SCALING OF HONEYCOMB COMPRESSIVE YIELD STRESSES

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ABSTRACT

In this study, the compressive yield stresses of honeycomb rings were scaled and correlated to honeycomb core bulk values. A honeycomb scaling factor and geometric end constraint factor were found to relate the rings and core through the relative yield stresses and their physical dimensions and properties of the honeycomb materials. The compressive properties of the honeycomb rings were also investigated using both a model and a commercial phenolic honeycomb dip resin. Honeycomb rings manufactured from the model resin were found to have higher compressive properties. These properties were attributed to the higher fracture toughness of the resin, and both resins were found to accurately scale from rings to core with the honeycomb scaling factor. Ultimately, this research can be used to innovate and efficiently characterize the compressive properties of different honeycomb webs and dip resins without having to make the significant investment of time and resources associated with large scale honeycomb testing.

INTRODUCTION

Honeycomb materials were first introduced in the 1940's for the manufacture of furniture and aircraft structures. In these initial applications, the honeycomb cores were fabricated from a wide variety of materials that included paper, cotton duck fabric, glass fabric and aluminum foil.(1) Since the 1940's, progress in developing and improving new honeycomb structures has been steadily increasing.(2) Today honeycomb cores can be fabricated from most types of papers, plastics, metals and ceramics.(3) However as the technology behind the production of honeycomb improves, the ability to innovate new honeycomb materials becomes more difficult.

The basic technology behind the manufacturing of honeycomb core has been around over four decades and has not fundamentally changed during this time.(1) As more companies have entered the honeycomb market, the differentiation between the different honeycomb producers has decreased. This diminishing product differentiation has caused honeycomb manufacturers to stringently protect the honeycomb production secrets which they feel differentiate them from their competitors. As a result, honeycomb producers are reluctant to share any information with outside companies which may one-day be shared with their competitors.

Ultimately, this protection has inhibited material development by forcing material producers to rely on the honeycomb manufacturer to screen and test new materials. Dip resin and web manufacturers cannot screen new materials because they to do possess the specialized knowledge required to manufacture honeycomb structures. Honeycomb producers do not have the specialized knowledge required to manufacture and optimize dip resins or web materials. With the inability of the honeycomb manufacturer to share material development information, the resin and web suppliers are forced to rely on the honeycomb manufacturer for material testing and screening.

When web and resin suppliers approach honeycomb manufacturers with a new or novel honeycomb material, the screening process can be very time consuming and costly. The time required to screen a new honeycomb material can often take weeks to perform and frequently small scale or production size honeycomb blocks are required to evaluate

a material's honeycomb potential. This type of screening process makes multiple material iterations and improvements difficult for the honeycomb material suppliers.(4) The work presented in this study attempts to address some of these material development concerns.

In this study, the scaling of honeycomb compressive properties was explored. Using stability mechanical arguments, the compressive properties of honeycomb rings and cores were theoretically correlated to a geometric end constraint factor and a honeycomb scaling factor. Through experimental measurements of Nomex® based honeycomb rings and cores, using commercial and model phenolic dip resin system, the validity and limitations of these factors were determined. Testing was also conducted on phenolic dip resin laminates in order to characterize the important resin mechanical properties which influence the final performance of honeycomb structures. Ultimately, this research can be used to innovate and efficiently characterize the compressive properties of different honeycomb webs and dip resins without having to invest a significant amount of time or effort in large scale honeycomb testing.

THEORY

Honeycomb core fails under compressive loads in a predictable manner.(3) In the out-of-plane direction, the honeycomb core first deforms in a linear-elastic manner. During this deformation, the walls of the honeycomb core axially compress. When the honeycomb reaches its maximum compressive stress, it elastically buckles in the plane of the honeycomb core. The critical yield stress of commercial double-wall honeycomb with this mode of failure can be described by Equation 1 using stability mechanical arguments.(5, 6)

$$\sigma_{CRIT-H} = \frac{K_H E_S}{(1-\nu_S{}^2)} \cdot \left(\frac{t_H}{l}\right)^3 \frac{\left(1+4\frac{l}{h}\right)}{\cos\theta\left(\frac{h}{l}+\sin\theta\right)} \qquad \text{(Equation 1)}$$

In Equation 1, σ_{CRIT-H} is the honeycomb critical yield stress, t_H is the honeycomb single cell wall thickness, l is the length of the single cell wall, h is the length of a double

cell wall, θ is the angle of the cell wall, ν_S is the Poisson's ratio of the honeycomb material, E_S is the elastic modulus of the honeycomb material and K_H is an end constraint factor. K_H accounts for the fact that during compression the honeycomb cell wall is neither completely free to rotate nor is it rigidly clamped.

Under an axial load, a thin ring yields and fails in the same phenomenological way as a honeycomb structure. First, the ring wall axially compresses, and when the ring reaches its critical stress, it buckles. The buckling of a thin ring can be described by Equation 2 where r is the radius of the honeycomb ring, $\sigma_{CRIT\text{-}R}$ is the ring critical yield stress and K_R is an end constraint factor accounting for the geometry of the ring.(7)

$$\sigma_{CRIT-R} = \frac{K_R E_S t_R}{r\sqrt{3\,(1-\nu_S{}^2)}} \qquad \text{(Equation 2)}$$

Through these two equations, the critical yield stress of the honeycomb can be related to the critical yield stress of a honeycomb ring where the different geometric end constraint factors have been consolidated in a single geometric end constraint factor, K, as shown in Equation 3.

$$K = \frac{K_H}{K_R} = \left[\sqrt{\frac{(1-\nu_S{}^2)}{3}} \cdot \frac{\cos\theta\left(\frac{h}{l}+\sin\theta\right)}{\left(1+4\frac{l}{h}\right)}\right] \cdot \left[\frac{t_R l^3}{r t_H{}^3}\right] \cdot \frac{\sigma_{CRIT-H}}{\sigma_{CRIT-R}} \qquad \text{(Equation 3)}$$

EXPERIMENTAL PROCEDURE

Honeycomb Dip Resins

In this study, the mechanical responses of honeycomb rings and honeycomb cores manufactured from two different phenolic honeycomb dip resins were investigated. The first dip resin investigated was a commercial phenolic resole resin manufactured by Georgia Pacific with the trade name GP 5236 Redi-Lam Resin. The GP 5236 resin had a

weight average molecular weight around 1600 g/mol as determined through gel permeation chromatography (GPC). The second resin was a model resole honeycomb dip resin system that was manufactured from phenol and formaldehyde and catalyzed with ammonium hydroxide. The synthesis of this resin is described in elsewhere.[8] The model resin had a mass average molecular weight around 350 g/mol as determined through GPC.

In producing honeycomb dip resins, both phenolic resins were solvated with ethanol to a final solvent content of 60 weight percent. In order to determine the initial solvent weight percent of the resins, thermogravimetric analyses were performed. The initial volatile content of each resin was measured by the weight loss of a 10 mg resin sample after 90 minutes at an isothermal TGA temperature of 130°C. The kinematic viscosities of the two dip resins systems were determined at 40°C using ASTM D445. The kinematic viscosities of both resins were in the range of 2.0 to 3.0 centistokes.

Honeycomb Fabrication and Testing

Honeycomb ring compression specimens were fabricated from 2.5 cm wide, 126.0 cm long and 0.08 mm thick strips of Nomex 410 paper. The Nomex strips were dipped in one of the solvated honeycomb dips resins. After dipping, the Nomex strips were wrapped twice around a steel rod with a radius of 10 mm. The strips were then wrapped with shrink-wrap tape and placed in an oven which had been preheated to 160°C. In the oven, the rings were held for two hours at 160°C, then cooled to room temperature at 2.7°C/min. While in the oven, the shrink-wrap tape contracted five percent. The five percent shrinkage provided the necessary compaction to consolidate the rings. To densify the rings, they were again dipped in the phenolic dip resin. After dipping, the excess phenolic resin was allowed to drain from the rings for two minutes. Once the excess resin had been removed, the rings were then cured in an air-circulating oven at 160°C for 10 minutes. Following the cure of the phenolic resin, the rings were allowed to cool and then redipped until they had been dipped a total of 1, 2, 5, 10, 12, 13, 17, 20, 25 or 30 times. After dipping, the rings were compressed in an Instron® 4505

mechanical tester with square 5.1 cm parallel platens at a rate of 0.25 cm/min until failure. Each compressive yield stress and standard deviation reported represents the average of five tests.

In manufacturing honeycomb core samples, large sheets of Nomex 410 paper 0.08 mm thick were cut into smaller sheets measuring 35.6 cm long and 7.8 cm wide. A model node adhesive was then printed on the individual Nomex sheets. The printed node lines were 2.0 mm wide and spaced 0.84 cm apart. The model node adhesive was synthesized from di-functional epoxies and solvated with 25 weight percent acetone. The epoxies and curing agents used in manufacturing the model node adhesive are listed in Table 1.

After printing, approximately 60 Nomex sheets were stacked on top of each other. The sheets were stacked in such a way that the node lines of every sheet were offset from the adjacent sheets by 0.42 cm. Next, expansion loops were adhered to the honeycomb stack and the entire stack was cured in an autoclave. In the autoclave, the honeycomb stack was ramped at 2.7°C/min to 177°C, held for 2 hours and ramped back to 27°C at 2.7°C/min with a total compaction pressure of 34.4 kPa. Following cure, the honeycomb stack was expanded to a final hexagonal cell size of 3.7 mm. The honeycomb block was then heat set at 350°C for 2 minutes to maintain the expanded shape of the honeycomb core. Lastly, the honeycomb was dipped in one of the two honeycomb dip resins. After dipping, air was forced through the honeycomb cells to prevent foaming and frothing of the phenolic resin. The dipped honeycomb was then cured in an air-circulating oven for 10 minutes at 160°C. Following the cure of the phenolic resin, the honeycomb blocks were allowed to cool and then redipped until they had been dipped a total of 1, 2, 5, 10, 12, 13 or 17 times. After dipping the honeycomb core blocks were cut to a thickness of 1.27 cm. The honeycomb core slices were trimmed to square 5.1 cm specimens and compressed in an Instron 4505 mechanical tester at a rate of 0.25 cm/min until failure. Each compressive yield stress and standard deviation reported represents the average of three or four tests.

Laminate Fabrication and Testing

Laminates were also fabricated in an autoclave to test the fracture and flexural properties of the phenolic resins. Laminates with an overall resin content of 39 to 40 weight percent were fabricated from 18 plies of a 7781 style fiberglass fabric from BFG Industries and sized with a soft A1100 finish. In the autoclave, specimens were ramped at 2.7°C/min from 27°C to 150°C, held for two hours, ramped to 177°C at 2.7°C/min, held for two hours, then ramped back down to 27°C at 2.7°C/min. The total compaction pressure used during cure was 1.4 MPa, and a nitrogen atmosphere was employed in all cure cycles. All plaques and laminates were post-cured at 130°C for four hours at an absolute pressure of 4.8 kPa.

Test methods for measuring the critical plane strain, G_{IC}, and plane shear, G_{IIC}, energy release rates are reported elsewhere.[8, 9] Each G_{IC} and G_{IIC} value and standard deviation reported represents the average of four and six tests, respectively. Three-point bend tests were conducted to measure the flexural modulus of the two phenolic resins. In this test, rectangular specimens measuring 8.0 cm long and 1.3 cm wide were evenly supported on a three-point bend apparatus with a span of 6.4 cm. The specimens were loaded at a crosshead speed of 0.17 cm/min until failure. Each flexural modulus, flexural yield stress and standard deviation reported represents the average of six tests.

RESULTS AND DISCUSSION

Correlation of Geometric end Constraint Factor

Experiments were conducted to measure the yield stresses of honeycomb materials fabricated from two dip resins. From the relative yield stresses of the cores and rings, the geometric end constraint factor was calculated for correlating the compressive properties of the rings and cores. However, prior to applying Equation 3, a number of experimental variables had to first be determined.

The first factor that was considered in applying Equations 1 - 3 was the elastic modulus of the honeycomb materials. In deriving Equation 3, it was assumed that the elastic moduli of the honeycomb rings and honeycomb cores are the same despite the

different resin to fiber ratios of these materials. In order to justify this assumption, it is necessary to understand the mechanisms of compressive failure in composite materials. In composites manufactured from aramid fiber materials, compression failure is most often observed to result from buckling or kink band formation in the composite.[10] This type of failure is caused by the loss of lateral support from the composite matrix.[11] The ability of the matrix to resist this deformation is determined by the thickness and mechanical properties of the dip resin. Because the modulus of the web does not dominate the mechanical behavior of the honeycomb material, the modulus contributions from a single or double wall in the honeycomb core or ring can be neglected, and the two elastic moduli to a first approximation can be considered equivalent. It is important to note that for honeycomb webs with higher elastic moduli (greater than 1.72 GPa), the mode of failure may change and the modulus of the web may begin to dominate the mechanical behavior of honeycomb materials.[10]

The thickness of the honeycomb walls is another variable that needs to be determined in correlating the properties of honeycomb rings and cores. In Equations 1 to 3, it has been assumed that the thickness of a single or double cell wall is uniform throughout the honeycomb rings and honeycomb cores. For the rings this assumption is valid, but on cores, the resin is not even distributed throughout the honeycomb. For ethanol based dip resins, surface tension and capillary forces cause relatively large amounts of resin to be deposited in the node bond fillet.[12] This uneven resin distribution causes the cell wall to be relatively thicker at the node bond and thinner in the middle of the cell wall. When a honeycomb or other composite structure buckles, the structure yields at the weakest point in the composite.[13] For honeycomb core this point is the center of the single cell wall. When the center of the single cell wall begins to yield, the local area around the wall begins to crack. This local cracking causes gross fracturing around the rest of the core and results in catastrophic yielding of the core. Based upon this analysis, the midpoint of the single cell wall was selected as the honeycomb core cell wall thickness, t_H, in Equations 2 and 3.

In analyzing Equation 3, it quickly becomes apparent that any set of honeycomb ring thicknesses and ultimate yield stresses can be compared to any set of honeycomb

core data. Through Equation 3, one can attempt to correlate the ultimate yield properties of a 25 kg/m³ or 75 kg/m³ dense honeycomb ring with the properties of a honeycomb core specimen which has a relative density of 50 kg/m³. With no physical relationship between the different ring and honeycomb core specimens, it becomes extremely difficult to draw any meaningful conclusions from Equation 3. It therefore becomes necessary to correlate the properties of the honeycomb rings and cores based upon similar physical characteristics. The honeycomb rings and honeycomb cores could not be correlated by density because of the large differences in specimen geometry. Additionally, the honeycomb rings and cores could not be correlated by cell wall thickness due to problems with specimen preparation at higher core densities. Ultimately, the number of dips was used as a basis for correlating the rings and honeycomb cores. By correlating the number of dips, it was assumed that each dip deposited a consistent amount of resin per dip. The resin may distribute itself in different ways on the cores and rings, but each deposition reinforces the rings in a similar manner.

In correlating the properties of the honeycomb rings and cores, both dip resins were considered together. This was done with the understanding that if the geometric end constraint factor is truly a variable which describes the mechanism of wall buckling, then it should not be a function of dip resin chemistry, but rather only depend upon the buckling behavior of the honeycomb wall. From the ultimate yield stresses and physical constants of the honeycomb rings and core, the geometric end constraint factor was calculated. In Figure 1, the geometric end constraint factor, K, is presented as a function of dip number.

From this figure it can be seen that above and below 10 dips, the geometric end constraint factor appeared to change. At higher honeycomb and ring densities, the average end constraint factor was found to be 170. For lower density honeycomb materials, the average scaling factor was found to be 222.

The change in the end constraint factor above 10 dips is believed to be due to a fundamental change in the nature of the honeycomb core specimens with increasing density or dip number. In Figure 2, photomicrographs of honeycomb core single cell walls are shown. As the honeycomb core is dipped, resin accumulates on the surface of

the cell walls, but the resin also collects in the areas in and around the node bond fillet. With increasing numbers of dips, the localized area around the node bond increases. With an increase in the local area around the node fillet, the manner in which the single cell walls are supported changes. Resin deposition in the corners of the honeycomb core reinforces the edges of the cell walls and changes the ability of the wall to rotate or move during compression. The resin reinforcement at the intersection of the cell walls restricts the movement of the cell and effectively shortens the buckling length of the wall. If the length of the single cell walls is shortened by 18% for all cores dipped over 10 times, the end constraint factor needed to describe this deformation jumps from K=170 to K=222. With a cell wall reduction of 18%, the scaling factors for the high and low dip honeycomb materials agree.

Using the high and low density geometric end constraint factors, the ultimate yield stress of the honeycomb core and honeycomb ring specimens can be correlated. Figure 3 shows the agreement between the experimental ultimate honeycomb yield stresses and the predicted value using honeycomb rings and Equation 3 for both the model NH_3 and GP 5236 resins.

Honeycomb Ring Testing

Although the properties of the honeycomb rings can be correlated to the compressive properties of honeycomb core, the honeycomb rings can also be used to evaluate the mechanical properties of various dip resins and web materials. When honeycomb core or honeycomb rings are compressed, the ability of the cell walls to resist compression and buckling is dictated by the fracture toughness and flexural strength and modulus of the reinforcing dip resin. During axial compression, the walls of the honeycomb bend and deform in a periodic manner. The resin coating the honeycomb structure must have a high flexural yield stress and modulus to resist this wall deformation. If the flexural modulus of the resin is low, the resin will reach its ultimate yield strain at relatively low compaction pressures. The fracture toughness of the dip resin is also a significant factor in the compression and ultimate buckling of the

honeycomb walls. As the honeycomb wall approaches its yield stress, microcracks begin to form in the reinforcement around the webbing. As the compressive stress increases, these microcracks propagate until the cracks extend all the way through the resin. At this point, the reinforcement around the honeycomb wall will yield and the honeycomb will elastically fail. If a dip resin can delocalize the stresses in the crack tip as the core is compressed, then the honeycomb yield stress will be higher than another honeycomb dip resin which cannot redistribute these stresses. The fracture toughness of a resin represents the ability of the resin to distribute these stresses.

The flexural modulus, flexural yield strength and the fracture toughness of the two phenolic resins investigated in this study are shown in Table 2.

As show in Table 2, the NH_3 model resin system had a higher fracture toughness than the commercial resin system. In compression or shear, the model resin system had a fracture toughness that was over 50% greater than the G_{IIC} toughness of the GP 5236 resin. In contrast, the GP 5236 resin outperformed the model NH_3 system in terms of flexural strength. Both the flexural modulus and the flexural yield stress of the commercial product exceeded the model resin system by 21% and 34%, respectively.

In an effort to further characterize the honeycomb properties, the peel strength of the phenolic dip resins was also investigated. Poor adhesion of the resin during the densification of the honeycomb can cause flaking of the reinforcing resin and premature failure of the honeycomb ring or core. For both the commercial and NH_3 model resin systems, the one and five dip peel specimens failed cohesively in the Nomex. The average peel energy for all specimens was around 1100 J/m^2. The cohesive failure of the Nomex suggests that there is good adhesion between the different layers of the dip resin and between the initial resin layer and the Nomex web substrate. The cohesive failure of the Nomex also indicates that the adhesive properties of the phenolic resin and the Nomex paper are most likely not responsible for compressive failure of honeycomb core or ring specimens.

In Figure 4, the ultimate yield stress of the honeycomb rings manufactured from both the NH_3 and commercial dip resins is plotted against ring weight. As shown in this figure, the rings dipped in the NH_3 dip resin had a higher compressive stress than rings

manufactured with the commercial resin system. This figure suggests that the fracture toughness of the resin may have a larger influence on the ultimate yield stress of honeycomb core than the flexural properties of the dip resin. This conclusion may be drawn because, as shown in Table 2, the model resin system had better fracture toughness than the commercial system, although the commercial system had better flexural properties than the model system.

In Figure 5, ring yield stresses are plotted as a function of dip number. In this figure, the GP 5236 resin was found to have a higher yield stress than the NH_3 model system. The contrast between Figure 4 and Figure 5 is attributed to the differences in the amount of resin picked up per dip.

After 30 dips, the honeycomb rings manufactured from the NH_3 model resin system had a yield stress of 2.2 MPa. After 15 dips, the commercial system had a yield stress of 1.9 MPa, and after 20 dips the yield stress of the GP 5236 ring exceeded the yield stress of the 30 dip NH_3 rings by 0.1 MPa. Overall, the GP 5236 resin system had a lower yield stress per gram of resin adsorbed than the NH_3 model system, but it retained a greater amount of resin per dip. In fact, the GP 5236 resin picked up 1.3 to 2.0 times more resin per dip when compared to the model NH_3 resin system as shown in Figure 6.

Differences in polymer-solvent interactions and/or differences in rheological properties may explain the different resin retention behaviors shown in Figure 6. However, previous thermogravimetric experiments coupled with gas chromatography and mass spectrometry analyses have shown that basic chemistries of the two dip resins are quite similar.[8] The similar polymer chemistries suggest that the two polymers most likely have very similar solubility parameters and polymer/solvent interactions. Rheological dissimilarities are most likely responsible for the behavior observed in Figure 6. Although determining which rheological variables make the greatest contribution to resin retention is difficult. Differences in surface tension, surface wetting, viscosity, and spreading pressure can account for the increased resin retention, but when time, temperature, surface area and changing chemical structure effects are taken into consideration, identifying the individual effects of these variable becomes extremely difficult.

Correlation of Honeycomb Scaling Factor

Although the significant surface and rheological properties which control the ultimate deposition and behavior of the dip resin are not well understood, a scaling relationship can still be established between the compressive properties of small scale honeycomb rings and honeycomb core.

In reexamining Equation 3, it is possible to factor the geometric end constraint factor into in three dimensionless terms consisting of constant material properties, variable material properties and critical buckling stresses. The first bracketed group to the right of the equal sign in Equation 3 represents the constant material properties of the core and rings. This quotient contains the cell angle, Poission's ratio and the cell wall lengths. These material and geometric properties were not varied and can be considered constant for the experiments conducted. The second bracketed term represents the variable, or scalable, material properties of the rings and core. The ring thickness, honeycomb cell wall thickness, and to some extent the single cell wall length changed depending on the number of times a specific specimen was dipped. This dimensionless group of variables, $(t_R\, l^3)/(r\, t_H^3)$, can be redefined as a honeycomb scaling factor. The last dimensionless group on the right hand side of Equation 3 is simply the ratio of the critical yield stresses.

If the dimensionless groups of Equation 3 are rearranged, the ring buckling stress can be shown to be a direct function of these dimensionless groups and the honeycomb yield stress. In Figure 7, the experimental ring and honeycomb yield stresses are plotted against each other. From this plot, a linear correlation (correlation coefficient of 0.98) can be established between the two yield stresses. Theoretically, this line should pass through the origin, but due to experimental error the correlation intercepted the ordinate at 0.2 MPa, as shown in Figure 7. The slope of the line is the product of the honeycomb scaling factor, the constant material properties and the reciprocal of the geometric end constraint factor. Because of the linear fit and the invariant nature of the constant material properties, the quotient of the honeycomb scaling factor and the geometric end constraint factor must also be constant. It has been shown in Figure 1 that above and below 10 dips

the geometric end constraint factor can be described with two constant numbers. If the geometric end constraint factor is constant over these ranges then the honeycomb scaling factor must also be constant over these ranges. Ultimately from Figure 7, it can be concluded that the scalability of the honeycomb rings and honeycomb core must be directly dependent upon the honeycomb scaling factor itself.

CONCLUSIONS

In this study, the compressive properties of honeycomb rings and honeycomb cores were scaled linked using stability mechanics. A honeycomb scaling factor and a geometric end constraint factor were used to correlate the relative yield stress of honeycomb rings and core specimens with the physical dimensions and properties of the honeycomb materials. In these relationships, the geometric end constraint factor described the ability of the cell wall to move and rotate during compression. In correlating the compressive properties of honeycomb cores and honeycomb rings, two end constraint factors were required to accurately describe the behavior of the core. At low dip numbers, the walls were found to be simply supported at the edges during compression. However, for the higher density cores, the effective cell wall length for buckling was found to decrease due to resin accumulation in the node fillet. This reduction in effective cell wall length subsequently changed the end constraint factor needed to describe the compression behavior at high dip numbers. The compression properties of the honeycomb rings was also extended to evaluate the compressive properties of a model and commercial phenolic honeycomb dip resin. Honeycomb rings manufactured from the model dip resin system were found to have higher compressive properties. These properties were attributed to the higher fracture toughness of the dip resin rather than higher flexural properties. Lastly, a honeycomb scaling factor was defined and was shown to directly influence the scalability of honeycomb ring to honeycomb core. Ultimately, this research can be applied to the development and innovation of new honeycomb webs and dip resins.

REFERENCES

1. T. Bitzer, *Honeycomb Technology - Materials, Design, Manufacturing, Applications and Testing*, London, Chapman & Hall, (1997).

2. A. Marshall, *Sandwich construction*, in *Handbook of Composites*, G. Lubin, ed., New York, Van Nostrand, (1982).

3. L. J. Gibson and M. F. Ashby, *Cellular Solids: Structure and Properties*, Cambridge, Cambridge University, (1997).

4. J. E. Shafizadeh and J. C. Seferis, editors, *Perception of Technological Innovation, Development and Transfer (Team Certificate Program Final Report)*, Seattle, University of Washington, (1998).

5. J. Zhang and M. F. Ashby, *The out-of-plane properties of honeycombs*, International Journal of Mechanical Science, **34**(6), p. 475-489, (1992).

6. J. Zhang and M. F. Ashby, *Buckling of honeycomb under in-plane biaxial stresses*, International Journal of Mechanical Science, **34**(6), p. 491-509, (1992).

7. S. P. Timoshenko and J. M. Gere, *Theory of Elastic Stability*, New York, McGraw Hill, (1961).

8. J. E. Shafizadeh, S. Guionnet, M. S. Tillman, and J. C. Seferis, *Synthesis and characterization of phenolic resole resins for composite applications*, Journal of Applied Polymer Science, **73**, p. 505-514, (1999).

9. J. M. Whitney, *Interlaminar response of composite materials*, in *Composite Material Series*, N.J. Pagano, ed., New York, Elsevier, (1989).

10. L. A. Pilato and M. J. Michno, *Advanced Composite Materials*, Berlin, Springer-Verlag, (1994).

11. G. C. Sih and A. M. Skudra, *Failure Mechanics of Composites*, New York, Elsevier, (1985).

12. J. E. Shafizadeh and J. C. Seferis, *High temperature thermal analysis characterization of honeycomb core*, Polymer Engineering and Science, **39**(4), (1999).

13. P. K. Mallick, *Fiber Reinforced Composites*, New York, (1993).