Dynamic and Static Compression Tests for Paper Honeycomb Cores and Absorbed Energy*

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In order to investigate the effect of loading rate on the strength and the absorbed energy of paper honeycomb cores, a series of compression tests were carried out at quasi-static and dynamic rates. The specimens used are polypropylene (PP) and polyester (PET) thermoplastic honeycomb cores, which are usually called paper honeycomb cores. It was found that the peak stress and average crush stress increased with the increase of loading rate and was especially remarkable in the results of the PP core. The absorbed energy obtained from dynamic tests was also greater than that obtained at quasi-static rates. It was ascertained that the polyvinyl chloride (PVC) long tube was quite useful as a device for measuring stress waves in dynamic compression tests, if the characteristics of the wave propagation in the PVC tube are obtained by preliminary wave propagation experiments, specifically to determine the rate of decrease in amplitude and/or the propagation velocity.

Key Words: Impact Strength, Buckling, High Polymer Materials, Honeycomb Core, Compression Test, Peak Stress, Average Crush Stress, Absorbed Energy

1. Introduction

Recently, honeycomb cores made of plastics, ceramics and papers instead of metals such as aluminum or stainless steel have been developed and used as cores of sandwich panels, and the use of honeycomb cores has expanded from airframe to more general area such as cars, trains and buildings^{(1),(2)}. Since the honeycomb core sandwich panels are usually used for structural elements, a lot of research has been performed with respect to bending tests or shearing tests⁽³⁾⁻⁽⁶⁾. As far as honeycomb core is concerned, the in-plane deformation of cores in compression, tension⁽⁷⁾⁻⁽¹⁰⁾ and shear⁽¹¹⁾⁻⁽¹³⁾ tests were investigated as well as the out-plane deformation in buckling tests⁽¹⁴⁾.

Honeycomb cores or sandwich panels are widely recognized as having a high performance as an shock

absorber. An application example of honeycomb cores to a steering column and a knee protector of cars for the increase of safety was reported⁽¹⁵⁾. In order to examine the properties about energy absorption of honeycomb cores, impact compression tests with single specimens^{(16),(17)} or multi-layered specimens⁽¹⁸⁾ and projectile impact tests using relatively large core targets^{(19),(20)} were carried out. However, most research performed so far has concerned aluminum honeycomb cores. The impact energy absorption of non-metal honeycomb cores has seldom been reported.

In this study, a series of compression tests for two kinds of paper honeycomb cores were carried out at quasi-static and dynamic rates. The specimens used are polypropylene (PP) and polyester (PET) thermoplastic honeycomb cores, usually called paper honeycomb cores. The polyvinyl chloride (PVC) long tube was used for the dynamic compression tests to obtain the load-deformation curves, peak load and mean collapse load of honeycomb specimens. The effect of loading rate on the peak and mean collapse loads and absorbed energy during crush was also investigated.

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2. Experiments

2.1 Honeycomb cores

The honeycomb cores used in this study are polypropylene (PP1003) and polyester (PET1015) thermoplastic honeycomb cores⁽¹⁵⁾ made by Hexcel (Pleasanton, California 94588 USA). The configuration of the core and cell size are shown in Fig. 1(a). In Table 1, a is the cell size, b is the thickness of cell wall, h is the height of the core, ρ' is the density of the core materials and, ρ is the density of the core. The cell size and the relative density, ρ/ρ' , of PP1003 and PET1015 are quite similar. In quasi-static compression tests, the core specimens with four different cell numbers in their one side, N ($=5, 7, 9, 11$), were used to examine the effect of the size of specimen on their deformation behaviour. In dynamic tests, however, only one type specimen with $N=5$ was used because of limitations in the ability of the testing apparatus.

2.2 Tensile tests for honeycomb core materials

In order to investigate the effect of loading rate on the strength of core materials, PP1003 and PET1015 spunbond cloths, tensile tests were carried out at three strain rates of 0.0005, 0.01, 0.1(1/s) by using an Instron universal testing machine (mode 5566). The tensile specimen used is a rectangular type specimen with the gauge length of 25 mm which was taken from a released honeycomb core wall (see Fig. 1(b)). Nominal stress and strain were obtained from the load and elongation divided by the original cross-

Table 1 Dimension and density of honeycomb cores

	a	b	h	ρ	ρ'	ρ/ρ'
	mm	mm	mm	kg/m ³	kg/m ³	
PP1003	6.35	0.35	25.2	50	370	0.14
PET1015	6.35	0.45	24.1	44	280	0.16

Fig. 1 Honeycomb core and crush test specimen and tensile specimen of core materials

sectional area and the gauge length of individual specimens, respectively.

2.3 Compression tests for honeycomb cores

Quasi-static compression tests for honeycomb core were performed in the axial direction of hexagonal cells by Instron testing machine at room temperature at three loading rates of 1, 10, 100 mm/min. The load and displacement were obtained from the testing machine. The double-decker specimen with aluminum plate (thickness of 1.2 mm) sandwiched by PP1003 cores was tested to check the effect of specimen volume on the absorbed energy.

The arrangement for dynamic crushing tests of honeycomb cores is shown in Fig. 2. In this arrangement, an impact bar with a flange (an aluminum circular plate, 75 mm in dia., 10 mm thick) accelerated by compressed air collides into a core specimen attached on one end of the stationary output bar. The impact bar is an aluminum pipe (A6061) with the outer diameter of 19 mm and wall thickness of 1.5 mm. The output bar is a long circular tube of polyvinyl chloride (PVC). Instead of the stress bars used here, a number of other load-cell types^{(21),(22)} were adopted in dynamic compression tests of hollow circular or square cylinders. However, the stress bar is a very simple system if the time for the measurement of stress wave can be accurately determined. In addition, the strength of paper honeycomb core is extremely small in comparison with that of ordinary metal honeycomb cores. It seems to be quite difficult to measure the stress wave transmitting in metal bars. These are the reasons why the PVC output bar was adopted in this study. The outer diameter, wall thickness and length of this PVC tube were 48 mm, 4 mm and 3 850 mm, respectively. Of course, a PVC circular plate with the same diameter was attached at one end of the tube. Two semiconductor strain gauges were glued axi-symmetrically on the surface of the tube 500 mm from the end. The output from the gauges was

Fig. 2 Arrangement for impact crushing of honeycomb core

recorded by a digital oscilloscope (Niclet model 400) after passing through the bridge boxes. The deformation of specimen was measured by using markers and an optical non-contact extensometer (Zimmer model 200X). Although this extensometer has sufficient responsibility for dynamic deformation speed of specimens, the range of measurement is little small, i.e. 5 mm maximum. Therefore, the measurement was limited to only initial stage of tests.

2.4 Stress wave propagation tests in PVC pipe

When a stress wave propagates through a PVC tube, the wave is generally attenuated because of the viscosity of PVC. To clarify the attenuation property of PVC, therefore, stress wave propagation tests were performed by using a PVC tube with strain gauges (G1-G4) glued 500 mm apart along its axis, as shown in Fig. 3(a). A typical stress waves measured by these strain gauges when an impact was given at an end of the tube are shown in Fig. 3(b). From the

Fig. 3 Location of strain gauges and typical stress waves measured on PVC tube

Fig. 4 Results of stress wave propagation tests through PVC tube: (a) Peak value ratio, (b) Duration ratio and (c) Velocity ratio

figure, it can be found that the peak of the stress wave gradually decreased with the propagation of the wave.

In order to estimate the attenuation of the wave quantitatively, the ratio, R_{pk} , which was obtained by dividing G1 value into others (G2-G4) is shown in Fig. 4(a). The ratio, R_{du} , shown in Fig. 4(b) is the ratio of duration measured at the 20% level of the peak value of each wave. The velocity of stress wave was calculated from the time needed while the peak of a stress wave propagates in the PVC tube between gauges, G1-G2, G2-G3 and G3-G4. Figure 4(c) shows the velocity ratio, R_{ve} , which is the ratio between each wave velocity and the average value of all data. It was found from these figures that the peak value of traveling waves decreased about 8%/m and the duration increased about 8%/m, respectively. In addition, the velocity of stress wave, C_0 , appears to be constant in the range of the measurement, and the average of wave velocity was $C_0=1670$ m/s.

The Young's modulus of this PVC tube was obtained to be $E_{pvc}=3.76$ GPa from lateral compression tests⁽²³⁾ using 50 mm long tubular specimens. While, the density of this PVC tube was measured to be $\rho_{pvc}=1.39 \times 10^3$ kg/m. By using a simple equation, $C_0=\sqrt{E_{pvc}/\rho_{pvc}}$, we can calculate that $C_0=1650$ m/s. This is very close to the wave velocity obtained directly from the propagation experiments, described above. This C_0 value, the location of strain gauge and the length of PVC tube suggest that about 4000 μ sec will be available for the measurement of stress wave.

Since stress waves were measured by G1 gauge in dynamic tests, a modified load-time curve can be obtained by multiplying the amplitude and the time scale of a measured curve by 1.04 and 0.96, respectively, considering the results shown in Fig. 4.

3. Experimental Results and Discussions

3.1 Strain-rate dependence of core materials

Stress-strain curves of PP1003 obtained from quasi-static tensile tests using a rectangular type specimen with the gauge length of $L=25$ mm are shown in Fig. 5. The strength of PP1003 spunbond cloth was affected by testing speed, i.e. the strength increased with the increase of testing speed, even though the testing speed is within the range of quasi-static rates, as shown in Fig. 5. Although the elongation of every specimen was more than 80%, a meaningful difference in elongation due to testing speed could not be found. For PET1015 specimens, similar results to PP1003 were obtained. The stresses at strains of $\epsilon=10, 40\%$ and tensile strength σ_T of PP1003 are shown in Fig. 6 taking the strain rates, $\dot{\epsilon}$, in horizontal axis. Figure 7 shows the stresses at strains of $\epsilon=5, 10\%$ and tensile strength σ_T of

PET1015, as well. It is found from these figures that PP1003 has relatively large strain-rate dependence even in quasi-static region, while the tensile strength

of PET1015 was smaller than a half of PP1003 strength and the strain-rate dependence of PET1015 was also small.

3.2 Compression tests of cores and specimen size

When an honeycomb specimen for compression test is regarded as a solid body, the initial cross-sectional area and the initial height of the specimen are denoted by A_0 and h , respectively. Load (P)-displacement (δ) curves obtained from compression tests of honeycomb cores were converted to nominal stress (σ^*)-non-dimensional displacement (δ^*) curves by using A_0 and h , i.e. $\sigma^* = P/A_0$, $\delta^* = \delta/h$. Figure 8 shows σ^* - δ^* curves obtained from four PP1003 specimens with different numbers of honeycomb cells in their one side, $N=5, 7, 9$ and 11 , tested at a quasi-static testing speed, $v_0 = 1.67 \times 10^{-4}$ m/s (10 mm/min). In the early stage of deformation, cell walls of honeycomb core in all specimens were compressed almost uniformly and σ^* went up linearly, and then cell walls began to collapse just after σ^* reached a peak value, σ_{peak} , following rapid drop of σ^* . At this time, the first plastic buckling of cell walls occurred near the upper or bottom edges of the specimens. With the advance of the deformation, plastic buckling of the cell walls continued to occur, and the cell walls were folded like an accordion and σ^* remained nearly constant. The constant stress in this stage is known as a mean crush stress⁽¹⁶⁾, σ_{crush} . At the stage of $\delta^* = 65\text{--}70\%$, honeycomb cells were crushed and condensed almost perfectly. Therefore, σ^* goes up rapidly. As clarified in Fig. 8, the effect of the difference of specimen size on σ_{peak} or σ_{crush} is small. This means that similar σ^* - δ^* curve can be expected if the specimen has $N \geq 5$.

As mentioned above, the non-dimensional displacement when cores started to condense, δ_1^* , was

Fig. 5 Stress-strain curves obtained from tensile tests for PP1003 core material

Fig. 6 Tensile strength and stresses at different strains obtained at three quasi-static rates (PP1003)

Fig. 7 Tensile strength and stresses at different strains obtained at three quasi-static rates (PET1015)

Fig. 8 Stress (σ^*)-non-dimensional displacement (δ^*) curves of PP1003 honeycomb cores with various specimen size

about 65-70%. The apparent change of specimen volume up to δ_1^* , ΔV_{crush} , may be given by $V_{sp} \times \delta_1^*$, where V_{sp} is an initial specimen volume ($=A_0 \times h$). Here, let us define the absorbed energy due to plastic deformation of honeycomb cores, W , by a products of σ_{crush} and ΔV_{crush} , i.e. $W = \sigma_{\text{crush}} \times \Delta V_{\text{crush}}$ for simplicity, although an integration technique might be more precise. The relation between W and V_{sp} with respect to PP1003 and PET1015 cores is shown in Fig. 9. It is found from this figure that the absorbed energy of both cores increases proportionally with increases in the initial specimen volume. For PP1003 core, especially, the data of double-decker specimens are on the line of single layer specimen data. Therefore, the number of specimen layer may not influence the absorbed energy, if total initial specimen volume is the same.

3.3 Effect of testing speed in compression tests of cores

Since both PP1003 and PET1015 materials have positive rate-dependence even in quasi-static range, as mentioned in section 3.1, it can be presumed that the effect of rate-dependence appears in compression tests of cores. The σ^* - δ^* curves obtained from dynamic compression tests ($v_0 \approx 10$ m/s) for PP1003 and PET1015 cores are shown in Fig. 10 and 11, respectively, with their static data. Because of the limitation in the measurement range of our extensometer, the displacement could not be measured until the end of deformation. Therefore, the σ^* - δ^* curves measured are denoted by a solid line and the other parts estimated from dynamic load-time curves and static data of δ_1^* are indicated by a broken line. From these figures, the dynamic deformation behaviour of cores is basically similar to the static one shown by dotted lines. In the results of both cores, however, the stress such as σ_{peak} or σ_{crush} of dynamic tests was greater than static data. Especially, the increase of

Fig. 9 Absorbed energy as a function of specimen volume

σ_{peak} was considerable.

Figures 12 and 13 show the rate-dependence of the peak stress and the mean crush stress for PP1003 and PET1015 cores, respectively. Although the dynamic data of PP1003 core varies more widely compared with static data, both σ_{peak} and σ_{crush} obtained from dynamic tests are 20-70% greater than those in static tests. This means that the strength of PP1003 core showed a relatively large positive rate-dependence. While, the increase of the dynamic σ_{peak} and σ_{crush} of PET1015 core was not so large in comparison with the data of PP1003 core. It may be considered that the difference of rate-dependence between PP1003 and PET1015 cores is caused by the difference of core material rate-dependence.

3.4 Absorbed energy of cores

The non-dimensional displacement at which honeycomb core begins to condense in dynamic compression tests appears not to be so different from that

Fig. 10 σ^* - δ^* curves of PP1003 core obtained from quasi-static and impact compression tests

Fig. 11 σ^* - δ^* curves of PET1015 core obtained from quasi-static and impact compression tests

Fig. 12 Peak stress and average crush stress of PP core observed in quasi-static and impact tests

Fig. 13 Peak stress and average crush stress of PET core observed in quasi-static and impact tests

obtained in static tests, because δ_1^* seems to depend on the cell size of honeycomb cores predominantly. In estimating the absorbed energy of the core specimen compressed dynamically, therefore, the mean value of δ_1^* obtained from static tests and each σ_{crush} in dynamic test were used. The absorbed energy per unit volume of specimen, w^* ($=\sigma_{crush} \times \delta_1^*$), is shown in Fig. 14 with taking the loading velocity in the horizontal axis. Since the dynamic test results of PP1003 core were about 20 - 60% greater than those obtained in static tests, it can be seen that the absorbed energy of PP1003 core is strongly influenced by loading velocity, as well as in its strength shown in Fig. 12. Although PET1015 core also has rate-dependence in the absorbed energy, it is relatively small.

4. Conclusion

By using two kinds of thermoplastic honeycomb cores made of polypropylene (PP1003) and polyester (PET1015) spunbond cloths, quasi-static tensile tests

Fig. 14 Absorbed energy per unit volume of honeycomb core obtained at dynamic and static rates

of core materials and a series of dynamic and quasi-static compression tests were carried out. For the dynamic compression tests, the polyvinyl chloride (PVC) long tube was used as an output bar to obtain the load-deformation curves, peak stress, mean crushing stress and absorbed energy. The effect of loading rate on these values was examined experimentally. Principal results obtained are as follows:

(1) The effects of loading rate on the peak stress, mean crushing stress and absorbed energy per unit volume of core are strongly related to the rate-dependence of core materials. In compression tests of honeycomb core, both PP1003 and PET1015 cores showed positive rate-dependence. However, the dependence of the PP1003 core is remarkable compared with the PET1015 core.

(2) It could be ascertained that a polyvinyl chloride (PVC) long tube is quite useful as a device measuring stress waves in dynamic compression tests, especially for low strength specimen like paper honeycomb cores, if the behaviour of the wave propagation in the PVC tube such as the amplitude, the duration and the propagation velocity of stress waves are obtained by preparatory experiments beforehand.

(3) The absorbed energy of compressed cores increases proportionally with increases in the initial specimen volume. Therefore, the absorbed energy can increase twice or three times without any increase of the area of the base, if we adopt a double or triple layer specimen instead of a single layer specimen.

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