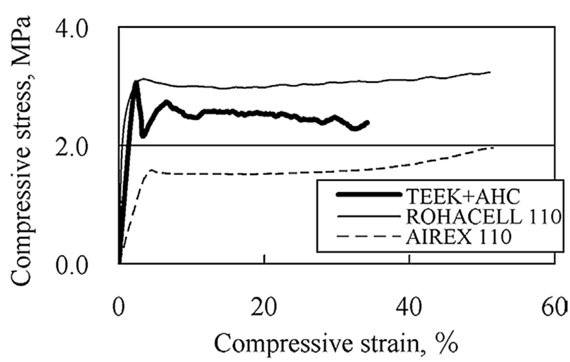

Figure 8. Typical examples of compressive stress–strain relationships of TEEK-filled aramid honeycomb, AIREX R82 110, and ROHACELL WF 110.

shows that the CV of ROHACELL WF 110 is 17% and especially high; however, the sample size is only two in this case. No other reason was found for such a large CV.

3.1.2. Effect of TEEK filling of aramid honeycomb cells on compressive mechanical properties. Table 1 shows that the compressive elastic modulus and strength of TEEK are about 8% and 17% of those of the aramid honeycomb, respectively. Figure 9 compares typical compressive stress–strain relationships of the TEEK-filled aramid honeycomb, the aramid honeycomb alone, and TEEK. The elastic modulus of the TEEK-filled aramid honeycomb is higher than the value obtained from the superposition of those of the aramid honeycomb and TEEK. The details of the superposition in compression test results will be discussed later. When the stress–strain relationships of the TEEK-filled aramid honeycomb and the aramid honeycomb in Fig. 9 are compared, the strain to give the maximum stress on both curves is equal and the variation of both curves is quite similar. Therefore, the stress–strain relationship of the TEEK-filled aramid honeycomb is considered to be dependent on that of the aramid honeycomb. The elastic modulus and strength of the TEEK-filled aramid honeycomb are improved to about 1.5 times those of the aramid honeycomb alone in Table 1. This fact is qualitatively explained as follows: Suppose the TEEK-filling improves the elastic modulus of the aramid honeycomb about 1.5 times by restricting the out-of-plane deformation of the honeycomb cell walls in addition to the superposition. The strain to give the maximum stress, i.e. the strain limit for the wrinkling, is the same for both the aramid honeycomb alone and the TEEK-filled aramid honeycomb as shown in Fig. 9. Then the strength of the TEEK-filled aramid honeycomb becomes about 1.5 times that of the aramid honeycomb alone, because two stress–strain relationships for the aramid honeycomb and the TEEK-filled aramid honeycomb are roughly considered to be linear up to the peak stress. The adequacy of the foam filling as an explanation is confirmed. However, its mass is nominally 2.3 times that of the aramid honeycomb alone.

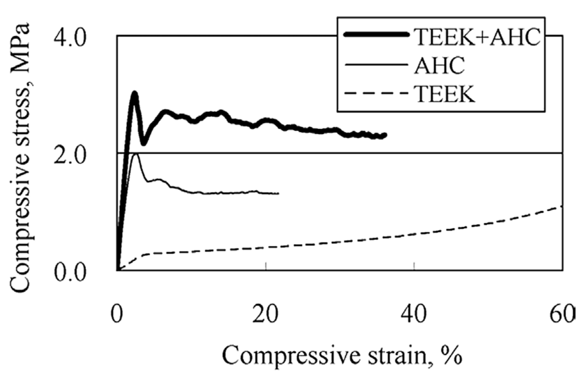

Figure 9. Compressive stress–strain relationships of TEEK, aramid honeycomb, and TEEK-filled aramid honeycomb.

Weiser *et al.* [9] presented the compression test results to show that the elastic modulus and strength were improved 1.27 and 1.21 times when Nomex core material was filled with TEEK-H, where its density was 88 kg/m^3. They pointed out this improvement due to the restriction on buckling of the cell walls by the foam, but the improvement due to the superposition was not mentioned.

3.2. Tension test results

Tension tests were conducted on TEEK and the aramid honeycomb alone, because the superposition of the tensile moduli or strengths of TEEK and the aramid honeycomb is expected to give sufficient results for the TEEK-filled aramid honeycomb. TEEK and the aramid honeycomb under flatwise tensile loading form a structure of approximately parallel members in the TEEK-filled aramid honeycomb. Table 2 presents the tensile mechanical properties of TEEK and the aramid honeycomb, as well as the catalogue data for AIREX R82 60 and ROHACELL WF 51. Figure 10 presents the tensile stress–strain relationships of TEEK and the aramid honeycomb. Table 2 indicates that the tensile elastic modulus and strength of TEEK are, respectively, about 30% and 40% of those of the aramid honeycomb.

Table 2.
Tensile mechanical properties

		TEEK		AIREX R82 60		ROHACELL WF 51		Aramid honeycomb	
		Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %
Sample size	—	5	—	—	—	—	—	5	—
Density	kg/m^3	76	2.8	60*	—	52*	—	49	1.04
Tensile modulus	MPa	27	12	45*	—	75*	—	91	10.6
Tensile strength	MPa	0.85	10.9	1.7*	—	1.6*	—	2.1	1.7

* Catalog data.

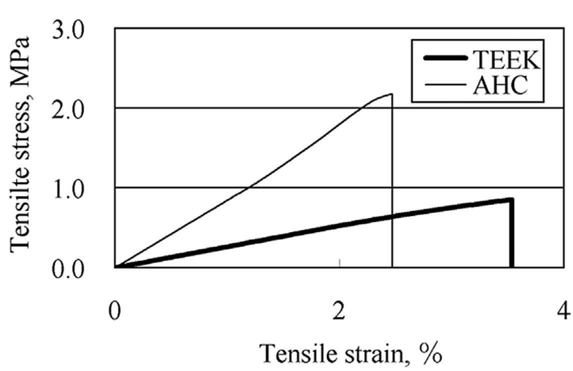

Figure 10. Tensile stress–strain relationships of TEEK and aramid honeycomb.

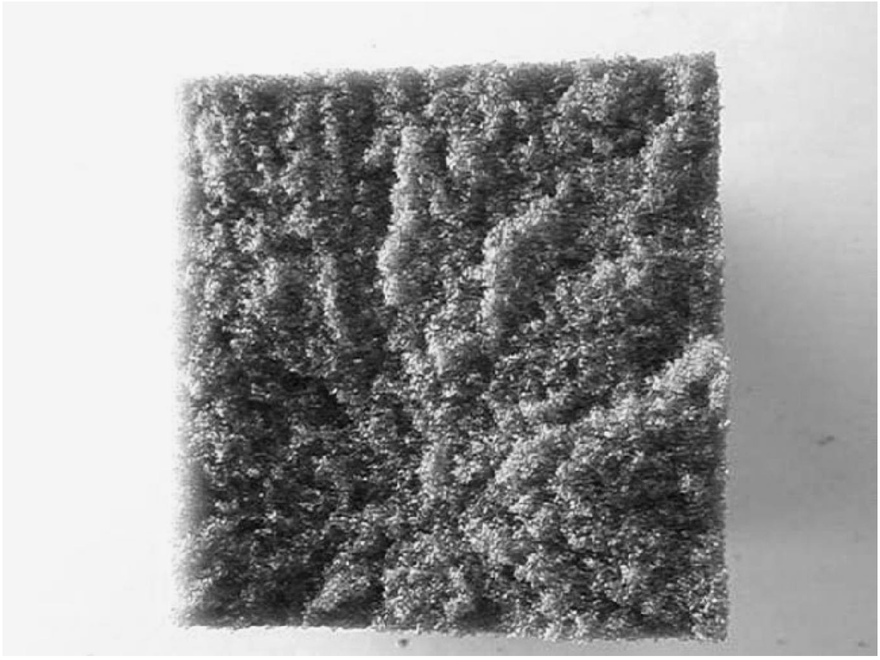

Figure 11. Tensile fracture surface of a TEEK specimen.

3.2.1. TEEK crack formation in tension tests. Figure 11 shows the tensile-fracture surface of a TEEK specimen. Cracking did not initiate at the edge of the specimen but nucleated inside of the specimen and propagated to the edges. This cracking behavior is clarified by the radial-roughness pattern originating from one point in the fracture surface. This typical roughness pattern was similar in all five specimens tested. This phenomenon can be explained thus. The tensile specimens are short (Fig. 3) and the upper and lower surfaces are bonded to metallic blocks (Fig. 4). The edge surfaces of the specimen in Fig. 4 are free surfaces and loaded by tensile stress only, but a multi-axial stress-state should exist in the interior of the specimen, because the deformation in the direction of the cross-section is restricted by the bonded metal blocks. Moreover, the authors confirmed that a non-linear stress–strain relationship contributes the higher internal tensile-stress. Therefore, a crack should originate in the inside of the specimen.

3.3. Plate-shear test results

Table 3 shows the sample size and the plate-shear test results, i.e., the shear elastic moduli and strengths of TEEK, the aramid honeycomb (L and W directions), the TEEK-filled aramid honeycomb (L and W directions), AIREX R82 60, 110, and ROHACELL WF 51, 110. The plate-shear strength is defined by the maximum stress for all plate-shear stress–strain relationships.

Table 3.
Plate-shear mechanical properties

		TEEK		AIREX R82 60		ROHACELL WF 51		Aramid honeycomb				TEEK + AHC				AIREX R82 110		ROHACELL WF 110	
								L direction		W direction		L direction		W direction					
		Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %	Mean	CV %
Sample size	—	5	—	4	—	4	—	5	—	5	—	5	—	5	—	4	—	3	—
Density	kg/m^3	77	1.4	67	0,81	54	5.4	56	7.6	52	4.1	94	1.7	96	1.5	99	1.3	130	1.6
Shear modulus	MPa	12	8.7	18	10.3	25	8.8	41	6.4	23	10.2	52	22	32	10.6	30	8.2	69	12
Shear strength	MPa	0.47	7.4	0.88	2.2	0.78	5.9	1.3	7.1	0.67	7.2	1.8	3.5	1.01	1.7	1.5	2.9	1.8	0.59

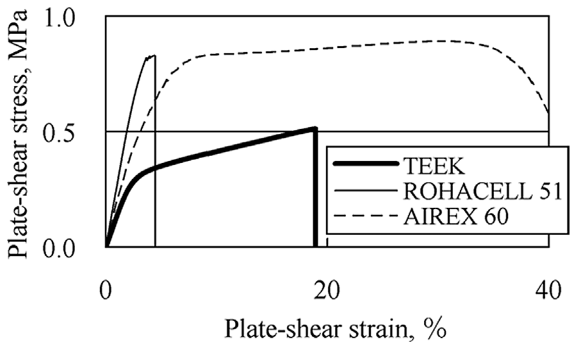

Figure 12. Plate-shear stress–strain relationships of TEEK, AIREX R82 60, and ROHACELL WF 51.

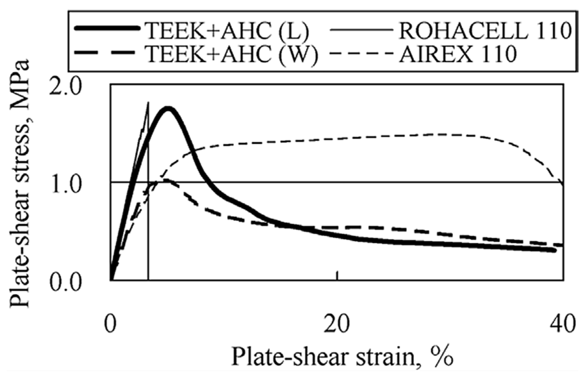

Figure 13. Plate-shear stress–strain relationships of TEEK-filled aramid honeycomb (L, W directions), AIREX R82 110, and ROHACELL WF 110.

3.3.1. Comparison of plate-shear mechanical properties. Figure 12 shows the stress–strain relationships obtained by plate-shear tests for TEEK, AIREX R82 60, and ROHACELL WF 51. Figure 13 shows the stress–strain relationships obtained by plate-shear tests for the TEEK-filled aramid honeycomb (L and W directions), AIREX R82 110, and ROHACELL WF 110.

Figure 12 and Table 3 indicate that the plate-shear elastic modulus and strength of TEEK are lower than those of AIREX R82 60 and ROHACELL WF 51. In the case of TEEK the stress increased with a gentle slope after showing a curvature with a relatively small radius.

Figure 13 and Table 3 show that the plate-shear elastic modulus and strength (peak stress) of the TEEK-filled aramid honeycomb (L direction) are almost the same as those of ROHACELL WF 110. As the strain increases, the shear stress of the TEEK-filled aramid honeycomb (L and W directions) increases with a parabolic shape up to the maximum stress and shows a rapid drop after the peak value. The plate-shear strength of the TEEK-filled aramid honeycomb is approximately 1.8 times greater in the L direction than in the W direction, probably reflecting the directional properties of the aramid honeycomb.

Figures 12 and 13 show that ROHACELL WF 51 and 110 are brittle and fracture rapidly after reaching maximum stress. In contrast, AIREX R82 60 and 110 are ductile, and their shear stress approaches a maximum around 8% strain, then slightly increases to the maximum at about 32% strain.

3.3.2. Plate-shear failure of a TEEK specimen. Figure 14 shows the failure of a TEEK specimen in a plate-shear test. Initially, two cracks of mode-II (in-plane shear) type initiated at the upper right and lower left locations of the specimen, but did not propagate. The final crack, generated by a tensile stress component, initiated inside the specimen at approximately 45° to the specimen thickness, then extended to both sides of the specimen, propagated upwards, and downwards, parallel to the loading plates as seen in Fig. 14. Since this foam material is of a soft balloon type, no sharp stress concentration occurred at the front ends of the initial corner cracks due to the high ductility of TEEK. This is the reason why the final crack was not one of the initial corner cracks that occurred at the specimen edges.

3.3.3. Effect of TEEK filling of honeycomb cells on plate-shear mechanical properties. Figure 15 shows the plate-shear stress–strain relationships of TEEK, the aramid honeycomb (L direction), and the TEEK-filled aramid honeycomb (L direction). Figure 16 shows the plate-shear stress–strain relationships of TEEK, the aramid honeycomb (W direction), and the TEEK-filled aramid honeycomb (W

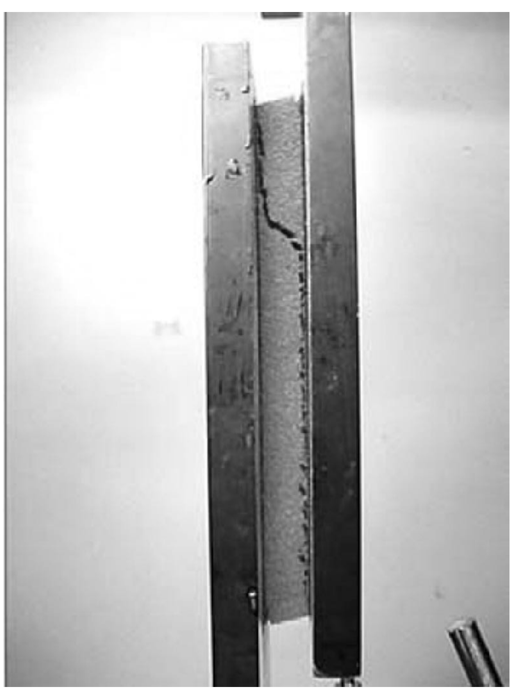

Figure 14. Failure of a TEEK specimen observed in a plate-shear test.

direction). The stress–strain relationship of TEEK is the same in both graphs. The stress–strain relationships of the aramid honeycomb (L and W direction) are represented by two types of curve. One is a smooth parabolic curve up to the maximum stress, and this case is denoted by AHC I. The other curve denoted by AHC II has a middle step up to the maximum stress. In the case of AHC II, visual observation of the specimen in a plate-shear test confirmed that the honeycomb cell-walls showed large deformation at the central part of the thickness on the lateral surface. On the other hand, the stress–strain relationships of the TEEK-filled honeycomb showed a smooth parabolic curve only up to the maximum stress. TEEK in honeycomb cells is considered to restrict the premature deformation of honeycomb cell walls in the course of plate-shear loading, which is one of the advantages of filling honeycomb cells with TEEK. The superposition for the plate-shear mechanical properties is discussed later.

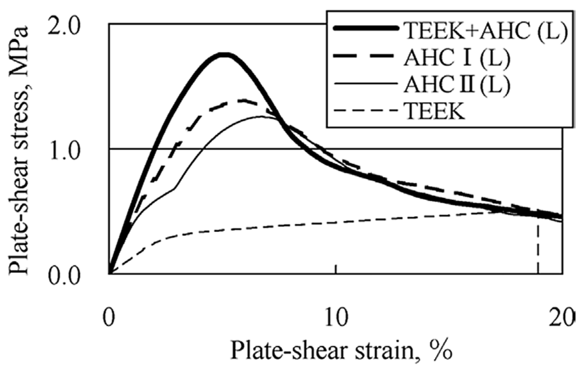

Figure 15. Plate-shear stress–strain relationships of TEEK, aramid honeycomb (L direction), and TEEK-filled aramid honeycomb (L direction).

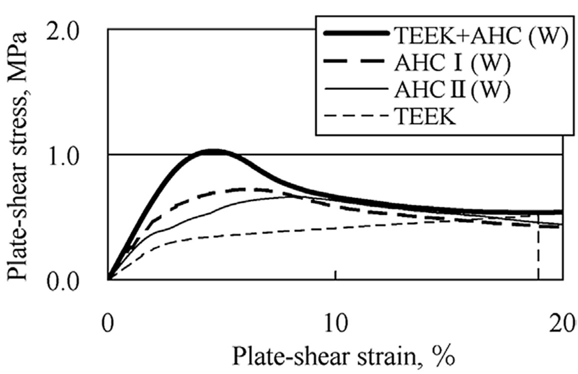

Figure 16. Plate-shear stress–strain relationships of TEEK, aramid honeycomb (W direction), and TEEK-filled aramid honeycomb (W direction).

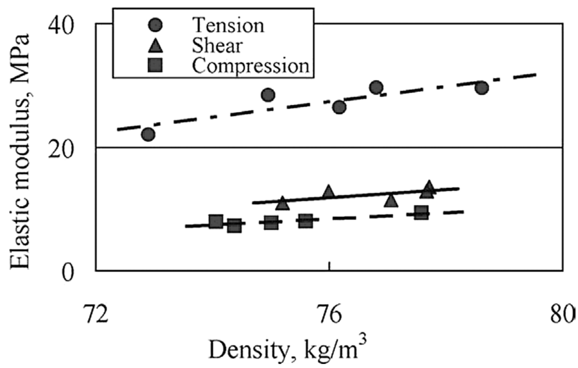

Figure 17. Elastic modulus as a function of density.

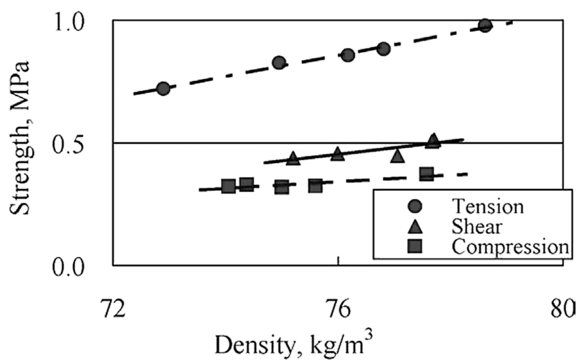

Figure 18. Strength as a function of density.

3.4. Elastic modulus and strength of TEEK as a function of density

Figure 17 presents the elastic modulus of TEEK as a function of the specimen density obtained by compression, tension, and plate-shear tests. Though the range of specimen density is not wide, a linear relationship exists between the elastic modulus and the specimen density in each kind of test. The deviations of data points from the approximation line are relatively small. Figure 18 illustrates the strength of TEEK as a function of the specimen density obtained by compression, tension, and plate-shear tests. A linear relationship clearly exists between the tensile strength and the specimen density. For compression and plate-shear tests, the strength increases slightly with the specimen density. Weiser *et al.* [9] also showed a linear relationship between flatwise compressive strength (50% deflection) and density for TEEK-H.

4. DISCUSSION

The TEEK-filled aramid honeycomb is considered to work fundamentally by providing a multi load-path or parallel structure in the compressive, tensile, and shear loading tests conducted in this study. Therefore, the basic effect on elastic modulus and strength of filling the honeycomb cells with TEEK arises from the principle of superposition of the properties of the aramid honeycomb and TEEK. Superposition in the compression and plate-shear test results is discussed below. Moreover, this chapter mentions the practical utility of TEEK-filled aramid honeycomb and the importance of test results obtained at room temperature.

4.1. Superposition and interference effect for compression test results

Figure 19 shows the averaged compressive stress-strain relationships of TEEK, the aramid honeycomb, the TEEK-filled aramid honeycomb, and the superposition of those of TEEK and the aramid honeycomb. In compression tests, TEEK-filling of aramid honeycomb cells can improve the compressive modulus and strength of the aramid honeycomb by about 1.5 times as described before. Figure 19 indicates that the stress–strain relationship of the TEEK-filled aramid honeycomb is much higher than that given by the superposition. Since the improvement of modulus and strength due to the superposition is evaluated to be 8% from Table 1 and 10% from Fig. 19, respectively; the remaining improvement of about 40% is due to the interference effect. TEEK's interference effect is considered to restrict the out-of-plane deformation of cell walls by the presence and the lateral expansion of TEEK balloons, where the latter arises from vertical compressive contraction. For aramid honeycomb alone, the compression force is mainly supported by the cell walls in the vicinity of hexagonal vertices because of the weakness of thin aramid-honeycomb cell walls under compressive load. The effective cell wall length from the vertices to withstand compressive load is short for aramid honeycomb alone. However, TEEK filling increases the effective cell-wall length around the vertices. If this increase is about 40%, the elastic modulus will increase by 40% and the compressive strength will also increase by 40% due to the almost linear stress–strain curves and the same strain limit for the honeycomb wrinkling in Fig. 19. This section confirmed the same fact again based on the averaged stress–strain relationships.

4.2. Superposition for plate-shear test results

Figure 20 shows the averaged plate-shear stress–strain relationships of TEEK, the aramid honeycomb (L direction), the TEEK-filled aramid honeycomb (L direction), and the superposition given by those of TEEK and the aramid honeycomb. Figure 21 similarly indicates the averaged plate-shear stress–strain relationships of TEEK, the aramid honeycomb (W direction), the TEEK-filled aramid honeycomb (W direction), and the superposition given by those of TEEK and the aramid honeycomb. The averaged curves for the aramid honeycomb (L or W direction) in Figs 20 and 21 were calculated from the relationships without any step up to the maximum stress shown in Figs 15 and 16. The stress–strain curves of the TEEK-filled aramid honeycomb (L or W direction) are very close to, or partly overlap, the curve obtained by the superposition up to the maximum stress of the TEEK-filled aramid hon-

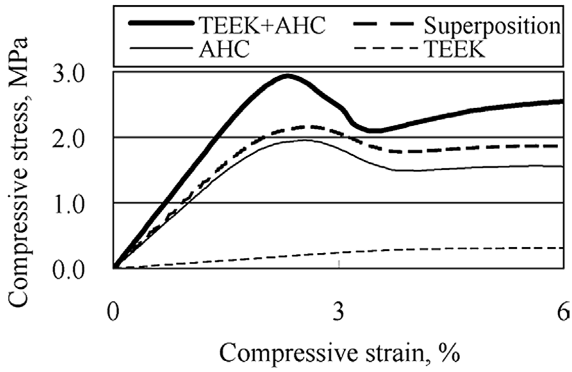

Figure 19. Averaged compressive stress–strain relationships of TEEK, the aramid honeycomb, the TEEK-filled aramid honeycomb, and the superposition given by those of TEEK and the aramid honeycomb.

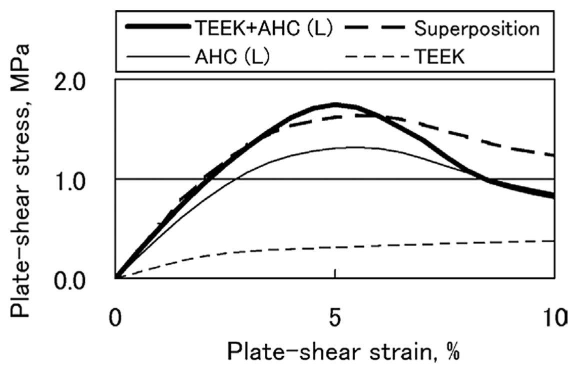

Figure 20. Averaged plate-shear stress–strain relationships of TEEK, the aramid honeycomb (L direction), the TEEK-filled aramid honeycomb (L direction), and the superposition given by those of TEEK and the aramid honeycomb.

eycomb. Since there is scatter in the plate-shear properties, these two graphs are considered to demonstrate that the superposition of the stress–strain relations of TEEK and the aramid honeycomb is valid for the results obtained by the plate-shear tests. Therefore, the effectiveness of TEEK filling in enhancing the plate-shear mechanical properties is explained by superposition. As shown in Table 3, for the L direction, the TEEK-filled aramid honeycomb presented an elastic modulus of 1.3 times, and a strength of 1.4 times greater than those of the aramid honeycomb alone (AHC L). Similarly for the W direction, the TEEK-filled aramid honeycomb had an elastic modulus 1.4 times, and a strength of 1.5 times, greater than those of the aramid honeycomb (AHC W). The numerical values of the elastic modulus and strength in Table 3 indicate that superposition holds approximately for the TEEK-filled aramid honeycomb for both L and W directions.

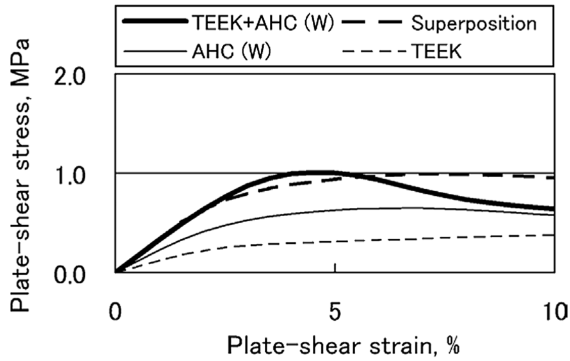

Figure 21. Averaged plate-shear stress–strain relationships of TEEK, the aramid honeycomb (W direction), the TEEK-filled aramid honeycomb (W direction), and the superposition given by those of TEEK and the aramid honeycomb.

4.3. Practical utility of TEEK-filled aramid honeycomb

As described in the introduction, TEEK has excellent physical and chemical characteristics. The results of this study and other known characteristics of TEEK show it to be of practical utility to fill aramid honeycomb cells with TEEK, although the weight of TEEK-filled aramid honeycomb in this study was increased by nominally 2.3 times that of empty aramid honeycomb. TEEK filling prevents a lot of water infiltration, because TEEK of a balloon type has only small internal space free for water absorption, though it may have gas permeability. Moreover, TEEK-filled aramid honeycomb is considered to be more durable against fatigue crack propagation and more damage tolerant than sandwich panels with a foam-only core, because of the aramid honeycomb cell walls. Since the properties of both aramid honeycomb-core materials and polyimide foam core materials are to be preferred, TEEK-filled aramid honeycomb core material has great potential as a new core material for aerospace sandwich panels.

4.4. Importance of test results on TEEK strength at room temperature

Veazie *et al.* [10] showed that TEEK-H has almost equal tensile and compressive strengths at room and cryogenic temperatures (−54°C) respectively. Resewski and Buchgraber [11] indicated that the compressive strength of TEEK-H and a TEEK-H filled Nomex honeycomb at −196°C was higher than or equal to that at 23°C. These facts suggest that the test results of three kinds of strength obtained in this study are unchanged or higher at cryogenic temperature. In this meaning the test results at room temperature are very important.

5. CONCLUSION

Compression, tension, and plate-shear tests determined the basic mechanical properties of TEEK-L of a balloon type with a nominal density 72 kg/m^3, aramid honeycomb, and a TEEK-L filled aramid honeycomb, as well as AIREX R82 60, 110, and ROHACELL WF 51, 110 for comparison. The major conclusions of this study are:

1. Compression, tension, and plate-shear tests have confirmed the basic mechanical properties of TEEK-L of a balloon type.
2. Compression and plate-shear tests have determined the basic mechanical properties of a TEEK-filled aramid honeycomb.
3. The compressive elastic modulus or strength of the TEEK-L filled aramid honeycomb is much higher than that given by the superposition of TEEK-L's value and that of the aramid honeycomb. This effect can be explained by the fact that TEEK-L in the honeycomb cells restricts the out-of-plane deformation of the honeycomb cell walls and increases the effective cell-wall-length capable of supporting a compression load.
4. The plate-shear elastic modulus or strength of TEEK-L filled aramid honeycomb is equivalent to that calculated by the superposition of TEEK-L's elastic modulus or strength and that of the aramid honeycomb, for which the stress–strain relationship does not have any step up to the maximum stress.
5. TEEK-L in honeycomb cells restricted the premature deformation of honeycomb cell walls, i.e. a middle step in the stress–strain relationship, in the course of plate-shear loading.
6. Tension and plate-shear tests on TEEK-L clarified its fracture behavior and fracture surface.
7. The elastic modulus and strength of TEEK-L are lower than those of AIREX R82 60 and ROHACELL WF 51 with equivalent densities in the compression, tension, and plate-shear tests.
8. The elastic modulus and strength of the TEEK-L filled aramid honeycomb in the compression and plate-shear tests are higher than those of AIREX R82 110 and equivalent to those of ROHACELL WF 110 with equal densities.
9. The elastic modulus and strength of TEEK-L obtained by compression, tension, and plate-shear tests are approximately represented by a linear function of the density of TEEK-L.
10. Filling the aramid honeycomb cells with TEEK-L is a practical measure to improve the mechanical properties of the aramid honeycomb significantly beyond what superposition indicates for compressive properties, and approximately equal to the values given by the superposition for plate-shear properties.
11. The TEEK-L filled aramid honeycomb has great potential as a new core-material for aerospace sandwich structures.

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