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Mechanical behavior and failure process during compressive and shear deformation of honeycomb composite at elevated temperatures

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The mechanical behavior and failure mechanism of honeycomb composite consisting of Nomex honeycomb core and 2024Al alloy facesheets were investigated. The compressive and shear deformation behaviors of honeycomb composite were analyzed at temperatures ranged 25–300°C. The compressive and shear strengths of honeycomb composite decreased continuously with increasing temperature up to 300°C. The stress-strain curves obtained from the compressive and shear tests showed that the stress increased to a peak value and then decreased rapidly to a steady state value, which is nearly constant up to failure with increasing strain. The compressive deformation behavior of honeycomb composite was progressed by an elastic and plastic buckling of cell walls, debonding fracture at the interfaces of cell walls, and followed by a fracture of resin layer on cell walls. The shear deformation of honeycomb composite was progressed by an elastic shear deformation, plastic shear deformation, fracture of resin layer on cell walls, and followed by debonding fracture at core/facesheet interfaces. The shear strength of honeycomb composite showed strong anisotropy dependent on the loading direction. The shear strength in longitudinal direction was about 1.4 times higher compared to that in transversal direction due to the different thickness of cell walls mainly loaded during the shear deformation.

1. Introduction

The honeycomb composites of sandwich structure, consisting with honeycomb core and facesheets, are attractive for the engineering applications requiring high rigidity with lightweight. The honeycomb composites have been widely applied in aerospace industries due to their excellent properties such as high structural integrity, low thermal conductivity, high resistance to aerodynamic load and good sound insulating capacity, which can be properly designed by selecting core, facesheet and cell foam materials [1–4]. The primary function of the honeycomb core is to carry the normal and the shear stress on the surface perpendicular to the axis of the hexagonal prisms in longitudinal (L) and transversal (T) directions as shown in Fig. 1. The longitudinal and transversal directions are generally designated according to the loading direction with respect to the direction of ribbons in honeycomb core. The ribbons in honeycomb core are bonded with two cell walls, thus the ribbons have double thickness compared to that of freewalls in honeycomb core as shown in Fig. 1. The honeycomb composites show anisotropic mechanical properties due to their geometrical characteristics [5].

Many researchers have studied the mechanical properties of the honeycomb composites during the past three decades. Kelsey [6] investigated the linear elastic properties during the shear deformation of aluminum honeycombs. The mechanical properties of honeycombs have been tested and analysed by Zhang and Ashby [7]. The axial deformation behavior such as buckling of honeycomb cells has been analysed by Timoshenko [8]. However, there have been not as yet a recognized explanation of the mechanical properties

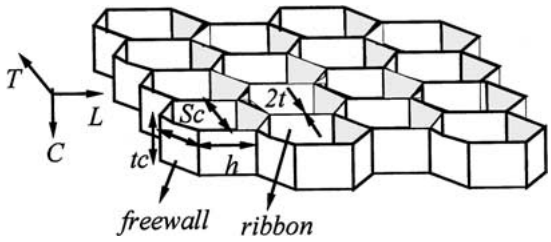

Figure 1 The geometry of honeycomb core consisting with hexagonal cells. T: transversal direction, L: longitudinal direction, C: compressive direction.

and failure processes of honeycomb composites at elevated temperature.

In this study, the compressive and shear deformation behavior and failure mechanism of honeycomb composites, consisting with Nomex honeycomb core and 2024Al alloy facesheets, were investigated at room and elevated temperatures. The experimental results were compared with the theoretical calculations based on the formulas for the compressive stress and shear stress on thin plates proposed by Roark and Young [9]. The thermal analysis was achieved in order to investigate the thermal properties of the cell walls in honeycomb composites.

2. Experimental procedures

Nomex honeycomb was used as core of honeycomb composite and the geometry of hexagonal cell was shown in Fig. 1. The cell walls were made of aramid woven fabric impregnated with phenolic resin, with the cell wall thickness(t) of 0.22 mm and the cell thickness(t_c) of 13 mm. The cell size(s_c) was 9.5 mm and the density of honeycomb core was 48.06 kg/m^3. The oblique planes in cell walls are designated as freewalls(l) and the parallel planes bonded with two cell walls are designated as ribbons(h). The 2024Al alloy sheets with thickness of 1.2 mm were used as facesheets. Two facesheets were bonded with a honeycomb core by using epoxy adhesive films having 0.32 mm thickness consisting with epoxy resin and nylon fabric. The honeycomb composites were fabricated by curing the stacked facesheets, core and adhesive films at 177°C for 1 hr using a hot press.

The compressive and shear test specimens were manufactured according to ASTM C365 and ASTM C273, respectively as shown in Fig. 2a and 2b. The dimension of the compressive specimen was 50 mm × 50 mm × 13 mm. The shear test specimen consisted with the honeycomb cores (50 mm × 160 mm × 13 mm) bonded with longer facesheets (50 mm × 180 mm × 1.2 mm). The compressive and shear tests were performed at temperatures ranged 25–300°C. The specimens were held 30 min. at test temperature for thermal equilibrium, and tested under constant cross-head speed of 1.2 mm/min. by using Instron 4206. The typical stress-strain curves obtained during the compressive and shear deformation behavior of honeycomb were analysed based on the observation of microstructural change during the deformation process. The shear tests were performed in both longitudinal (L) and transversal (T) directions, and the mechanical anisotropy in shear strength was analyzed. The tensile strengths of cell walls with and without phenolic resin were measured respectively as a function of temperature ranged 25–300°C according to ASTM D3039. The thermal analysis was measured by using DSC(differential scanning calorimetry) at temperature ranged 25–400°C and TGA(thermogravimetric analysis) at temperature ranged 25–900°C.

3. Results and discussion

3.1. Compressive deformation behavior

Fig. 3a shows a typical stress-strain curve obtained form the compressive test of honeycomb composite and Fig. 3b shows a schematic microstructural change during the compressive deformation of honeycomb composite. The compressive deformation process can be categorized into three regions (I, II and III) based on the compressive stress-strain behavior. The compressive stress increased almost linearly with increasing strain in region I due to the elastic buckling of cell walls, not the elastic axial shortening of cell walls. The cell walls of honeycomb composite were restrained with the neighboring cell walls and very thin. Therefore, when the compressive deformation is performed to the honeycomb composites, it is more difficult to be happened

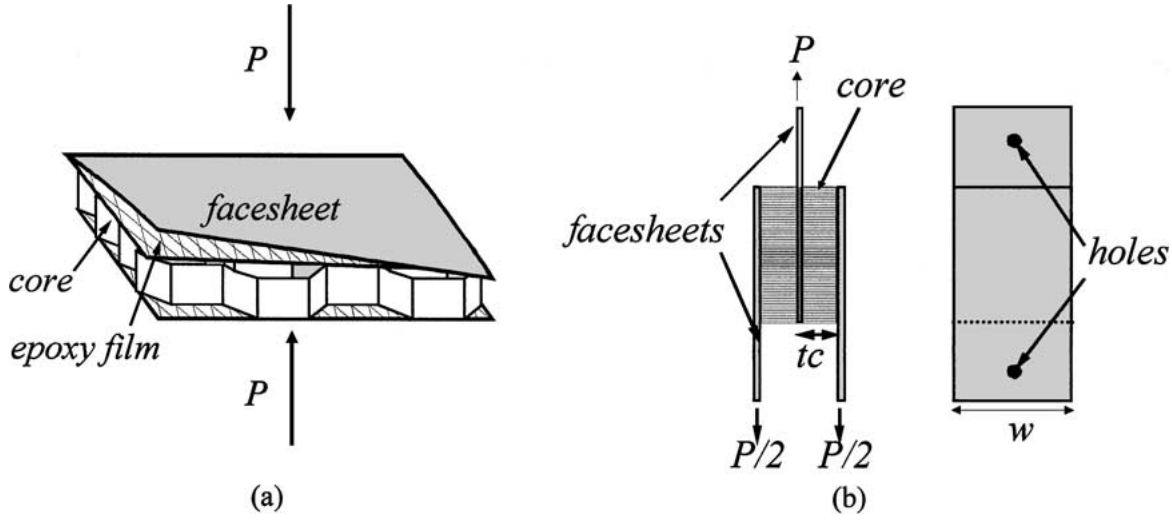

Figure 2 Shapes and dimensions of test specimens. (a) Compressive test specimen, (b) shear test specimen.

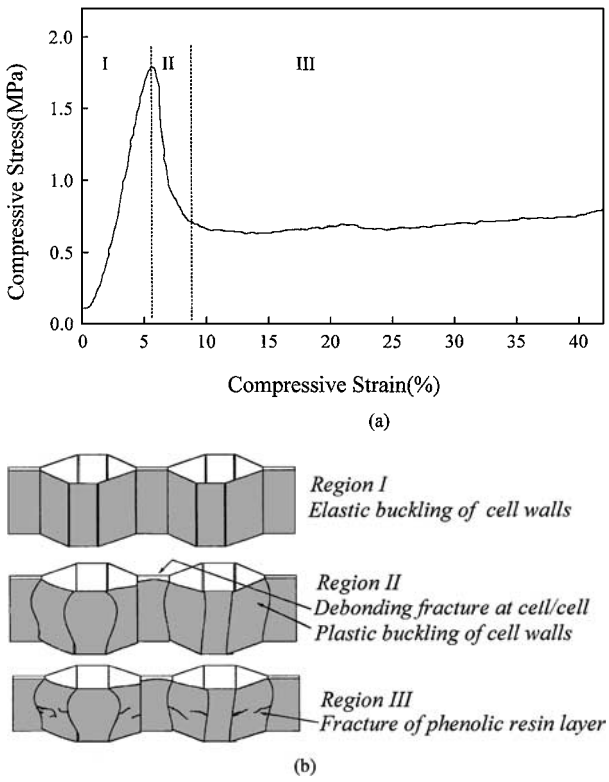

Figure 3 Typical stress-strain curve obtained from the compressive test and the microstructural change during the compressive deformation of honeycomb composites in regions of I, II and III. (a) Typical stress-strain curve, (b) schematic microstructural change during the compressive deformation of specimen.

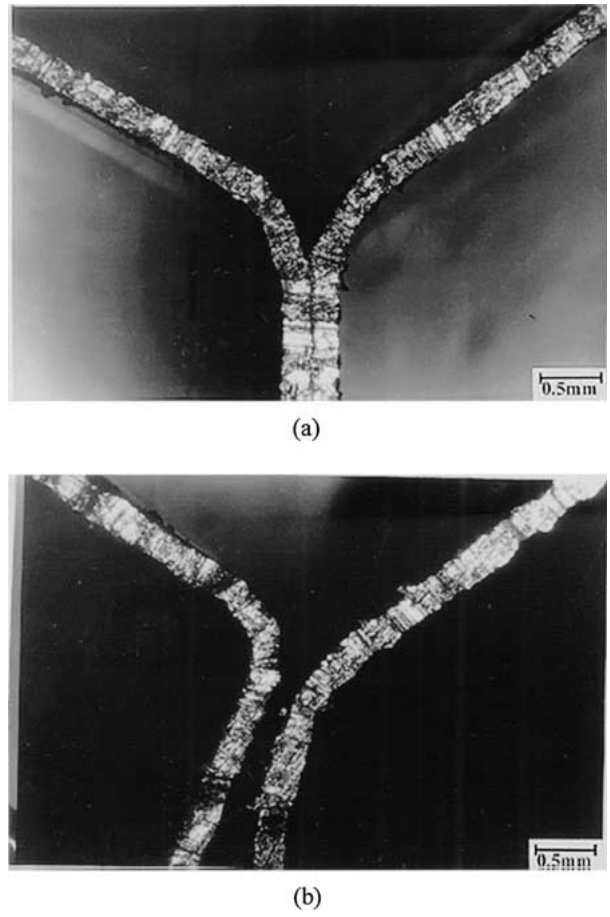

Figure 4 Debonding fracture of cell/cell interfaces at ribbon in the elastic buckling and the plastic buckling of cell walls. (a) elastic buckling of cell walls, (b) plastic buckling of cell walls.

by the elastic axial shortening of cell walls rather than by the elastic buckling of cell walls. When the stress-strain curve passed a maximum stress, a rapid drop of the compressive stress appeared in region II due to the on set of the plastic buckling of cell walls. The reason of a rapid drop of the compressive stress in region II is that the elastic buckling of cell walls was converted quickly to the plastic buckling of cell walls.

The plastic buckling was initiated at the freewalls and propagated into the ribbon. Then, the debonding fracture of cell/cell interfaces at ribbon was followed in region II. Fig. 4a and b showed the debonding fracture of cell/cell interfaces at ribbon when the cell walls were under the elastic buckling and instantly the plastic buckling of cell walls, respectively. The debonding fracture of cell/cell interfaces at ribbon becomes extreme due to the increase of plastic buckling of cell wall. The debonding fracture at core/facesheets interfaces was not observed in the compressive test, since the compressive stress was applied normal to the core/facesheet interfaces. In plateau region III, the fracture of phenolic resin layer on cell walls proceeded continuously. It is reasonably thought as the plastic shortening that the nearly constant load proceeded in region III with the fracture of phenolic resin layer on cell walls. The crack initiation at core/facesheets or cell/cell interfaces was followed by the buckling of cell walls. The compressive stress was maintained nearly constant up to a failure in region III.

When the honeycomb composite was loaded in compressive mode, it was assumed that a uniform compression was achieved on the two edges parallel to the

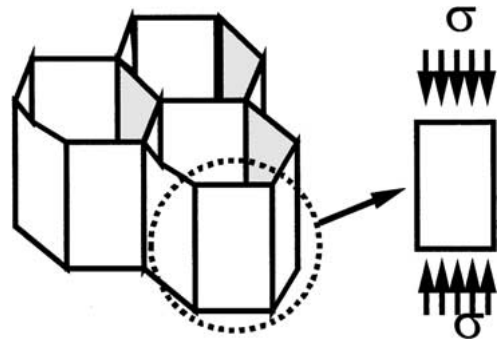

Figure 5 Rectangular cell wall under equal uniform compression on two edges. It is assumed that the cell walls of honeycomb composites are rigidly constrained by neighboring cell walls and all cell walls are deformed with the same strain.

compressive loading direction of each wall as shown in Fig. 5. And also, it was assumed that the cell walls of honeycomb composite are rigidly constrained by neighboring cell walls and all the cell walls were deformed to the same strain. Therefore, the compressive stress of honeycomb composite is the sum of the stresses carried out by the individual cell walls. The formulas for a rectangular cell wall under equal uniform compression on two opposite edges, l, was shown as following Equation 1. The theoretical compressive stress on a cell wall used in this study was based on Zhang and Ashby's model and could be expressed as following [7, 9, 10]:

$$P = K_C \frac{E}{1-\nu^2}\left(\frac{t^3}{l}\right) \quad (1)$$

where K_C is end constraint factor in compression mode and its value [9] is 5.73, E is elastic modulus of cell walls, ν is poisson's ratio of cell walls, t is thickness of cell wall and l is length of freewall. Equation 1 is expressed for the load, P on a cell wall.

The compressive load of the individual hexagonal cell of honeycomb core is the sum of the loads carried out by the individual cell walls. The total compressive load is $10P$ which is the sum of the compressive load, $2P$, carried out by the freewalls with single thickness and the compressive load, $8P$, carried out by the ribbon with double thickness because the load is proportional to the cube of thickness as shown in Equation 1. The area, A_{hex}, of individual hexagonal cell in honeycomb core is calculated as $(2l\cos\alpha \times l\sin\alpha) + (2l\cos\alpha \times l)$, where the α is the angle of the inclined cell wall. The compressive strength, σ_C, carried out by unit hexagonal cell, is expressed as following Equation 2:

$$\sigma_C = \frac{10P}{A_{\text{hex}}} = \frac{5K_C E}{(1-\nu^2)\cos\alpha(1+\sin\alpha)}\frac{t^3}{l^3} \quad (2)$$

Fig. 6 shows the variation of compressive strength calculated from the maximum value in stress-strain curve with increasing temperature. The measured compressive strengths of 1.7 MPa were compared with the calculated compressive strengths of 1.97 MPa based on Zhang and Ashby's model. And then, those results were shown in Table I. The main reason of discrepancy between the measured and the calculated results is that the bonding strength at cell/cell interfaces is not considered in calculation. This theoretical result was calculated based on the assumption that all the walls of honeycomb core experience the same deflection without the debonding fracture of cell/cell interfaces. However, the debonding fracture of cell/cell interfaces was observed during the compressive deformation of cell walls as shown in Fig. 4. Therefore, the measured compressive strength was 14% lower than the theoretical compressive strength. The measured compressive strengths of honeycomb composites were decreased as 1.7 MPa, 1.63 MPa, 1.48 MPa and 1.10 MPa with increasing temperature ranged from 25°C to 300°C as shown in Fig. 6 due to the degradation of cell walls.

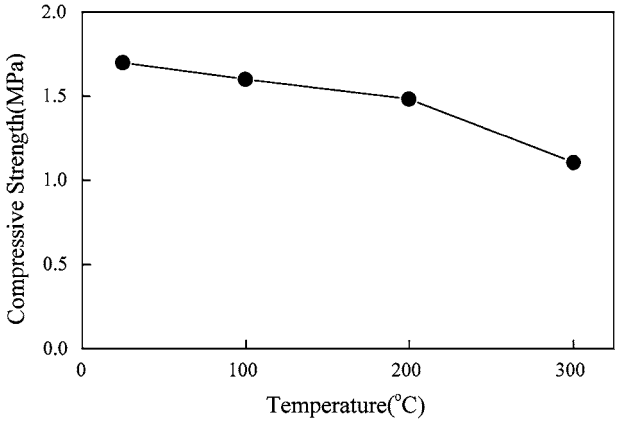

Figure 6 Variation of compressive strength of honeycomb composites with increasing temperature.

3.2. Shear deformation behavior

The typical stress-strain curve of honeycomb composites during the shear test was shown in Fig. 7a and b. The process of shear deformation can be categorized into four regions (I, II, III and IV) based on the characteristic stress-strain behavior at each region. The elastic shear deformation of cell walls was observed in region I. After the maximum stress was obtained, the plastic shear deformation of cell walls was observed and the debonding fracture at cell/cell interfaces was followed in region II. As a result, the shear strength decreased rapidly in region II. In this region, the cell walls of honeycomb composites were deformed as shown in Fig. 7b. The nearly constant stress lower than the maximum shear stress was maintained in region III, in which a continuous fracture of phenolic resin layer on cell walls was observed. During proceeding the plateau deformation from shear stress-strain curve, the fracture of specimen by the core/facesheet interfaces debonding occurred finally in region IV with a decrease of shear stress on honeycomb composites.

3.2.1. Mechanical anisotropy during shear deformation

The deformation behavior of the cell walls during shear test was analysed by the Zhang and Ashby's model [7] as shown in Fig. 8a and b which show the basic cell carrying out the shear stress in honeycomb composites. The arrows around cell walls indicate the shear force performed on the cell wall during shearing in longitudinal and transversal direction. The a, b and c in these figures indicate the length of cell walls, respectively. The P_a, P_b and P_c indicate the shear load carried out by the a, b and c cell walls, respectively. A α indicates the angle of the inclined cell wall. It was assumed that the length of all cell walls was same. When the lengths of all cell walls are the same, it is reasonably thought as

TABLE I The comparisons of the experimental results and the calculated results for the compressive and shear strengths of honeycomb composites

Temperature (°C)	Compressive strength (MPa)		Shear strength(MPa)					
			L-direction		T-direction		L/T ratio	
	Exp.	Zhang & Ashby	Exp.	Zhang & Ashby	Exp.	Zhang & Ashby	Exp.	Zhang & Ashby
25	1.70	1.97	1.63	0.76	1.14	0.44	1.4	1.7
100	1.63	–	1.53	–	1.08	–	1.4	–
200	1.48	–	0.9	–	0.68	–	1.3	–
300	1.10	–	0.17	–	0.17	–	1.0	–

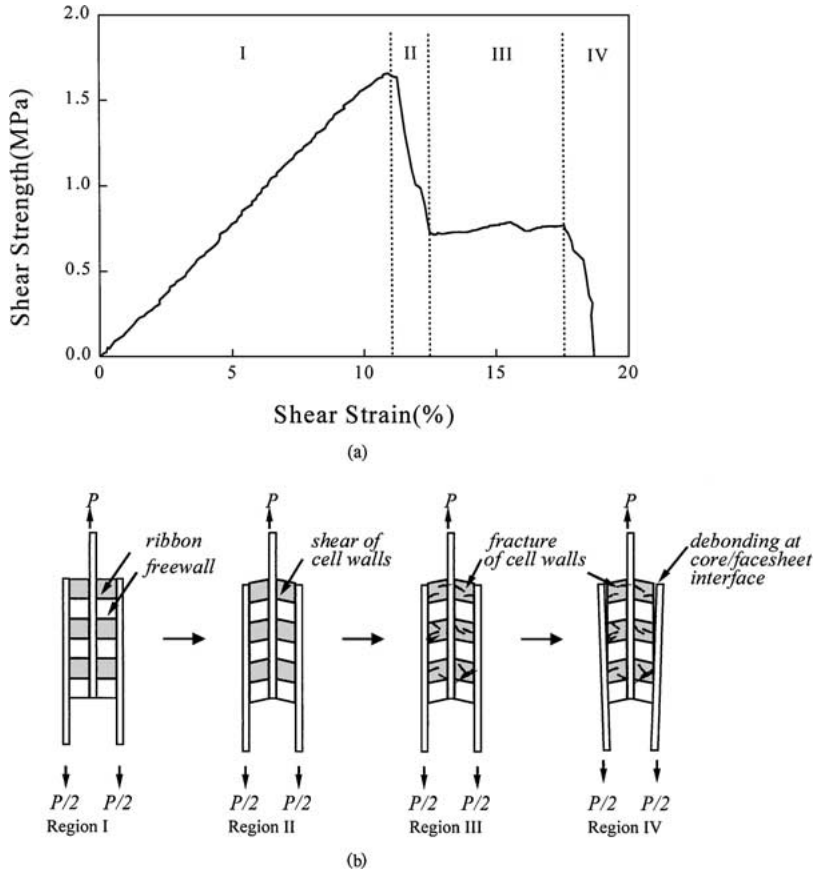

Figure 7 Typical stress-strain curve obtained during the shear deformation and the schematic diagram of specimens during the shear deformation. (a) Shear stress-strain curve, (b) schematic figures of specimens during the shear deformation (region I: elastic shear deformation of cell walls, region II: plastic shear deformation of cell walls and debonding at cell/cell interface, region III: continuous fracture of phenolic resin layer on cell walls, region IV: fracture of specimen by the debonding of core/facesheet interfaces).

that the angle, α, of the inclined cell wall is 30° and the force components on each cell wall should be identical as expressed in Equation 3.

$$P_a = P_b = P_c = P \tag{3}$$

When the honeycomb composites is deformed with shear mode, the theoretical shear stress on a cell wall constrained by neighboring cell walls is as following equation [9, 10]:

$$\tau_L = \frac{K_S E}{(1-\nu^2)(\cos\alpha)}\frac{t^3}{l^3} \tag{4}$$

$$\tau_T = \frac{K_S E}{(1-\nu^2)(1+\sin\alpha)}\frac{t^3}{l^3} \tag{5}$$

where K_S is end constraint factor in shear mode and its value [9] is 7.38, E is elastic modulus of cell walls, ν is poisson's ratio, t and l are thickness and length of cell wall, respectively. The measured shear strengths of 1.63 MPa in longitudinal direction and 1.14 MPa in transversal direction were compared with the calculated shear strengths of 0.76 MPa and 0.44 MPa, respectively, from Equations 4 and 5. And then, those results were also shown in Table I. The main reason of discrepancy between the measured and the calculated results is that the bonding strength at core/facesheet interfaces is not considered in calculation. The theoretical calculation in Equations 4 and 5 assumed that all the honeycomb core were only deformed in shear mode by the cell walls but, in reality, honeycomb core were deformed by adhering the honeycomb core between the two facesheets. Therefore, both the shear strength of the honeycomb core and the bonding strength at core/facesheet interfaces affect the shear strength of honeycomb composites. As a result, the measured shear strengths were 2–2.6 times higher than the theoretical shear strengths with the loading direction.

The measured shear strengths in longitudinal direction were 1.63 MPa, 1.53 MPa, 0.9 MPa and 0.17 MPa, and those in transversal direction were 1.14 MPa, 1.08 MPa, 0.68 MPa and 0.17 MPa at temperatures ranged from 25°C to 300°C as shown in Fig. 9a. From Equations 4 and 5, the ratio of shear stress in longitudinal direction to transversal direction can be calculated as following:

$$\frac{\tau_L}{\tau_T} = \frac{1+\sin\alpha}{\cos\alpha} \approx 1.7 \tag{6}$$

where α is 30° based on the assumption of calculation. The measured shear strengths of honeycomb composite were anisotropic depending on the loading direction. The ratio of the measured shear strengths in longitudinal direction to transversal direction were 1.4 which was kept almost constant up to 200°C as shown in Fig. 9b. The ratio of measured shear strengths is

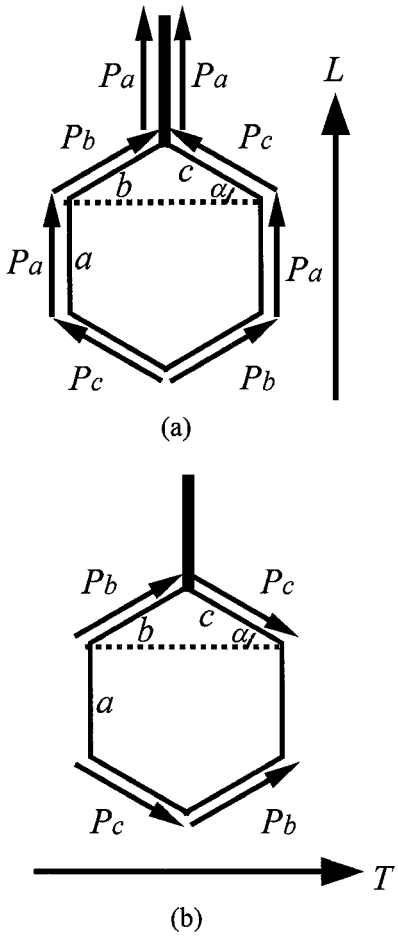

Figure 8 Modeling of shear deformation behavior of cell walls with different load directions. (a) Loading in longitudinal (L) direction, (b) Loading in transversal (T) direction.

comparable to the ratio of theoretical shear strengths of 1.7 obtained from Equation 6. Anisotropy of the honeycomb composites was happened mainly due to the different thickness of the freewalls and the ribbons. The freewalls and ribbons of honeycomb composites support the load during shear deformation. The loads performed on cell walls are changed according to the angle between the loading direction and the cell walls. That is to say, in longitudinal direction, the ribbons with double thickness are mainly loaded, while, in transversal direction, the freewalls with single thickness are loaded mainly but the ribbons are loaded negligibly. Therefore, anisotropy of honeycomb composites occurred due to the different thickness of cell walls mainly loaded during the shear deformation.

However, anisotropy of honeycomb composites was nearly same with increasing temperature above 200°C. The variation of shear strength with increasing temperature of honeycomb composite in longitudinal direction and transversal direction, and the ratio of shear strength was measured shown in Fig. 9b. The shear strength of honeycomb composites decreased with increasing temperature but the anisotropy of honeycomb composites was maintained constant up to 200°C. The shear strength in longitudinal direction was about 1.4 times higher compared to that in transversal direction up to 200°C. However, the shear strengths of honeycomb composite in longitudinal and transversal directions became almost the same above 200°C and the anisotropy

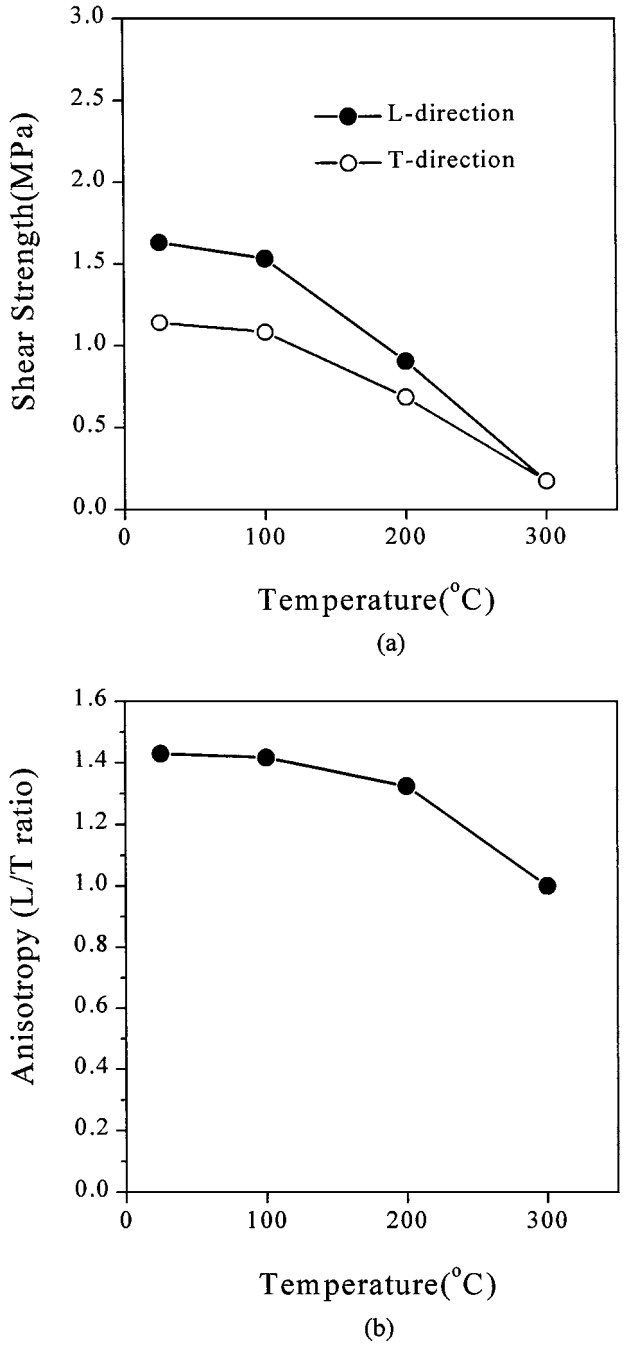

Figure 9 Variation of shear strength of honeycomb composite with increasing temperature. (a) Shear strengths in longitudinal and transversal directions, (b) anisotropy in shear strength.

of honeycomb composite was lost at 300°C. It is mainly due to the degradation of the cell walls consisting with aramid fabric and phenolic resin with increasing temperature above 200°C.

3.3. Temperature dependence of compressive and shear strength

The compressive and shear strength of honeycomb composite was influenced mainly by the strength of cell walls in honeycomb core. The compressive and shear strength decreased with increasing temperature ranged from 25°C to 300°C. It is mainly due to the elimination of binding effect of the phenolic resin layers on the cell walls. Fig. 10 shows the tensile strength of cell walls with or without phenolic resin with varying

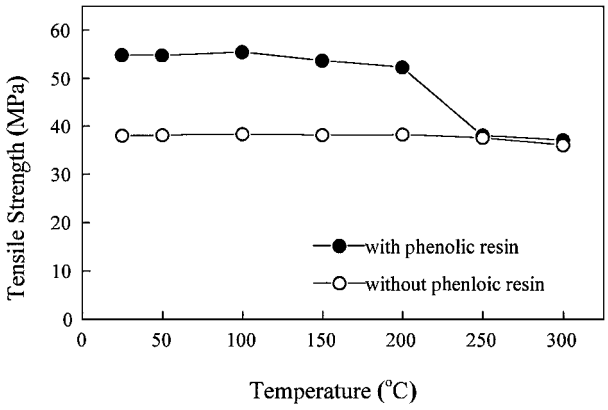

Figure 10 Variation of tensile strength of cell walls with increasing temperatures.

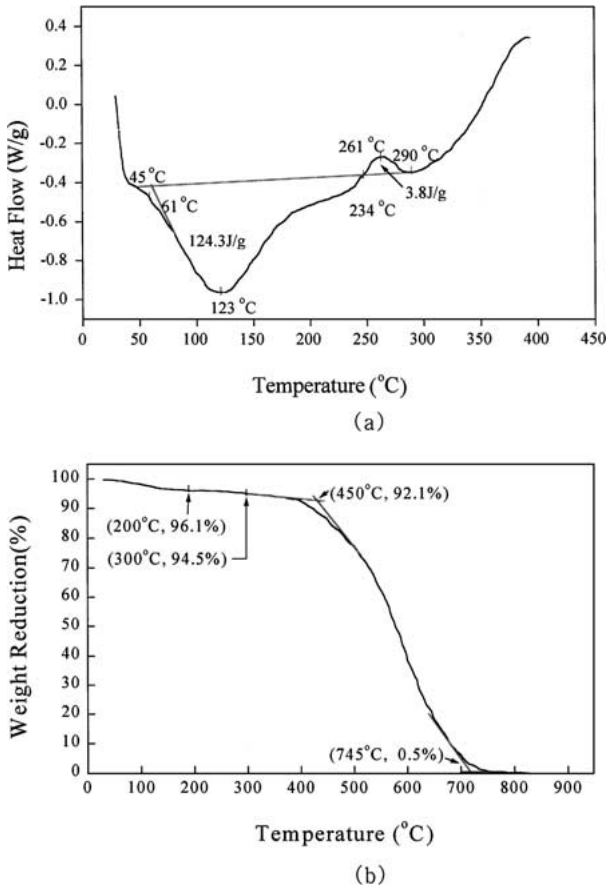

Figure 11 Thermal analyses of cell walls in honeycomb composite. (a) DSC (differential scanning calorimetry) curve, (b) TGA (thermogravimetric analysis) curve.

temperature. Tensile strength of honeycomb cell walls consisting with aramid fabric and phenolic resin decreased with increasing temperature. However, the tensile strength of honeycomb cell without phenolic resin was much lower than that with phenolic resin, which showed relatively constant tensile strength with increasing temperature as shown in Fig. 10. This indicates that the phenolic resin of cell walls plays an important role of strong binding effect with aramid fabric. Therefore, the variation of compressive strength and shear strength with increasing temperature is mainly due to the phenolic resin of cell walls rather than aramid fabric.

Fig. 11a and b shows the DSC (differential scanning calorimetry) and TGA (thermogravimetric analysis) analyses of cell wall in order to investigate the thermal properties of honeycomb composite. DSC curve of cell wall revealed an endothermic reaction at temperature ranged 61–234°C and an exothermic reaction at temperature ranged 234–290°C. The endothermic reaction at 124°C is due to the evaporation of moisture in cell wall and the curing of remaining uncured part of phenolic resin in cell walls [11]. The exothermic reaction at 261°C was associated with network rearrangement of cured phenolic resin which is crucial to make the cell wall brittle. The phenolic resin in cell wall became brittle and loose its binding effect with aramid fabric as increasing the temperature above 200°C. Therefore, the compressive strength and shear strength of honeycomb composite decreased rapidly above 200°C. TGA curve of cell wall in honeycomb composite represents the weight loss of specimens with increasing temperature as shown in Fig. 11b. The weight loss of cell walls was observed significantly above 490°C due to random chain scission of phenolic resin and aramid paper by the pyrolysis [12, 13]. The main chains in a cross-linked polymer are held together by the primary covalent bonds. When the thermal energy exceeds the dissociation energy of covalent bonds in polymer, the main network chains are broken. The weight of cell wall was decreased by 5.5% at 300°C. DSC and TGA curves showed that the phenolic resin layers on cell walls became brittle at temperatures above 200°C. At the same time, the compressive and shear strengths decreased with increasing temperature by a degradation of phenolic resin layers in cell walls.

4. Conclusions

The deformation behavior and failure mechanism of the honeycomb composite during the compressive and shear test was investigated. The conclusions could be summarized as follows:

1. The compressive deformation of honeycomb composite proceeded by an elastic buckling of cell walls, a plastic buckling and debonding fracture at core/facesheet interfaces, and followed by fracture of phenolic resin layer on cell walls.

2. The shear deformation honeycomb progressed by an elastic deformation of cell walls, a plastic deformation and debonding fracture at cell/cell interfaces, fracture of phenolic resin layer on cell walls, and followed by debonding fracture at core/facesheet.

3. The compressive strengths were measured as 1.70 MPa, 1.63 MPa, 1.48 MPa and 1.10 MPa and the shear strengths were measured as 1.63 MPa, 1.52 MPa, 0.9 MPa and 0.17 MPa in longitudinal direction and 1.63 MPa, 1.52 MPa, 0.9 MPa and 0.17 MPa in transversal direction at temperature ranging 25–300°C. The measured ratio of shear strengths in longitudinal to transversal direction was 1.4, which was similar to the theoretically calculated ratio of shear strengths. Anisotropy is mainly due to the different thickness of cell walls such as freewall and ribbon mainly loaded during the shear deformation.

4. The compressive and shear strength of honeycomb composite decreased with increasing temperature up

to 300°C. It is mainly due to the degradation of cell walls and the decrease in binding effect between phenolic resin layers and aramid fabric in cell walls with increasing the temperature.

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